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The Global Wheat Improvement System:

Prospects for Enhancing Efficiency in the Presence of Spillovers

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Abstract: Through global analysis and country-level case studies, this report analyzes the efficiency of investments in wheat improvement research at a disaggregated level and explores a range of options for restructuring research programs to enhance efficiency. Particular attention is devoted to evaluating "spillovers" (i.e., benefits which flow from one program to another) that result from large research systems with the potential to exploit economies of size and scope. The impacts of such spillovers on both research productivity and research strategy are explored, as are the relative roles of international agricultural research centers (IARCs) and national agricultural research systems (NARS) in generating technology. The homogeneity of agroecological environments across developing countries is clarified and a megaenvironment classification system is described. The authors address the question of whether research managers should suppress genotype-by-environment (GxE) interactions and develop widely adapted varieties or exploit GxE interactions and develop specifically adapted varieties. Econometric evidence is presented to suggest that broadly adapted varieties may be more robust and create greater spillovers than has previously been reported. Research costs and intensities in developing countries are shown to be of the same magnitude or higher than in industrialized countries because the former have a large number of scientists per research program combined with a smaller mandate area for each program. Evidence suggests that many countries or regions within a country are investing more than is economically justifiable in wheat improvement research, either because of the small size of their mandate area or because they could capture research spillins at lower costs-or, more commonly, both. A cost-benefit framework is used to assess the threshold levels of wheat production in a mandate region required to justify a breeding program rather than a testing program. The results indicate that many research programs could significantly increase their efficiency by reducing their research programs and screening varieties developed elsewhere. A case study from India reveals that investment inefficiencies at the sub-national level have frequently been underestimated and that large nationally mandated programs have a comparative advantage in generating successful technologies across wide areas. A case study of Australia clarifies the role of spillovers in industrialized countries. The report has important implications at the conceptual level in the methods used for research evaluation and at the policy level for decisions on crop improvement research.

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Preface

With the advent of the Green Revolution in the mid-1960s, a truly global wheat improvement system was born. Since that time, a growing number of international, regional, and national wheat improvement organizations have continued to collaborate on research that has made unprecedented contributions to human welfare.

In recent years, as resources for research have become increasingly scarce, partners in the international wheat improvement system and the development community have become more concerned with evaluating the efficiency and impact of their research. These evaluations have generally focused on individual partners in the system.

The scope of this report is wider. It synthesizes the findings of research conducted over several years on various aspects of the international wheat improvement system. The report gives particular attention to the system's potential to generate spillovers and the implications for improving the efficiency of the research system. (Spillovers are products—in this instance, usually wheat varieties—that are useful in several geographical areas or in areas other than those for which they were originally developed.) Among its many contributions, this report:

- provides an overview of the resources invested in wheat improvement research, at the national and international levels;
- outlines how diverse research programs contribute to and benefit from the international wheat improvement system;
- summarizes the system's achievements;
- develops a conceptual framework for evaluating the efficiency of crop improvement research, taking spillovers into account; and
- offers new information for policy decisions on investment in national and international crop improvement research—again taking spillovers into account.

We believe that this report provides a strong endorsement of the collaboration between national research organizations, CIMMYT, and other partners in the international wheat improvement system, and we would like to draw readers' attention to some of the findings.

First, the authors estimate that the return on investments in spring wheat breeding research in the "post-Green Revolution era"—the years since the first large impacts of the Green Revolution were made—has exceeded 50%. They project that the international wheat breeding system will provide a return on future investments of 37–48%.

Second, efficiency indicators suggest that the international system is a low-cost producer of improved germplasm. There are considerable economies of size and specialization in wheat breeding research. These economies result from the geographic aggregation of crossing and early selection activities by CIMMYT and from collaboration by CIMMYT and national programs in testing and evaluating new varieties.

Third, the authors report that there is a strong complementarity between CIMMYT and national-level investments in wheat improvement research. Support for CIMMYT's two main activities—producing widely adapted varieties and coordinating the global network for testing and distributing germplasm—enhances the effectiveness of national crop improvement programs at all levels of sophistication.

Finally, the report discusses the challenges that the international wheat improvement system can expect to face in the future. Despite dwindling resources, the system will need the flexibility to serve many smaller national programs, which require finished research products, while investing in strategic research to provide intermediate products, especially for larger national programs. The authors observe that CIMMYT and national research programs have sought to meet this challenge by developing various types of partnerships within the context of the international system.

We at CIMMYT know that the world still has an acute need for the products of the international wheat improvement system. We value the information presented in this report, because it helps to clarify global issues related to one of our most important activities, wheat improvement research. We expect this report to become an essential reference for researchers and policy makers who are concerned with these issues.

Timothy Reeves

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Director General

Executive Summary

1. Introduction

Despite the evidence of high productivity and profitable returns, international agricultural research centers (IARCs) and many national agricultural research systems (NARS) are facing reduced budgetary support. Such reductions suggest that research efficiency and resource allocations need to be reexamined if agricultural research is to remain effective.

Since 1990, the International Maize and Wheat Improvement Center (CIMMYT) has funded various studies on investments, impacts, and "spillovers" (i.e., benefits that flow from one program to another) related to wheat improvement research. This report builds on that work by analyzing the efficiency of research investments at a disaggregated level and exploring the range of options for restructuring wheat research programs to enhance efficiency. Particular attention is focused on the number, size, scope, type, and location of research programs, as well as on the relative roles of IARCs and NARS in generating technology. Through global analysis and national case studies, this report suggests that specialization in wheat research creates spillovers that can improve research efficiency worldwide.

2. Realizing Research Spillovers and Economies of Size from Market Aggregation

Biological technologies are often assumed to be location specific. Decentralized research programs that target specific environments and market niches are thus thought to have a comparative advantage in developing finished products. Because the boundaries of environments and markets rarely coincide with political borders, however, there is a strong case for establishing centralized agricultural research programs to generate technologies that are widely applicable for given environments across political borders—states, regions, or countries.

The conventional wisdom about location specificity arose from attempts to transfer finished technologies from temperate areas in industrialized countries to subtropical and tropical areas in developing countries. Across developing countries, however, there is considerable agroecological similarity. As national research systems have developed, the potential for direct and indirect spillovers across the developing world has increased significantly.

Likewise, little attention has been given to potential economies or diseconomies of size and scope in agricultural research. *Economies of size* imply that the unit cost of research decreases as the size of the research effort dedicated to a specific activity increases. *Economies of scope* imply that the unit cost of research decreases when input and overhead costs are shared across related activities. For specialized agricultural research, the overhead cost of experiment stations, libraries, and laboratories can be considerable.

The potential for generating spillovers and exploiting economies of size and scope provides a strong rationale for aggregated research systems. Such research might be organized in a variety of ways, including national and international specialized breeding centers, networks, regional associations, or the private sector. The emergence of multinational private seed firms is one example of the underlying efficiency of centralized varietal improvement research.

3. Wheat Breeding Environments: A Conceptual and Empirical Analysis

To help national and international research systems determine their comparative advantages, economists must quantify costs and spillovers for different types of research and program sizes. Crucial to such determinations is an understanding of the agroecological environments for which breeders develop specific genotypes.

Agroecological similarities across developing countries allow crop environments to be aggregated into "megaenvironments" (MEs) for the purpose of breeding research. An ME is a broad (but not necessarily contiguous) area, usually international and frequently transcontinental. Each ME is defined in terms of similar biotic and abiotic stresses, cropping system requirements, and consumer preferences. Market size greatly influences net returns to research. Production levels across wheat MEs vary from 2.0 million to 105.5 million tons. Global research, such as that conducted by an IARC, would thus favor large environments to take advantage of economies of market size. An IARC or a national program could be an important source of direct spillins (i.e., benefits received from another program) for small environments that occur in many countries.

"Environmental distance" is another important consideration, particularly as it affects the value-added of establishing a research program targeted at a specific environment. This phrase describes the extent to which agroclimatic differences between two locations affect a genotype's ability to adapt to these locations; it describes differences in adaptation (i.e., plant response) rather than absolute agroclimatic differences. Thus a "low rainfall" location may not be environmentally distant from a "high rainfall" location if the relative performance of a set of genotypes is similar in each environment.

In designing a crop improvement program, research managers face a fundamental decision: Should they *suppress* genotype-by-environment (GxE) interactions by developing varieties that can be released in all the environments in the target domain (widely adapted) or should they *exploit* GxE interactions and develop varieties that meet the specific needs of each environment in the domain (specifically adapted)?

The empirical estimation of yield curves demonstrates that widely adapted varieties can often yield more than specifically adapted varieties. One explanation for this outcome is that annual variations in climate often blur environmental differences. By making decisions to accommodate a predetermined environmental boundary, research managers may select varieties adapted to an *average* growing season at *one location* within that environment. However, a program that develops broadly adapted germplasm is likely to produce varieties that perform well under *divergent* seasonal conditions at a *given location* within the environment.

4. Assessing Potential International Transferability of Wheat Varieties

The empirical, quantitative estimates of potential spillovers presented in this report focus on the following question: Do varieties developed for a specific target environment outyield varieties developed for other environments or varieties developed by the international system? In the past, such assessments have been based on subjective guesses. To answer these questions, an econometric model was developed to analyze international yield trial data over many years and locations, as well as national yield trial data for two countries. Three major results emerged from this analysis:

- Wheat varieties developed by other NARS in the same megaenvironment performed significantly better than varieties developed in different megaenvironments, indicating the robustness of the megaenvironment concept.
- Wheat varieties developed by CIMMYT in collaboration with NARS perform well across many megaenvironments. Within irrigated and high rainfall MEs, the yield advantage of varieties developed by this CIMMYT-NARS collaboration was as high as 11 and 13%, respectively. In other MEs, the yields of CIMMYT-developed varieties were not significantly different from locally developed varieties.
- National yield trial data confirm the superiority of CIMMYT-origin varieties in many MEs, especially irrigated and high-rainfed MEs. The analysis offers little evidence of substantial yield gains for those countries whose breeding program develops new varieties targeted to specific environments.

In the age of shrinking budgets, these results suggest that efficient national programs should take advantage of research spillins—not only from NARS in similar environments, but also from regional and international systems.

5. Investment in Wheat Improvement in Developing Countries

An overview of the resources invested in wheat improvement research, both at the national and the international levels, underscores the potential importance of exploiting research spillins to enhance research efficiency. Since the 1960s, wheat improvement research has attracted considerable resources, measured in number of scientists and size of budgets. By the early 1990s, developing countries employed more than 1,200 scientists and spent more than US$ 100 million on wheat improvement research.

Many developing countries that are small wheat producers have established research programs that are quite large in relation to their mandate areas. Even developing countries that are large wheat producers may support programs that have small mandate regions (such as a state that produces little wheat) or that have overlapping mandate areas. Overall, a typical wheat improvement program in a developing country employs more researchers per million tons of wheat and spends more on wheat research per ton of wheat produced than do comparable programs in industrialized countries.

This comparative analysis leads to a clear conclusion: Research costs and intensities are higher in developing countries because they have a larger number of scientists per research program combined with a smaller mandate area for each program. Many national programs, particularly in small wheat producing countries, spend more than 1% of the value of wheat production on wheat improvement research (although research intensity for large producers, such as India and China, is very low).

6. Estimation of Actual Spillovers of National and International Wheat Improvement Research

Analyzing the resources employed by—and the output and spillovers generated by—the international system of spring wheat improvement highlights the role of IARC-generated technology in the post-Green Revolution era. Varieties with some CIMMYT parentage dominate developing country wheat production. Nearly twice as much area was sown to directly transferred CIMMYT wheat varieties in 1990 as at the height of the Green Revolution, and two-thirds of all spring wheat area is sown to either direct or adaptive varieties.

Ex-post analysis of investments in wheat improvement research during the post-Green Revolution era indicates a rate of return above 50%, and we project that the system will provide a return on future investments of between 37 and 48%. A strong complementarity exists between CIMMYT and NARS investments in wheat improvement research at present. Increased financial support for CIMMYT's two main activities—producing widely adapted varieties and coordinating the global nursery network for testing and distributing germplasm—is likely to enhance the effectiveness of NARS crop improvement programs of all levels of sophistication. Small NARS depend *relatively* more on direct spillins from the international research system, but large NARS reap the largest *absolute* gains from the system.

The prospects for technical change are similarly improved as NARS expand their capacity to capture spillovers by adapting or efficiently screening CIMMYT varieties. Given the international system's ability to serve a diverse range of NARS by generating both direct and indirect spillovers, NARS research and CIMMYT research are not likely to become substitute investments in the foreseeable future.

7. Measure of Technical Efficiency of National and International Wheat Research Systems

The international wheat research system is truly a collaborative effort: Developing country NARS in aggregate spend more than CIMMYT (75% of the total research expenditures) to screen, test, evaluate, and release varieties based on CIMMYT crosses. By contributing both human and financial resources, NARS play a major role in realizing benefits generated by the international system.

Various efficiency indicators suggest that this collaborative CIMMYT-NARS system is a low-cost producer of improved germplasm. In general, the research output of this international system per unit of input is higher than the NARS system's average on all efficiency indicators, except for the cost per hectare adopted in the largest NARS (such as India). Costs per unit of output are strongly related to the national wheat area—NARS with a small wheat area have the highest costs. These results also suggest that there are considerable economies of size and specialization in wheat breeding research. These economies result from the geographic aggregation of the crossing and early generation selection activities by CIMMYT and the division of labor in varietal testing and evaluation between CIMMYT and NARS.

In a world without political boundaries, efficiency would improve considerably by having one or a few centralized breeding programs linked to small testing programs located at key sites. Although we do not inhabit such a world, the efficiency of the present system can still be improved considerably by consolidating and rationalizing many existing programs and by improving regional and international collaboration.

8. Economic Efficiency of Wheat Improvement Research Investments in the Presence of Spillins

To help assess the efficiency of investments by NARS in light of potential spillins, we develop a cost-benefit framework to determine the threshold levels of wheat production in a mandate region required to justify a breeding program and a testing program with different levels of spillins. This framework is used to analyze the efficiency of investments in 69 spring wheat improvement programs in 35 developing countries and of investments in the joint CIMMYT-NARS international collaborative system.

The results show that, given the magnitude of potential spillins from the international research system, many wheat research programs could significantly increase their efficiency by reducing their research programs and focusing on the screening of varieties developed elsewhere. At the global level, the joint CIMMYT-NARS investment in directly transferable wheat technology is shown to be efficient in almost all of the spring wheat MEs. More specifically our results reveal the following:

- Under a baseline scenario in which only other NARS are the potential sources of spillins, investments in a national-level adaptive breeding program, while earning good rates of return, are less profitable than testing-program investments unless the varieties produced account for more than 100,000 t of wheat in the region.
- Under a scenario in which CIMMYT is a potential source of research spillins, it becomes very difficult to justify a local adaptive breeding program based on yield benefits alone in most important MEs of the developing world: a production level of at least 275,000 t and an internal rate of return of 38% are needed.
- When the cost-benefit framework is used to project ex-ante the net present value of current levels of investment devoted to wheat improvement research, 28 of the 69 developing country research programs we evaluated would be over-investing in wheat improvement research if empirical evidence of research spillins from the international system were taken into account.

The study therefore underscores the importance of incorporating estimates of direct spillins in the economic evaluation of research programs.

9. A Case Study in India

India has one of the largest and most successful wheat research programs in the world. Nonetheless, growth in public funding for agricultural research in India has slowed in recent years, and there is increasing concern about research duplication and overstaffing.

Those concerns are addressed here with a framework that computes the internal rate of return on investments at a very disaggregated level: With over 20 research programs (defined by agroecological zone, environment, and species) spread across 50 research institutes, the Indian wheat improvement research system resembles the international research system in many respects. Thus, many of the issues and concepts discussed above are also relevant in analyzing the efficiency of a large national research system. Several important findings are reinforced by this case study:

- On aggregate, investment in wheat improvement research in India has produced high returns, averaging 51%.
- The nationally mandated research programs of the Indian Agricultural Research Institute (IARI) appear to have a comparative advantage in generating successful technologies across many environments. In three of India's five zones, the varieties developed by IARI occupied more area than the varieties developed by centers targeting only that zone.
- Spillover benefits were dominant characteristics of technical change at the national level, similar to that observed at the international level.

- IARI's research programs and those serving the Northwest Plains Zone generated 75% of all benefits but absorbed only one-quarter of resources invested. The pattern of spillins appears to have been stable over time (i.e., there has been little switching in status from "technology borrowers" to "technology generators"). The elimination or redesign of weak institutes in these programs would therefore appear to present relatively little risk of reducing the overall rate of technical change and at the same time would enhance efficiency.

These results have two broad implications for studying of rates of return at a country level:

- High aggregate rates of return can hide considerable heterogeneity in the performance of research programs that make up the overall effort.
- Rates of return are quite sensitive to whether spillins from other programs are explicitly incorporated. Most studies in the past have ignored such spillins and have thus biased rates of return to research.

Together these results imply that many previous evaluations of investment in agricultural research have underestimated the extent of investment inefficiencies at the sub-national level.

10. A Case Study in Australia

Although the bulk of this report focuses on wheat breeding in developing countries, concerns about resource allocation, research spillovers, and research efficiency are being raised in industrialized countries as well. Australia has devoted considerable resources to wheat improvement, employing more than 100 FTE researchers in a number of cooperative public-sector programs. Research spillovers from other countries—and especially from CIMMYT—have been extremely important.

As a result of funding pressure, Australia now faces important changes with implications for the structure and mix of public and private wheat breeding efforts. While there is little scope for immediate privatization of Australia's wheat breeding programs, there is considerable scope to increase the cost-recovery of public programs.

The impact of Australian wheat breeding efforts has been substantial. An economic analysis of a representative Australian breeding program found an internal rate of return to research investments in the order of 19%. Over the last three decades, all the major wheat producing states have had a regular flow of new varieties, averaging 0.63 varieties each year per million hectares of wheat planted. In the 20 years since their first release, semidwarf wheats have contributed an upward shift in wheat yields of 5.3% on average over what they would have been.

Over the past 20 years, spillovers from CIMMYT to Australia have been significant. However, Australian breeders are currently making less use of CIMMYT material than in the past, largely because of perceived problems with the grain quality of more recent breeding materials. Nevertheless, it seems likely that Australian breeders will continue to obtain benefits from the CIMMYT material. Recent developments in information technology allow breeders to target particular characteristics in the wide range of CIMMYT material; consequently, Australian wheat industry should continue to obtain spillover benefits.

11. Implications: Toward Efficient Allocation of Resources in the Presence of Spillovers

This report has important implications at both the *conceptual level*, in methods used for research evaluation, and at the *policy level*, for decisions on investment in crop improvement research.

Implications for Economic Analysis

Spillovers have been widely recognized in the literature on agricultural research and development (R&D), but rarely have they been incorporated into the economic analysis of research investments. Benefits occurring in a particular area are usually attributed to research conducted in that area. Given that spillovers are pervasive in agricultural R&D, the result is clear: estimates of returns on investment have been biased. Because spillovers tend to flow from large regions and from central research programs, the failure to assess spillovers has inflated estimates of returns to research in smaller regions and underestimated returns in larger programs.

Ex-ante assessments of research efficiency must take spillovers into account. And economists must ask: Given the *potential for spillins*, what is the value added from establishing a full breeding program locally as compared to a testing program that screens imported materials?

On this basis, many wheat breeding programs evaluated in this study are producing low or negative benefits *at the margin*. Most of the inefficient programs serve relatively small mandate areas, so economies of market size are a key determinant of efficiency. Moreover, many of the inefficient programs had a relatively high *average* rate of return on investment; they were inefficient because they gave lower net present values than would a smaller program that tested and screened technologies. In other words, the average rate of return for an individual program is an inappropriate guide for research investment decisions in the presence of spillins because it does not measure the marginal return from changing the size of program.

This assessment runs contrary to previous analyses and conventional practices: Research spillovers are usually assumed to be indirect (e.g., exchange of germplasm for parent materials and exchange of breeding methods and scientific information) and hence have been modeled to shift upward the research production function of other research programs. The theoretical argument for under-investment in agricultural research is based on this basic premise. However, as shown by this study, research spillins will not only affect *research productivity* but also the choice of the research *strategy* (i.e., the type of research program to establish).

Implications for Designing National Research Programs

Spillin potential should be explicitly considered in the design of national research programs. Exploiting economies of *market size* is critical to enhancing the efficiency of research investments. Public research programs established on the basis of political rather then natural boundaries are likely to serve markets of less-than-optimal size.

Institutional mechanisms that facilitate both two-way and one-way flows of technology must be encouraged to facilitate spillins and spillovers.

- Formal and informal research networks are the most common means of facilitating two-way flows. These networks usually involve national or international performance trials that allow varietal technologies from different origins to be tested in many locations; the networks also give breeders access to a wide range of new varieties for local screening. In some cases these networks are more formal, involving joint decisions on trial entries and coordination of research (e.g., national coordinated programs for major crops). Internationally, a similar function is performed by germplasm testing nurseries run by the IARCs, as well as a variety of specialized research networks. With the growing complexity of science and the reduced cost of international cooperation due to the Internet, other collaborative research mechanisms—such as regional consortia and biotechnology networks involving both the private and public sectors—are being established to facilitate spillins and reduce research costs.

- One-way flows of spillovers result from the efforts of public research programs to solve the problem of market size and economies of size by creating centralized research facilities at the national, regional, or international level for the sole purpose of generating spillovers. Most large countries have a federal-state system, in which the federal component is meant to conduct research with significant economies of size and potential for wide spillovers. However, in most cases, the roles of the federal and state research systems have not been well defined, a fact which leads to overlaps and redundancies. In recent years, the trend has been toward regional research associations among neighboring countries, although it is not yet clear that NARS have reduced their nationally targeted effort to complement the rise in regional programs and realize the potential efficiency gains.

But full exploitation of spillovers involves risk. A region or country that designs a research program to exploit spillins assumes a continuing and free supply of spillins and thus exposes itself to fluctuations in the productivity and priorities of the spillover-generating institutions. In addition, the free flow of technologies is at risk with the increasing use of intellectual property rights to protect research products, even in the public sector. Dependence on a few centralized research programs may also create technological risks, such as genetic uniformity.

Finally, the success of the IARCs in varietal development indicates that they are low-cost producers of finished germplasm products and that they have a *competitive* advantage in research on applied plant breeding. However, this does not establish their *comparative* advantage in this type of applied research. As for other central research organizations designed to produce one-way spillovers, the comparative advantage is likely to occur more in basic and strategic research that builds on their unique access to international germplasm collections and advances in science to provide intermediate research products that shift upward the research production function for national programs to produce finished varieties.

In practice the IARCs tend to invest a relatively small share of their resources in this type of pre-breeding research even though the potential payoffs are high. The challenge is how to serve the needs of many small NARS for finished products while investing in strategic research to provide intermediate products, especially for large NARS. Since many large NARS were also shown in this study to be low-cost producers of finished products (in some cases lower than CIMMYT), some type of sub-contractual arrangement may be needed with these NARS to ensure a balanced supply of international public goods to NARS of all types—both finished products and intermediate products. To some extent, the various types of partnership, collaborative, and shuttle breeding programs used by CIMMYT reflect this orientation. The rise of regional networks should also provide an alternative source of research products.

Resumen

1. Introducción

A pesar de su gran productividad y rentabilidad comprobadas, los centros internacionales de investigación agrícola (IARC) y muchos sistemas nacionales de investigación agricola (NARS) afrontan reducciones presupuestarias. Esas reducciones indican que es preciso volver a examinar la eficiencia de la investigación y la asignación de los recursos si se desea que siga siendo provechosa la investigación agrícola.

Desde 1990, el Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) ha patrocinado diversos estudios sobre las inversiones, los efectos y los "beneficios derivados" (es decir, beneficios que pasan de un programa a otro) relacionados con el mejoramiento fitotécnico del trigo. Este informe se basa en esa labor: analiza mediante un desglose la eficiencia de las inversiones en investigación y explora la gama de opciones para reestructurar los programas de investigación de trigo con el fin de aumentar su eficiencia. Se dedica particular atención al número, el tamaño, el alcance, el tipo y la localización de los programas de investigación, así como a las funciones de los IARC y los NARS en la generación de tecnología. Con base en el análisis a nivel mundial y los estudios de casos en los países, este informe señala que la especialización en la investigación de trigo crea beneficios derivados que pueden mejorar la eficiencia de la investigación en todo el mundo.

2. Concretar los beneficios derivados de la investigación y las economías de tamaño resultantes de la concentración de mercados

Se suele dar por sentado que las tecnologías biológicas son específicas para el lugar. Por esa razón, se considera que los programas descentralizados de investigación orientados a ambientes específicos y a ciertos nichos del mercado tienen una ventaja comparativa en la generación de productos terminados. No obstante, como los límites de los ambientes y los mercados rara vez coinciden con las fronteras políticas, hay razones convincentes para establecer programas centralizados de investigación agrícola con el fin de generar tecnologías ampliamente aplicables en determinados ambientes más allá de las fronteras políticas: estados, regiones o países.

La idea tradicional de la especificidad para el lugar surgió de los intentos de transferir tecnologías terminadas desde zonas templadas en los países industrializados a zonas tropicales y subtropicales de los países en desarrollo. Sin embargo, en los países en desarrollo existe una gran similitud agroecológica. A medida que se han desarrollado los sistemas nacionales de investigación, la posibilidad de que fluyan beneficios derivados directos e indirectos por todo el mundo en desarrollo ha crecido de manera considerable.

Por otra parte, se ha prestado poca atención a las posibles economías o deseconomías de tamaño y alcance en la investigación agrícola. En las *economías de tamaño*, el costo unitario de la investigación disminuye a medida que aumenta la magnitud del esfuerzo de investigación dedicado a una actividad específica. En las *economías de alcance,* el costo unitario de la investigación disminuye cuando se comparten los insumos y los costos generales entre actividades relacionadas. En el caso de la investigación agrícola especializada, pueden ser considerables los costos generales de las estaciones experimentales, las bibliotecas y los laboratorios.

El hecho de que se pueden generar beneficios derivados y explotar economías de tamaño y alcance constituye un argumento sólido a favor de la concentración de los sistemas de investigación. Esa investigación se podría organizar en diversas formas, por ejemplo mediante centros fitotécnicos especializados nacionales e internacionales, redes, asociaciones regionales o el sector privado. La aparición de empresas multinacionales productoras de semilla es un ejemplo de la eficiencia implícita en la investigación centralizada para el mejoramiento de variedades.

3. Los ambientes donde se mejora el trigo: Análisis conceptual y empírico

Para ayudar a los sistemas nacionales e internacionales de investigación a determinar sus ventajas comparativas, los economistas deben cuantificar los costos y los beneficios derivados de distintos tipos de investigación y de programas de diversos tamaños. Es esencial para esa determinación conocer los ambientes agroecológicos para los cuales los fitogenetistas desarrollan genotipos específicos.

Las similitudes agroecológicas entre los distintos países en desarrollo permiten reunir los ambientes de cultivo en "mega–ambientes" (ME) para los propósitos del fitomejoramiento. Un ME abarca zonas extensas (pero no necesariamente contiguas), por lo general internacionales y con frecuencia transcontinentales. Cada ME se define en función de la semejanza de los factores bióticos y abióticos desfavorables, las necesidades de los sistemas agrícolas y las preferencias de los consumidores. El tamaño del mercado influye mucho en la rentabilidad neta de la investigación. Los niveles de producción en los distintos ME de trigo varían entre los 2.0 millones y 105.5 millones de toneladas. En consecuencia, las investigaciones a nivel mundial, como las efectuadas por un IARC, favorecerán a ambientes extensos y aprovecharán las economías de tamaño del mercado. Un IARC o un programa nacional podría ser una importante fuente de beneficios colaterales directos (es decir, beneficios recibidos de otros programas) para ambientes pequeños en muchos países.

La "distancia ambiental" es otra consideración importante, en particular porque afecta el valor agregado resultante de establecer un programa de investigación orientado a un ambiente específico. Ese término indica la medida en que las diferencias agroclimáticas entre dos sitios afectan la capacidad de un genotipo de adaptarse a esos sitios; describe las diferencias en la adaptación (es decir, la respuesta de la planta), más que diferencias agroclimáticas absolutas. En consecuencia, un sitio con "escasa precipitación" tal vez no esté distante desde el punto de vista ambiental de un sitio con "elevada precipitación" si el comportamiento de un conjunto de genotipos es similar en ambos ambientes.

Al diseñar un programa fitotécnico, los directores de la investigación afrontan una decisión fundamental: ¿deben *suprimir* las interacciones genotipo por ambiente (GxE) desarrollando variedades que puedan ser lanzadas en todos los ambientes del territorio beneficiario (es decir, que tienen adaptación amplia) o deben *explotar* las interacciones GxE y desarrollar variedades que satisfagan las necesidades particulares de cada ambiente en el territorio (es decir, que poseen adaptación específica)?

La estimación empírica de las curvas de rendimiento demuestra que las variedades con adaptación amplia a menudo tienen un rendimiento mayor que el de las variedades específicamente adaptadas. Una explicación de este resultado es que las variaciones anuales en el clima a menudo opacan las diferencias ambientales. Al tomar decisiones conforme a un límite ambiental predeterminado, los directores de la investigación tal vez seleccionen variedades adaptadas a un ciclo *medio* de cultivo en *un solo* sitio dentro de ese ambiente. Sin embargo, es probable que un programa que desarrolla germoplasma con adaptación amplia produzca variedades que tienen un buen comportamiento en condiciones estacionales *divergentes* en un *sitio determinado* dentro del ambiente.

4. Evaluación de la transferibilidad de las variedades de trigo

Las estimaciones cuantitativas empíricas de los posibles beneficios derivados que se presentan en este informe se basan en la siguiente pregunta: Las variedades desarrolladas para un ambiente específico, ¿tienen un rendimiento superior al de las variedades generadas para otros ambientes o al de las variedades desarrolladas por el sistema internacional? En el pasado, las evaluaciones de ese tipo se han basado en conjeturas subjetivas. En este caso, para responder a esa pregunta se elaboró un modelo econométrico con el fin de analizar los datos de los ensayos internacionales de rendimiento en muchos años y localidades, así como los datos de ensayos nacionales de rendimiento en dos países. A partir de este análisis se llegó a tres resultados importantes:

- Las variedades de trigo desarrolladas por otros NARS en el mismo mega–ambientes tuvieron un comportamiento considerablemente mejor en un sitio dado que el de las variedades generadas en mega–ambientes diferentes, lo cual indica la legitimidad del concepto de mega–ambientes.
- Las variedades de trigo desarrolladas por el CIMMYT en colaboración con los NARS tienen un buen comportamiento en muchos mega–ambientes diferentes. Dentro de los ME con riego o precipitación elevada, la ventaja de rendimiento de las variedades generadas mediante esta colaboración llegó a 11% y 13%, respectivamente. En otros ME, los rendimientos de las variedades generadas por el CIMMYT no fueron considerablemente diferentes de los de las variedades desarrolladas en el lugar.
- Los datos de los ensayos nacionales de rendimiento confirman la superioridad de las variedades generadas por el CIMMYT en muchos ME, especialmente en los irrigados o con precipitación elevada. El análisis ofrece pocas pruebas de aumentos sustanciales de rendimiento en los países cuyos programas de mejoramiento desarrollan variedades nuevas destinadas a ambientes específicos.

En una época de presupuestos cada vez más exiguos, estos resultados indican que para ser eficientes, los programas nacionales deben aprovechar los beneficios provenientes de otras investigaciones, no sólo las realizadas por los NARS en ambientes similares sino también las efectuadas por los sistemas regionales e internacionales.

5. La inversión en el mejoramiento de trigo en los países en desarrollo

Un examen general de los recursos invertidos en el mejoramiento de trigo a nivel tanto nacional como internacional subraya la importancia de explotar los beneficios provenientes de otras investigaciones para aumentar la eficiencia de la propia investigación. Desde los años 60, el mejoramiento de trigo ha atraído recursos considerables en términos del número de científicos y la magnitud de los presupuestos. Para comienzos de los años 90, los países en desarrollo empleaban más de 1,200 científicos y gastaban más de 100 millones de dólares estadounidenses en el mejoramiento de trigo.

Muchos países en desarrollo que son pequeños productores de trigo han establecido programas de investigación bastante grandes en relación con los territorios que abarcan. Asimismo, algunos países en desarrollo que son grandes productores de trigo patrocinan programas que abarcan regiones pequeñas (como un estado que produce poco trigo) o que incluyen áreas que se traslapan. En general, un típico programa de mejoramiento de trigo en un país en desarrollo emplea más investigadores por millón de toneladas de trigo y gasta más en investigación de trigo por tonelada producida que programas similares en los países industrializados.

Este análisis comparativo lleva a una conclusión evidente: los costos y la intensidad de la investigación son más altos en los países en desarrollo porque tienen un mayor número de científicos por programa de investigación y una superficie beneficiaria más pequeña para cada programa. Muchos programas nacionales, en particular en los países pequeños productores de trigo, gastan más del 1% de la producción en el mejoramiento de trigo (sin embargo, la intensidad de investigación de los grandes productores, como la India y China, es muy baja).

6. Estimación de los beneficios derivados reales de la investigación nacional e internacional

El análisis de los recursos empleados —y los resultados y beneficios derivados obtenidos— por el sistema internacional de mejoramiento de trigo de primavera destaca la función de la tecnología generada por los IARC en el período posterior a la Revolución Verde. Las variedades con algún progenitor del CIMMYT predominan en la producción de trigo de los países en desarrollo. La superficie sembrada con variedades de trigo directamente transferidas desde el CIMMYT en 1990 casi duplicó la superficie sembrada en el apogeo de la Revolución Verde; dos tercios de la superficie total dedicada al trigo de primavera se siembran con variedades ya sea directamente importadas o adaptadas.

El análisis *ex post* de las inversiones en investigación fitotécnica de trigo durante el período posterior a la Revolución Verde indica una tasa de rentabilidad superior al 50% y pronosticamos que en el futuro el sistema proporcionará una rentabilidad de entre 37 y 48%. En la actualidad las inversiones del CIMMYT y las de los NARS en el mejoramiento de trigo se complementan mucho. El aumento del apoyo financiero a las dos actividades principales del CIMMYT — producir variedades con adaptación amplia y coordinar la red mundial para ensayar y distribuir germoplasma— probablemente intensificará la eficiencia de los programas nacionales de mejoramiento de cultivos de todos los niveles técnicos. Los NARS pequeños dependen *relativamente* más de los beneficios provenientes del sistema internacional de investigación, pero los NARS grandes obtienen el mayor provecho *absoluto* del sistema.

La posibilidad de que ocurran cambios tecnológicos también se incrementa a medida que los NARS expanden su capacidad de captar los beneficios derivados adaptando o seleccionando con eficiencia variedades del CIMMYT. Dada la capacidad del sistema internacional de servir a una gama diversa de NARS generando beneficios derivados tanto directos como indirectos, no es probable que la investigación de los NARS y la del CIMMYT se conviertan en inversiones sustitutivas en un futuro cercano.

7. Medición de la eficiencia técnica de los sistemas nacionales e internacional de mejoramiento de trigo

El sistema internacional de investigación de trigo realiza su labor con base en una colaboración verdadera. El conjunto de NARS de los países en desarrollo gasta más que el CIMMYT (75% de los gastos totales de investigación) en seleccionar, ensayar, evaluar y lanzar variedades basadas en cruzas del CIMMYT. Los NARS aportan recursos tanto humanos como económicos y cumplen la importante función de concretar los beneficios generados por el sistema internacional.

Diversos indicadores de la eficiencia revelan que esta colaboración entre el CIMMYT y los NARS produce germoplasma mejorado a bajo costo. En general, el producto por unidad de insumos obtenido por este sistema internacional es más alto que el promedio correspondiente a un sistema de los NARS según todos los indicadores de la eficiencia, con la excepción del costo de adopción por hectárea en los NARS más grandes (como la India). Existe una fuerte relación entre los costos por unidad de producción y la superficie de trigo en un país: los NARS con una superficie de trigo pequeña tienen los costos más altos. Esto también indica que existen considerables economías de tamaño y especialización en el mejoramiento de trigo, consecuencia de la concentración geográfica de las actividades de cruzamiento y de selección de generaciones tempranas efectuadas por el CIMMYT y de la división del trabajo de ensayo y evaluación de las variedades entre el CIMMYT y los NARS.

En un mundo sin fronteras políticas, la eficiencia mejoraría de manera sustancial teniendo uno o varios programas centralizados de mejoramiento vinculados con pequeños programas de ensayo situados en sitios clave. A pesar de que no vivimos en un mundo así, se puede aumentar considerablemente la eficiencia del sistema actual consolidando y racionalizando muchos programas existentes y mejorando la colaboración regional e internacional.

8. La eficiencia económica de las inversiones en el mejoramiento de trigo en presencia de beneficios provenientes de otras investigaciones

Con el fin de estimar la eficiencia de las inversiones hechas por los NARS a la luz de posibles beneficios provenientes de otras investigaciones, elaboramos un marco de los costos y beneficios para determinar los niveles de umbral de la producción de trigo en una región necesarios para justificar un programa de mejoramiento y un programa de ensayo con diversos beneficios provenientes de otras investigaciones. Se usa este marco para analizar la eficiencia de las inversiones en 69 programas de mejoramiento de trigo de primavera en 35 países en desarrollo y la de las inversiones en el sistema internacional de colaboración entre el CIMMYT y los NARS.

Los resultados revelan que, dada la magnitud de los posibles beneficios provenientes del sistema internacional de investigación, muchos programas de mejoramiento de trigo podrían aumentar considerablemente su eficiencia reduciendo sus programas de investigación y concentrándose en la verificación de variedades desarrolladas en otra parte. En el plano mundial, se comprueba que la inversión conjunta del CIMMYT y los NARS en tecnología de trigo directamente transferible es eficiente en casi todos los ME de trigo de primavera. Más específicamente, nuestros resultados revelan lo siguiente:

- En una situación hipotética inicial en la cual los otros NARS son las únicas fuentes de beneficios provenientes de otras investigaciones, las inversiones en un programa de mejoramiento de adaptación a nivel nacional, si bien tienen buenas tasas de rentabilidad, son menos rentables que las inversiones en un programa de ensayos, a menos que las variedades generadas produzcan más de 100,000 t de trigo en la región.

- En una situación hipotética en la cual el CIMMYT es una posible fuente de beneficios provenientes de otras investigaciones, se vuelve muy difícil justificar un programa local de adaptación teniendo en cuenta sólo los incrementos de rendimiento en los ME más importantes del mundo en desarrollo; para ello se requiere un nivel de producción de por lo menos 275,000 t y una tasa de rentabilidad interna de 38%.

- Cuando se emplea el marco de los costos y beneficios para proyectar *ex ante* el valor actual neto de los niveles presentes de inversión en el mejoramiento de trigo, 28 de los 69 programas de investigación de los países en desarrollo que evaluamos están haciendo inversiones excesivas si se tienen en cuenta los datos empíricos sobre los beneficios provenientes del sistema internacional.

Por consiguiente, el estudio subraya la importancia de incluir estimaciones de los beneficios directos provenientes de otras investigaciones en la evaluación económica de los programas de investigación.

9. Estudio de casos en la India

La India tiene uno de los programas de investigación de trigo más grandes y de mayor éxito en el mundo. No obstante, en los últimos años ha menguado el incremento de los fondos públicos dedicados a la investigación agrícola en ese país y crecen las preocupaciones por la duplicación y el exceso de personal en la investigación.

Esas preocupaciones se abordan aquí mediante un marco que permite calcular la tasa de rentabilidad interna de las inversiones en una forma muy desglosada. Con más de 20 programas de investigación (definidos según la zona agroecológica, el ambiente y las especies) distribuidos en 50 institutos, el sistema de mejoramiento de trigo de la India en muchos aspectos se asemeja al sistema internacional de investigación. Por eso, muchas de las cuestiones y conceptos examinados antes también se deben tener en cuenta al analizar la eficiencia de un sistema nacional grande de investigación. Con este estudio de casos se confirman varias conclusiones importantes:

- En conjunto, la inversión en el mejoramiento de trigo en la India ha tenido una rentabilidad elevada, que promedia el 51%.

- Los programas de investigación a nivel nacional del Instituto de Investigación Agrícola de la India (IARI) parecen tener una ventaja comparativa en la generación de tecnologías que funcionan bien en muchos ambientes. En tres de las cinco zonas de la India, las variedades desarrolladas por el IARI ocuparon más superficie que las variedades generadas por centros cuyas investigaciones se orientaban a una sola zona.

- Los beneficios derivados fueron características predominantes del cambio tecnológico a nivel nacional, algo similar a lo observado en el ámbito internacional.

- Los programas de investigación del IARI y los que se ocupan de la zona de las llanuras noroccidentales generaron el 75% del total de beneficios, pero absorbieron sólo el 25% de los recursos invertidos. El patrón de beneficios provenientes de otras investigaciones parece haber sido estable en el transcurso del tiempo (es decir, ha habido muy poco cambio de la condición de "prestatarios de tecnologías" a la de "generadores de tecnologías"). Por tanto, la eliminación o el rediseño de los institutos menos fuertes en estos programas al parecer crea poco riesgo de reducir la tasa global de cambios tecnológicos y, al mismo tiempo, aumentaría la eficiencia.

Estos resultados repercuten en un estudio de las tasas de rentabilidad a nivel nacional de dos maneras:

- Las tasas elevadas de rentabilidad global pueden ocultar una considerable heterogeneidad en el desempeño de los programas de investigación que contribuyen a la labor total.
- Las tasas de rentabilidad son muy sensibles a la incorporación explícita de beneficios provenientes de otros programas. La mayoría de los estudios realizados en el pasado han ignorado esos aportes y, por consiguiente, se han introducido sesgos en las tasas de rentabilidad de la investigación.

En conjunto, estos resultados indican que muchas evaluaciones anteriores de la inversión en investigación agrícola han subestimado el grado de ineficiencia de las inversiones a nivel subnacional.

10. Estudio de casos en Australia

Si bien la mayor parte de este informe se concentra en el mejoramiento de trigo en los países en desarrollo, también en las naciones industrializadas surgen preocupaciones acerca de la asignación de los recursos, los beneficios derivados y la eficiencia de la investigación. Australia ha dedicado muchos recursos al mejoramiento de trigo; emplea más de 100 investigadores de tiempo completo en una serie de programas cooperativos del sector público. Los beneficios derivados de investigaciones en otros países — especialmente las del CIMMYT— han sido en extremo importantes.

Como resultado de las presiones generadas por la escasez de fondos, Australia afronta significativos retos que repercutirán en la estructura y las actividades específicas de mejoramiento de trigo de los sectores público y privado. Si bien existen pocas posibilidades de que se privaticen de inmediato los programas de mejoramiento de trigo en Australia, hay muchas oportunidades de aumentar la recuperación de costos de los programas públicos.

El efecto de las actividades de mejoramiento de trigo en Australia ha sido sustancial. Un análisis económico de un típico programa de mejoramiento reveló una tasa de rentabilidad interna de las inversiones en investigación del orden del 19%. En los tres últimos decenios, todos los principales estados productores de trigo han tenido un flujo regular de variedades nuevas, con un promedio de 0.63 variedades introducidas cada año por cada millón de hectáreas sembradas con trigo. En los 20 años transcurridos desde su primer lanzamiento, los trigos semienanos han producido un aumento medio de 5.3% con respecto a los rendimientos que se hubieran obtenido con otras variedades.

En los últimos 20 años, han sido considerables en Australia los beneficios derivados de la investigación del CIMMYT. No obstante, los mejoradores australianos actualmente utilizan menos que en el pasado los materiales del CIMMYT, en gran medida a causa de los problemas con la calidad del grano de los materiales mejorados más recientes. Sin embargo, es probable que los mejoradores australianos continúen obteniendo beneficios del material del CIMMYT. Los recientes adelantos en la tecnología de la información permiten a los fitogenetistas seleccionar para obtener determinadas características en la amplia gama de materiales del CIMMYT; por consiguiente, la industria australiana del trigo continuará recibiendo beneficios derivados.

11. Consecuencias: Hacia una asignación eficiente de los recursos en presencia de beneficios derivados de la investigación en otros países

Este informe tiene importantes consecuencias tanto a *nivel conceptual*, en los métodos usados para evaluar la investigación, como a *nivel de las políticas*, para las decisiones sobre la inversión en investigación fitotécnica.

Consecuencias para el análisis económico

En la literatura sobre la investigación y el desarrollo (IyD) agrícolas se han reconocido ampliamente los beneficios derivados de la investigación en otros países, pero rara vez se han incluido en el análisis económico de las inversiones en investigación. Los beneficios que se producen en una zona determinada generalmente se atribuyen a las investigaciones realizadas en esa zona. Dado que los beneficios derivados se han generalizado en la IyD agrícolas, el resultado es evidente: han resultado sesgadas las estimaciones de la rentabilidad de las inversiones. Como los beneficios derivados tienden a provenir de las regiones grandes y los programas centrales de investigación, por no haber cuantificado esos beneficios se han inflado las estimaciones de la rentabilidad de la investigación en las regiones más pequeñas y se ha subestimado la rentabilidad en los programas más grandes.

La evaluación *ex ante* de la eficiencia de la investigación debe tener en cuenta los beneficios derivados de otras investigaciones. Los economistas deben preguntar: tomando en cuenta *los posibles beneficios provenientes de otras investigaciones*, ¿cuál es el valor agregado resultante de establecer un programa completo de mejoramiento, en comparación con un programa de ensayos que seleccione materiales importados?

Sobre esta base, muchos programas de mejoramiento de trigo evaluados en este estudio producen *un margen* de beneficios bajos o negativos. La mayoría de los programas ineficientes abarcan zonas relativamente pequeñas y, por lo tanto, las economías de tamaño del mercado son un elemento fundamental determinante de la eficiencia. Además, muchos de los programas ineficientes tienen una tasa relativamente alta de rentabilidad *media*; fueron ineficientes porque produjeron valores actuales netos más bajos que los que obtendría un programa más pequeño que ensayara y seleccionara tecnologías. En otras palabras, la tasa de rentabilidad media de un programa no es una base adecuada para tomar decisiones sobre inversiones en la investigación cuando existen beneficios provenientes de otras investigaciones porque esa tasa no mide la rentabilidad marginal resultante de cambiar el tamaño del programa.

Esta evaluación contradice los análisis anteriores y las prácticas tradicionales. Comúnmente se supone que los beneficios derivados de la investigación son indirectos (por ejemplo, el intercambio de germoplasma para usarlo como material progenitor y el intercambio de métodos fitotécnicos e información científica) y, por lo tanto, han sido modelados para elevar la función de producción de la investigación de otros programas. El argumento teórico según el cual se recomienda subinvertir en la investigación agrícola se funda en esta premisa básica. No obstante, como muestra este estudio, los beneficios provenientes de otras investigaciones no sólo afectarán la *productividad de la investigación* sino también la elección de la *estrategia de investigación* (es decir, el tipo de programa de investigación que se establecerá).

Consecuencias para el diseño de programas nacionales de investigación

Hay que tomar en cuenta explícitamente los beneficios provenientes de otras investigaciones al diseñar los programas nacionales de investigación. Explotar las economías de *tamaño del mercado* es fundamental para aumentar la eficiencia de las inversiones en la investigación. Si los programas públicos de investigación se establecen sobre la base de fronteras políticas, más que naturales, es probable que abarquen mercados de un tamaño inferior al óptimo.

Es preciso estimular la creación de mecanismos institucionales que favorezcan el flujo tanto recíproco como unidireccional de tecnologías para facilitar la afluencia de los beneficios derivados y los provenientes de otras investigaciones.

- Las redes formales e informales de investigación son el instrumento más frecuente para favorecer el flujo recíproco de beneficios. Estas redes por lo general incluyen ensayos nacionales o internacionales que permiten observar variedades de diversos orígenes en muchas localidades; las redes también dan a los mejoradores acceso a una amplia gama de variedades nuevas para la selección local. Algunas redes son más formales y requieren decisiones conjuntas acerca de las entradas de los ensayos y la coordinación de la investigación (por ejemplo, los programas de cultivos importantes coordinados a nivel nacional). En el plano internacional, los ensayos para evaluar germoplasma manejados por los IARC cumplen una función similar, tal como lo hacen las diversas redes especializadas de investigación. Con la creciente complejidad de la ciencia y la reducción del costo de la cooperación internacional gracias a la Internet, se están estableciendo otros mecanismos de investigación conjunta —como los consorcios y las redes de biotecnología a nivel regional, con la participación de los sectores público y privado— con el fin de facilitar el aprovechamiento de los beneficios provenientes de otras investigaciones y reducir los costos de la investigación.

- Los flujos unidireccionales de beneficios derivados son el resultado de los esfuerzos de los programas públicos de investigación por resolver el problema del tamaño del mercado y las economías de tamaño creando instalaciones centralizadas de investigación a nivel nacional, regional o internacional, con el único propósito de generar beneficios derivados. La mayoría de los países grandes tienen un sistema federal y estatal, en el cual el componente federal tiene que realizar la investigación con considerables economías de tamaño y que genere amplios beneficios derivados. No obstante, en la mayoría de los casos no han sido bien definidas las funciones de los sistemas de investigación en el plano federal y el estatal, lo que lleva a traslapos y duplicaciones. En los últimos años, ha habido una tendencia a establecer asociaciones regionales de investigación entre países vecinos, si bien todavía no es claro que los NARS hayan reducido sus esfuerzos a nivel nacional para complementar el aumento en los programas regionales y concretar los incrementos potenciales en la eficiencia.

Sin embargo, el aprovechamiento total de los beneficios derivados entraña un riesgo. Una región o país que diseñe un programa de investigación para aprovechar los beneficios provenientes de otras investigaciones supone que habrá un suministro continuo y libre de beneficios y, por lo tanto, está expuesto a las fluctuaciones de la productividad y las prioridades de las instituciones que generan los beneficios derivados. Por otra parte, el flujo irrestricto de tecnologías está en peligro a causa del creciente empleo de los derechos de propiedad intelectual para proteger los productos de la investigación, incluso en el sector público. La dependencia de unos pocos programas centralizados de investigación puede también crear riesgos tecnológicos, como la uniformidad genética.

Por último, el éxito de los IARC en el desarrollo de variedades indica que generan productos terminados de germoplasma a bajo costo y tienen una ventaja *competitiva* en la investigación fitogenética aplicada. No obstante, esto no establece su ventaja *comparativa* en este tipo de investigación aplicada. En cuanto a otros organismos centralizados de investigación orientados a producir beneficios derivados unidireccionales, es probable que la ventaja comparativa esté más en la investigación básica y estratégica, que aprovecha su acceso excepcional a las colecciones internacionales de germoplasma y los adelantos de la ciencia para proporcionar productos intermedios de la investigación que elevan la función de producción de los programas nacionales para generar variedades terminadas.

En la práctica, los IARC tienden a invertir una parte relativamente pequeña de sus recursos en este tipo de investigación de premejoramiento, aun cuando las ganancias potenciales son altas. El reto es cómo satisfacer las necesidades de productos terminados de muchos NARS pequeños y, al mismo tiempo, invertir en investigación estratégica para proporcionar productos intermedios, especialmente a los NARS grandes. Como en este estudio se mostró que muchos NARS grandes también generan productos terminados a bajo costo (en ciertos casos más bajo que el del CIMMYT), tal vez se requiera algún tipo de arreglo subcontractual con esos NARS con el fin de asegurar un suministro equilibrado de bienes públicos internacionales –tanto productos terminados como intermedios– a todos los tipos de NARS. En cierta medida, los diversos tipos de colaboración y asociación y el mejoramiento alternado usados por el CIMMYT reflejan esta orientación. El establecimiento de redes regionales proporcionará otra fuente más de productos de la investigación.

Chapter 1

Introduction

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Research Focus and Report Objectives

The success of the Green Revolution in the 1960s and 1970s stimulated political and financial support for a major expansion in agricultural research capacity at both the national and international levels. Global investments in agricultural research rose in real terms at an annual rate of 6.25% over the period from 1961–65 to 1981–85 (Pardey et al. 1991b). Much of this expansion was focused on increasing the size and number of commodity research programs, which were dominated by plant breeding efforts.[1] With respect to national agricultural research systems (NARS), this rapid expansion can be explained, in part, by:

- the success of the Green Revolution, which highlighted the role of improved technology (Ruttan 1982);
- the estimated high rates of return on research investments;
- the presumed inability to transfer biological technologies, such as varieties, because of their location specificity (Evenson and Kislev 1975; Hayami and Ruttan 1985; Englander 1991); and
- concerns about food security and national prestige (Winkelmann 1994; Douglas 1980).

Today, most developing countries have national commodity research programs for major cereal, legume, root, and tuber food crops. Some national programs support only a small group of scientists; others support several hundred scientists working at various research stations throughout the country. Many of the same factors listed above also led to the establishment and rapid growth of the international agricultural research centers (IARCs), which were specifically designed to generate benefits for other programs — or spillovers[2] — and thus increase the efficiency of the global research effort.

The funding situation has changed markedly since the late 1980s and early 1990s. Expenditures on agricultural research in the public sector, including the IARCs, have stagnated and in some cases declined sharply. In recent years, the general apprehension of international donors and national governments towards agricultural research has led policy-makers and researchers to devote increasing attention to research efficiency issues. Particular attention has been focused on the number, size, scope, type, and locations of their research programs, as well as on the relative role of IARCs and NARS in generating technology.

1 This emphasis on plant breeding programs, in particular, stems from the catalytic role of seeds in developing-country agriculture. Seeds are the primary means of delivering improvements in crops to farmers' fields. For centuries, farmers have improved crops by saving seeds of plants that exhibit traits perceived as most useful. Scientific plant breeding accelerated this improvement by altering the genetic makeup of the plants in order to provide potential for higher yield, greater pest resistance, or shorter growing season. The perceived potential benefits from the spread and use of improved seeds — such as enhanced productivity, reduced risks, and increased incomes to the farmers — made plant breeding research an important prerequisite for an effective agricultural research system.

2 The words "spillovers" and "spillins" are interchangeably used in this report depending on the context — i.e., a program that generates benefits for other programs (spillovers) or a program that receives benefits from other programs (spillins).

This report examines efficiency issues as they relate to wheat improvement research.[3] Without question, investments in such research have been remarkably successful. Wheat is the second most important food crop in developing countries, and wheat yields in those countries have grown faster than yields of any other food commodity. Numerous ex-post studies on investment in individual countries have found that average annual rates of return range from 25 to 80%. Such numbers suggest that wheat research has been a profitable investment (Bohn and Byerlee 1993).

Caution should be used, however, in extrapolating these results to all developing countries and into the future. Many of the countries studied have large and well-established wheat research programs; they are known *a priori* to be "winners" (e.g., Mexico, Pakistan, India, Argentina, and Brazil). Moreover, most of the rate-of-return studies cover periods of rapid growth in wheat productivity, especially the Green Revolution period of the late 1960s and 1970s, when returns to research were unusually high. Returns to the research investments probably declined in the 1980s and early 1990s, however, because most of the wheat area in developing countries had already been planted to high yielding varieties. In other words, the gains in productivity of varieties released in the last decade or so have probably increased less rapidly than investments in wheat research, whether measured in terms of real dollars or number of scientists (Byerlee 1994).

Since 1990, the International Maize and Wheat Improvement Center (CIMMYT) has undertaken or funded various studies of the investments, impacts, and spillovers of wheat improvement research. This work began with an extensive survey in 1990, which inventoried and documented the origins of all the wheat varieties released by NARS in the developing world for the past 30 years (Byerlee and Moya 1993). A subsequent survey assembled information on the size of about 100 public and private research programs and on expenditures for wheat improvement research (Bohn and Byerlee 1993). These studies did more than document investments and their impacts; they also served as a starting point from which to explore the various options for structuring efficient wheat breeding programs. Research and analysis based on these studies have focussed on efficiency, economies of size, research spillovers, and the role of international research (Maredia 1993; Byerlee and Traxler 1995). These issues have become increasingly important in light of donor fatigue, financial retrenchment in both NARS and IARCs, and recent calls for "radical restructuring of the IARC/NARS relationship" (Byerlee and Traxler 1995).

The studies presented here suggest that specialization in wheat improvement research creates spillovers that, properly exploited, can improve research efficiency worldwide. Although the food-security and other arguments that triggered the expansion in agricultural research investment in the 1960s and 1970s still hold true for some crops and countries, many NARS could become much more efficient if they rationalized the number and size of wheat research programs and examined the opportunities to import technology from other programs, including CIMMYT. Within large countries, such as India, there is evidence of spillovers from

3 We define wheat improvement research to include all research aimed at the development of improved wheat varieties (i.e., breeding as well as supporting activities in disciplines such as agronomy, pathology, cereal chemistry, physiology, and molecular biology).

larger and centralized research programs to smaller programs (Chapter 9). These results challenge the conventional wisdom that biological technologies are location specific, and they make a strong case for broader collaboration in wheat research in small countries or small regions within a country.

This report integrates findings from complementary studies of wheat improvement research. It provides the first in-depth examination of investments, impacts, spillovers, and efficiency of crop improvement research (for an individual crop) in developing countries. The report has three primary objectives:

- to analyze the available data;
- to document the information on investments, impacts, and spillovers of wheat improvement research; and
- to identify the key policy issues that research administrators must address in the next decade if agricultural research in general, and wheat research in particular, is to remain efficient and effective.

Report Outline

The report consists of 11 chapters. Chapter 2 describes the broad conceptual framework for the discussion in subsequent chapters. It explores the concepts of *potential* and *actual* research spillovers; it also examines economies of size in agricultural research. Later chapters show how these concepts can guide strategies for national and international wheat improvement research systems so that each can identify its comparative advantage.

Chapter 3 presents an empirical and conceptual analysis of the genotype-by-environment (i.e., GxE) phenomenon. The focus here is the environment, which determines, in large part, the potential spillovers of a biological technology such as a wheat variety. Wheat producing regions in developing countries are characterized according to the megaenvironment (ME) classification system currently used by breeders at CIMMYT. A descriptive analysis of the number, size, distribution, and concentration of wheat MEs at the international and national level clarifies the concept of environmental diversity. These analyses help to develop a measure of environmental diversity within a country and to examine the relevance and importance of "environmental distance" (as determined by GxE interactions) in designing crop improvement research programs.

Determining whether a research program should rely on direct spillovers from an international research program such as CIMMYT (or from other sources) requires an evaluation of the yield advantage of locally developed and imported varieties. If the yield advantage is small, then technology importation could be an efficient alternative for that research program. In Chapter 4, an econometric approach is applied to international yield trial data to estimate the yield advantage (*potential* spillovers) of varieties developed for a "home" ME compared to varieties developed for other MEs. The estimated spillover matrix is used to test the hypothesis that varietal technology is location specific; the matrix is also used to assess how readily CIMMYT varieties can be transferred across MEs. Analysis of international data is complemented by the analysis of country-level data for Pakistan and Kenya to calculate the yield advantage of varieties developed by NARS for the "home" environment over those imported from CIMMYT.

Chapter 5 gives a general overview of the resources invested in wheat improvement research both at the national and international levels. It also presents a comparative analysis of the size, composition, expenditures, and intensity of wheat research efforts by global region and national production levels.

Chapter 6 discusses the role of IARC-generated technology in the global wheat improvement research system in the post-Green Revolution period. The data on released varieties are used to assess the *actual* spillovers of wheat improvement research and to clarify the focus of, and the degree of complementarity between, national and international crop improvement efforts. The research costs estimated in previous chapters and information on the adoption of varieties released are used to estimate the costs and benefits of global spring wheat breeding research and to calculate the rate of return generated by this research in the post-Green Revolution period.

Chapter 7 illustrates the concepts related to economies of size and specialization. Cost estimates from previous chapters and the varietal release and adoption data from Chapter 6 are used to examine various measures of economies of size and the efficiency of different-sized wheat breeding programs at the national and international levels. The cost of varietal development through a CIMMYT-NARS collaboration is estimated; particular attention is paid to the resources contributed by NARS.

Chapter 8 examines the efficiency of investments by NARS in light of *potential* spillins. A cost-benefit framework is developed to determine the threshold levels of wheat production in the mandate region required to justify a breeding program and a testing program with different levels of spillins. This framework is applied to determine the profitability of 71 wheat improvement programs in 35 developing countries. The question addressed is this: Given the potential for spillins (as estimated in Chapter 4), what is the marginal gain (i.e., the "value added") from establishing a local *breeding* program, compared to a *testing* program, to screen imported materials? The cost-benefit framework is also applied to determine the threshold level of wheat production at the global ME level to justify investment by the international research system in a given environment.

Chapters 9 and 10 present case studies of wheat improvement research in India and Australia, respectively, to address some of the issues explored in previous chapters at a national level. The framework used in the Indian case study (Chapter 9) is based on computing the internal rate of return on investments at a very disaggregated level — in this case, 20 subprograms targeting specific production environments, which have been defined in terms of wheat species and agroecological conditions, taking interzonal spillovers into account. In addition, the case study describes the wheat improvement effort in India and assesses research allocations, productivity, and impact by environment.

Chapter 10 describes the size, structure, and impact of the wheat breeding industry in Australia. Costs and returns from wheat improvement research are also described. Evidence is presented of substantial international and interstate spillovers of wheat varieties; the prospects for the Australian wheat breeding industry are discussed in light of the recent pressures for rationalizing public breeding programs.

The final chapter outlines the major implications for investment analysts, NARS, the CGIAR, and donor organizations in national and international research. Although the studies discussed in this report focus specifically on wheat improvement research, an attempt is made to speculate on how the conceptual framework and results of these studies might apply to other commodities and types of research.

Chapter 2

Realizing Research Spillovers and Economies of Size from Market Aggregation: A Conceptual Framework

Derek Byerlee

Widespread opinion holds that agricultural technology is quite location specific. For this reason, a decentralized organization that has agricultural research programs directed at specific environments and market niches would be expected to have a comparative advantage in developing finished products. However, because the boundaries of environments and markets rarely coincide with political borders, there is a strong case for establishing centralized agricultural research programs to generate technologies and other products that are widely applicable for given environments or markets across states, provinces, regions, and countries. In other words, there is a strong argument in favor of research that generates spillovers. The degree to which the research effort is centralized depends, of course, on the trade-off between the location specificity that will be sacrificed because research cannot be tailored to a specific environment or market and the cost efficiency that will be gained in geographic (or market) aggregation.

Today, the global agricultural research system is a complex assemblage of international research centers, regional research centers, and an extremely diverse array of NARS. Together, the international research centers, regional research centers, and federally funded national research centers within a country exemplify the "aggregated/centralized" model, in which a central research program is linked to various decentralized research programs in major production zones at a country, state, or county level. In this complex system, the comparative advantages and roles of aggregated/centralized and decentralized research systems will vary greatly by country and type of research.

McCalla (1994) and Winkelmann (1994) have developed a broad conceptual framework that offers a rationale for international agricultural research — i.e., an aggregated/centralized research system. They have argued that an international research system may contribute to growth in agricultural productivity by generating technology spillovers that reduce the cost for individual countries of providing new technologies to their farmers. An international research system may also contribute to productivity growth by developing capacity in national research systems through training and other capacity-building exercises.

Concepts related to economies of size and scope in agricultural research and to the potential for spillovers can help national and international research systems develop strategies for exploiting their comparative advantage.[1] This chapter describes those concepts, which are illustrated in later

1 We focus only on activities aimed at producing technology spillovers, which depend, at least in part, on the absence of an enforceable market relationship (in other words, on the nature of the product as a public good). Other types of spillovers and related concepts often distinguished in the literature but not discussed in this report include spillovers that occur through markets (i.e., price spillovers, which occur through the product and market effects of adopting new technologies), externalities, and technology transfers that occur in an enforceable commercial or market relationship.

chapters by an in-depth case study of spring wheat improvement research. It should be noted at the outset that the concepts of "national" and "international" research systems used here denote geographic (or market) aggregation from a global perspective. However, the principles discussed are equally applicable for analyzing the relative role of federal and state research systems in large countries that have such a system.

Two concepts are crucial to assessing the comparative advantage of a geographically aggregated research system: (1) the potential for and the realization of spillovers and (2) the potential for realizing cost efficiency gains from market aggregation (i.e., economies of size). The comparative advantage of international research is enhanced to the extent that there is significant potential to realize spillovers and to the extent that economies of size provide a cost advantage.

Technology Spillovers

Types of Technology Spillovers

Agricultural research generates spillovers through various types of products:

1. Improved technologies that can be released directly to farmers after initial in-country screening (*direct spillovers*).
2. Technological products that can be adapted through local research to fit local conditions (*indirect spillovers* or *adaptive transfers*). In some cases, these products may be the same as in 1 (above), and the NARS has the choice of testing and releasing the technology or modifying it further to fit local conditions. In other cases, research may provide "unfinished products" that are unsuited for immediate release but can be adapted by local research programs to fit local conditions (e.g., germplasm with specific disease-resistance traits but poor agronomic type).
3. Nontechnological products — such as scientific information, new knowledge, and research methods — which can improve the efficiency of research systems. These products are usually provided in written form but may also be supplied through workshops, training courses, prototype equipment, and in other ways.

In some cases, spillovers are generated when technologies are introduced independently of the public-sector international research centers and NARS. Private-sector input suppliers frequently introduce new technologies, especially in the form of direct transfers of chemical inputs and farm machinery technology. In most cases, however, these introductions must take into account government regulations such as quarantine laws and safety regulations on chemicals. In addition, crop varieties often cross borders through farmer-to-farmer transfer (e.g., Morris et al. 1994). However, this type of spillover usually occurs among neighboring countries and is not important on a global level.

Factors Determining the Potential Spillovers of Technologies

For a biological technology such as a crop variety, the *potential* spillover can be approximated by $S_{ij} = Y_{ij}/Y_{jj}$, where Y_{jj} is the yield in environment *j* of varieties developed for that environment, and Y_{ij} is the yield of varieties developed for environment *i* when evaluated in environment *j* (Evenson 1994). Several factors condition the extent of these spillovers (i.e., the size of S_{ij}, which is assumed to vary between 0 and 1).

1. **Agroecological similarity between the originating and receiving region.** Agroecological similarity is usually measured by rainfall and temperature (their seasonal distribution and year-to-year variability), as well as by soils. However,

agroecological variables can be greatly modified by physical investments, especially in irrigation and water control. Therefore a definition of agroecological zones (AEZs) should include at least the most important of these modifications. In addition, AEZs are best defined with respect to specific crops and types of research problems (Pardey and Wood 1994; Chapman and Barreto 1994). Thus, an AEZ for wheat will differ from one for rice, and an AEZ for wheat *improvement* research will differ from an AEZ for wheat *crop-management* research.

An AEZ is also a dynamic concept that can be modified as new technologies become available. For example, the first semidwarf wheat varieties spread successfully through irrigated areas but were less successful in high-rainfall areas because they lacked resistance to the disease Septoria. However, with the incorporation of resistance to this disease in most semidwarf materials, the distinction between irrigated and higher rainfall AEZs became less meaningful for wheat improvement research.

2. **Local food tastes and preferences.** Even if agroecological conditions are perfectly homogeneous, cultural preferences modify the acceptance of new technologies, especially crop varieties. In many cases, these differences are reflected in local market prices and can be partially captured in a modified spillover coefficient, $S_{ij}^{*} = P_{ij}Y_{ij}/P_{jj}Y_{jj}$, where P_{ij} is the price in environment *j* of varieties developed for environment *i* relative to home-grown varieties.

3. **Factor prices.** Prices of labor and capital are likely to have an important influence on spillovers of labor-saving technologies such as farm machinery and some types of chemicals. In some cases, differences in scarcity of particular types of labor, especially skilled labor, condition spillovers.

4. **Institutions.** Institutions such as land tenure or property rights may condition spillovers of some types of technologies, especially technologies related to the management of natural resources.

With respect to agricultural technologies, major emphasis has been given to the role of agroecological factors in technology spillovers. As noted, the conventional wisdom is that biological technologies are quite location specific and must be adapted to fit local AEZs. A close examination of the literature shows that, in the 1960s, this perception provided a strong argument for research investments in tropical and subtropical areas in developing countries since technologies from temperate countries — where most agricultural research on food crops had been conducted — proved poorly adapted to these areas. Since that time, however, the organization and capacity of agricultural research in developing countries have changed substantially. Research investment in developing countries now rivals that in industrialized countries (Chapter 5), and several international research centers are working to develop improved technologies suitable for tropical and subtropical environments. The potential for spillovers between developing countries with similar AEZs is therefore much greater than previously assumed. Only recently has this potential received attention.

Realizing Potential Spillovers

Until now we have considered only *potential* spillovers. *Actual* spillovers depend on how fully this potential is realized. What influences the realization of this potential?

1. **Historical and cultural links between countries.** Cross-national flows of technologies and scientific information may occur more readily in regions where common cultural and historical links transcend national boundaries, as in Central

America (Eyzaguirre 1993). In other regions, language differences or historical enmities may impede such flows.

2. **Geographical proximity.** Technological spillovers are affected by the degree of contact between scientists and farmers across countries: Proximity tends to increase such spillovers, distance to inhibit them. Farmers in the Terai of Nepal obtain much of their technology from across the border in India (Morris et al. 1994). On the other hand, farmers and scientists in Sudan and Central India, who grow irrigated crops under very similar conditions, have little contact.
3. **Institutional factors.** Some kinds of institutions, such as research networks, may foster spillovers, whereas others, such as a legal system that lacks intellectual property rights, may limit private-sector participation in technology transfer. Quarantine laws and local rules on testing and releasing agricultural technologies also influence the degree and speed of spillovers (Gisselquist 1994).
4. **Complexity of the problem.** Some spillovers occur through the intervention of only a few actors. For example, seed imported from another country might move with relative ease through a local research station or private seed company to farmers if the seed is suited to the environment in the new country. Technologies that require more intensive extension efforts, policy changes, or specific complementary inputs often prove harder to transfer.

Economies of Size in Research

The comparative advantage of aggregated research is also affected by the potential for economies of size and scope that arise as a result of geographic and/or market aggregation. Economies of size imply that the unit cost of research decreases as the size of the research effort dedicated to a specific activity increases. This concept is closely related to, but distinct from, the concept of economies of scope, in which unit research costs are reduced when input and overhead costs are shared across related research activities (Pardey et al. 1991a). In this report, we group these two concepts under the generic heading "economies of size." Several factors may lead to economies of size in agricultural research.

1. **Fixed cost of research.** Most research programs have certain minimum establishment costs in the form of research stations, laboratories, equipment, and administrative overhead. These costs increase less than proportionally with the size of the research program's market and thus generate economies of size.
2. **Specialization of scientific expertise and equipment.** Because much agricultural science is specialized, the addition of research capacity in a given field may be relatively "lumpy" and result in economies of size.
3. **Portfolio management and risk bearing.** Research is by nature a risky undertaking: Only a small proportion of research activities lead to directly usable products. Thus a large research program with many research activities is more likely than a small one to produce results in a given period of time (Alston and Pardey 1994). Efficient portfolio management of this type may help ensure continued funding.
4. **Team interaction.** For some types of problems, researchers working in a team may be intellectually stimulated, and hence more productive, than isolated researchers.

Several factors may also lead to diseconomies of size:

1. **Diminishing marginal returns as one moves along the research production function (RPF).** At some point in most research programs, the addition of more scientists will lead to returns at the margin, which are less than the benefits derived from economies of size and scope noted above.
2. **Higher transactions costs in conducting research for a larger and more dispersed mandate area.** These may include costs of regional testing activities, travel, and meetings. For these reasons, research programs tend to be most effective in their own backyard.
3. **Lack of competition.** More competition may be generated by having several smaller rival programs rather than one large "monopoly" program. Competition may enhance innovative approaches to research. In a single large program, lack of competition may lead to diseconomies of size.
4. **Increased risk from relying on a few research institutes and technological choices.** This may include biological risk from genetic uniformity as well as institutional risk from the natural cycles of productivity in research institutes.

Trade-offs between Economies of Size and Spillovers

Geographically aggregated research programs are founded on their ability to do the following:

1. To generate spillovers and compensate for underinvestment in research by disaggregated programs (when investment is measured from a global — i.e., aggregated — perspective). Although technologies frequently spill across political boundaries, countries invest in research only on the basis of benefits captured by producers and consumers within their boundaries. The argument in favor of internationally aggregated research programs is similar to the argument made for a federal research system in a country where research is essentially a state function (Ruttan 1982).
2. To capture economies of size in agricultural research up to the point that they no longer outweigh the advantages of location-specific technologies.

Determining the extent of economies of size in research and wide adaptation of products are empirical questions. Even within a particular area of research on new technologies, there will be differences between strategic, applied, and adaptive components. These trade-offs are illustrated in Figure 2.1. Technological areas may fall into one of the four quadrants of the graph with respect to the relative degree of spillovers and economies of size. Some types of research, such as biotechnology, are likely to be characterized by considerable size economies (because of high fixed costs) and wide applicability of the products, whereas others, such as agronomic research to develop crop management recommendations, are at the other extreme on both counts. In a few cases, an AEZ may be so specific to a given country

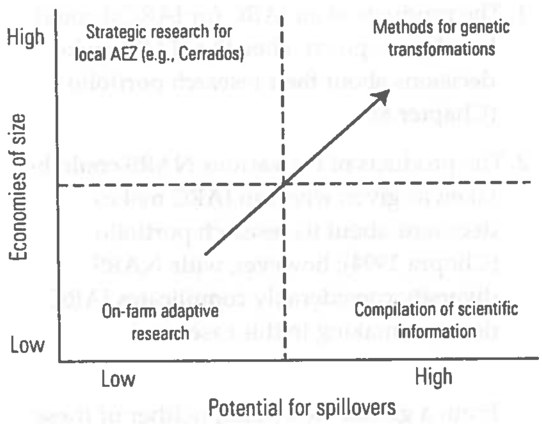

Figure 2.1. Categorization of research activities in terms of economies of size and spillovers.

that there are few opportunities for international spillins or spillovers (e.g., the Cerrados of Brazil). In other cases, an activity with few economies of size may have high international applicability. One example is the provision of scientific information services tailored to specific research areas. For example, a very small staff at CIMMYT provides scientific information on specific wheat diseases to practically all scientists in the developing world conducting research on those diseases.

Aggregated (national or international) research is therefore most applicable for activities on the right-hand side of Figure 2.1. Determining precisely where to draw the line, however, is a more difficult matter. In a world *without* political boundaries and *with* centralized funding of agricultural research, an economic model could be developed to determine the optimum level of investment in research at different levels of centralization. In practice, however, the situation is much more complex: Research decisions occur and funding is provided at multiple levels. Consider the common case in which one IARC and many NARS all focus on a particular area of research. Each organization has a fixed source of funding and each makes decisions independently. Two scenarios are possible:

1. The products of an IARC (or IARCs) could be taken as given when the NARS make decisions about their research portfolio (Chapter 8).
2. The products of the various NARS could be taken as given when an IARC makes decisions about its research portfolio (Chopra 1994); however, wide NARS diversity considerably complicates IARC decision-making in this case.

From a global viewpoint, neither of these situations will likely result in anything close to an optimum allocation of resources. The marginal rate of return to additional research investments is likely to vary widely between the IARC and the NARS as a group, as well as between individual NARS, indicating suboptimal use of resources at the global level. Discussion between the IARC and the NARS to exploit complementarities in their research can improve resource allocation. However, as long as resources are relatively immobile between the IARC and the NARS, and between individual NARS, globally optimal resource allocation is not likely to be achieved.

These options sometimes lead to interesting decisions, as illustrated in Figure 2.2. Assume, for example, that a national plant breeding program determines its research portfolio on the basis of what is available from the IARCs (as in scenario 1 above) and assume that the IARCs produce both intermediate and finished products. The national plant breeding program then has two options: (1) to test only materials imported from IARCs and other NARS, with a research production function of ABC in Figure 2.2, or (2) to conduct its own crossing program, with a research production function of FBD or GCE, depending on the fixed costs of a crossing program. The overall research production function ABD shows a discontinuity at B where the local crossing program begins to add value to the imported

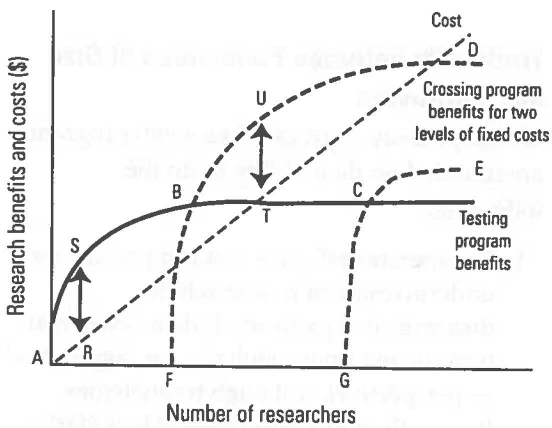

Figure 2.2. Possible research production functions for a varietal testing and a crossing program.

materials by making them more applicable to local conditions.[2]

If costs increase linearly with the number of scientists, several scenarios are possible. For an overall research production function ABCE (i.e., a testing program with a production function ABC and a crossing program with a production function GCE), only a testing program is profitable, while for an overall research production function ABD (i.e., a crossing program with a production function FBD), both a testing and crossing program are profitable with returns SR and UT, respectively. But the choice between the two options will depend on the relative sizes of SR and UT. If SR is greater than UT, the result can be the anomaly of a crossing program that provides a positive return although investment is still suboptimal (Chapter 8).

An important additional consideration is that an IARC cannot operate in isolation. To develop widely adapted and useful technologies, the international research center must have an extensive network for testing technologies, which in practice is provided by national research systems. Thus, complementarity is fostered not only because joint decisions are made on the types of products to be provided by each party, but also because, in practice, most products are developed jointly.

Conclusion

We have dealt briefly with the role of technology spillovers and economies of size and scope in agricultural research as the underlying rationale for aggregated national and international agricultural research. In the past, biological technologies were *assumed* to be quite location specific. However, much of this conventional wisdom arose from attempts to transfer *finished* technologies from temperate areas (i.e., industrialized countries) to subtropical and tropical areas (i.e., developing countries). But there is considerable homogeneity of AEZs across developing countries and regions, and with the establishment of NARS in developing countries and the international agricultural research system, the *potential* for direct and indirect spillovers within the developing world is likely to be large.

Likewise, little attention has been given to potential economies or diseconomies of size and scope in agricultural research. Because of a considerable overhead cost for much research in the form of experiment stations, libraries, chemical analysis laboratories, and so on, and because of the highly specialized nature of much research, these economies are likely to be considerable.

The potential for generating spillovers and the possibility of exploiting economies of size and scope provide a strong rationale for aggregated research systems — though not necessarily for international research centers, since aggregated international research might be organized in various ways (e.g., through networks, regional associations, or the private sector). Indeed, the emergence of large multinational private seed firms reflects the underlying efficiency of aggregated agricultural research.

Determining the extent of research spillovers and economies of size and scope in research are largely empirical questions. To help national and international agricultural research systems establish their comparative advantages, economists must quantify costs and spillovers for different types of research and sizes of research programs. The following chapters present this sort of empirical evidence through global analysis and country case studies.

2 Note that Figure 2.2 ignores discounting and the lag between research and adoption.

Chapter 3

Wheat Breeding Environments: A Conceptual and Empirical Analysis

Mywish K. Maredia and Richard Ward

The basic aim of plant breeding research is to improve genotypes for a given environment. Genotype (G) and environment (E) are thus the two explicit components that define a plant breeding research program and that also determine the potential for technology spillovers. The genotypes define the sources (raw materials) of genetic improvement; the environments define the size, scope, and objectives of breeding research. A third component is implicit in a plant breeding program, however: the differential response of genotypes to different environments (i.e., GxE interactions). These interactions influence the design of the breeding program and ultimately the rate of genetic gains. GxE interactions are present when there is more than one environment in the research domain (i.e., the region to which breeding research is targeted) and when there are different genotypes that respond differently to each environment. Plant breeding research would be immensely simplified were it not for GxE interactions.

Much research has focused on statistically measuring GxE interactions. As Eiseman et al. (1990) observed, this emphasis on statistical methods has distracted breeders from more effective analysis and understanding of the biological mechanisms involved in GxE interactions. To better exploit GxE interactions, a breeder needs to understand how they influence breeding decisions. It is not enough simply to determine their existence or magnitude.

This chapter presents an empirical and conceptual analysis of the GxE phenomenon. We examine one of the GxE components — the environment — in the context of wheat breeding research in developing countries. Environments give a spatial and temporal dimension to plant breeding research. They are the basis for defining and differentiating breeding research domains, if not breeding programs *per se*, within a given geographical region. The role of environment in defining the focus of a breeding program is so important that research resources cannot be allocated optimally unless the nature and magnitude of environmental variation of the targeted crop production area have been well characterized. Resource allocation decisions for breeding research — and their justification at both the national and international levels — are greatly influenced by the size and distribution of environments within a country and across countries, respectively.

Each country has its own system for defining target research environments and allocating research resources correspondingly (see Chapters 9 and 10 on India and Australia). Target environments have also been defined for international plant breeding research. This chapter describes how CIMMYT has characterized the major wheat-producing regions in developing countries using a megaenvironment (ME) classification system. This system can be used to make cross-country comparisons of size, distribution, and concentration in major wheat environments in the developing world; the system also helps us to evaluate — and then justify or rethink — decisions about international and/or regional research efforts aimed at different environments. This classification system will also be used in later chapters to assess the international spillovers of wheat varieties and to determine the efficiency of research resources allocated to wheat improvement at national and international levels.

We begin with a description of the CIMMYT ME database and characteristics of MEs, followed by a descriptive analysis of the number, size, distribution, and concentration of wheat MEs at both the international and national level. Based on this analysis, we develop a measure of environmental diversity for countries that produce spring wheat. Last, we discuss the concept of "environmental distance" as determined by GxE interactions and its relevance and importance in designing crop improvement programs.

The Megaenvironment Database

The ME database compiled by CIMMYT contains information on 26 developing countries, each of which had a wheat area of at least 100,000 hectares (ha) as of the mid-1980s. The variables in the dataset include wheat area, production, type, ME class, maturity, and moisture code; also included is information about disease and insect stress. These data were obtained for each country based on surveys of national research programs and CIMMYT staff. The surveys determined zones for each country, which in turn were grouped into MEs. The area and production data for these 26 countries have been regularly updated. The data used in this analysis correspond to the 1993–95 FAO data (CIMMYT ME database). No data, however, are available for other countries that may now cultivate more than 100,000 ha of wheat.[1]

Major Characteristics of Wheat Megaenvironments

As defined by CIMMYT, an ME for wheat improvement is a broad, not necessarily contiguous area, usually international and frequently transcontinental. Each ME is defined in terms of similar biotic and abiotic stresses, cropping system requirements, and consumer preferences for types of wheat (Rajaram et al. 1995) (Table 3.1). Unlike the general Papadakis or FAO system, the CIMMYT ME system is crop specific and based explicitly on the moisture and temperature regimes in the wheat growing season. In addition, the system distinguishes irrigated from nonirrigated areas within an environment, a distinction that is especially important for wheat. Thus, compared with the general Papadakis or FAO system, the CIMMYT ME system is more representative of wheat growing environments in the developing world and makes the assessment of spillovers more accurate (Chapter 4).

1 In light of the recent updates, several caveats must be noted. The mid-1980s database included information for two countries, Jordan and Peru, which now cultivate less than 100,000 ha of wheat. These countries are still included in our analysis. On the other hand, the database does not include a number of countries that do cultivate more than 100,000 ha of wheat. These countries include South Africa, which was not considered a "developing country" in the mid-1980s; Saudi Arabia; Myanmar; Bolivia, where wheat area expanded rapidly in the late 1970s and early 1980s; Mongolia, which had environments not targeted by the CIMMYT wheat program; and Yemen, where wheat area has expanded rapidly and the country now consists of North and South Yemen. Also, the ME database does not include any information on the former Soviet Union, particularly the developing countries of the Central Asian republics. Despite these missing countries, however, the ME database contains information on countries that still make up 97% of the total wheat area in the "developing world" (i.e., excluding any countries from the former Soviet Union).

Table 3.1. Characteristics of wheat megaenvironments (MEs)

Wheat type and ME	Latitude (degrees)	Moisture regime[a]	Temperature regime[b]	Sown	Breeding objectives[c]	Representative locations or regions	Breeding began at CIMMYT
Spring wheat							
ME1[d]	<40	Low rainfall, irrigated	Temperate	Autumn	Resistance to lodging, SR, and LR	Yaqui Valley, Mexico; Indus Valley, Pakistan; Gangetic Valley, India; Nile Valley, Egypt	1945
ME2	<40	High rainfall	Temperate	Autumn	As ME1 + resistance to YR, *Septoria* spp., *Fusarium* spp., and sprouting	Mediterranean Basin; Southern Cone; Andean Highlands; East African Highlands	1972
ME3	<40	High rainfall	Temperate	Autumn	As ME2 + acid soil tolerance	Brazil; Andean Highlands; Central Africa; Himalayas	1974
ME4A	<40	Low rainfall, winter rain	Temperate	Autumn	Resistance to drought, *Septoria* spp., and YR	Aleppo, Syria; Settat, Morocco	1974
ME4B	<40	Low rainfall, winter drought	Temperate	Autumn	Resistance to drought, *Septoria* spp., *Fusarium* spp., LR, and SR	Marcos Juárez, Argentina	1974
ME4C	<40	Mostly residual moisture	Hot	Autumn	Resistance to drought	Indore, India	1974
ME5A	<40	High rainfall/ irrigated, humid	Hot	Autumn	Resistance to heat, *Helminthosparium* spp., *Fusarium* spp., and sprouting	Joydebpur, Bangladesh; Encarnación, Paraguay	1981
ME5B	<40	Irrigated, low humidity	Hot	Autumn	Resistance to heat and SR	Gezira, Sudan; Kano, Nigeria	1975
ME6	>40	Moderate rainfall, summer dominant	Temperate	Spring	Resistance to YR, LR, *Fusarium* spp., *Helminthosporium* spp., and sprouting	Harbin, China	1989
Facultative wheat							
ME7	>40	Irrigated	Moderate cold	Autumn	Rapid grain fill, resistance to cold, YR, PM, BYD	Zhenzhou, China	1986
ME8A	>40	High rainfall, long season	Moderate cold	Autumn	Resistance to cold, YR, *Septoria* spp	Temuco, Chile	1986
ME8B	>40	High rainfall, short season	Moderate cold	Autumn	Resistance to *Septoria* spp., YR, PM, *Fusarium* spp., sprouting	Edirne, Turkey	1986
ME9	>40	Low rainfall	Moderate cold	Autumm	Resistance to cold, drought	Diyarbakir, Turkey	1986
Winter wheat							
ME10	>40	Irrigated	Severe cold	Autumn	Resistance to winterkill, YR, LR, PM, BYD	Beijing, China	1986
ME11A	>40	High rainfall, long season	Severe cold	Autumn	Resistance to *Septoria* spp., *Fusarium* spp., YR, LR, PM	Odessa, Ukraine	1986
ME11B	>40	High rainfall, short season	Severe cold	Autumn	Resistance to LR, SR, PM, winterkill, sprouting	Lovrin, Romania	1986
ME12	>40	Low rainfall	Severe cold	Autumn	Resistance to winterkill, drought, YR, bunts	Ankara, Turkey	1986

Source: Rajaram and Van Ginkel (1996).
[a] Rainfall refers to just before and during the crop cycle. High = > 500 mm, low = < 500 mm.
[b] Refers to the mean temperature of the coolest month. Hot = >17°C; temperate = 5 to 17°C; moderate cold = 0 to 5°C; severe cold = -10 to 0°C.
[c] Factors additional to yield and industrial quality. SR = stem rust, LR = leaf rust, YR = yellow (stripe) rust.
[d] Further subdivided into: (1) optimum growing conditions, (2) presence of Karnal bunt, (3) late planted, and (4) problems of salinity.

Global production levels across wheat MEs vary from 2.0 M t in the environment characterized by acid soils, high rainfall, and a temperate[2] climate (ME3) to 105.5 M t in the irrigated, low rainfall, temperate environment (ME1) (Table 3.2). ME1 dominates the other environments in cropped area as well as in production, accounting for nearly one-third of the total wheat area and 40% of total wheat production in the developing world (including China).

The size of an environment greatly influences net returns to research. Global research, such as that conducted by an IARC, would thus favor large environments such as ME1 (irrigated low rainfall) and ME2 (high rainfall) to take advantage of economies of market size. Not surprisingly, these two environments were among the earliest areas targeted at the international level by the CIMMYT wheat breeding program (Fischer and Rajaram 1990).

The MEs defined in Table 3.1 are further subdivided by the types of wheat that the research programs target (i.e., bread or durum wheat) although one research program can often handle both types (Table 3.2). Durum wheats are less extensive than bread wheats. In terms of relative importance, about two-thirds of durum wheat is produced in spring-

Table 3.2. Distribution of area and production, and percentage area and production, under bread and durum wheat in developing countries by megaenvironments (MEs), 1993-95

Megaenvironment	Area (000 ha)	Production (000 t)	Area (%)		Production (%)	
			Bread	Durum	Bread	Durum
Spring type						
ME1 irrigated	34,300	105,490	99	1	99	1
ME2 high rainfall	9,490	25,710	76	24	81	19
ME3 acid soil	1,270	1,950	100	0	100	0
ME4A low rainfall, winter rain	8,600	8,620	53	47	51	49
ME4B low rainfall, winter drought	2,500	3,420	100	0	100	0
ME4C low rainfall, stored moisture	6,410	7,820	74	26	80	20
ME5A high temperature, high humidity	4,380	12,350	100	0	100	0
ME5B high temperature, low humidity	3,400	3,660	100	0	100	0
ME6 severe winter, high latitude	4,980	15,300	100	0	100	0
Total spring wheat	75,330	184,320	88	12	93	7
Facultative type						
ME7,8A,8B moderate cold, high rainfall	5,610	22,020	100	0	100	0
ME9 moderate cold, low rainfall	4,920	6,470	100	0	100	0
Winter type						
ME10,11A,11B severe cold, high rainfall	6,980	23,200	98	2	96	4
ME12 severe cold, low rainfall	7,460	11,460	83	17	84	16
Total facultative/winter wheat	24,970	63,150	94	6	95	5
Grand total	**100,300**	**247,470**	**90**	**10**	**93**	**7**

Source: CIMMYT wheat megaenvironment data files.

2 Temperate climate in the context of wheat MEs refers to the temperature regime during the wheat growing season. Tropical environments are defined as temperate if the mean temperature in the coolest month is more than 5°C but does not exceed 17°C.

habit environments: ME2 (high rainfall) and ME4A (low rainfall, winter rain). Bread wheats are grown in all environments, but MEs that are well-supplied with water, either through irrigation or high rainfall, clearly dominate bread wheat production. These MEs account for about three-quarters of the bread wheat produced in developing countries.

Distribution of Spring Wheat MEs across Countries and Regions

There is considerable agroecological diversity in regions that produce spring wheat in developing countries.[3] Table 3.3 shows the extent of spring wheat MEs across regions and countries, the mean size of an ME at a country level, and the Gini ratio, which reflects the concentration of an environment across countries. This information has important implications for the roles of international and regional research and for whether such research is justified in different environments.

First, international research can be justified on the grounds that it will generate spillovers for a large number of countries. In this respect, an IARC would have a greater advantage in conducting research directed at ME1, ME2, and ME5A — which occur in a large number of countries across regions. On the other hand, ME3 and ME6 occur only in one country, implying that there is little justification for international research.[4]

Second, some spring wheat MEs are concentrated in one geographic region, such as ME4A, which is concentrated in West Asia/ North Africa. Such a high concentration of one ME in a region can be conducive to regional cooperation in wheat research. Third, from an international perspective, the size of an environment is as important as the number of countries with that environment. About 20% of all environments are small at the country level, producing less than 100,000 t of wheat each. At the country level, a full-fledged breeding program for a small environment is unlikely to be justifiable, but an IARC could be an important source of direct spillins for small environments that occur in many different countries. In general, the durum wheat MEs are smaller than bread wheat MEs.

Fourth, the opportunity for spillins from within the ME will also depend on how concentrated the MEs are in different countries. Assuming that research effort in a given country-level environment is proportional to its size, a high concentration of production in a few large countries would suggest a greater research capability in these countries and greater opportunity for research spillovers from those countries to other countries within the environment. The concentration ratio in Table 3.3 represents the skewness in distribution of total production of each ME by country-level environments of different sizes. The concentration ratios are measured by the Gini coefficient adjusted by the number of country-level environments in a given ME. The closer the ratio is to 1, the higher is the concentration of total production in a few large country-level environments. The MEs with a high concentration ratio are generally found in large wheat producing countries. For example, in bread wheat ME1 (irrigated), about 90% of wheat production is concentrated in the three largest country-level

[3] Because of a lack of disaggregated data on wheat area and production for some facultative and winter MEs, this and the following sections focus only on spring wheat MEs.

[4] Unlike some of the spring wheat environments, MEs for winter/facultative wheats are very sparsely and widely distributed among different developing regions, which might make international research more justifiable. However, relatively few countries grow winter/facultative wheats, which may make international research less advantageous.

environments: China, India, and Pakistan. Research spillovers in this ME are likely to be greater than those in other MEs, such as bread wheat in ME4A or ME4C.

Distribution and Diversity of Spring Wheat MEs at the Country Level

Countries vary greatly in the number of spring wheat MEs they contain. Kenya, Sudan, and Uruguay constitute one homogeneous wheat ME, whereas Turkey has 10 wheat environments, China has 9, Chile has 7, and Iran has 6 (these include durum wheat). The number of environments in a country is one indicator of the size of the research effort (in numbers of research programs and researchers) needed for a given commodity. *Ceteris paribus*, countries with great environmental diversity will require a relatively greater research effort than countries with less diversity.

The size of an environment (measured in terms of production level) is an important factor in deciding whether and how much to spend on research in that particular environment. This question is particularly important for small countries. The size of ME1 (irrigated, low rainfall) varies from as little as 9,000 t in Jordan to as large as 34 M t in India. Given the large size of this ME, India has a clear advantage in economies of size in research on irrigated wheat. Jordan, on the

Table 3.3. Distribution of megaenvironments (MEs) by regions and size of production

	Number of countries in a given region, by ME						Number of country-level environments by size of wheat production (000 t)					
	Sub-Saharan Africa	West Asia & North Africa	South Asia	East Asia	Latin America	Total	<100	100-500	500-1,500	>1,500	Mean	Gini coefficient[a]
Bread wheat												
ME1 irrigated	0	7	3	1	2	13	1	4	4	4	6,284	0.82
ME2 high rainfall	2	7	0	1	6	16	3	9	1	3	1,243	0.77
ME3 acid soil	0	0	0	0	1	1	0	0	0	1	2,394	1.00
ME4A low rainfall, winter rain	0	9	0	0	0	9	2	3	4	0	499	0.48
ME4B low rainfall, winter drought	0	0	0	0	2	2	0	1	0	1	1,999	0.94
ME4C low rainfall, stored moisture	0	0	3	1	0	4	0	1	2	1	1,188	0.44
ME5A high temperature, high humidity	1	1	2	1	2	7	1	1	3	2	1,342	0.57
ME5B high temperature, low humidity	0	0	2	0	2	4	1	2	0	1	711	0.74
ME6 severe winter, high latitude	0	0	0	1	0	1	0	0	0	1	12,939	1.00
Durum wheat												
ME1 irrigated	0	6	1	0	1	8	3	3	2	0	222	0.62
ME2 high rainfall	1	7	0	0	2	10	3	3	4	0	446	0.52
ME4A low rainfall, winter rain	0	8	0	0	0	8	3	1	4	0	485	0.54
ME4C low rainfall, stored moisture	0	0	0	0	0	0	0	0	0	0	0	0
All spring wheat	**3**	**11**	**4**	**1**	**7**	**26**	**17**	**28**	**25**	**14**	**0**	**0**

[a] Reflects the concentration of an environment across countries.

other hand, is unlikely to be able to justify a full-fledged wheat breeding program targeted towards this environment. It may have to rely on importing technologies (direct spillins) from other countries or an IARC.

To compare the environmental diversity across countries, we constructed an index in which D is based on the number of country-level environments (considering durum wheats as a separate environment) M, weighted inversely by its size weight, W_i.

$$D_i = \frac{M}{W_i}$$

where,

$$W_i = \frac{A_i}{\sum_{i=1}^{N} \sum_{j=1}^{M} \left| \frac{E_{ij}}{NM} \right|}$$

and where A_i is the size of total wheat area in country i, E_{ij} is the size of the j^{th} environment in country i, and N is the number of countries. The index thus tries to factor out the effect of size of wheat area on the number of environments a country would have. The mean ratio of 0.9 million hectares (M ha) per environment was taken as the base for constructing the size weights and diversity index.

Environmental diversity for spring wheat seems to decline with increasing size of total wheat area at the country level (Figure 3.1). Thus some of the largest wheat producing countries are the least diverse. Clearly some small countries have a high degree of environmental diversity (i.e., many small wheat producing environments). This makes the problem of organizing local research more difficult, because only a small area will benefit from research on a given environment.

Environmental Distance: A Conceptual Analysis

The descriptive analysis of the size and distribution of environments that we have just presented is helpful in addressing issues related to the organization of research at the global and national level and in determining the *dispersal* of research benefits. Here we discuss another aspect of environment, "environmental distance," which influences the design of a breeding program by affecting the *level* of research benefits.

What Is "Environmental Distance"?

The plant environment is made up of agroclimatic factors that can be grouped as climatic, edaphic, geographic, and biotic. These factors affect plant growth, structure, and reproduction (Billings 1952). It is very unlikely that a research domain, which often corresponds to politically bounded jurisdictions (i.e., a region of a continent, country, state, county) will be homogeneous, because of the random distribution and dynamic nature of the environmental factors. "Environmental distance" is the extent to which agroclimatic differences between two locations within the same research domain affect a given plant's ability to adapt to these

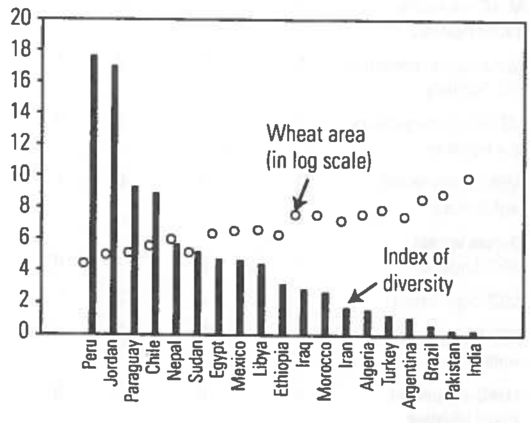

Figure 3.1. Index of environmental diversity by size of spring wheat area for 19 countries.

locations. Note that environmental distance refers to differences in adaptation (i.e., plant response) rather than absolute differences in agroclimatic factors such as rainfall and temperature. Environmental distance is basically determined by GxE interactions. For example, a location characterized as "low rainfall" (receiving, say, less than 300 mm of rainfall annually) is not necessarily environmentally distant from a location characterized as "high rainfall" (receiving more than 500 mm of rainfall) if the genotypes do not respond differently to these rainfall variations.

Environmental distance is a dynamic concept: It changes as genotypes and the environment change. Plant breeders constantly develop new varieties, some of which have attributes that reduce the distance between two environments. In case of wheat, for example, the environmental distance between ME1 and ME2 is determined by the presence of Septoria and Fusarium diseases in ME2. As more wheat varieties developed for ME2 have built-in resistance to these diseases, the distance between ME1 and ME2 for the purpose of breeding research is diminishing (Chapter 4).

Similarly, socioeconomic factors add or subtract to the environmental distance within a target region. Unlike the biological factors that cause GxE interactions, which are reflected in the performance indicator (yield), these socioeconomic factors cause GxE interactions in other plant traits, such as quality, maturity, and biomass production, which ultimately affect the adoption of a crop technology by farmers. For instance, over the past several years, economic factors have caused the cropping pattern to change in some locations of ME1, and farmers now plant wheat later. This change requires plant breeders to define new wheat environments within ME1, even though the agroecological base remains unchanged. Also, consumer preferences for taste, texture, color, and cooking quality often add to the environmental distance within the same agroecological base, and specialized breeding efforts become necessary to satisfy varied consumer demands.

Constantly changing socioeconomic factors in developing countries can make environmental distance even more dynamic. Rapid urbanization in much of the developing world may mean an increasing emphasis on bread-making quality or more demand for durums to make pasta. Urbanization could even reduce the emphasis on locally distinct quality characteristics in favor of mass production to feed the growing population. The implication for plant breeding research is that the boundaries of a target environment change not only as a result of changes in its agroecological base but also as a result of the changes in program objectives in response to changing socioeconomic factors.

GxE Interaction: Implications for the Design of Crop Improvement Programs

The design of a crop improvement program entails decisions about the number of separate breeding programs, the type of research program (testing germplasm versus crossing), and the selection strategy of a research program (selecting germplasm for wide versus specific adaptation). All of these decisions depend on the environmental distances between locations within the research domain, but the decision about selection strategy is the basic underlying decision faced by research managers. Should the research program suppress GxE interactions by developing varieties that can be released in all the environments in the target domain (widely adapted)? Or should it exploit GxE interactions and develop varieties that meet the specific needs of each environment in the domain (specifically adapted)?

Figure 3.2 illustrates this decision problem (Evenson et al. 1979). Suppose the crop-growing locations in a region fall under five environments, E1, . . . , E5. If there are five separate breeding programs, each targeting a single environment, the expected yield increments are represented by 11', 22', . . . , 55'. These yield curves comply with the theoretical assumption that the potential for spillovers — $S_{ij} = Y_{ij} / Y_{jj}$ — will vary between 0 and 1 (Chapter 2). In other words, in a given environment *j*, the yields of varieties developed by the local breeding program (Y_{jj}) are higher than or equal to the yields of varieties developed by other breeding programs (Y_{ij}). The magnitude of the potential spillover coefficient, S_{ij}, will depend on the environmental distance between environments *i* and *j*.

In contrast, curves AA' and BB' depict two possible scenarios for the performance of materials developed by breeding programs that select for wide adaptation. Curve AA' represents the conventional viewpoint that a wide adaptation program will not generate the highest yielding varieties in any environment. Given the tradeoffs between higher yields but higher costs and *vice versa*, a research manager is therefore faced with the problem of choosing between the extreme options of five breeding programs versus one breeding program, and a varied number of possible combinations between these two extremes with respect to number of programs, types of programs, and selection strategy — each with different implications for resource allocation and expected benefits.[5]

Yield curve BB' represents the scenario of wide adaptation under which the spillover coefficients, S_{ij}, are greater than 1 in three environments — E1, E3, and E4 — implying that the wide adaptation strategy can potentially serve a number of environments. Although this scenario seems theoretically implausible, it is demonstrated and supported by the empirical estimation of yield curves in Chapter 4. One plausible explanation for this outcome is that, in reality, annual variation in weather and climatic factors blurs the environmental boundaries considerably.[6] A research program that selects the varieties that perform best in locations within a predetermined environmental boundary may develop varieties that are specifically adapted only to an average growing season in that environment. However, a research program that develops broadly adapted germplasm, testing materials across locations and years, is likely to develop varieties that perform well under divergent seasonal conditions at each

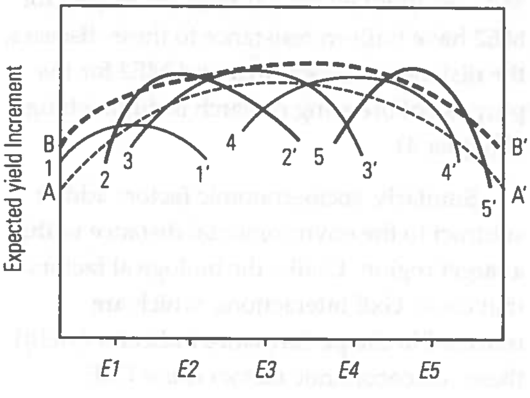

Figure 3.2. Expected yield increments from research programs targeted to specific environments.
Source: Adapted from Evenson et al. (1979).

5 For example, there could be two breeding programs each in E2 and E4, and environments E1, E3, and E5 could test varieties from these "neighboring" environments and select the best-suited materials. At an extreme, the region could decide not to have a breeding program at all but only testing programs in each environment if there are external sources of research spillins (i.e., if there are breeding programs in similar or "neighboring" environments in other regions).

6 For example, in the case of wheat MEs, the clustering analysis by DeLacy et al. (1994) confirmed some but not all MEs.

location. Widely adapted varieties generally show a high degree of disease resistance, abiotic stress tolerance, and photoperiod neutrality; thus they generally exhibit high yield potential and increased stability. As shown in Chapter 4, the organization of international wheat breeding efforts, spearheaded by CIMMYT's large-scale crossing and selection strategies — and by multilocation, international testing by national programs — has resulted in broadly adapted varieties that yield better than varieties bred by national breeding programs directed at specific environments in several MEs.

Of course, the resource allocation implications under the second scenario (yield curve BB′) are not as clear-cut as they might seem, given the yield advantage conferred by the broad adaptation program. Organizing crop improvement research that produces broadly adapted varieties as depicted by curve BB′ involves investing substantial resources in a large-scale crossing program, early and late generation selection, and a multilocation testing program. It also requires research screening and testing capabilities at the local level in each of the environments. Resource allocation decisions thus have to be based on the economic costs and benefits of each option under consideration. Some of the resource allocation issues for spring wheat improvement research, at the global and national levels, are addressed in greater detail in Chapters 7 and 8.

Conclusion

Plant breeding research would be immensely simplified were it not for the variation in environments and the correspondingly variable response of genotypes. Environmental variability and complexity have important implications for the research resource allocation decisions at both the national and international level.

The ME classification system presented in this chapter is a useful tool for analyzing the economics of environmental complexity in wheat improvement research at a global level. Information on the size and distribution of these MEs across different countries and within a country can be used to explain the opportunities for international technology spillovers, to justify different research options, and to generate support for regional and international cooperation in wheat improvement research.

The relative advantage of national and international research will depend not only on the size and distribution of environments but also on the *potential* and *actual* spillovers generated in these environments, which will be a function of the environmental distance between locations in the mandate region. The concept of environmental distance is helpful for conceptualizing the resource allocation decisions faced by plant breeding programs. We will return to this concept in the next chapter when we examine the *potential* spillovers from different spring wheat MEs.

Chapter 4

Assessing Potential International Transferability of Wheat Varieties

Mywish K. Maredia, Richard Ward, and Derek Byerlee

The major objective of the international agricultural research centers (IARCs) is to develop widely adapted technologies that national research programs can use either directly or indirectly (i.e., to generate technology spillovers). As noted in the previous chapter, however, technology spillovers from IARCs to national research programs may be constrained by the "environmental distance" between locations, as determined by genotype-by-environment (GxE) interactions. If not for GxE interactions, one international breeding program per commodity could have served the whole world.

After studying the international transferability of wheat varieties, Englander reports that "one striking result is that all countries but one showed positive domestic yield bonuses — that is, [*domestically developed*] varieties virtually always yielded more at home than abroad. . . . This suggests that varieties tend to be highly specialized to local conditions" (Englander 1991, p.307). Englander's findings concur with the yield curves 11′, . . . , 55′ and AA′ depicted in Figure 3.2. Nevertheless, the evidence provided in this and the following chapter tends to support the scenario of yield curve BB′ (Figure 3.2), suggesting that broadly adapted wheat varieties may be more robust and create greater spillovers than previously reported.

In this chapter we examine the international transferability of wheat varieties. Our focus is on estimating *potential* spillovers, $S_{ij} = Y_{ij}/Y_{jj}$, defined in Chapter 2. The yield in environment j of varieties developed in environment i, Y_{ij}, is estimated using multiple regression analysis of CIMMYT's International Spring Wheat Yield Nursery (ISWYN) trial data. These yield trials are conducted each year by CIMMYT, Mexico, with the cooperation of national research programs (both in industrialized and developing countries).[1] These international trials disseminate germplasm to different countries and test their adaptability to different environments. National programs contribute their best-performing varieties, which are tested at several locations internationally along with improved germplasm and advanced lines developed by CIMMYT. Similar trials are also conducted at a country level by national programs. National yield trial data of Pakistan and Kenya are also analyzed to provide additional evidence on the transferability of wheat varieties.

The analyses focus on the following question: To what degree is wheat varietal technology location-specific? In other words, do varieties developed for a specific target environment outyield varieties developed for other environments and by the international research system?[2]

1 Since 1995, the ISWYN trials have been discontinued to make way for more specifically targeted nurseries (Fox 1996).

2 It should be noted that in these analyses, yield is considered the sole performance indicator of a technology. This is in accordance with other studies on GxE interactions (Finlay and Wilkinson 1963; Hardwick and Wood 1972) and research productivity (e.g., Evenson and Kislev 1975) in which yield is associated with technological attainment. Implicitly, CIMMYT and other plant-breeding research programs make the same association as they use the ISWYN and similar data to identify superior varieties.

Statistical Procedure and Data Sources

CIMMYT's ISWYN trial data for the years 1979–80 to 1987–88 are used to estimate the *potential* spillovers both at the global and country level.[3] This data set includes more than 24,000 yield observations, of which about 23,000 were used after excluding all observations pertaining to triticale and durum wheats. Also, local checks were excluded because many variety names were not reported by the cooperators, were not identifiable because of inadequate information on cross and selection history, or were duplicated as one of the non-local check entries.[4] There were 209 unique wheat varieties in the 364 entries over the eight-year period.[5] There were 195 locations in 81 countries. The trial locations were classified according to CIMMYT's megaenvironments (MEs) discussed in Chapter 3. The wheat varieties were classified by their institutional origin as either:

- NARS varieties (i.e., crossed, selected, and tested by national programs) or
- CIMMYT varieties[6] (i.e., developed through the international CIMMYT-NARS collaborative research system as follows: crossing and initial selections by CIMMYT; testing by national programs).

The NARS varieties were further classified by their environmental origin based on the dominant megaenvironment in the country or region of development and on information about the environmental niche (rainfed, irrigated, etc.) for which the variety was released. CIMMYT varieties were further classified as those released in Mexico (CIM1) and those released in countries other than Mexico or not released by any national program (CIM2).[7] Appendix Table 4A.1 lists the number of entries and unique varieties from these origin groups for each megaenvironment.

The question addressed in estimating a global spillover matrix is this: In a given testing megaenvironment, how do varieties developed for that ME perform relative to varieties developed in other MEs (irrespective of their country of origin)?[8] Also, we are interested in the issue of transferability of wheat varieties developed by the international wheat improvement research system spearheaded by CIMMYT in partnership with NARS around the world. The system works to develop high yielding, widely adapted wheat varieties that can be released by NARS after testing or used as breeding parents in their wheat improvement programs.

3 With the exception of ISWYN year 1982–83, which was not included because it was incomplete.

4 Since local checks are likely to be the best varieties grown by the farmers in a given location, their exclusion from the analysis may bias the results downward. However, local checks are not synonymous with locally developed varieties. In fact, about 70% of the local checks that were reported and identified were CIMMYT- bred varieties released by the national programs.

5 Unique wheat varieties refer to the unique cross. Two entries with two different names entered in different trial years were considered as one unique variety if they represented the same unique cross.

6 CIMMYT's research mandate is to provide improved germplasm that can be used by a national program either as parent materials in its breeding program or released after local screening and testing. "CIMMYT variety" as used in this report is shorthand for "advanced breeding line developed by CIMMYT in collaboration with NARS" and should not be equated with the notion that these are varieties released by CIMMYT in any given country.

7 Although CIMMYT's headquarters is in Mexico, varieties developed by CIMMYT have to undergo the same procedure for release in Mexico as they would in any other country.

8 Since technology transfer is constrained by differences among environments, the objective is to analyze technology transfer across MEs and not across political boundaries (i.e., countries) as done by Englander (1991). Relating the transferability of a technology to environmental zones is important because it allows us to determine the yield change as a function of variables which are based on GxE knowledge. Moreover, estimates of technology transferability based on political boundaries are often difficult to interpret (since it is very unlikely that a country or politically defined region will have a homogeneous crop growing environment).

The following regression model was estimated separately for seven MEs described in Table 4.1[9]: ME1, ME2, ME3, ME4A, ME4B, ME5A, and ME6.

$$(1) \quad Y_{hgt} = a + \sum_{h=1}^{H} b_h \,\text{DLOC}_h + \sum_{t=1}^{T} c_t \,\text{DYEAR}_t + v \,\text{VINT}_g + \sum_{i=1}^{m} w_i$$

where:

Y^j_{hgt} is the observed yield (kg/ha) of the g^{th} entry at the h^{th} trial location in environment j and in t^{th} trial year.

DLOC_h is a vector of dummy variables equal to one if the data point belongs to location h, zero otherwise.

DYEAR_t is a vector of dummy variables equal to one if the data point belongs to trial year t, zero otherwise.

VINT_g is a variable to reflect the age or vintage of a variety, approximated by the trial year in which the g^{th} variety first appeared.

DORIG_i is a vector of dummy variables equal to one if the g^{th} variety belongs to the origin group i (i.e., developed for megaenvironment i), zero otherwise. There are nine such dummy variables — seven correspond to NARS varieties classified by their megaenvironment origin (DOME1, DOME2, DOME3, DOME4A, DOME4B, DOME5A, DOME6) and two correspond to CIMMYT varieties released in Mexico (DCIM1) and elsewhere (or not at all) (DCIM2).

MR is the inverse Mill's ratio (described further below).

a, b, c, w, r, and *v* are the parameters to be estimated.

ε is the error term.

The performance of a variety is thus assumed to be a function of environmental variables (DLOC, DYEAR) and technology variables (VINT, DORIG). The variables VINT and DORIG represent characteristics of a varietal technology. Since we are using panel data, the location and year dummies (DLOC and DYEAR) are included to factor out the site and time effect on the observed yields.

The yield trial data are characterized by varietal attrition due to the replacement of older varieties by better-yielding varieties in successive years of the trials. Since the probability of varietal attrition is correlated with experimental response (i.e., yield), the traditional statistical techniques for panel data estimation will provide biased and inconsistent estimators (Hsiao 1986). The variable MR (inverse Mill's ratio) is included in the equation to correct for this selection bias of non-randomly missing varieties in the yield trials conducted over a number of years (Maredia, Ward, and Byerlee 1996).

Since the model is estimated separately for each ME, the coefficients for DORIG represent the performance of varieties from different environmental origins in a given ME relative to the "home varieties." The varietal group originating from the test ME was the benchmark variable (i.e., dummy variable DORIG_j was dropped from the equation for each ME). Therefore, the coefficients of DORIG_i are the differential yields defined as ($w_{ji} = Y_{ij} - Y_{jj}$). These coefficients were used to estimate the *potential* spillovers $S_{ij} = Y_{ij}/Y_{jj}$, based on the constant Y_{jj} (approximated by the arithmetic mean) for each ME.

9 Because of an insufficient number of observations, the equations were not estimated for two spring wheat MEs defined by CIMMYT (ME4C and ME5B).

Empirical Results and Estimation of the Global Spillover Matrix

Model parameters in Equation 1 were estimated using the ordinary least squares method. The statistical results of the regression analyses are summarized in Table 4.1. The results indicate that including dummy location variables had a significant positive effect on the R^2 of all the seven regression models. Similarly, the dummy variables for trial years also significantly increased the R^2 of the estimated models.

The coefficient of VINT variable measures the gain in average yield/ha/year of new varieties in a given ME. Note that the coefficient is an average for all the varieties and is not specific to a particular origin group. Except in ME3 (high rainfall, acid soils) and ME4B (low rainfall, winter drought), yield improvements are not significantly different from zero. The non-significant coefficients of VINT variable in many environments, including ME1 (irrigated), confirm the difficulty that wheat breeders have faced in maintaining a significant growth rate in yield potential since 1980 (Bell et al. 1995). As indicated by coefficients of the MR variable, there is a positive and highly significant (in most of the megaenvironments) relationship between observed yields and the probability of retention in the trials.

The coefficients of origin variables (w_i) estimate the yield advantage (or disadvantage) of varieties originating in different environments relative to the test environment (kg/ha). The dashes on the diagonal indicate that the coefficient of a variety group with the same environmental

Table 4.1. Regression results of potential spillovers at the megaenvironment level using ISWYN data, 1980s

Independent variable		ME1 Irrigated	ME2 High rainfall	ME3 Acid soils	ME4A Winter rain	ME4B Winter drought	ME5A High temperatures	ME6 High latitude
1. Constant[a]		4880 ***	3390 ***	336 **	2041 ***	1942 **	2221 ***	3394 ***
2. Dummies for year	R^2 change[b]	0.02	0.02	0.23	0.17	0.17	0.05	0.08
	F change[c]	35 ***	32 ***	184 ***	144 ***	46 ***	15 ***	124 ***
3. Dummies for location	R^2 change[b]	0.56	0.44	0.27	0.40	0.21	0.29	0.52
	F change[c]	166 ***	131 ***	287 ***	159 ***	59 ***	113 ***	154 ***
4. VINT[d]		4.27	31.2	10.9*	2.5	28.1**	-2.2	4.7
5. Mill's ratio, MR[a]		155 ***	135 ***	111 ***	93	141 **	97 **	87.7 **
6. Origin, DORIG[a,e]								
DOME1:	Irrigated	—	-189 **	-406 ***	-374 ***	-346 **	34	-223 ***
DOME2:	High rainfall	-232 ***	—	-509 ***	-307 *	- 275 *	-177	-175 **
DOME3:	Acid soils	-507 ***	-141	—	-568 ***	-282 *	-31	1
DOME4A:	Winter rain	-66	-226 *	-565 ***	—	-483 **	- 154	-259 **
DOME4B:	Winter drought	-486 ***	-101	-290 **	-334 *	—	161	-56
DOME5A:	High temperature	-593 ***	-525 ***	-219	- 672 ***	-328	—	-334 **
DOME6:	High latitude	-588 ***	-395 ***	-414 ***	-507 ***	-270 *	- 264	—
DCIM1	CIMMYT/Mexico	527 ***	490 ***	- 14	20	191	23	-91
DCIM2	CIMMYT/Other	227 ***	230 ***	-138	-105	16	7	-131 **
Number of observations		4641	4248	719	1824	850	935	2913
R^2		0.61	0.53	0.78	0.65	0.40	0.53	0.68

Note: *P < 0.05, **P < 0.01, ***P < 0.001.

[a] Number given is the estimated coefficient (kg/ha).

[b] Number given is the change in R^2 when a given set of dummy variables is entered in the equation that includes all the other variables.

[c] Number given is the F-ratio of the R^2 change.

[d] Number given is the estimated coefficient (kg/ha/yr).

[e] Origin groups DOME1 to DOME6 represent varieties developed by national programs for respective megaenvironments. DCIM1 indicates CIMMYT varieties released in Mexico and DCIM2 indicates CIMMYT varieties released in countries other than Mexico or not released anywhere.

origin as the test environment is defined as the "benchmark" and that all the other coefficients in that column represent deviations from the "benchmark" value.

The negative values of NARS varieties in all the megaenvironments confirm the hypothesis that varieties developed in a test ME perform better than varieties developed in other MEs. For example, the second number in the first column shows that NARS varieties of ME2 (high rainfall) origin yield 232 kg/ha less on average in ME1 (irrigated) than the NARS varieties developed for ME1 (after adjusting for other variables). The strength of this relationship is evident in that nearly all the off-diagonal elements are negative and usually statistically significant. The genetic differences among varieties and a difference in the selective environment at the test versus origin environments suggest that the matrix need not be symmetric (i.e., $w_{ji} \neq -w_{ij}$). The abundance of negative values both above and below the diagonal show that CIMMYT's ME system reflects true differences in selective environmental properties.[10]

The last two rows show that CIMMYT varieties perform well in most MEs, especially in ME1 (irrigated) and ME2 (high rainfall). For example, CIMMYT varieties released in Mexico (DCIM1) enjoy a yield advantage of 527 kg/ha in ME1 (irrigated) compared to NARS varieties of ME1 origin. The positive yield advantage of CIM1 in many test MEs indicates the spillover potential of CIMMYT varieties to these test MEs.[11]

Akin to previous studies, the spillover coefficients are presented in Table 4.2 in terms of coefficient ratios based on the average yields of the benchmark variable (i.e., $S_{ij} = Y_{ij}/Y_{jj}$) (Table 4.2). Off-diagonal values less than one indicate that directly introduced wheat varieties from other MEs yield less than those developed by local breeding programs in the test ME. Similarly, values greater than one (as in the case of CIMMYT varieties) indicate that directly introduced wheat varieties from these sources yield more than those developed by local breeding programs in the test ME. The average yield advantage of varieties developed by local breeding programs in a test environment compared to those developed by NARS in the other three closest MEs ranges from 2 to 12% across MEs, with an overall average of 6%.

The significant yield advantages expressed by varieties developed and evaluated in ME1, ME2, ME3, and ME6 relative to varieties developed in other MEs (implying less direct spillins of NARS varieties from other MEs) may occur because these MEs are found in countries with strong wheat research programs — for instance, India and Pakistan in ME1 (irrigated), Turkey and Spain in ME2 (high rainfall), Brazil in ME3 (acid soils), and the industrialized countries of Europe and North America in ME6 (high latitude). On the other hand, environmental distance plays a role in explaining the significant yield advantage

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10 These results provide analytical support for CIMMYT's ME classification system. However, using the same data set, but a different statistical procedure, namely cluster analysis, DeLacy et al. (1994) could not statistically differentiate between several of the MEs. They therefore argue that the ME classification system needs to be refined to reflect the true differences in environmental properties.

11 A note of caution on the comparability of the coefficients across columns: The values of the coefficients reported in Table 4.1 are relative to the benchmark origin group (represented by zeros) and are therefore comparable across rows (varietal technology groups) but not across columns (environments). Thus, we can say that in ME2, ME1 varieties yield 189 kg/ha less than ME2 varieties, but it is erroneous to say that ME1 technology yields 189 kg/ha less in ME2 than in ME1.

enjoyed by domestic varieties in ME4A and ME4B (low rainfall environments). To a certain extent, this also holds true for ME3 (acid soils) and ME6 (high latitude). For example, the growing conditions in ME3, except for the acid soil, are very similar to those in ME2 in terms of water supply and temperature. Thus, ME3 varieties perform relatively well in ME2. However, in ME3 the soil toxicity adds to the distance between the two environments and constrains the transferability of technology from ME2. This is evident from the highly significant yield disadvantage of ME2 varieties (19%) when planted in ME3 compared to the small and lower significant yield disadvantage of ME3 varieties (4%) planted in ME2. The asymmetry in the spillover matrix (i.e., $S_{ij} \neq S_{ij}$) can be explained by a trait (acidity tolerance) present in ME3 varieties and beneficial in ME3 but not detrimental in ME2. The more such traits are incorporated into most breeding materials, the more broad adaptation becomes feasible. The hexaploid nature of wheat may favor the accumulation of such traits and thus broad adaptation.

Regression analyses on the performance of CIMMYT varieties (CIM1 and CIM2) across MEs reveal the prominent wide adaptability and transferability of CIMMYT varieties to different environments. Figure 4.1 illustrates this broad adaptation of CIMMYT varieties for a sample of five MEs, and it supports the scenario of yield curve BB′ depicted in Figure 3.2. The environmental specificity and

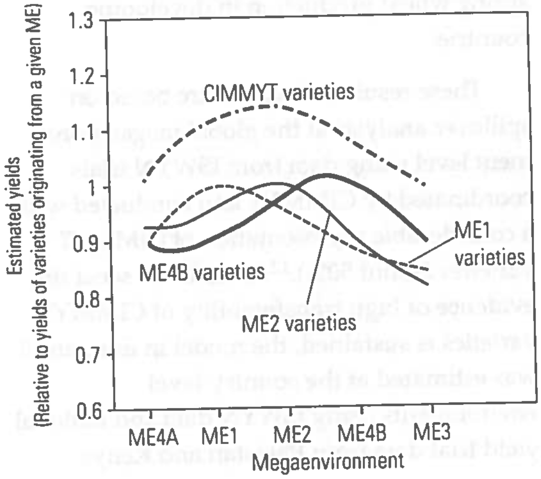

Figure 4.1. Estimated yields of wheat varieties originating from ME1, ME2, ME4B, and CIMMYT in five megaenvironments (MEs).

Table 4.2 Estimated spillover matrix for wheat improvement research at the global megaenvironment (ME) level

Origin of variety		MEs where varieties are tested[a] 1 Irrigated	2 High rainfall	3 Acid soils	4A Winter rain	4B Winter drought	5A High temperature	6 High latitude
ME1	Irrigated	1.00	0.95	0.84	0.90	0.88	1.02	0.94
ME2	High rainfall	0.95	1.00	0.81	0.92	0.90	0.89	0.96
ME3	Acid soils	0.89	0.96	1.00	0.85	0.90	0.98	1.00
ME4A	Winter rain	0.99	0.94	0.78	1.00	0.83	0.91	0.93
ME4B	Winter drought	0.90	0.97	0.89	0.91	1.00	0.90	0.99
ME5A	High temperature	0.88	0.86	0.92	0.82	0.89	1.00	0.92
ME6	High latitude	0.88	0.89	0.84	0.87	0.91	0.84	1.00
CIM1	CIMMYT/Mexico	1.11	1.13	0.99	1.01	1.07	1.01	0.98
CIM2	CIMMYT/Other	1.05	1.06	0.95	0.97	1.01	1.00	0.97

[a] Yield expressed relative to the yield of varieties originating in that ME = 1.00.

associated selective environmental heterogeneity evident in the comparison of NARS varieties are minimized when CIMMYT varieties are compared across different megaenvironments. This points to the success of the international research system in reducing GxE interactions and developing widely adapted varieties, at least in the irrigated and high rainfall environments, which account for about 70% of the spring wheat production in developing countries.

These results, however, are based on spillover analysis at the global megaenvironment level using data from ISWYN trials coordinated by CIMMYT and conducted with a considerable representation of CIMMYT varieties (about 50%).[12] In order to see if the evidence of high transferability of CIMMYT varieties is sustained, the model in Equation 1 was estimated at the country-level environments using ISWYN data and national yield trial data from Pakistan and Kenya.

Estimating Wheat Improvement Spillovers at the Country Level

Econometric Procedure and Data Sources

The multiple regression model of Equation 1 was estimated using ISWYN data for the specific MEs and countries as follows: (1) ME1 (irrigated) — India and Pakistan; (2) ME2 (high rainfall) — Kenya; (3) ME3 (acid soils) — Brazil; (4) ME4B (low rainfall, winter drought) — Argentina; (5) ME5A (high temperature/high humidity) — Bangladesh.

The trial entries were classified by their origin as follows:

DORIG1: varieties developed by a given NARS for the test environment

DORIG2: CIMMYT varieties released in the test environment

DORIG3: all other CIMMYT varieties

DORIG4: varieties developed by other NARS for the test environment

DORIG5: all other varieties developed by NARS

In addition, a model similar to Equation 1[13] was estimated using national yield trial data and country-specific environmental classification systems for Pakistan (normal- and short-duration irrigated environments) and Kenya (high rainfall environment). In the national yield trials, the entries were either locally developed NARS varieties or CIMMYT varieties. Thus, only two origin groups (DORIG1 and DORIG2) are defined for the Pakistan and Kenya equations using national yield trial data.

For Pakistan, the National Uniform Wheat Yield Trial (NUWYT) data were used. Two types of yield trials with different sets of varieties are conducted each year. The "normal planting" trials (with the date of planting ranging from November 10 to 24) are of the same planting date as CIMMYT's ISWYN trials and represent the optimal planting period for the region. The "late-planting" or "short-duration" trials with the date of planting after December 1 represent an environmental niche that has become very

[12] The high proportion of CIMMYT varieties in the analysis, however, does not bias the data in favor of the CIMMYT materials; it only makes the results with respect to CIMMYT more reliable.

[13] The variable MR (Mill's ratio) was not included in models using national yield trial data. The estimation of Mill's ratio requires average yield data over all the locations in a given year of the trial. Since we used the average yields for three provinces and only one environment (irrigated) in the case of Pakistan, data were not sufficient to estimate the Mill's ratio. The potential danger of its exclusion from the model is that it may over- or underestimate the yields of an origin group depending on its rate of attrition in the trial data set. However, this is not likely to be an important problem in the present data set since only two or three origin groups are compared in the model. Moreover, as a group, there is not much attrition over the years analyzed.

important due to increased cropping intensity in the irrigated regions of Pakistan (Byerlee et al. 1987).

The analysis is based on 14 years of data (1978–79 to 1991–92) for the normal-duration trials and 12 years (1978–79 to 1989–90) for the short-duration trials. The number of entries in the normal-duration trials varied from 16 to 24 each year with a total of 274 entries over the 14-year period. Similarly, the number of entries in the late planting trials ranged from 7 to 15 each year with a total of 129 entries over the 12 years analyzed. The data set analyzed includes 158 unique varieties in the normal-duration yield trials and 76 unique varieties in the short-duration trials.

For Kenya, the National Performance Trial (NPT) data for the years 1980–1984 and 1986–1992 were used. About 25 entries are planted each year at different locations in Kenya. Most of these varieties were developed by the Kenyan national program or CIMMYT's program in Mexico. The data set includes 287 entries and 140 unique varieties from 12 trial years. The number of entries and unique varieties in the ISWYN, NUWYT, and NPT data for country-level analysis is reported in Appendix 4A by their origin (Tables 4A.2 and 4A.3).

Empirical Results and Estimation of Spillover Coefficients

The results of the regression analysis are given in Tables 4.3 and 4.4. The interpretation of the year, location, and vintage variable is as in the previous models. The coefficients of the DORIG variables indicate the yield effects of a given origin group. As in the previous models, the yields of locally developed varieties are used as the benchmark coefficients. Thus, the coefficients of other origin groups indicate the yields relative to locally developed NARS varieties in the test environment.

A comparison of Tables 4.3 and 4.4 reveals that results of country-level analysis using the ISWYN data are very similar to those using national yield trial data. The 101 kg/ha and 314 kg/ha yield advantages of CIMMYT varieties in Pakistan and Kenya in national yield trials respectively are comparable to the 142 kg/ha and 261 kg/ha yield advantages estimated using the country-level data from the ISWYN data set. These figures indicate that results based on the international trials are a good proxy for estimating the yield advantages of varieties with different origins, at least for the environments with a normal-duration growing season.

Three results of these regressions are worth noting. First, as indicated by the positive coefficients of the DORIG2 variable (Tables 4.3 and 4.4), CIMMYT-developed varieties (which were not statistically significant in the ISWYN data but highly significant in the national data) outyield locally developed varieties for the respective local environment (except for Brazil, ME3). This implies that even large countries like Pakistan, India, and Argentina can import much of their wheat varietal technology, especially in the normal-duration irrigated and high rainfall environments. However, compared to varieties developed by other NARS for the same environment (DORIG4), locally developed varieties did yield higher in three out of five cases (Table 4.3), indicating the advantage of a local breeding program in the absence of the international research system. These results confirm the findings of the global analysis discussed earlier. They also make a strong case for intelligent borrowing, adaptation trials, and some selective local crossing.

Second, CIMMYT varieties released for a test environment in a country generally yielded higher than other CIMMYT varieties (Table 4.3). This indicates that NARS are efficient at selecting from the international research system. They select and release the best-suited varieties in the local environment from the available pool of potential spillovers from the international research system.

Third, in Pakistan the yield difference of locally developed varieties and CIMMYT varieties is insignificant in the late planting trials (14 kg/ha) relative to the normal planting trials (101 kg/ha) (Table 4.4). In other words, the length of the season is an important factor constraining research spillins from other sources, thus creating scope for locally developed varietal technology. The CIMMYT megaenvironment classification has only recently recognized the importance of late-planted irrigated wheat and has further classified ME1 into normal and late planting for breeding purposes (Rajaram and Van Ginkel 1996).

Synthesis of Major Findings and Implications

Many important results about transferring wheat varietal technology emerge from the statistical analyses presented in this chapter.

Table 4.3. Regression results of the spillover analysis at the country level using ISWYN data, 1980s

Independent variable		ME1 Irrigated		ME2 High rainfall	ME3 Acid soils	ME4B Winter rainfall	ME5A High temperature
		India	Pakistan	Kenya	Brazil	Argentina	Bangladesh
1. Constant[a]		4688 ***	3161 ***	994 *	811 **	2945 ***	1817 ***
2. Dummies for year:[b]	R^2 change[c]	—	0.47	0.41	0.36	0.26	0.23
	F change[d]		138 ***	54 ***	236 ***	62.4 ***	42 ***
3. Dummies for location:[b]	R^2 change[c]	0.73	0.00	—	0.27	0.22	0.01
	F change[d]	248 ***	1.79	—	289 ***	87.4 ***	11.4 ***
4. VINT[e]		-5.35	-2.39	58.7 ***	7.15	25.6 ***	-11 *
5. Mill's ratio, MR[a]		49.4	234 ***	207 *	116 **	212 ***	146 ***
6. Origin, DORIG[a]							
DORIG2: CIMMYT/test ME		53	142	261	-85	463	294
DORIG3: CIMMYT/other ME		-111	73	333	-104	25	64
DORIG4: Other NARS/test ME		-506 ***	-196	178	—	-310	226
DORIG5: NARS/other ME		-706 ***	-658 ***	-265	-422 ***	-386 **	-75
Number of observations		213	646	270	728	683	362
R^2		0.80	0.64	0.50	0.78	0.67	0.60

Note: $^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

[a] Number given is the estimated coefficient (kg/ha).

[b] The year and/or location dummies for some countries are missing for one of the following reasons: (1) There was only one trial location for the given years; (2) Either the location or year dummies were dropped out from the regression because of perfect collinearity. This would happen in cases when a trial location appears in only one year and that year has only one trial location.

[c] Number given is the change in R^2 when a given set of dummy variables is entered in the equation that includes all the other variables.

[d] Number given is the F-ratio of the R^2 change.

[e] Number given is the estimated coefficient (kg/ha/yr).

First, the results do not support the location-specificity argument (at least in terms of yields) when the international research system is considered as a source of research spillins. Wheat varieties originating from the collaborative CIMMYT-NARS international research system have proven highly transferable within MEs and across different countries around the world. The yield advantage of varieties developed by the international research system was as high as 13 and 11% in the high rainfall and irrigated environments, respectively. In other MEs (such as low rainfall, acid soils, and high temperatures), the yields of CIMMYT varieties, although higher than imported NARS varieties, were not significantly different from yields of locally developed varieties.[14]

Also, the results of the analysis based on the national yield trial data of Pakistan and Kenya clearly indicated the superiority of CIMMYT-origin varieties in most MEs. The country-level analysis offers no evidence of substantial yield gains for these countries whose own breeding program develops new

Table 4.4 Regression results of the country-level analysis using the national yield trial data (NUWYT and NPT) of Pakistan and Kenya, 1980s

Independent variable		Pakistan (irrigated) Normal duration	Pakistan (irrigated) Short duration	Kenya High rainfall
1. Constant[a]		3304 ***	3312 ***	1715 ***
2. Dummies for year	- R^2 change[b]	0.23	0.23	0.14
	- F change[c]	19.6 ***	9.2 ***	37.0 ***
3. Dummies for location	- R^2 change[b]	0.02	0.12	0.20
	- F change[c]	12.3 ***	27.5 ***	51.0 ***
4. VINT[d]				
5. Origin, DORIG[a] DORIG2: CIMMYT/test ME		101 ***	14.2	314 ***
Number of observations		694	321	1834
R^2		0.37	0.35	0.37

Note: $^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.
[a] Number given is the estimated coefficient (kg/ha).
[b] Number given is the change in the R^2 when the given set of dummy variables are entered in the equation that includes other variables.
[c] Number given is the F-ratio of the R^2 change.
[d] Number given is the estimated coefficient (kg/ha/yr).

[14] These results are different from Englander's results which ". . . suggest that varieties that incorporate CIMMYT technology and are developed locally outperform both traditional varieties (that do not incorporate CIMMYT genetic materials) and CIMMYT varieties" (Englander 1991, p. 310). These differences in results stem partly from the differences in data analyzed and partly from the differences in the estimation procedures. Englander employed the country of variety *release* (rather than variety *development*) as the measure of the origin. However, this is misleading because a country frequently releases a CIMMYT variety under a local name. Also, Englander's measures of yield advantages were based on political boundaries rather than the environmental boundaries used in this study. Given that one country often has multiple wheat growing environments, Englander's results are difficult to interpret.

varieties specifically targeted to the respective environments.

The overarching result of the global and country-level analyses is that varieties developed by the international research system perform better than or on a par with the NARS varieties in most of the major spring wheat environments. This parity reveals the success of the international research system in developing widely adapted wheat varieties. Success in combining high yield potential and wide adaptation can be attributed to:

- the large number of crosses (12,000 per year) made by CIMMYT breeders in Mexico;
- the use of "shuttle breeding," which allows CIMMYT scientists to alternate selection cycles in high-yield environments that differ in altitude, latitude, photoperiod, temperature, rainfall, soil type, and disease spectrum; and
- the wide testing of advanced lines in collaboration with NARS throughout the world (Romagosa and Fox 1993).

The comparative advantage of this international research system is its ability to conduct such a large breeding operation. However, it should be noted that wheat varieties are probably more "environmentally robust" than varieties of many other crops in terms of international transferability because the differences among production environments and local quality preferences are not as marked as in crops such as rice, maize, or beans.

There are a few caveats to be noted about the analysis presented in this chapter. First, given that ISWYN trials are conducted by CIMMYT to disseminate its germplasm, there is a large representation of CIMMYT varieties (about 50%) in the data analyzed in this chapter. However, the results of the analysis based on national trial data for Pakistan and Kenya do substantiate the conclusions from the analysis of ISWYN data.

Second, the results are based on the ME classification system that may overlook important variations within MEs such as late planting in intensively cropped irrigated areas. As the results based on NUWYT data for Pakistan indicate, the transferability of CIMMYT varieties may differ within an ME depending on the cropping system of a region and other country-specific factors.

Third, this analysis ignores other important factors like grain color and quality, which may be important in determining the local acceptability of varietal technology.[15] If the technology available from other sources is high yielding in the local environment but not compatible with the socioeconomic environment, then national programs can justify a local breeding program on the basis of other traits. But breeders agree that in a field crop like wheat, yield is the most important trait used in making decisions about releasing technology to farmers. Survey evidence suggests that, in general, farmers agree with this assessment (Traxler and Byerlee 1992).

[15] The analysis in this chapter also does not explicitly address the yield stability issue. However, the high average yield over several locations and trial years used in the analysis measures, albeit crudely, yield stability. We thus believe that stability is not completely ignored in the present analysis.

Conclusion

This chapter has provided empirical quantitative estimates of *potential* spillovers, which have hitherto been based on subjective guesses (e.g., Davis et al. 1987). In the age of shrinking budgets for agricultural research, national programs will have to take advantage of research spillins from not only other NARS in similar or varied environments, but also from the regional and international research systems. This chapter has demonstrated the usefulness of national and international yield trial data in providing estimates of *potential* spillins from other research programs and the international research system. Such information can be used to make strategic decisions about the design of crop breeding programs, both at national and international levels, that would lead to a more efficient global system of agricultural research.

Appendix 4A

Number of Entries and Unique Varieties in the ISWYN, NUWYT, and NPT Data Used in Various Analyses

Table 4A.1. Number of entries and unique varieties used in the global analysis using ISWYN data, grouped by their origin

Origin	Megaenvironment (ME) ME1	ME2	ME3	ME4A	ME4B	ME5A	ME6
ME1	46 (28) [a]	46 (28)	41 (25)	46 (28)	41 (25)	46 (28)	46 (28)
ME2	25 (18)	25 (18)	21 (14)	25 (18)	21 (14)	25 (18)	25 (18)
ME3	18 (14)	18 (14)	17 (13)	18 (14)	17 (13)	18 (14)	18 (14)
ME4A	13 (8)	13 (8)	9 (5)	13 (8)	9 (5)	13 (8)	13 (8)
ME4B	16 (9)	16 (9)	15 (8)	16 (9)	15 (8)	16 (9)	16 (9)
ME5A	8 (5)	8 (5)	8 (5)	8 (5)	8 (5)	8 (5)	8 (5)
ME6	27 (15)	27 (15)	23 (12)	27 (15)	23 (12)	27 (15)	27 (15)
CIM1	59 (13)	59 (13)	51 (13)	59 (13)	51 (13)	59 (13)	59 (13)
CIM2	95 (70)	95 (70)	76 (54)	95 (70)	76 (54)	95 (70)	95 (70)
Total							
Entries	307	307	261	307	261	307	307
Varieties	(180)	(180)	(149)	(180)	(149)	(180)	(180)

[a] Numbers in parentheses indicate unique varieties.

Table 4A.2. Number of entries and unique varieties used in the country-level analysis using the ISWYN data

Country by mega-environment (ME)	NARS varieties bred for a given ME	CIMMYT varieties bred or released by NARS for a given ME	Other CIMMYT varieties	Other NARS varieties bred for a given ME	Other NARS varieties bred for other MEs
ME1					
Pakistan	13 (8)[a]	9 (7)	145 (74)	33 (20)	116 (75)
India	5 (3)	3 (2)	31 (24)	11 (8)	34 (30)
ME2					
Kenya	4 (4)	9 (7)	126 (65)	18 (11)	113 (73)
ME3					
Brazil	17 (13)	8 (5)	119 (60)	—	126 (75)
ME4B					
Argentina	11 (7)	4 (2)	123 (63)	4 (1)	129 (81)
ME5A					
Bangladesh	4 (2)[b]	4 (2)	150 (79)	4 (3)	153 (98)

[a] Numbers in parenthesis indicate unique varieties.
[b] Varieties bred by Indian national program and released in Bangladesh for a given ME.

Table 4A.3. Number of entries and unique varieties in the normal-duration and short-duration NUWYT trials of Pakistan and the national performance trials of Kenya, grouped by their origin

Origin group	Pakistan		
	Normal-duration trials	Short-duration trials	Kenya
1.Cross and selection made by Pakistani research program	90 (63)[a]	59 (39)	200 (90)
2.Cross made by CIMMYT, but at least one further selection made by a Pakistani research program	22 (13)	7 (4)[b]	0 (0)[b]
3.Cross and selection made by CIMMYT in Mexico	119 (79)	48 (33)	87 (50)
4.Cross and selection made by another NARS	4 (3)[b]	0 (0)[b]	0 (0)[b]
Total			
Entries	235	114	287
Unique varieties	(158)	(76)	(140)

[a] Numbers in parentheses indicate unique varieties.
[b] Not included in the regression analysis.

Chapter 5

Investment in Wheat Improvement in Developing Countries

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Following the success of the Green Revolution in the 1960s, wheat improvement research attracted considerable resources, measured in number of scientists and size of budgets. In this chapter, we examine the resources currently invested in wheat improvement research (both at the national and international levels), and we profile wheat research programs in developing countries. We also present a comparative analysis of the size, composition, expenditures, and intensity of wheat research efforts by global region and national production levels. Our purpose is not only to document investments but also to provide information that policy-makers and research administrators can use to ensure that investments in wheat research remain productive.

Data Sources and Method

Our analysis of investments in wheat breeding research in developing countries is based on data from three sources:

1. A 1992 CIMMYT survey of wheat research programs in developing countries[1] provides information on 66 programs in 37 countries, including China (Appendix 5A). For each research program, information was collected on mandate area, number of researchers, type of research, targeted wheat types, number of crosses per year, breeding environments and objectives, and research expenditures.
2. A CIMMYT survey of 20 wheat research programs in 11 industrialized countries (Appendix 5A — an abridged version of the first survey — provides information on variables crucial for comparing research programs in developing and industrialized countries).
3. Various secondary sources of information.

National estimates of numbers of researchers reported in this chapter are based on either the first or third source.[2] When responses were received from all the wheat research programs in a given country (most of the small and medium-sized countries), national figures were estimated by aggregating over these programs. For a few large countries where coverage of wheat research programs was incomplete (Turkey, India, Pakistan, China, Brazil, and Argentina), country-level data for the number of researchers were either projected based on program-level information obtained from the

1 A wheat research program is defined as a research organization, public or private, that has a mandate to conduct research on wheat; it is usually identified with an experiment station.

2 To compare and aggregate the number of researchers dedicated to wheat improvement, we standardized the definition of research scientist across countries and converted the numbers to full-time equivalents. The survey data provided information on each scientist's discipline, level of training, and time devoted to wheat breeding research, seed production, crop management research, and administration. The number of scientist-years assigned to wheat improvement research was taken to include all time spent on the first two activities as well as each researcher's relative share of administration, regardless of the researcher's discipline. All researchers with a B.S. degree or above were included.

survey or supplemented by secondary sources. For some high-income countries (Australia, Germany, the UK, and the USA), secondary sources provided useful aggregate data for some variables that were included in the analysis for comparison.

The program-level analysis presented here is based on data from 63 programs in 35 developing countries.[3] These countries cover 94% of the developing world's wheat area (including China) and account for 97% of its wheat production.

Estimation of Expenditures on Wheat Improvement Research

The data on wheat research expenditures reported in the 1992 CIMMYT survey of developing countries suffered from many limitations, including inconsistencies in the definitions of wheat improvement, program-specific research expenditures, and currency units. Such inconsistencies made it difficult to aggregate and compare research expenditures across countries.[4] As an alternative, we estimate total expenditures based on the number of full-time equivalent (FTE) scientists in wheat improvement, derived from the 1992 survey, multiplied by the cost per scientist in 1990 purchasing power parity (PPP) dollars derived from Pardey et al. (1991a).[5] This methodology has the disadvantage of assuming that the cost per scientist is the same for wheat research as for the research system as a whole. However, we have no reason to suspect that the cost per scientist in wheat research deviates greatly from the average cost per scientist for other commodities. The major advantage of this method is that the cost estimate is comprehensive. It includes all the overhead costs and is a better way of aggregating and comparing expenditures across countries (Appendix 5B).

Since the cost estimates in PPP dollars convey a different concept of money than that which underlies financial transactions, which are almost always quoted using official exchange rates (OER), variables for aggregate expenditures are quoted both at the PPP exchange rate as well as the official rate as means of comparison.[6] These cost estimates at the official exchange rate are used in a later chapter to analyze the program-level decision to invest in wheat improvement research (Chapter 8).

3 Egypt and Iran were not included in the program-level analysis because they provided national-level information, which could not be disaggregated by program.

4 The need to compare wheat research expenditures across countries presents other complications. Expenditures can be converted to a common currency (usually the US dollar), but this is not as simple as it appears. Problems arise because of multiple exchange rates in some countries, day-to-day currency fluctuations, and frequent over- or under-valuation of currencies.

5 Pardey et al. (1991a) express cost per scientist-year in 1980 US $PPP. Following the World Bank approach (World Bank 1993), we approximated 1990 US $PPP by inflating it using the US consumer price index. Our methodology assumes that expenditures on wheat improvement research have neither decreased nor increased in real terms. In actual fact, expenditures per researcher have been declining in the majority of developing countries (on average by 2.4% annually from mid-1970s to the mid-1980s, as reported in Pardey et al. 1991a). To the extent that expenditures per scientist have continued to decline, our method will overestimate expenditures in the early 1990s.

6 The following approach was used to estimate the cost per researcher at the official exchange rate (OER) (1992 US dollars): First, PPP dollar estimates for each country for the most recent year available (as given in Pardey and Roseboom 1989) were converted to local currency units (LCU). Next, these figures were inflated to 1992 LCU using the individual country's consumer price index, based on the assumption that costs per researcher in LCU have remained constant in real terms. Then, the projected costs in LCU were converted to US dollars using the 1992 OER.

CIMMYT Resources Dedicated to Wheat Improvement

A 1991–92 survey of all staff was used to estimate the number of FTE scientists working on wheat improvement at CIMMYT. The following research activities were included: all of wheat crop improvement research, half of the genetic resources research (the other half was assumed to be devoted to conserving resources for humankind), half of the crop protection research (in addition to the time that crop protection scientists spent directly serving crop improvement research), crop management and physiology activities, and a prorated share of wheat research program administration.

Of the 30 senior scientists in the CIMMYT Wheat Program, we estimated that 19.5 FTE staff were engaged in wheat improvement activities (65% of total staff time). This estimate of FTE scientists includes only senior international staff. To make comparisons with national research systems, we included all persons engaged in wheat improvement research who had at least a B.S. degree (i.e., associate scientists, postdoctoral fellows, and *ingenieros*[7]), assuming that in aggregate their time was allocated to wheat improvement in the same ratio as that of senior scientists (65%). This gave a total of 36 FTE scientists engaged in wheat improvement research at CIMMYT in 1992.

To estimate CIMMYT's expenditure on wheat improvement, we multiplied the number of 19.5 senior staff by the average cost per senior scientist at CIMMYT in 1992. To this figure, we added an estimated 26% overhead. Thus, in 1992, the total expenditure on wheat improvement by CIMMYT was US$ 8.3 million.

Global Investments in Wheat Improvement Research

We estimate that national wheat research systems in developing countries (including China) employ more than 1,200 FTE scientists (B.S. degree and above) and spend more than US$ 100 million (1990 US$ PPP) or equivalently US$ 33 million (in 1992 US$ OER) annually on wheat improvement research.[8,9] The distribution of these resources varies widely across regions in the developing world (Table 5.1). In general, the investment in wheat research (in terms of number of scientists and expenditures) in a given region is congruent with the importance of wheat in that region. About 80% of the value of global wheat research in developing countries is spent in the two greatest wheat-producing regions in the developing world: Asia and West Asia/North Africa. Sub-Saharan Africa, the region of the developing world that produces the least wheat, has the fewest wheat scientists and the lowest expenditures on wheat improvement research. More than half of the researchers in the developing world are employed in the two largest wheat-producing countries, India and China.

The figures on expenditures per researcher reflect the costliness of research in different regions. In general, regions where human resources are scarce but state revenue (or revenue from other sources) is ample will have higher spending per researcher than regions where the number of researchers is expanding rapidly without a corresponding increase in research budgets. This explains the generally higher expenditure per researcher in West Asia/North Africa and the generally

7 An *ingeniero* has the equivalent of a B.S. degree in agricultural sciences.
8 Note that this does not include crop management and other agronomic research on wheat.
9 These findings can be compared with estimates of total wheat research expenditures in developing countries (excluding the two large wheat producers, China and Iran) in the 1970s of US$ 67 million (in US$ 1980) (Judd et al. 1991). Our estimate of US$ 33 million (at OER) is considerably lower than that of Judd et al., even considering that our estimate includes only wheat improvement.

lower expenditure per researcher in South Asia. In the past two decades, however, South Asia, unlike other regions, has experienced a steady increase in this indicator, perhaps because it has relatively mature research systems (Pardey et al. 1991b). An international research center, CIMMYT spends more per researcher than even the industrialized countries.

Compared to research expenditures in some industrialized countries, the estimated annual investment of US$ 100 million by developing countries seems moderate. The US alone spends 40% of the combined expenditures on wheat improvement research by developing countries. But the various research measures reported in Table 5.1 suggest that, even when one considers the large wheat area and production in industrialized countries, developing country expenditures on wheat improvement research are considerable. Developing countries employ an average of five wheat improvement researchers per million tons (M t) of wheat produced, or US$ 0.45/t. These figures are comparable to intensities in the industrialized countries. However, the data for developing countries are dominated by a few large nations (especially China and India) that have relatively low research intensities (measured in research expenditures per ton of wheat). Many developing countries have smaller mandate areas and therefore have research intensities that are considerably higher than those in industrialized countries. For example, half of the developing countries surveyed produce less than half a million tons of wheat (Table 5.2). On average, they employ more than 30 scientists per million tons of wheat and spend more than US$ 4 in wheat improvement research per ton of wheat produced. The number of researchers and research expenditures per million tons decreases dramatically as the national wheat production increases from less than 0.1 million tons to more than 5 million tons.

Table 5.1. A regional analysis of national wheat improvement research, early 1990s

Region/country	Number of NARS	Number of scientists (FTE)	Total research expenditure (M 1990 PPP US$)	Expenditure per scientist (000 1990 PPP US$)	Total wheat production, 1990-92 (M t)	Number of scientists per M t of wheat	Research expenditure per ton of wheat (1990 PPP US$)	Research expenditure as % of gross value of wheat produced[a]
Sub-Saharan Africa	9	39	4.4	113	2.1	18.4	2.10	0.18
West Asia and North Africa	12	344	45.3	131	46.5	7.4	0.97	0.25
Asia	6	719	41.3	57	168.3	4.3	0.25	0.02
Latin America	11	133	16.3	123	19.5	6.8	0.84	0.17
All developing countries	38	1,234	107.0	87	236.4	5.2	0.45	0.08
			(33.0) [b]	(35) [b]	–	–	(5.9) [c]	(0.87) [d]
CIMMYT	–	36	8.3	230	NA [c]	NA	NA	NA
Australia	1	109	8.8	81	14.0	7.7	0.63	0.30
Germany	1	50	9.4	188	15.5	3.2	0.61	0.34
UK	1	128	18.4	144	13.6	9.4	1.35	0.75
USA	1	278	44.0	158	65.1	4.6	0.73	0.55

[a] Since wheat production is valued at the international price, research expenditures are estimated at the official exchange rate.
[b] At official exchange rate (1992).
[c] Not applicable.
[d] Unweighted average across all countries.

The average intensity for wheat improvement research in developing countries was estimated to be 0.08% of the gross value of wheat production in the early 1990s. This is less than the average intensity in industrialized countries. Even considering that these expenditures only include crop improvement research, developing countries, on average, spend less than the average research intensity of 0.41% on all commodities in developing countries (Roe and Pardey 1991). However, as with the other measures of research intensity, the average for developing countries is biased downward because of a few large countries (such as India and China) that have a relatively low cost per researcher. As reflected in the unweighted average (0.87%), many national research programs, particularly in small wheat-producing countries, spend more than 1% of the value of wheat production on wheat improvement research alone (Table 5.2).

Wheat Improvement Research Programs in Developing Countries: A Profile

The previous section examined research investments at the aggregate level, encompassing all wheat improvement research programs in a developing country. This section presents a descriptive profile of an "average" wheat research program in a developing country.

A wheat research program is responsible for a "mandate region" to which it targets its products. Usually this region is defined by political boundaries. Although most small countries have only one wheat research program, many countries have numerous programs at various levels of government (e.g., provincial, state, federal) as well as at universities and private companies. An "average" developing country wheat improvement research program is described in Table 5.3. Such a program employs seven full-time equivalent (FTE) scientists in wheat improvement activities. These researchers make up, on average, 70% of all the scientists working in the program. The remaining 30% are involved in crop management research (including that part of crop protection that is unrelated to developing new wheat varieties). The average cost of a wheat improvement program in a developing country is about US$ 617,000 (in 1990 US$ PPP) or US$ 194,000 (in 1992 US$ OER). More than 70% of the wheat improvement programs in developing

Table 5.2. Some measures of wheat improvement research intensities by the size of national wheat production in developing countries, early 1990s

Wheat production (M t)	Number of NARS	Number of scientists per country (FTE)	Expenditure per country (1990 PPP US$)	Number of scientists per M t of wheat	Research expenditure per ton of wheat (1990 PPP US$)	Research expenditure as percent of gross value of wheat[a]
<0.1	11	8	0.7	149.8	13.23	1.19
0.1 - 0.5	8	6	0.8	29.5	4.32	1.18
0.5 - 1.0	4	9	1.0	10.5	1.13	0.10
1.0 - 5.0	9	26	2.7	9.1	0.95	0.23
>5.0	6	139	10.8	4.1	0.32	0.05
All developing countries	**38**	**32**	**2.8**	**5.2**	**0.45**	**0.08**

[a] Since wheat production is valued at the international price, research expenditures are estimated at the official exchange rate.

countries focus on spring bread wheat, which is congruent with the share of spring bread wheats in total wheat area in those countries. Two of every three scientists employed in a research program have postgraduate degrees; three of every four scientists are breeders.

The average amount of wheat produced in the mandate region of a wheat improvement research program was about 3 M t. This amount varies tremendously from region to region, however, from less than 0.4 M t in sub-Saharan Africa to more than 5 M t in Asia (Table 5.4). Average wheat production in the mandate regions of the industrialized countries surveyed (9.5 M t) is much larger than in developing countries. However, mandate regions overlap more in industrialized countries than in developing countries, since many industrialized country programs are run by the private sector and compete in the same mandate region.

Table 5.3. Profile of an average wheat improvement research program in a developing country

Size of mandate region (M t)	2.9	(1.5)[a]
Size of the program (FTE)	7.2	(5.0)[a]
Cost of the program per year		
1990 US$ PPP	617,000	(337,000)[a]
1992 US$ OER	194,000	(89,000)[a]
Share of wheat improvement component in total wheat research effort in a research program (based on number of FTE scientists) (%)	73	
Average number of wheat types (e.g., bread, durum) targeted by a research program	1.6	
Average number of environments (e.g., irrigated or rainfed, high or low altitude, short- or long-season) targeted by a research program	3.4	
Wheat improvement research by type of wheat (based on number of scientists)		
Spring bread wheat (%)	72.3	
Spring durum wheat (%)	14.7	
Winter bread wheat (%)	12.5	
Winter durum wheat (%)	0.5	
Degree composition		
Ph.D. (%)	32	
M.S. (%)	35	
B.S. (%)	35	
Disciplinary composition		
Breeder (%)	74.2	
Pathologist (%)	11.2	
Agronomist (%)	4.6	
Cereal technologist (%)	3.2	
Entomologist (%)	1.5	
Physiologist (%)	1.4	
Others[b] (%)	3.9	

[a] Numbers in parentheses indicate the median measure.
[b] Includes agricultural engineer, soil scientist, administrator, weed scientist, nematologist, seed production specialist, irrigation specialist, computer scientist, and statistician.

The average size of the wheat improvement programs in Asia and in West Asia/North Africa (more than 8 FTE) is almost double the size in sub-Saharan Africa and Latin America (3.5 FTE). However, given the low cost per researcher, the average cost per program is lowest in Asia. Industrialized countries on average employ 4 FTE scientists per program, considerably fewer than developing countries, especially considering the larger average size of the mandate region.

Costs per program (in US$ PPP) in developing countries, on average, are comparable to those in industrialized countries. However, these broad comparisons do not account for differences in research costs arising from differences in the size of a program's mandate region. Research intensity indicators that take these differences into account provide a better comparative measure of expenditures among programs (Table 5.4 and Table 5.5).[10]

Table 5.4. A regional analysis of wheat breeding programs, early 1990s

Region	Number of programs surveyed	Number of scientists (FTE) per program	Total research expenditure (M 1990 US$ PPP) per program	Average wheat production in the mandate region (M t)	Number of scientists per M t of wheat	Research expenditure per ton of wheat (1990 US$ PPP)
Sub-Saharan Africa	6	4.5	0.505	0.37	12.0	1.35
West Asia/North Africa	17	9.4	0.941	1.41	6.7	0.67
Asia	23	8.1	0.464	5.39	1.5	0.09
Latin America	17	4.5	0.530	1.97	2.3	0.27
All developing countries	**63**	**7.2**	**0.614**	**2.91**	**2.5**	**0.21**
Europe	13	2.6	0.337	12.33	0.2	0.03
USA	4	7.9	1.233	4.40	1.8	0.28
Australia	3	6.7	0.543	3.74	1.8	0.15
All industrialized countries	**20**	**4.3**	**0.547**	**9.45**	**0.4**	**0.06**

Table 5.5. Measures of research intensity of wheat breeding programs in developing and industrialized countries, early 1990s

Size of mandate region (M t)	Number of research programs surveyed		Number of scientists per M t of wheat (FTE)		Research expenditure per M t of wheat (1990 US$ PPP)	
	Developing countries	Industrialized countries	Developing countries	Industrialized countries	Developing countries	Industrialized countries
<0.1	7	0	109.7	—	8.65	—
0.1-0.5	9	2	17.3	9.9	2.73	0.91
0.5-1.0	9	0	5.4	—	0.49	—
1.0-2.5	21	3	5.2	2.0	0.41	0.17
>2.5	17	15	1.1	0.4	0.08	0.05
All	**63**	**20**	**2.5**	**0.4**	**0.21**	**0.06**

10 Reporting research intensities for a specific wheat program assumes only one program per mandate region. In fact, a given region may have more than one wheat research program, and these programs may have overlapping mandates (e.g., a government research station and a university). For these reasons, caution must be used in interpreting research intensities at the program level. These reasons also explain differences in the intensities at the program and national levels in Tables 5.1 and 5.2.

In a small mandate region that produces less than 100,000 t of wheat, the relative costs of research programs are several times the costs of programs in larger mandate regions and in industrialized countries. For example, research expenditure per ton of wheat produced in the mandate region declines from nearly US$ 9.00 in the 7 smallest programs (which produce less than 100,000 t) to less than US$ 0.10 in the 17 largest programs (which produce more than 2.5 M t) (Table 5.5). Similarly, the number of scientists per million tons of wheat drops dramatically from more than 100 FTE in the smallest programs to about 1 FTE in the largest programs.

These regional differences have important implications. First, research intensity, measured either by number of scientists per million tons or expenditure per ton, is much lower in Asia than in sub-Saharan Africa, which has research programs with smaller mandate regions. Second, and somewhat more surprising, research costs and intensities in developing countries, with the exception of the large programs, are considerably higher than in industrialized countries.

Two reasons for the difference in wheat research investment are the smaller mandate area and larger number of scientists per program in developing countries, realities which more than offset the lower cost per scientist. On the other hand, mandate areas more frequently overlap in industrialized countries, which explains part of the difference in research intensities.

Conclusions

Over the years, resources devoted to crop improvement research — both the number of research programs and number of researchers per program — have risen in developing countries. In the early 1990s, developing countries employed more than 1,200 scientists and spent more than US$ 100 million on wheat improvement research. Many developing countries that are small wheat producers have established research programs that are quite large in relation to their mandate regions. Even developing countries that are large wheat producers may support programs that have small mandate regions (such as a state that produces little wheat) or that have overlapping mandate areas. Overall, wheat improvement programs in developing countries employ six times more researchers per million tons of wheat and spend three times more on wheat research per ton of wheat produced than programs in industrialized countries.

The conclusion of this comparative analysis is clear: Research costs and intensities are higher in developing countries because they have a larger number of scientists per research program combined with a smaller mandate area for each program.

Appendix 5A

Table 5A.1. Countries participating in the 1992 CIMMYT Survey of Wheat Research Programs

Sub-Saharan Africa	West Asia and North Africa	Asia	Latin America	Industrialized countries
Burundi	Algeria	Bangladesh	Argentina[a,b]	Australia[a]
Ethiopia	Egypt	China[a]	Bolivia	Belgium[b]
Kenya	Jordan	India[a]	Brazil[a,b]	Denmark[b]
Nigeria	Lebanon	Myanmar	Chile	Finland[b]
Sudan	Libya	Nepal	Colombia	France[a,b]
Tanzania	Iran	Pakistan[a]	Ecuador	Germany[a,b]
Zambia	Morocco		Guatemala	Portugal
Zimbabwe	Saudi Arabia		Mexico	Spain[a,b]
	Syria		Paraguay	Sweden[b]
	Tunisia[a]		Peru	UK[a,b]
	Turkey[a]		Uruguay	USA[a]

[a] Several programs from these countries responded.
[b] Includes responses from private companies.

Appendix 5B

Purchasing Power Parity

The Purchasing Power Parity (PPP) represents a synthetic exchange rate that seeks to compare the relative cost in local currencies of a specific basket of (traded and non-traded) goods and services. It is defined as the price of a commodity bundle in local currency divided by the dollar price of the same bundle.

Increasingly, the PPP exchange rate is used to make cost comparisons across countries The International Monetary Fund, for example, has begun to categorize countries by income levels defined by per capita dollar income at the PPP exchange rate rather than at the official exchange rate (OER). The PPP exchange rate accounts for the fact that a given sum of money can purchase more or less of a standard basket of goods in different countries due to differences in prices. Thus a given salary in a low-price country implies a higher purchasing power than the same salary in a high-price country. Therefore the salary in the low-price country should be valued higher to improve comparability. This is achieved by using the PPP exchange rate.

The cost of a basket of goods in the US serves as the reference base for defining the PPP rate (i.e., $1.0 spent in the US is worth exactly $1.0 PPP). PPP exchange rates can be calculated based on different standard baskets of goods. One could argue that the "basket" to use in this analysis should be the goods and expenses related to research. The first complication is that such rates are not available for a wide range of countries. We therefore used a PPP over GDP estimate, i.e., a general, economy-wide basket of goods, as in Pardey and Roseboom (1989).

Compared to the OER, the PPP exchange rate tends to increase expenditure data in developing countries. This occurs because the cost of goods and services is generally lower in these countries than in the US. The reverse is true for many European countries. For comparative purposes, Table 5B.1 lists the PPP and OER exchange rates of developing countries included in the analysis of this and other chapters of this report. As can be seen from this table, the exchange rate in terms of local currency unit per US$ is 30–50% lower in most of the developing countries when measured at purchasing power parity rather than at the official exchange rate.

Table 5B.1. PPP and OER exchange rates (local currency unit per US$) by country, 1980

Country	PPP	OER
Algeria	4.33	3.84
Argentina	2305.00	1837.00
Bangladesh	4.88	15.45
Bolivia	15.11	24.51
Brazil	32.34	52.71
Burundi	58.44	90.00
Chile	22.67	39.00
China	0.80	1.50
Colombia	23.90	47.28
Ecuador	14.82	25.00
Egypt	0.43	0.70
Ethiopia	0.72	2.07
Guatemala	0.63	1.00
India	3.02	7.86
Iran	55.15	70.61
Jordan	0.18	0.30
Kenya	4.78	7.42
Lebanon	2.59	3.44
Libya	0.34	0.30
Mexico	14.22	22.95
Morocco	3.04	3.94
Myanmar	2.39	6.59
Nepal	3.26	12.00
Nigeria	0.67	0.55
Pakistan	3.47	9.90
Paraguay	94.96	126.00
Peru	137.42	288.86
Saudi Arabia	3.77	3.33
Sudan	0.33	0.50
Syria	1.94	3.93
Tanzania	6.14	8.20
Tunisia	0.30	0.41
Turkey	42.03	76.04
Uganda	28.46	7.42
Uruguay	7.05	9.10
Yemen A.R.	1.95	4.56
Zambia	0.74	0.79
Zimbabwe	0.54	0.64

Chapter 6

Estimation of Actual Spillovers of National and International Wheat Improvement Research

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This chapter presents some empirical indicators of research output and *actual* spillovers from the international wheat research system. Estimates of research spillovers are used to clarify the impact of global wheat improvement efforts by both CIMMYT and NARS, as well as the degree of complementarity between the two. First, with respect to the worldwide wheat improvement efforts, we estimate research costs, benefits, and the rate of return generated in the post-Green Revolution period (i.e., the period since the mid-1970s). Second, we examine the hypothesis of declining returns on wheat improvement research by projecting the payoff to continued investments.

Our analysis focuses on crop improvement research for spring wheat produced in low latitudes (less than 40°).[1] These wheats account for more than 70% of the wheat area in developing countries, but are relatively unimportant in industrialized countries and hence have been the main focus of CIMMYT's international wheat breeding effort. However, many industrialized countries with agroclimates similar to developing countries have benefitted from CIMMYT's wheat research. Research spillovers to industrialized countries are also documented in this and the penultimate chapter.

Conceptual Framework

Our analysis is based on a model of NARS development that identifies three phases of international technology transfer or spillovers (Evenson 1988; Hayami and Ruttan 1985): material transfer, design transfer, and capacity transfer. According to this model, the scientific capacity of spillover recipients develops from merely accepting finished technologies, to screening and adapting technologies, to generating their own technologies once scientific capabilities have been fully transferred. The different methods of using CIMMYT germplasm can be broadly interpreted within the context of this model.

Chapter 7 describes a collaborative global system of germplasm development which has evolved over the past three decades. As part of this system, CIMMYT makes crosses and selections (often using material supplied by NARS) to produce advanced lines which are extensively tested in international nurseries run by more than 80 countries. CIMMYT does not release varieties for direct use by farmers. Rather, CIMMYT makes advanced lines available to NARS, which may then choose to name and release these varieties after testing and, sometimes, further in-country selection (category 1 of germplasm use, below). In Chapter 5, these were referred to as "CIMMYT varieties" as against the "NARS varieties,"

1 CIMMYT did not have a winter wheat improvement program until 1986.

which are developed (crossed, selected, and tested) by the national programs. The "NARS varieties" include varieties developed by NARS using CIMMYT lines as parents (category 2) and varieties developed without using any CIMMYT parents directly, although CIMMYT material is often present in grandparents or an earlier generation (category 3). The following taxonomy is used to classify "CIMMYT varieties" and "NARS varieties"; it is also used to indicate different types of spillovers:

Direct transfer of technology — varieties developed at CIMMYT (i.e., "CIMMYT varieties") and released after in-country testing and evaluation by NARS.

Adaptive transfer of technology — varieties developed by NARS (i.e., "NARS varieties") from crosses using at least one CIMMYT line as a parent.

NARS technology — "NARS varieties" developed from crosses with no CIMMYT parents.[2] These include both semidwarf, or modern, varieties (MVs) and improved tall varieties (TVs).

Data Sources

The major source of data for the empirical analysis is a 1990 survey of wheat research programs in 38 developing countries which produce about 80% of all low-latitude spring wheat (Byerlee and Moya 1993). This survey collected information on the output of wheat breeding programs, including:

- the names, pedigrees, and origins of all wheat varieties released from 1966 to 1990;
- the estimated area under individual varieties[3] in 1990; and
- the human resources committed to wheat improvement in 1990, measured in full-time equivalent (FTE) scientist person-years (B.S. degree and above).

We also collected data from yield evaluation trials of released varieties in over 20 countries to estimate the genetic gains in yield attributable to wheat breeding research. Finally, the 1992 survey on the size, scientific capacity, and costs of wheat research programs discussed in Chapter 5 was used to estimate the wheat improvement costs for NARS.

We stratify wheat areas in four geographic regions: sub-Saharan Africa (SSA), West Asia/ North Africa (WANA), South Asia (SA), and Latin America (LA);[4] we also refer to four major agroecological environments: irrigated, high rainfall (over 500 mm just prior to and during the growing season); drought-stressed (less than 500 mm of rainfall); and (4) high rainfall with acid soils. These four environments broadly correspond to ME1, ME2, ME4 (A,B,C), and ME3, respectively, as described in Chapter 3.

Evolution of the Global Wheat Research System: Analysis of Output and Spillovers, 1966–1990

Research Output

One indication of increased NARS scientific capacity in developing countries is that research output — measured by number of varieties released and area planted to MVs — has increased rapidly over the past three

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2 Virtually all semidwarf spring wheat varieties have some CIMMYT ancestry.

3 Area estimates were based on annual government surveys (in some countries), special surveys at regional or country levels, seed sales (in some countries), and wheat researchers' estimates. In a few large countries, questionnaires were sent to all major wheat research stations to elicit estimates of varietal use.

4 China, Iran, and Afghanistan are excluded from our analysis because data were lacking and because winter wheat dominates production in these countries.

decades. NARS released nearly twice as many varieties per year in the 1980s as in the 1960s (an average worldwide total of 64 releases per year from 1986 to 1990 compared to 35 releases per year from 1966 to 1970). From 1966 to 1990 more than 1,300 improved wheat varieties were released in developing countries; more than 90% of these varieties are spring wheats (Table 6.1).

Farmers in the major wheat growing areas now have access to a continual stream of new varieties, and varieties are being developed for more specialized agroecological niches. Because there is more wheat grown in Latin America and Asia, the NARS in these regions had more releases per year than the African regions (Table 6.2). In general, smaller countries release more varieties per million hectares, so it is not surprising to find that more varieties are released per million hectares of wheat production in sub-Saharan Africa. Even the number of varieties released in Latin America (in excess of 2.0 varieties per million hectares per year) is much higher than in industrialized countries (such as Australia and the U.S.), which on average release 0.1 to 1.0 varieties per million hectares per year.

Area sown to semidwarf varieties expanded from 12 million ha in 1970 (Dalrymple 1978) to nearly 50 million ha in 1990. Most of this expansion occurred in the post-Green Revolution period, 1975–90. Nearly all irrigated area was already sown to MVs in 1977, so diffusion during the post-Green Revolution period has occurred largely in rainfed areas. In 1990, some 80% of the spring wheat area in developing countries and more than 90% of production was based on MVs. Remaining areas of tall varieties (improved or local) are largely characterized by severe drought stress, often combined with extreme cold or heat stress.

Estimates of Actual Spillovers

Several important changes have occurred in the global system for producing varietal technologies since 1966. These changes reflect the increasing mobility of wheat varieties (spillovers) across international boundaries (Figure 6.1). The biggest change has been the

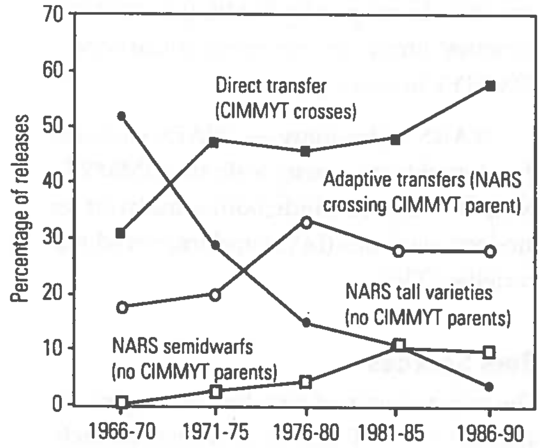

Figure 6.1. Categorization of NARS spring bread wheat releases by type of transfer.

Table 6.1. Varieties released in developing countries, by wheat type, 1966-90

Type of wheat	Number of varieties released	Percent of total varieties released	Percentage of developing country wheat[a]	
			Area	Production
Spring bread	1,090	82.8	71	77
Spring durum	126	9.6	13	9
Winter bread	96	7.3	14	11
Winter durum	5	0.4	2	2
Total	**1,317** [b]	**100**	**100**	**100**

[a] Excludes China, Iran, and Afghanistan.
[b] Excludes minor wheat types (e.g., *Triticum dicoccon*).

fall in the proportion of TVs from 52% of releases in 1966–70 to less than 5% in 1986–90. Increases have occurred in all other spillover categories. The proportion of releases that are direct CIMMYT transfers increased by 26%, adaptive or indirect transfers increased by 11%, and NARS semidwarfs increased from zero to 10%. In 1986–90, 85% of NARS releases were based on CIMMYT germplasm (i.e., direct plus adaptive transfers), compared to just 48% in 1966–70. The slightly paradoxical conclusion concerning the evolution of NARS

Table 6.2. Spring wheat area, number of variety releases, and releases per million hectares

	Area (000 ha)	Total releases (1966-90)	Releases/ M ha/yr	Average releases/ country/yr
Burundi	11	4	15.2	
Ethiopia	667	35	2.2	
Kenya	152	34	9.3	
Nigeria	50	6	5.0	
Sudan	200	8	1.7	
Tanzania	47	15	13.0	
Zambia	10	14	20.0	
Zimbabwe	52	25	5.0	
Total Sub-Saharan Africa	**1,189**	**141**	**4.9**	**0.7**
Algeria	1,211	23	0.8	
Egypt	687	18	1.1	
Iran	1,536	14	0.4	
Jordan	75	13	7.2	
Lebanon	25	10	16.7	
Libya	291	22	3.2	
Morocco	2,545	28	0.5	
Saudi Arabia	688	9	0.5	
Syria	1,104	11	0.4	
Tunisia	600	14	1.0	
Turkey	2,569	38	0.6	
Yemen	78	12	6.4	
Total West Asia and North Africa	**11,409**	**212**	**0.8**	**0.7**
Bangladesh	588	16	1.1	
China	657	61	3.9	
India	23,482	161	0.3	
Nepal	600	14	1.0	
Myanmar	124	10	3.4	
Pakistan	7,620	50	0.3	
Total Asia	**33,071**	**312**	**0.4**	**2.1**
Argentina	5,207	104	0.8	
Bolivia	83	22	11.0	
Brazil	3,141	179	2.4	
Chile	359	62	7.2	
Colombia	39	11	11.8	
Ecuador	25	10	16.7	
Guatemala	32	17	22.1	
Mexico	997	85	3.6	
Paraguay	236	21	3.7	
Peru	104	20	8.0	
Uruguay	209	20	4.0	
Total Latin America	**10,432**	**551**	**2.2**	**2.1**

breeding programs is that while the direct spillover of CIMMYT technology has increased markedly, the increase in adaptive transfers and NARS-developed semidwarf varieties indicates that the scientific capacity of NARS programs is greater than at any previous time. Certainly more developing country farmers have access to a steady stream of improved technologies today than ever before. This success is the result of a coordinated system of germplasm testing and the sharing of materials between CIMMYT and NARS, and among NARS.

By 1990, 57% of the spring wheat varieties released in developing countries were direct CIMMYT transfers and another 28% were adaptive transfers. The use of CIMMYT germplasm is consistently high across regions (Table 6.3). Adaptive transfers of CIMMYT materials are greater in Asia, where most advanced wheat breeding programs are located, compared with sub-Saharan Africa, West Asia and North Africa, and Latin America, where a greater number of varieties are based on direct transfers.

In 1990, 42% of the total spring wheat area was sown to directly transferred varieties, and another 24% of the area was sown to adaptive transfers (Table 6.4). Important inter-regional differences exist in the manner in which NARS make use of CIMMYT varieties. Only South Asia has a substantial area sown to NARS semidwarfs, and virtually all of this area is in India. Just 15% of the area is sown to NARS semidwarfs worldwide. The greatest impact of adaptive varieties has been in Latin America, but sub-Saharan Africa and South Asia also have substantial areas under adaptive crosses. CIMMYT varieties have had little impact in sub-Saharan Africa but are the major technology class in West Asia and North Africa.

The importance of direct CIMMYT transfers is also evident from Table 6.5, which indicates that most of the smaller NARS have depended on direct transfers for more than half of their varieties; a third of the NARS have depended completely on direct spillovers. Some larger producers also depend on direct transfers, including Mexico (where CIMMYT is located) and Pakistan (where the wheat-growing environments are very similar to those in Mexico). There are also significant country-to-country direct spillovers; some countries with small wheat programs — such as Sudan, Bangladesh, and Nepal — import

Table 6.3. Percent of spring wheat varieties released in developing countries by type of technology transfer, by region, 1986-90

	Sub-Saharan Africa	West Asia and North Africa	South Asia	Latin America	Total
	(Percent of total varieties released in a region)				
Direct transfer[a]	85	68	34	57	57
Adaptive transfer[b]	12	21	42	29	28
NARS semidwarf	0	9	24	7	10
NARS tall varieties and local varieties	4	3	0	7	4
Total	**100**	**100**	**100**	**100**	**100**

[a] Varieties based on CIMMYT crosses.
[b] Varieties based on NARS crosses using CIMMYT parents.

varieties from neighboring countries. Most larger NARS, on the other hand, have demonstrated a significant ability to develop varieties from their own crosses. We would classify Brazil, India, Argentina, and China as having reached the "scientific capacity transfer" phase within the Evenson/Hayami-Ruttan model. India, for example, increased its proportion of releases derived from its own crosses and lines so that now some 31% of semidwarf wheat varieties released are NARS technology (i.e., Indian crosses with no immediate CIMMYT parent) (Chapter 9). Access to CIMMYT germplasm, however, is crucial to the wheat improvement programs in these large countries; even the Indian and Chinese spring wheat programs make use of CIMMYT germplasm as a parent in more than 50% of their releases.

Although progress has been uneven among countries, the scientific capacity of NARS programs is greater than at any previous time. The increased coordination between CIMMYT and NARS in the global system of testing and sharing of germplasm has been an important component of this progress. Several developments have been

Table 6.4. Percentage of wheat area by type of technology transfer, by region, 1990

	Sub-Saharan Africa	West Asia/ North Africa	South Asia	Latin America	Total
Direct transfer[a]	15	51	40	44	42
Adaptive transfer[b]	27	10	25	42	24
NARS semidwarf	7	6	23	1	15
NARS tall varieties and local varieties	51	34	13	13	19
Total	**100**	**100**	**100**	**100**	**100**

[a] Varieties based on CIMMYT crosses.
[b] Varieties based on NARS crosses using CIMMYT parents.

Table 6.5. Classification of NARSs by the extent of released varieties based on direct transfers, 1966-90

Percentage of releases based on direct transfers				
<25%	**26-50%**	**51-75%**	**76-99%**	**100%**
Kenya	Argentina	Ecuador[a]	Guatemala	Algeria
Peru	Brazil	Egypt	Libya	Bangladesh[a]
	Chile	Ethiopia[a]	Mexico	Bolivia
	Colombia	Iran	Morocco	Burundi
	India	Jordan	Saudi Arabia	Lebanon
	China (South)	Pakistan	Sudan[a]	Myanmar[a]
	Zimbabwe	Paraguay	Yemen[a]	Nepal[a]
		Syria		Nigeria
		Tunisia		Tanzania[a]
		Turkey		Zambia
		Uruguay[a]		

[a] Countries with significant number of varieties directly transferred from other countries (rather than CIMMYT).

crucial to the increase in crop improvement capacity of NARS; all have received reduced financial support in the 1990s:

- overall funding for NARS,
- NARS investments in human capital development,
- germplasm sharing through a network of international wheat nurseries coordinated by CIMMYT scientists since 1964, and
- ongoing training and scientific exchanges between CIMMYT and NARS wheat breeders.

The nursery system in particular appears to significantly reduce the transaction costs of transferring varieties developed anywhere in the world.

Estimates of Research Spillovers to Industrialized Countries

CIMMYT is mandated to serve developing countries, and that is where its products are most widely adopted. Nonetheless, CIMMYT wheat germplasm has been used extensively in industrialized countries, especially where spring bread wheat and durum wheat are grown. A number of sources provide partial information on these technology spillovers. The summary of information for a few industrialized countries given in Table 6.6 indicates that 20 million hectares in industrialized countries are sown to indirectly transferred wheat varieties from CIMMYT. We do not have data for some of the countries in southern Europe — such as Spain, Portugal, and Greece — where CIMMYT germplasm is widely used. But even with conservative "guestimates" for these countries, at least 25 million hectares of wheat in industrialized countries are planted to varieties with CIMMYT ancestry.

Among industrialized countries, Australia has benefited the most from direct and indirect spillovers from CIMMYT wheat research. Chapter 10 presents a more comprehensive analysis of these spillovers to Australia; however, it is worth noting here that the spillovers from CIMMYT have contributed millions of dollars to Australian farm income. According to Brennan and Fox's (1995) estimate, by 1993, CIMMYT germplasm, which occupied 86% of Australia's wheat area, had contributed an average of 147 million Australian dollars (in 1993–94 values) annually to Australian farm income. Similarly, New Zealand has made extensive use of CIMMYT germplasm, beginning with selections from CIMMYT

Table 6.6. Partial estimates of the area sown in industrialized countries to varieties based on direct and adaptive transfers from CIMMYT

	Year	Wheat area (M ha)	Percentage of area with CIMMYT germplasm[a]	Total area with CIMMYT germplasm (M ha)
Australia	1990	8.7	85	7.4
Italy (durum only)	1990	1.7	60	1.0
New Zealand	1987	0.04	79	0.03
United States	1984	25.5	34	8.7
Western Canada	1992	12.3	28	3.5
Total		**48.24**		**20.63**

Source: See text.

[a] Includes varieties from CIMMYT crosses (direct transfers) as well as varieties with one or more CIMMYT lines in their ancestry (indirect transfers).

crosses and, more recently, moving toward using CIMMYT lines as parents in local crosses. Burnett et al. (1990) estimated that from 1973 to 1986 the proportion of wheat area sown to varieties based on CIMMYT germplasm increased from 0% to 79%; they estimated the annual average economic benefits of these varieties at US$ 0.5 million in this period.

Direct and adaptive transfers from CIMMYT have also been significant in other industrialized countries. As noted in Table 6.6, some 60% of the wheat area in South Africa (CIMMYT 1993), 60% of durum wheat area in Italy (INTERAGRES 1990), and about 28% of the main wheat growing provinces of the prairies in Western Canada (R. McKenzie, pers. communication) are sown to CIMMYT-based varieties.

Research spillovers from CIMMYT to the U.S. are also quite substantial. According to Dalrymple (1986), 34% of the wheat area in the U.S. in 1984 was sown to varieties based on CIMMYT germplasm. Since then, this area has certainly increased, especially in the spring wheat environments. Pardey et al. (1996) have recently updated these estimates of wheat research spillovers from CIMMYT to the U.S. As per the GrainGenes database cited in Pardey et al., since 1960 a total of 407 wheat varieties released in the U.S. were identified as either developed by CIMMYT (49) or containing a CIMMYT-developed ancestor (358). Pardey et al. estimate that from 1970 to 1993, CIMMYT contributed nearly 40% to the realized benefits of spring wheat improvement research in the U.S. In 1990 alone, CIMMYT's contribution amounted to more than US$ 400 million.

Returns to Wheat Improvement Research at National and International Levels

Economic analysis of the impacts documented in the previous section underscore the efficiency of investments in a global research system relative to other investments. However, our analysis estimates the costs and benefits of wheat improvement research in developing countries only. Previous studies estimated the benefits of the new wheat varieties released in the Green Revolution period, 1966–73, at US$ 625 million in 1973, or US$ 1.85 billon (in 1990 dollars) (Dalrymple 1977). In this section, we estimate the economic contribution of the new varieties of spring wheat in developing countries in the post-Green Revolution period (1977–90) and beyond.

Estimating Costs

Total NARS expenditures estimated in Chapter 5 are projected backward to 1973 using Pardey et al. (1991a) data on research expenditures by country, assuming that wheat research expenditures had increased at the same rate as research expenditures on all crops. Although this method of estimating the investment in spring wheat research introduces a number of simplifying assumptions (e.g., that the cost of supporting a wheat researcher is the same as the average cost per researcher for other commodities and that wheat research expenditures have commanded a constant share of total expenditures), the estimates are a reasonable approximation. CIMMYT's expenditures on spring wheat improvement were estimated for the period 1968–90 based on its budget and number of researchers working on spring wheat improvement.

Estimation of MV Yield Advantage

It is useful to distinguish between two types of varietal technical change (Morris et al. 1994). Type I change occurs in areas where MVs are replacing tall varieties, usually producing a sharp increase in productivity. Type II change occurs in areas where farmers are adopting a newer generation of MVs to replace the older generation of MVs. This replacement of varieties produces a steady gain in average yield and assures the maintenance of yield stability in the face of evolving pest biotypes.

Type I changes, of course, are the characteristic Green Revolution technical change considered in previous studies (Dalrymple 1977; Hertford et al. 1977). In the post-Green Revolution period under examination here, Type I changes have been important only in rainfed areas. Type II changes more often describe the situation in post-Green Revolution agriculture; they have been of primary importance in irrigated areas where farmers now periodically replace MVs to maintain disease resistance and to take advantage of higher yields from newer releases. One measure of the frequency of varietal replacement is the average age (in years since release) of varieties grown, weighted by the area sown to each variety. The weighted average varietal age ranges from 3.1 years in Mexico to 11.1 years in the Pakistan Punjab, with an average of about 7 years[5] (Brennan and Byerlee 1991).

Because the yield advantage of MVs is sensitive to the growing environment, benefit calculations were disaggregated into 16 production environment/geographic region combinations for both Type I and Type II changes (Table 6.7). The Type II yield increases for the irrigated and high rainfall areas were

Table 6.7. Rate of yield increase from Type I and Type II genetic gain, and annual rate of increase in average farm yields, by region, 1977-90

	Region			
Environment	Sub-Saharan Africa	West Asia and North Africa	South Asia	Latin America
		Type I yield increases (%)		
Irrigated	na	25	25	25
High rainfall	20	20	na	20
Acid soils	na	na	na	25
Drought	na	10	10	10
		Type II yield increases (% yr)		
Irrigated	na	1.2[a]	1.2[a]	1.5[a]
High rainfall	1.2[a]	1.2[a]	na	1.5[a]
Acid soils	na	na	na	3.0[a]
Drought	na	0.5	0.3	0.5
Annual rate of increase of farm-level wheat yields by region	1.6	2.4	3.0	3.4

na Spring wheat not grown under this agroclimatic condition in this region.
[a] Including a yield maintenance component.

5 An exception is northeastern India, where a large area is still sown to the original Green Revolution variety, Sonalika, and the weighted average is 19 years.

estimated as a sum of gains in yield potential from genetic improvement and the gains from maintaining disease resistance in the face of evolving pest biotypes (maintenance effect). In the drought environment, the maintenance benefit was assumed to be zero because disease pressure is typically low in these areas. The method used to derive these estimates is explained in Appendix 6A. Our estimates appear quite conservative; only in sub-Saharan Africa and in the acid soils areas of Latin America is genetic improvement estimated to contribute more than half of the total average increase in regional farm yields.

Calculating Economic Surplus

Type I production increases are calculated from the change in aggregate MV area multiplied by the yield effects presented in Table 6.7. Aggregate adoption information by region and agroecological environment is available at three points in time: 1977 (Dalrymple 1978), 1983 (Dalrymple 1986), and 1990 (our survey). These data show that aggregate adoption increased approximately linearly over the benefit period 1977–90. The yield effect from adoption of MVs over TVs is assumed to be constant through time, but to vary across regions and agroecological environments. The annual increase in production due to Type I technical change generated in each region and agroecological environment was calculated as:

$$\text{Type I} \quad \Delta Q_t = k^I Y_{TV} \bar{A} (MV_t - MV_0)$$

where k^I is the Table 6:7 yield increase estimate, $\bar{A}$ is average wheat area in 1977–90, MV_t is the percent of wheat area planted to MVs in year t, MV_0 is the percent of wheat area planted to MVs in 1977, and Y_{TV} is the average yield of tall varieties in 1977.

The annual increase due to Type II technical change for each region and environment is:

$$\text{Type II } \Delta Q_t = (k_t^{II} - 1)\, Y_{MV} \bar{A}\, MV_0 (s/7)$$
$$\text{for } t = 1978\text{–}1983$$

$$\text{Type II } \Delta Q_t = (k_t^{II} - 1)\, Y_{MV} \bar{A}\, MV_0$$
$$\text{for } t = 1984\text{-}1990$$

The research-induced yield advantage is assumed to grow at a compound rate, i.e., $k_t^{II} = (1 + g)^s$, where g is the environment-specific annual yield contribution given in Table 6.7 and $s = (t–1977)$. Y_{MV} is the average MV yield in 1977, and the $s/7$ term is included to allow Type II impacts to diffuse linearly over the first seven years of the benefit period beginning in 1978 before rising to a maximum area in 1983 to a level equal to the area planted to MVs in 1977.

The total economic surplus (ES) generated by wheat improvement research was calculated assuming linear demand and supply schedules and a parallel supply shift (Hertford and Schmitz 1977). For each region, annual surplus is

$$ES_t = P_t Q_t K_t (1 + .5K_t/(n+e))$$

where K_t is the percentage increase in production (DQ_t/Q_t) attributable to technical change, and P_t is the real wheat price defined in terms of whether the region was an importer (e.g., sub-Saharan Africa and West Asia and North Africa), or close to self sufficiency (Latin America and South Asia). The import price was approximated by the CIF Rotterdam price, and the self-sufficiency price by the average of the Rotterdam CIF price and Gulf Ports FOB price. Parameters n and e are the absolute values of the demand and supply elasticities.[6]

6 Demand and supply elasticities used are: $n = 0.11$, $e = 0.30$ for West Asia and North Africa and for sub-Saharan Africa; $n = 0.30$, $e = 0.38$ for Latin America; and $n = 0.35$, $e = 0.40$ for South Asia (Harwood and Bailey 1990). Estimates of total surplus are not sensitive to the elasticity assumption. As in similar studies, the IRR estimated with our model was not affected by the elasticity values.

Total annual benefits are the sum of Type I and Type II benefits in all four regions, each with up to four agroecological environments. A lag of 10 years between the initiation of CIMMYT research investments and the initiation of benefit flows is assumed. CIMMYT scientists take five years to develop advanced wheat lines[7] for transfer to NARS, and NARS spend an average of five years to evaluate the lines and initiate seed production.[8] A lag of five years on NARS research investments was assumed.

By the late 1980s, the total annual economic surplus generated by the joint research effort was estimated at nearly US$ 2.5 billion (excluding benefits generated in industrialized countries). Although annual total costs never exceed US$ 70 million, the benefits are heavily discounted because of the long lags that were assumed — 17 years from initial investment to peak benefits. The global research efforts by CIMMYT and NARS generated an IRR of 52%. By 1990 more than two-thirds of benefits were flowing from Type II technical change, and this share will continue to increase. The regional benefit shares are roughly congruent with production shares; nearly 65% of the benefits were generated in South Asia, while sub-Saharan Africa had just a 2% share.

An IRR was also calculated for each region while treating the CIMMYT research spillin as a free public good, so that the full surplus generated in each region was considered to accrue entirely to the regional NARS research investment. Under this assumption, regional IRRs were as follows: 91% in South Asia, 82% in Latin America, 71% in West Asia/North Africa, and 23% in sub-Saharan Africa.

Simulation of Future Returns to the Global Wheat Research System

The IRR calculated above is an average rate of return, rather than a marginal rate of return, so it is of limited usefulness in judging the merit of future financial commitments to wheat improvement research. Also, since MVs of spring wheats have now been adopted in all but the most marginal areas, sources of Type I technical change benefits have been nearly exhausted. Can this more expensive research system be supported by Type II benefits alone?

The model was used to simulate the performance of a global wheat improvement system with the following characteristics:

- world wheat area at 1990 levels,
- only Type II benefits are generated,
- CIMMYT and NARS expenditures continue at 1990 levels, and
- world wheat prices are fixed at the average price for the 1981–90 period.

The model generated an IRR of 48% when the annual rate of yield increase from genetic gain was assumed to hold at historical levels (i.e., the rates in Table 6.7). When the rate of genetic gain was assumed to be half the historical level — implying that only yield maintenance benefits are generated — the IRR fell to 37%.

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7 CIMMYT's shuttle breeding program produces two generations per year; thus, in five years, lines selected for ten generations are available.

8 The cost of the breeding program was phased in as described by Brennan (1889b). We assumed that generations one and two were sown in year 1, that two more generations were added in year 2, and so on until all ten generations became active in year 5. Therefore, year 1 costs are 11% of the cost of the mature (year 5) breeding program costs, year 2 costs are 39%, year 3 are 68%, and year 4 are 96%.

The simulations suggest that the global system of wheat breeding has considerable momentum. It seems quite certain that the system will at least be able to maintain current yield levels, so the 37% return might be considered a lower limit. We should also note that all the above calculations ignore the considerable spillovers occurring in developed countries.

Conclusions

We have assembled information on the resources *employed* and the output and spillovers *generated* by the global system of spring wheat improvement. Our objective was to examine the role of IARC-generated technology in the post-Green Revolution era. The data on varietal releases and diffusion confirm that farmers in all regions have greater access to superior varieties than at any previous time and that Type II productivity increases are now the primary source of technical change in spring wheat. The data also indicate the enormous success of the CIMMYT-NARS international collaborative system in generating both direct and indirect spillovers in developing countries — as varieties with CIMMYT parentage dominate developing country wheat production. Nearly twice as much area was sown to directly transferred CIMMYT wheat varieties in 1990 as at the height of the Green Revolution, and two-thirds of all spring wheat area is sown to varieties that were either directly or indirectly transferred.

Ex-post analysis of investments in wheat improvement research during the post-Green Revolution era indicates a rate of return above 50%, and we project that the system will provide a return on future investments of 37–48%. A strong complementarity exists between CIMMYT and NARS investments in wheat improvement research at present. Increased financial support for CIMMYT's two main activities — producing widely adapted varieties and coordinating the global nursery network for testing and distributing germplasm — is likely to enhance the effectiveness of NARS crop improvement programs of all levels of sophistication. The prospects for technical change are similarly improved as NARS expand their capacity to capture spillovers by adapting or efficiently screening CIMMYT varieties. Given the ability of the international system to serve a diverse range of NARS by generating both direct and indirect spillovers, NARS research and CIMMYT research are not likely to become substitute investments in the foreseeable future.

Appendix 6A

Estimation of Yield Gains for Type I and Type II Technical Change

A yield gain of 35–50% from Type I adoption of MVs in irrigated areas has been widely documented (Sidhu 1974; Byerlee 1993; Waddington et al. 1986; Dalrymple 1986). With the spread of MVs to rainfed areas, yield gains of 15–25% over TVs have been observed (Gafsi 1976; Macagno and Gómez Chao 1992). In dry areas, gains on the order of 10% are more commonly observed (Ahmad et al. 1991; Brennan 1989a). These estimates of observed yield gains were the basis for estimating the benefits of Type I varietal change.

The effect of Type II technical change on output can be approximated by the trend in genetic gains in yield potential of successive varietal releases.[9] Several statistical models have been used to estimate the average rate of genetic yield gain from varietal trial data (Patterson 1978; Godden 1988; Byerlee 1993). These trials include candidate varieties for release, as well as the main commercial varieties, and usually a long-term check. Over time the trials tend to be unbalanced, with older varieties being dropped from the trials and newer varieties added. In this study, we employed a variant of the "vintage" model (Godden 1988). Yields, Y_i, from unbalanced varietal evaluation trials are regressed on a set of dummy variables (D_t) for the year of the experiment and a variable (V), which is the vintage (number of years between release and the trial date) of the variety. The estimated parameter g is the negative of the annual yield growth rate.

(1) $$\ln Y_i = a + \Sigma_i b_t D_{ti} + \gamma V_i = e_i$$

The estimated annual yield gains calculated for 16 sets of varietal trial data are reported in Table 6A.1. Fairly consistent gains of approximately 1% annually were observed in the post-Green Revolution period in the main irrigated environments. Rates of gain were more variable in rainfed areas, averaging about 0.5 to 1.0% annually in high rainfall areas and approaching no gain in very dry areas. The most rapid gains have been made in rainfed areas with acid soils.

In the absence of varietal replacement, rust diseases erode yields rapidly in irrigated and high rainfall areas. In connection with this study, an agronomic experiment was conducted to measure the impact of maintenance research. Genetic gains in yield potential can be separated from the effect of improved or "maintained" disease resistance through trials with a factorial design that includes historical varieties grown with and without fungicide treatment. A set of MVs released in Mexico between 1966 and 1986 was grown with and without fungicide, and equation (1) was re-estimated with dummy variables:

(2) $$\ln (Y_i) = a + bF_i + \gamma_d V_i + \gamma_m V_i F + e_i$$

9 Evidence from farmer-managed trials and on-farm surveys indicates that the proportional yield gain in farmers' fields is similar to that achieved in varietal evaluation trials (Byerlee and Moya 1993).

where $F = 1$ for plots where fungicide was applied, and zero otherwise. The coefficient g_d is the annual rate of yield gain when varieties are unprotected from disease pressure; it includes both a yield potential effect and a yield maintenance effect. Because the annual rate of increase of protected varieties is expected to be less than that of unprotected varieties, the coefficient g_m has a negative sign. The value of $(g_d + g_m)$ is the rate of genetic increase, net of maintenance effects. Estimated values of –2.4% per year were obtained for g_d, and of 1.7% for g_m. Because disease pressure is unusually high on the experiment station, this undoubtedly overestimates the maintenance effect achieved in farmers' fields.

A significant share of research resources is devoted to maintaining disease resistance in the face of evolving pest biotypes (Plucknett and Smith 1986). For our model of benefits we assumed a maintenance effect equal to the gain in yield potential for the irrigated and the high rainfall areas. In drought areas, we assumed no maintenance benefit because disease pressure is typically low in these areas.

Table 6A.1. Summary of experimental evidence on rates of genetic gain in yields in spring wheat due to release of new varieties, yield maintenance effect not included[a]

Environment/location	Period	Rate of gain (%/yr)	Data source
Irrigated			
Sonora, Mexico	1962-75 [b]	1.1	Fischer and Wall (1976)
	1962-83 [b]	1.1	Waddington et al. (1986)
	1962-81 [b]	0.9	P. Wall, CIMMYT[c]
	1962-85 [b]	0.6	Ortiz-Monasterio et al. (1990)
	1962-89 [b]	0.7	K. Sayre, CIMMYT[c]
Nepal	1978-88 [b]	1.3	Morris et al. (1994)
Northwest India	1966-90 [b]	1.0	Jain and Byerlee (1994)
Pakistan	1965-82 [b]	0.8	Byerlee (1993)
Sudan	1967-87	0.9	Byerlee and Moya (1993)
Zimbabwe	1967-85 [b]	1.0	Mashiringwani (1989)
Rainfed			
Paraguay	1972-90	1.3	M. Kohli, CIMMYT[c]
Victoria, Australia	1850-1940	0.3	—
Victoria, Australia	1940-81	0.8	O'Brien (1982)
New South Wales, Australia	1956-84	0.9	Antony and Brennan (1988)
Western Australia (low rainfall)	1884-82	0.4	Perry and D'Antuono (1989)
Central India	1965-90	0.0	Jain and Byerlee (1994)
Acid soils (rainfed)			
Rio Grande do Sul, Brazil	1976-89	3.2	Byerlee and Moya (1993)
Paraná, Brazil	1969-89	2.2	Byerlee and Moya (1993)

[a] Regression results and data available from authors.
[b] Semidwarfs only.
[c] Unpublished data.

Chapter 7

Measures of Technical Efficiency of National and International Wheat Research Systems

Derek Byerlee and Mywish K. Maredia

With stagnating and in many cases declining budgets, wheat research efforts worldwide have come under increasing scrutiny. Reduced government and donor support for agricultural research and increased research costs have focussed attention on using research resources efficiently, both by NARS and IARCs. Questions have also been raised about the comparative advantage and roles of international and national research systems. In this chapter, we address these questions as they relate to spring wheat improvement research worldwide.

So far, this report has dealt with conceptualizing and empirically assessing spillovers in wheat improvement research. The evidence has revealed high *potential* and *actual* research spillovers from an international CIMMYT-NARS collaborative research system (Chapters 4 and 6). In this chapter we discuss the comparative advantage of the international research system. More specifically, we examine economies of size or cost-effectiveness and efficiency gains from geographic aggregation and research specialization. Our aim is to provide some technical efficiency measures that can help research managers, donors, and governments make informed decisions about the comparative advantages of national and international research systems. In the process, we will illustrate the cost-effectiveness of aggregated and specialized agricultural research. We begin with a brief overview of the global wheat improvement effort.

Wheat Improvement Research Systems in Developing Countries

Today wheat improvement research is conducted by a complex system that includes an international research center (i.e., CIMMYT) located in Mexico and an extremely diverse array of NARS; together they spend more than US$ 100 million annually on wheat improvement in developing countries (Chapter 5). Almost all countries where wheat is produced have national wheat research programs; two-thirds of these are involved in crop improvement research and most are led by plant breeders. As noted, national wheat improvement efforts vary in size (from China's program, with over 400 FTE scientists, to national programs with only 1 FTE scientist); organization (from one wheat research program for the entire country in Burundi, Bolivia, and Guatemala to more than 50 wheat improvement programs in India); and research capacity (in terms of a program's ability to generate new varietal technologies).

Global wheat improvement efforts in developing countries can be grouped into the following two research systems:

The CIMMYT-NARS international research system, consisting of the collaborative research and testing efforts by CIMMYT and NARS around the world. The salient features of the international system are: (1) the large number of crosses (12,000 per year) made by CIMMYT breeders in Mexico; (2) the use of "shuttle breeding" that allows CIMMYT scientists to alternate selection cycles in high-yield environments that differ in altitude, latitude, photoperiod, temperature, rainfall, soil type, and disease spectrum; (3) the wide testing of advanced lines in collaboration with NARS throughout the world; (4) the selection and release of wheat varieties (by NARS) that best suit local conditions; and (5) the sharing of information.

The NARS research system, consisting of separate national wheat breeding programs (one or many within a country) that develop locally adapted wheat varieties. The salient features of the NARS system are: (1) the "vertically integrated" nature of the breeding research, in which all stages of varietal development (crossing, selection, and testing) are managed separately by each of the NARS; (2) the use of varieties/advanced lines developed by the international research system or other NARS as parent materials in the local crossing program; and (3) a significant degree of national coordination and sharing of parent materials and information between NARS, especially large NARS.

In the taxonomy of spillovers described in the previous chapters, the CIMMYT-NARS international research system generates and uses *direct transfers*; the NARS research system generates its own technology (*NARS technology*) and uses *adaptive transfers* from its own research system and from the international research system.

Global wheat improvement efforts attempt to exploit the possibility of aggregation and specialization (in the CIMMYT-NARS international research system) and to accommodate political realities (in the NARS system). The hundreds of separate NARS programs, some operating in target areas too small to justify the costs of a breeding program, confront the complex political reality of independent decision-making, resource immobility, and regional pride. The CIMMYT-NARS international research system, on the other hand, is governed less by political boundaries and more by the biological reality of GxE interactions.

The international research system does not operate in isolation, however. Strong complementarities exist between the national and international systems. CIMMYT uses landraces improved by farmers over the centuries and germplasm improved by NARS as the basic genetic materials to develop widely adapted wheat varieties, which in turn are used by NARS, either as final products or intermediate products (i.e., parent materials) in their breeding programs.

In Chapter 2, we alluded to strong theoretical arguments in favor of an aggregated research system because of economies of size and the potential for research spillovers. Empirical evidence, however, should be the basis for determining economies of size and making decisions about the wide adaptation of products. Moreover, the roles and comparative advantage of the international and national research systems will vary greatly by country depending on the market size of the target region and the size and capacity of the research system. In this chapter, we present some empirical indicators to measure the technical efficiency of the international (CIMMYT-NARS) and national (NARS) spring wheat improvement system and to provide evidence of market size cost efficiency in wheat research.

Method and Data Sources

Measurements of Research Efficiency

Research efficiency is defined here as research productivity per unit of research input. Various productivity indicators have been used in the research-and-development (R&D) literature. The three output measures most commonly used are patents, publications, and products. Studies dealing with agricultural R&D have tended to use the number of scientific publications per unit of time (Evenson and Kislev 1975). This method is best suited to basic research or instances in which knowledge (rather than technological products) is still the main goal of the work.

In this chapter, products are used to measure research productivity. For applied research such as plant breeding, the product is very often a variety. But the number of varieties released by a program is often determined by factors that have nothing to do with research productivity (e.g., varietal release regulations or the personal pride of the breeder). Hence, we supplement this measure with figures on the adoption of released varieties. These output measures allow the attribution of the research product either to the international CIMMYT-NARS research system or to the NARS system, depending on the origin of the cross.

It is difficult to use a single measure that represents the input into the research process. The productivity of a research system is determined by many variables; some are quantifiable (e.g., the size of the program, research expenditures, research facilities), and some are less so (e.g., the quality of the scientific staff, morale and motivation of the researchers, research strategies). Research input in this study is defined by three quantifiable measures: the number of full-time equivalent (FTE) scientists, research expenditures (measured in 1990 US$ PPP), and number of crosses made per year.

Methodology

We measure research efficiency by various ratios of research output to per-unit research input. These ratios are calculated by size groups for national programs. Ideally, a measure of research efficiency should take into account the lag between the research input and output. For example, the number of publications in period t is related to research expenditures in period $t - n$. Since in reality it is difficult to establish a causal relationship in time between the input and output, the value of n is unknown. Moreover, the value of n varies with the input and output measures (e.g., hiring researchers may increase the number of publications at one rate and the number of varieties released at another).

As in most studies, we measure technical efficiency as a relationship between research inputs and outputs at a given point in time or an average over a given period. Due to data availability (or lack of it) measurements of research inputs correspond to the early 1990s; measurements of research output are approximated by the average over the 1981–90 period. Since the output measure precedes the input measure, we stress that they do not indicate a causal relationship, but provide only a crude indicator of productivity. The underlying assumption is that future output of current investments can be approximated by evaluating the research system's recent performance.

Data

Information on research output (i.e., the number of varieties released and the area of adoption for these varieties) was obtained from the CIMMYT impact study (Chapter 6). Based on their origin of cross, varieties are grouped as either *CIMMYT-NARS* or *NARS*. Data on the number of FTE scientists and the number of crosses per year were obtained from the 1992 CIMMYT survey (Chapter 5).

Expenditures on spring wheat improvement research for each NARS were estimated based on the total wheat improvement research costs in 1990 US$ PPP

(Chapter 5) adjusted by the area under spring wheats.[1] Estimates of CIMMYT spring-wheat research expenditures were based on the total budget for wheat improvement (Chapter 5) multiplied by the percentage of resources allocated to spring wheats by CIMMYT breeders.

No information was available on how the NARS divided their total wheat improvement costs for different stages of varietal development (e.g., crossing, testing). However, Brennan (1986) provides cost estimates of a breeding program by generations (F_1 to F_{10}). He estimates that a representative wheat breeding program in Australia spends about 83% of its resources on generations F_1 to F_6 (crossing, selection stage) and 17% on generations F_7 to F_{10} (testing stage). In other words, the pretesting component of the breeding program costs roughly about 6 (α) times the testing component. This information, combined with information on the percentage of varietal releases from the international system (x), was used to partition NARS' total costs (TO) into costs incurred on (1) the testing and releasing component of the international research system (cx), and (2) the crossing, selection, testing, and releasing component of the national research system [$\alpha c(1-x)$] as follows:

$$TO = cx + \alpha c(1-x)$$

where c is the cost of testing and releasing (locally developed and imported) varieties. Given the availability of information for each country on TO and x, and Brennan's (1986) estimate for $\alpha = 6$, the above equation was solved for c and the total cost partitioned into cx and $\alpha c(1-x)$. The proportional shares of CIMMYT-NARS and NARS in total research expenditures at a country level were also used to partition the total number of researchers working in the two systems.

A drawback of this method is that it assumes that the percentage of varieties released from the two systems reflects the relative efforts invested by NARS in these systems. But because many NARS in developing countries have active wheat breeding programs, yet in the past have released all or a majority of varieties based on CIMMYT crosses, this method may overestimate NARS costs in the international research system.

In order to estimate the joint costs of CIMMYT and NARS (i.e., all the stages of wheat improvement including crossing, selection, testing, and release) in the international research system by size groups, we first estimated the CIMMYT cost per hectare planted to CIMMYT-NARS varieties (h) (i.e., total CIMMYT costs divided by the total wheat area under CIMMYT-NARS varieties). This per–hectare cost was then multiplied by the total area under CIMMYT-NARS varieties (X) in each country to apportion the global CIMMYT costs to different countries. For each country, then, the total costs of the CIMMYT-NARS research system were calculated as the sum of $cx + hX$.

Global Spring Wheat Improvement Research System: A Descriptive Profile

Table 7.1 gives a regional perspective on the inputs and outputs of spring wheat improvement research programs. In general, the measures of research output (i.e., the number of varieties released and their adoption) seem to increase with the measures

[1] Research expenditures are based on the purchasing power parity (PPP) exchange rates rather than the official exchange rate because they are more appropriate for comparing cost estimates across countries.

of research inputs (i.e., the number of researchers and expenditures). For example, sub-Saharan Africa, which has the smallest research programs (4 FTE per NARS) and research expenditures ($0.5 M), releases the lowest number of varieties. Given the small mandate region, the area under adoption of released varieties is also smaller in sub-Saharan Africa than in other regions.

Although research teams in Latin America are much smaller than in Asia, researchers in Latin American NARS release on average as many varieties per year as researchers in Asian NARS. This productivity is also reflected in the large number of crosses made per year (about 2,000) by Latin American researchers. However, given the smaller size of the mandate region in Latin America (1.8 M t) relative to Asia (17 M t), the number of varieties released per ton of wheat produced in Latin America is much higher than in other regions, including Asia.

CIMMYT's wheat improvement research program (29 FTE) is comparable in size to an average developing-country NARS. However, other input measures, namely, the research expenditures and number of crosses per year, are much higher for the CIMMYT program than an average developing-country NARS. The international nature of CIMMYT's wheat breeding program — which involves international traveling, wide-scale disease screening in the field and the laboratory, and shuttle breeding — is reflected in both the higher costs and the large number of crosses made per year.

The relative shares of the CIMMYT-NARS system and the NARS system in global spring wheat improvement research is highlighted in Table 7.2. In the CIMMYT-NARS system, the crossing and early generation selection and testing are done by CIMMYT, and the late generation testing is done by NARS in yield trials at various locations to select locally adapted varieties. The CIMMYT-NARS research system uses about 30% (or 26 million US$ PPP) of the total resources allocated to global spring wheat improvement research. In the NARS system, on the other hand, each nation carries out all the components of a

Table 7.1. A regional perspective on the inputs and outputs of spring wheat improvement research in developing countries

Region	No. of NARS	Wheat production, early 1990s (M t)	Researchers, 1992 (FTE)	Research expenditure, 1992 (1990 M $PPP)	Number of crosses per year, 1992 (000)	No. of varieties released per year[a] (1981-90)	Adoption of varieties released in 1981-90[a] (1990) (M ha)
				(Mean per country)			
Sub-Saharan Africa	6	0.31	4	0.5	0.24	0.7	0.04
West Asia and North Africa	9	2.34	24	2.8	0.76	1.0	0.48
Asia	4	17.02	75	5.5	4.47	2.9	3.65
Latin America	11	1.78	12	1.4	2.03	2.5	0.50
Developing countries[b]:							
Average	—	3.69	22	2.2 (0.7)[c]	1.61	1.7	0.82
Total	30	110.60	673	66.5 (21.7)[c]	48.42	51.7	24.70
CIMMYT	—	NA[d]	29	6.6	12.00	NA[d]	NA[d]

[a] Includes varieties developed by CIMMYT-NARS research system.
[b] Excludes China.
[c] Estimated using official exchange rate (1992 000 US$).
[d] Data reported for CIMMYT correspond to its research program and not the international CIMMYT-NARS research system. Hence the production, variety release and adoption variables are not applicable to CIMMYT.

breeding program itself (i.e., crossing, selection, and wide-scale testing)[2] and utilizes about 70% of the global wheat improvement resources.

In relative terms, the CIMMYT-NARS research system is most "active" in sub-Saharan Africa, where it has more than a 40% share of the regional resources, and least "active" in Asia, where it has less than a 25% share. Direct spillins from CIMMYT may be more important in sub-Saharan Africa because NARS are smaller and national wheat production is lower in that region.

In terms of the relative overall shares of NARS and CIMMYT in the CIMMYT-NARS international research system, NARS in aggregate employ seven researchers (FTE) for every researcher (FTE) employed at CIMMYT. Similarly, on every dollar spent by CIMMYT in crossing and early generation selection and testing, the NARS in aggregate spend US$ 2.5 (in US$ PPP)[3] on selection and wide-scale yield testing of this material. A true collaboration, the international system requires a large amount of NARS resources at the global level to realize the direct spillins generated by CIMMYT.

Even though the total number of crosses made per year by CIMMYT is just one-fourth of the total number of crosses made per year by NARS in aggregate, the CIMMYT-NARS research system releases about 27 varieties per year, more than 50% of the varieties released in developing countries (Table 7.2). However, the average adoption area per variety is lower for CIMMYT-NARS varieties than for NARS.[4] This is partly because many varieties from CIMMYT crosses are disproportionately released by countries with a small wheat area. Also, NARS figures are dominated by the success of two varieties derived from Indian crosses. If India is excluded, the adoption area under CIMMYT-NARS varieties increases to almost 60% of the global area (Table 7.2).

Table 7.2. Share of CIMMYT-NARS and NARS research systems in global wheat research input and output, early 1990s

Region	Researchers			Expenditures			Number of crosses/yr		Varieties/yr			Adoption area[e]		
	CIMMYT-NARS (%)	NARS (%)	Total	CIMMYT-NARS (%)	NARS (%)	Total	CIMMYT-NARS	NARS	CIMMYT-NARS (%)	NARS (%)	Total	CIMMYT-NARS (%)	NARS (%)	Total (M ha)
Sub-Saharan Africa	47	53	100	43	57	100	0	1,460	59	41	100	31	69	100
W. Asia and N. Africa	37	63	100	37	63	100	0	6,803	55	45	100	67	33	100
Asia	24	76	100	20	80	100	0	17,866	38	62	100	30	70	100
Latin America	31	69	100	30	70	100	0	22,293	58	42	100	40	60	100
Developing countries	31	69	100	30	70	100	12,000	48,422	53	47	100	39(59)[a]	61(41)[a]	100
Share in total (%):														
NARS	88	100	—	75	100	—	0	100	—	—	—	—	—	—
CIMMYT	12	0	—	25	0	—	100	0	—	—	—	—	—	—
Total (absolute)	**234[b]**	**467[b]**	**701[b]**	**26[c]**	**47[c]**	**73[c]**	—	—	**27.4**	**24.3**	**51.7**	**9.6[d]**	**15.2[d]**	**24.7**

[a] Excluding India.
[b] FTE researchers.
[c] 1990 M US$ PPP.
[d] Million hectares.
[e] The adoption area refers to varieties released between 1981-90.

2 At the global aggregate level, the NARS research system includes all the NARS varieties, no matter where they are released (i.e., it includes NARS-to-NARS direct transfers).

3 At official exchange rates, NARS costs are estimated to be US$ 1, in aggregate, to every dollar spent by CIMMYT.

4 Note that the adoption figure corresponds to the wheat area sown in 1990 to varieties released from 1981 to 1990.

Although the worldwide area under CIMMYT-NARS varieties is relatively less than the area under NARS varieties, the number of countries dependent on these varieties is very high. For example, 15 of the 30 countries surveyed had more than 75% of their wheat area under varieties from the CIMMYT-NARS research system. In nine countries, the figure was 100%.

A global perspective reveals the efficiency with which the CIMMYT-NARS component uses its share of the total resources allocated to wheat improvement research: In all regions of the developing world, the CIMMYT-NARS output share is proportionally higher than its input share. In other words, a dollar expended under the CIMMYT-NARS research system yields a higher output than under the NARS system. This is reflected in the various efficiency measures discussed below.

Measures of Technical Efficiency in the National and International Research Systems

To clarify how size affects efficiency, we grouped NARS by national wheat production levels (Table 7.3.). This size measure is highly correlated with the number of FTE researchers. NARS that produce less than 0.1 million tons of wheat per year average 4 FTE; that number increases to 80 FTE for NARS that produce more than 5 million tons. Other measures of research input (i.e., number of crosses/year) and research output (varieties/year) also increase linearly with the size of the NARS.

As a NARS gets bigger, inputs and outputs from the NARS system become increasingly important relative to those of the CIMMYT-NARS system (Table 7.3). The percentage of research expenditures devoted to NARS crosses, for example, increases from 34% in the smallest NARS to 84% in the largest NARS. The corresponding shares in the number of varieties and area under those varieties also increase almost linearly with NARS size. In other words, small NARS depend *relatively* more on direct spillins from the CIMMYT-NARS international research system (62–95%). Nonetheless, large NARS reap the largest *absolute* gains from the international system. For example, more than 85% of total wheat area under varieties from CIMMYT crosses is in countries that produce more than 2.5 million tons of wheat.

Table 7.3. Comparative indices of efficiency of spring wheat improvement research programs by size of wheat production, early 1990s[a]

NARS by size of wheat production (M t)	No. of NARs	Wheat prod. (M t)	No. of researchers (FTE)	No. of crosses	Percent varieties No. of varieties per year	Percent research expenditure from own crosses	Percent area in devoted to NARS crosses	Percent area in size group size group under own crosses[b]	Percent of global under CIMMYT crosses[b]	area under CIMMYT crosses	FTE/M t	Crosses/FTE/yr
< 0.1	7	0.05	4	171	0.6	9	34	5	95	1	92	38
0.1-0.5	7	0.29	5	263	0.8	43	66	18	62	4	18	52
0.5-2.0	6	0.96	10	1073	1.1	24	43	16	58	8	11	102
2.0-5.0	6	3.25	37	2140	2.8	42	70	49	51	28	12	57
> 5.0	4	20.76	80	6527	4.6	54	84	64	32	59	4	82
Average across all NARSs		**3.69**	**22**	**1614**	**1.7**	**41**	**70**	**57**	**39**	**100**	**6**	**72**

[a] All columns are per-country basis, except for the column that estimates the percent of global area under CIMMYT crosses. Figures for the area refer to the 1990 area under varieties released between 1981-90.

[b] These two categories do not add up to 100 for some groups because of the NARS-to-NARS direct transfers.

Research intensity, measured by the number of researchers per million tons of wheat, declines dramatically from 92 FTE/M t in the smallest NARS to only 4 FTE/M t in the largest. However, when measured by the number of crosses made per FTE researcher, research intensity increases with NARS size. This reiterates the observation that large NARS focus more on creating their own varietal technology and that smaller NARS rely more on testing varieties developed by the CIMMYT-NARS international research system.

Table 7.4 provides various comparative efficiency measures of the NARS and the CIMMYT-NARS research systems by the size of the NARS. Overwhelmingly, the output-to-input ratios (e.g., variety/FTE) are higher and cost-to-output ratios (e.g., cost/variety) lower for the CIMMYT-NARS research system at all sizes of NARS. On average, the CIMMYT-NARS system releases almost double the number of varieties per million US$ PPP and FTE researcher than the NARS system. The number of varieties per 1,000 crosses is almost four times higher in the international research system than in the NARS system.

Varietal adoption is probably the best measure of productivity. The cost per hectare adopted[5] is lower for the CIMMYT-NARS research system in all size groups except in countries with 0.5 to 2.0 M t of annual wheat production. At the official exchange rate, for the largest NARS (i.e., those producing > 5 M t — mostly in Asia), the cost per hectare adopted to NARS varieties is significantly lower than the cost per hectare adopted to CIMMYT-NARS varieties, making the overall average cost per hectare under adoption lower for the NARS system. As shown by the estimates in parenthesis, however, the largest NARS size group (i.e., > 5.0 M t) is dominated by India, which has almost 80% of its wheat under NARS varieties. If India is excluded from the analysis of the largest NARS, the estimated costs per hectare at the OER are the same ($0.8/ha) for both the CIMMYT-NARS and the NARS research system.

The difference in the efficiency ratios of the international and national research system is more striking in smaller NARSs than in larger ones. In other words, wheat improvement research in larger NARS is

Table 7.4. Comparative measures of efficiency of the national and international research systems by the size of national wheat production, early 1990s

NARS by size of wheat production (M t)	No. of NARS	Variety/1,000 crosses		Variety/FTE/yr		Cost/variety (US$ PPP)		Cost/ha adopted (US$ PPP)		Cost/ha adopted (US$ OER[a])	
		CIMMYT-NARS	NARS	CIMMYT-NARS	NARS	CIMMYT-NARS	NARS	CIMMYT-NARS	NARS	CIMMYT-NARS	NARS
< 0.5	7	NA[b]	0.5	0.15	0.10	442	1,376	28.5	276.1	6.1	30.0
0.51.0	7	NA	1.7	0.24	0.12	847	1,307	5.9	16.3	3.6	7.4
1.0-2.0	6	NA	0.3	0.11	0.09	1,089	1,550	6.4	5.8	2.0	1.2
2.0-5.0	6	NA	0.6	0.12	0.05	1,091	2,445	3.6	6.9	1.9	3.0
> 5.0	4	NA	0.4	0.09	0.04	1,045	1,837	1.3	1.7	0.8 (0.8)[c]	0.3 (0.8)[c]
All NARS	**30**	**1.9**	**0.5**	**0.12**	**0.05**	**964**	**1,920**	**2.8**	**3.1**	**1.4**	**1.0**

[a] Official exchange rate.
[b] In the international CIMMYT-NARS system, individual NARS do not make crosses. Hence only the global average is reported for this variable.
[c] Estimates excluding India.

5 Cost per hectare was calculated by dividing total research expenditures on a given research system in a given size group by the total area in a given size group sown to the varieties developed by a given research system.

almost as efficient as the CIMMYT-NARS research system in large countries. This similarity may occur because research organization within the larger NARS closely resembles the international research system (as is the case in India), reinforcing the notion that there are economies of specialization in breeding research. The large apparent economies of size in wheat improvement research are confirmed by the finding that as NARS size increases, more varieties are adopted (from both the NARS and the CIMMYT-NARS systems) per unit of research expenditure.

Conclusions

For wheat improvement, various efficiency measures indicate that the CIMMYT-NARS international research system has a comparative advantage over the NARS system. The technical efficiency of the international research system measured in terms of crosses made by CIMMYT and varieties tested and released by NARS per FTE researcher more than compensates for the high cost per scientist at CIMMYT.

Various efficiency indicators suggest that an IARC such as CIMMYT, in collaboration with NARS, is a low-cost producer of improved germplasm. In general, the research output of the international system per unit of input is higher than the NARS system's average on all efficiency indicators, except for the cost per hectare adopted in the largest NARS (such as India) at the official exchange rate. Small NARSs depend *relatively* more on direct spillins from the international research system, but large NARS reap the largest *absolute* gains from the system.

Given the limitation of the methodology and the chronological discrepancy in the data used to measure research inputs and outputs, we reiterate that some of our results are merely indicative and represent crude measures of efficiency. Nonetheless, the evidence presented in this chapter indicates that the international wheat research system is truly a collaborative effort between CIMMYT and NARS. Developing country NARS in aggregate spend more than CIMMYT (75% of the total research expenditures) to release varieties based on CIMMYT crosses. By contributing both human and financial resources, NARS play a major role in realizing research spillins generated by the CIMMYT wheat improvement research program.

The results also suggest that there are economies of size and specialization in wheat breeding research. These economies result from the geographic aggregation of the crossing and early generation selection activities by CIMMYT and the division of labor in wheat improvement research between CIMMYT and NARS. In a perfect world without political boundaries, efficiency would improve considerably by having one or a few centralized breeding programs, such as CIMMYT's, linked to small testing programs located at key sites (Winkelmann 1994). Although we do not inhabit such a world, the efficiency of the present system can still be improved considerably by consolidating and rationalizing many existing programs and by improving regional and international collaboration. Moreover, in a world divided by political boundaries, an international research center has even a greater role to play by becoming an honest broker and helping NARS circumvent the political problems that sometimes hinder useful country-to-country collaboration.

Chapter 8

Efficiency of Wheat Improvement Research Investments in the Presence of Spillins

Mywish K. Maredia and Derek Byerlee

Budget pressure has raised questions about how to allocate limited agricultural research funds and how to justify the continuation, expansion, or (in many cases) downsizing of programs. In principle, research resources should be allocated to every product or sector in which the expected present value of research is positive. Because research funds are limited, however, not all such projects can be undertaken. To allocate research resources efficiently, decision-makers should rank research alternatives according to the net present value (NPV) and select the project with the highest benefits. This allocation principle is used here to analyze the efficiency of current investments in 69 spring wheat improvement programs in 35 developing countries and of the joint CIMMYT-NARS investments in wheat improvement at a global level for different spring wheat megaenvironments.

The basic premise of this chapter is that the investment alternatives for crop improvement research should be determined using a global model that incorporates direct research spillins. Such an analytical model is developed to determine the threshold levels of crop production in a country (or a region within a country) to justify crop improvement programs of different sizes. We conclude that, given the magnitude of potential spillins from the international research system, many wheat research programs could significantly increase their efficiency by reducing their research programs and focusing on the screening of varieties developed elsewhere. At the global level, the joint CIMMYT-NARS investment in directly transferable wheat varietal technology is shown to be efficient in almost all of the spring wheat megaenvironments.

Conceptual Framework

To account for the different impacts of direct and indirect spillins, resource allocation decisions are viewed in terms of research options (Evenson and Binswanger 1978). Two options are considered for wheat improvement research:

1. Investment in a testing program that evaluates imported germplasm and releases the best-adapted lines/varieties, or
2. Investment in an adaptive breeding program that creates new varieties, usually by crossing local and/or imported germplasm and selecting for the best-adapted materials.

These options correspond to the two research systems described in the previous chapter: a CIMMYT-NARS international system and a NARS system. Each option has different associated costs and benefits depending on the size of the commodity sector, the plant growing environment, resource costs, economies of size in research, and potential research spillins. Choosing efficiently between options requires a cost-benefit analysis which takes these variables into account (Binswanger 1974).

Figure 2.2 illustrates the benefit and cost functions for three of these variables as they relate to a breeding and a testing program: the size of the commodity sector, the potential research spillins, and the research costs. The four possible scenarios for different-sized commodity sectors (measured by the production level) are illustrated in Figure 8.1. The advantage of a local breeding program (option 2, above) is reflected in the increased slope of the benefit function at B in Figure 8.1.

If costs increase linearly with the number of scientists, four possible scenarios result, based on the net profitability of research investments. These scenarios are depicted in Panels 1–4 in Figure 8.1. In Panel 1, production in the mandate region is so low that crop improvement research is not profitable at all. In Panel 2, only a testing program is profitable with returns SR. In Panel 3, increased production in the mandate region makes both testing and breeding profitable. However, investment in a breeding program is inefficient at this level of production, since the returns from a testing program (SR) are greater than the returns from a breeding program (UT). Only in Panel 4 are returns from a breeding program greater than returns from a testing program.

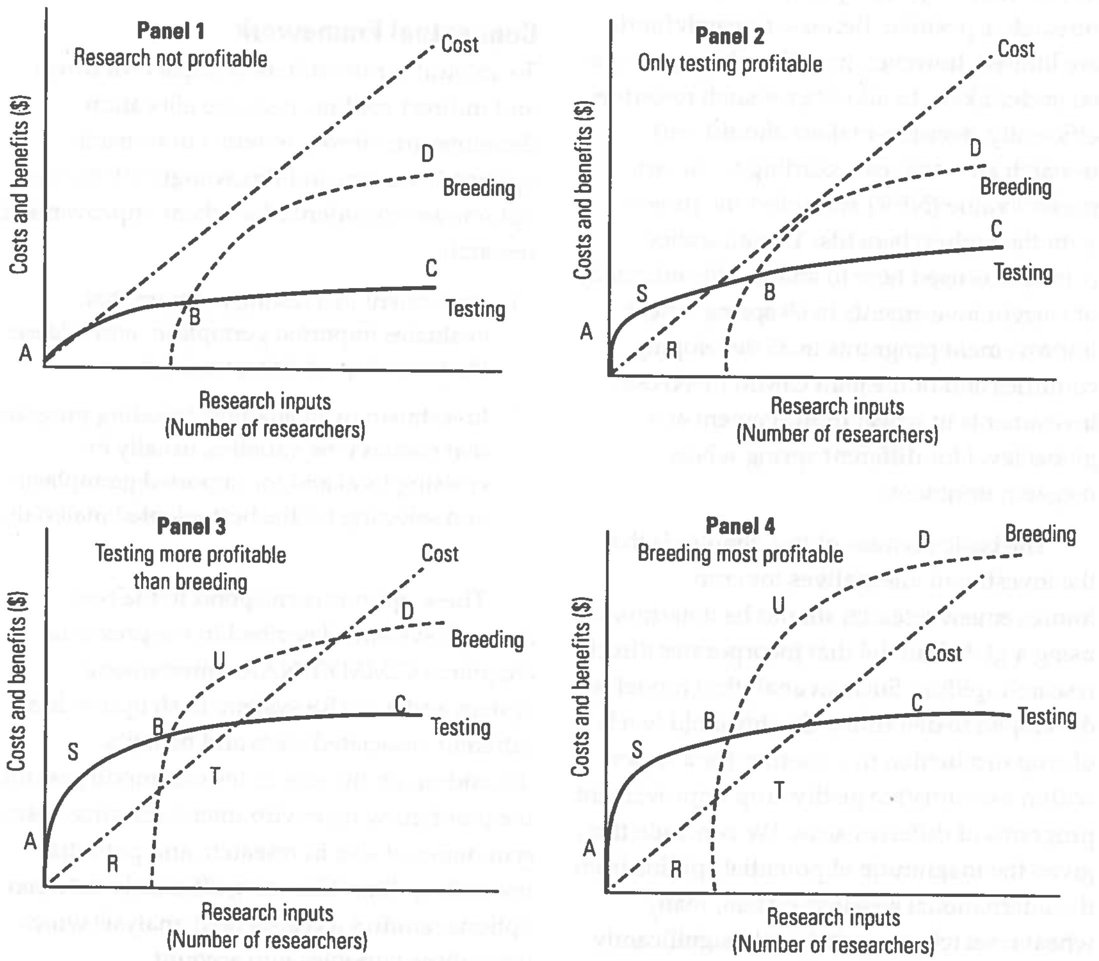

Figure 8.1. The impact of increased size of mandate area on the net profitability of a testing program and a breeding program.

Figure 8.2 shows how increasing direct spillins affects the efficiencies of both testing and breeding options for a mandate region where crop production corresponds to the region in Figure 8.1. An increase in direct spillins will increase the yield gains realized by a testing program relatively more than by a breeding program. This difference is reflected in the increased slope of the benefit function of a testing program in Panels 1–4 in Figure 8.2. In other words, for a mandate region of a given size, an increase in direct spillins makes a testing program relatively more profitable than a breeding program. A comparison of Panel 4 in Figures 8.1 and 8.2 reveals that a sufficient increase in direct research spillins can make a testing program more profitable than a breeding program in a region where breeding research was previously the most profitable alternative.

Figures 8.1 and 8.2 illustrate the various efficiencies of testing and breeding research options as a mandate region increases in size and as direct spillins increase in level. This basic framework is used throughout the chapter to determine the threshold levels of wheat production needed to justify testing and breeding research programs for a given level of potential spillins. More specifically, this chapter addresses the question: At what

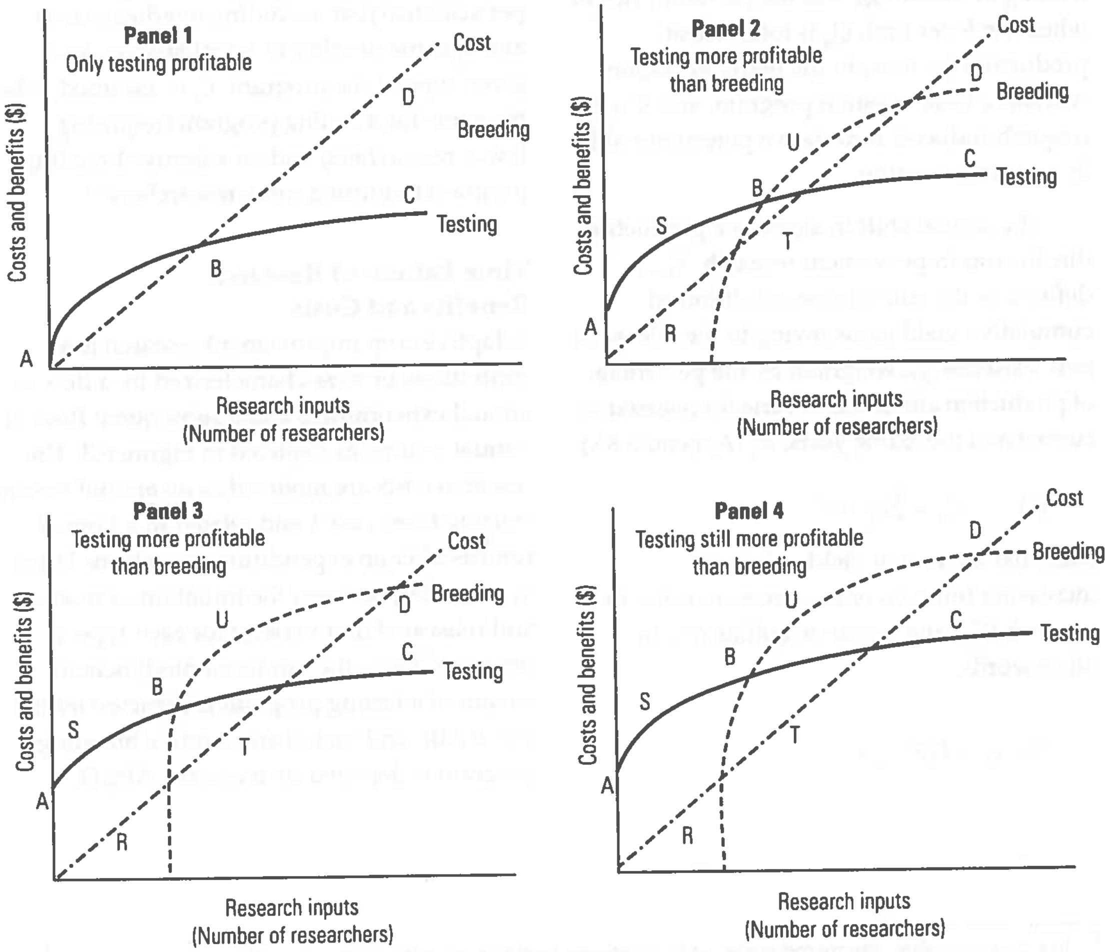

Figure 8.2. The impact of increased direct spillins on the net profitability of a testing program and a breeding program.

ranges of wheat production in the mandate region do the scenarios depicted in Figure 8.1 hold true? We also test the sensitivity of these ranges to changes in direct wheat research spillins from international programs, other national programs, or both.

The Cost-Benefit Model

Defining Research Benefits and Costs

Returns from research (B) in a given time period (T) are defined as:

$$(1) \quad B_{fT} = P_T Q_0 K_{fT}$$

where f denotes the type of research program (testing or breeding), P is the per-unit price of wheat (in $ per ton), Q_0 is total wheat production (in tons) in the mandate region without a local research program, and K is the research-induced cumulative percentage shift in wheat production.

The annual shift in aggregate production due to crop improvement research, K_{fT}, is defined as the sum of research-induced cumulative yield gains owing to the release of new varieties, g_f, weighted by the percentage of production attributed to varieties released in current and preceding years, w_i^T (Appendix 8A):

$$(2) \quad K_{fT} = \sum^{T}(g_f i) w_i^T$$

such that the rate of yield gain is an increasing function of resources invested in research (C_f) and research spillins (R). In other words,

$$(3) \quad g_f = F(R, C_f)$$

If we assign $f = 1$ for a testing program and $f = 2$ for a breeding program, then for a given level of direct spillins, R, the yield gains of a breeding program are greater than those of a testing program (i.e., $g_2 > g_1$) and so are the resources invested (i.e., $C_2 > C_1$). The difference ($g_2 - g_1$) reflects marginal gains from developing more location-specific varieties through adaptive breeding.

Given the available data on the total costs per scientist-year in plant breeding programs, the cost function used is:

$$(4) \quad C_f = C_s S_f$$

where C_f is the total cost for a given type of a research program; C_s is the average total cost per scientist-year, including overhead costs; and S_f is the number of scientist-years in a given type of the program. C_s is assumed to be the same for a testing program (requiring fewer researchers) and an adaptive breeding program (requiring more researchers).[1]

Time Pattern of Research Benefits and Costs

Adaptive crop improvement research is a continuous process characterized by a flow of annual expenditures and a subsequent flow of annual returns as depicted in Figure 8.3. The research costs are modeled as an annual stream starting from year 1 and related to a flow of returns after an expenditures-to-returns lag of n_1 years (lag between the initiation of research and release of first variety) for each type of program. Thus, the (undiscounted) benefit stream of a testing program is depicted by the curve ABE and that of an adaptive breeding program is depicted by the curve ABCD.

[1] In a given program, the marginal cost of an additional scientist will differ by program size, and therefore average costs may not accurately capture marginal costs. However, until additional data are available to clarify this issue, this study assumes that the marginal cost is closely approximated by the average cost.

The n_1 and n_2 in Figure 8.3 represent the expenditures-to-returns lags (including the research lag and seed-production lag), with subscript 1 representing a testing program and 2 representing an adaptive breeding program. Since an adaptive breeding program will release locally tested varieties in the initial years, the benefit stream includes two components: (1) the benefits of tested varieties (with yield gains = g_1) from period n_1 to n_2, and (2) the benefits of locally developed varieties (with yield gains = g_2) from year n_2+1.

The S-shaped benefit curves for both the testing and breeding programs from year n_1 to T_c reflect the shape of the logistic diffusion rate of new varieties in the mandate region, with the diffusion reaching its peak in the year T_c.

The net present value (NPV) of investment in each type of research program (breeding and testing) is calculated by discounting the estimated annual returns and costs. To compare the profitability of investments in a testing versus an adaptive breeding program, the NPV is used to apply the profitability criterion as follows: Given the parameter values, accept the alternative with the largest (and positive) NPV when discounted at the opportunity cost of capital

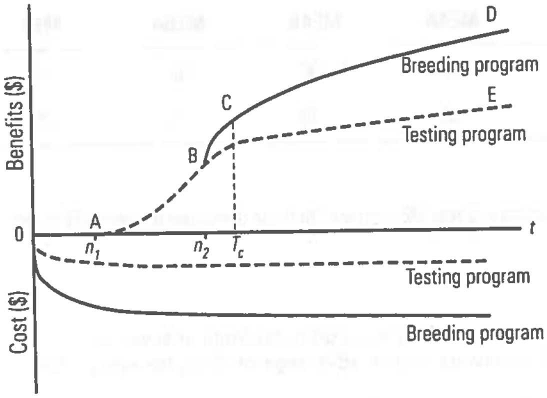

Figure 8.3. Time pattern of undiscounted cost and benefits of a testing program and a breeding program.

(Gittinger 1982). Thus, the decision to establish an adaptive breeding program in a given environment is negatively related to direct spillins from other programs, g_1 (which positively determines the NPV of a testing program). This is an important and distinctive feature of this framework, since it makes resource allocation decisions a function of direct spillins, which are assumed to be available to a program free of cost and with complete certainty.

We use the cost-benefit model discussed above for three purposes:

- to develop a baseline for a "median" wheat improvement program, using median values of key parameters in developing countries, in order to estimate ex ante the threshold levels of wheat production needed to justify a testing and adaptive breeding program at different levels of spillins;
- to analyze the efficiency of 69 specific wheat improvement programs spread across 35 developing countries, using, as far as possible, country- and program-specific data; and
- to analyze the efficiency of aggregated global CIMMYT-NARS investments in wheat improvement in 12 spring wheat megaenvironments.

All these analyses are based on the following assumptions: (1) past research costs are sunk costs (i.e., benefits of past research are not accounted for in the years before current research starts yielding benefits); (2) the size of wheat area, number of researchers, and real costs per researcher in each program are assumed to remain constant over the period of analysis at 1992 levels; (3) locally developed varieties are assumed to enjoy yield increments higher than imported ones throughout the period of analysis;

(4) research managers make decisions independently, assuming that they will not affect the global technology transfer pool; and (5) research spillins are assumed to continue.

Parameter Estimation

Estimation of Wheat Research Spillins

The value of g_1 that measures spillins is critical in the model. The results presented in Chapter 4 on the potential spillovers of wheat improvement research are used to estimate the value of g_1. The results in Table 4.2 can be viewed under two scenarios: with CIMMYT as a potential source of direct spillins and without CIMMYT. *Without CIMMYT,* the average yield advantage of varieties developed by local breeding programs in a test megaenvironment (compared to those developed by NARS in the other three closest megaenvironments) ranges from 20 kg for every 1,000 kg (i.e., 20 kg/t) to 120 kg/t, with an overall average of about 60 kg/t (Table 8.1).[2] *With CIMMYT* as a potential source of spillins, the overarching result of the regression analyses is that NARS cultivars developed for local environments have no (or minimal) advantage over CIMMYT cultivars. The largest gain with CIMMYT as a source of spillins is 20 kg/t, which is considered a more realistic estimate of the maximum advantage of a local breeding program. However, we recognize that the coverage of environments in the ISWYN data is incomplete and that there are undoubtedly areas where locally developed cultivars give significant yield advantage. Hence, we use the estimated yield advantage under both scenarios (ranging from 20 kg/t to 60 kg/t) to estimate the parameter g_1 in kg/t/yr.

Estimation of Model Parameters

For the market price of wheat, the long-term trend price was determined based on the average of the real import price (CIF Rotterdam) and export price (FOB US gulf) of wheat from 1964 to 1993.[3] The cost parameter C_s was based on the median cost per researcher in developing countries, estimated in Chapter 3 at US$ 20,000 (expressed in US$ 1992 at official exchange rates). The median number of researchers (S_f) for a wheat testing and adaptive breeding program was estimated to be 2 and 5 full-time equivalent (FTE) scientists,

Table 8.1. Estimation of wheat research spillins, with and without CIMMYT as a potential source of spillins

Sources of direct spillins	Yield gains of "home-developed" varieties (kg/t)[a] for each megaenvironment (ME)						
	ME1	ME2	ME3	ME4A	ME4B	ME5A	ME6
Other NARS[b]	50	40	120	70	100	30	20
CIMMYT	–110	–113	10	–10	–70	–10	20

Source: Chapter 4, Table 4.2.

[a] Rounded to the closest zero.

[b] Average yield advantage of varieties developed by local breeding programs in a test ME compared to those developed by the NARS in the other three closest MEs.

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[2] The percentage yield advantages given in Table 4.2 are represented here in kg/t to facilitate analysis and interpretation. Thus, a 0.2% yield advantage in Table 4.2 translates into an advantage of 20 kg for every 1,000 kg (1 t) of wheat production.

[3] CIF and FOB prices for wheat from 1964 to1993 were deflated by the US producer price index to obtain real-price series in US$ 1992. A log-linear trend was fitted to these price series to obtain the trend equations, which were used to calculate the trend prices for the years 1994–2042 in US$ 1992.

respectively, based on a survey of wheat improvement research programs in developing countries (Table 3.3).

Since most wheat varieties are selected after developing advanced lines of F_9 or F_{10} generation (i.e., lines that are selected for 9 or 10 generations consecutively) and require 2 years for release (seed certification and production), a research lag of 12 years was used for an adaptive breeding program (n_2). An average lag of 5 years was used for a testing program (3 years for testing and 2 years for release procedures) (n_1).[4]

The research program is assumed to release a new variety every year after the first release. The typical adoption pattern of a single variety (w_i) is assumed to follow a logistic growth curve in its adoption phase and a reverse growth curve in its disadoption phase (i.e., a bell-shaped curve).[5] According to Brennan and Byerlee's (1991) estimates, only about 5 years is required for a variety to reach peak adoption in some of the mature wheat research programs of developing and industrialized countries. However, based on the data collected in a 1990 survey of wheat varieties released in developing countries (Chapter 6), the average weighted age of wheat varieties was 11 years, suggesting a longer lag from adoption initiation to full adoption in many developing countries.

To test the sensitivity of the results, we use parameters that reflect these two observed adoption patterns (5 and 11 years). If in the base model we assume that disadoption of a variety takes the same number of years as required to reach peak adoption, the life of a variety is estimated to be 10 years (5 years for a single variety to reach peak adoption and 5 years for disadoption) (i.e., $w_i = 0$, for $i > 11$), and the diffusion (or cumulative adoption) of new varieties is assumed to reach 100% in the 11th year after the first release of a wheat variety (i.e., $T_c = n_1 + 11$). In the alternative scenario, the life of a variety and the diffusion lag are estimated to be 22 years (11 years for a single variety to reach peak adoption and 11 years for disadoption). The discount rate was assumed to be 12% per annum.

The average rate of yield gains of 10 kg/t/yr (i.e., 1% per year) for an adaptive breeding program (g_2) was based on Byerlee and Moya's (1993) estimates of the varietal component of yield gains for the well-watered environment in a number of countries. This estimate for g_2 and the estimate of spillins from the previous section are used to estimate the parameter g_1 as described below.

We assume that in 15 years after the first release of a locally bred variety (i.e., in less than two breeding cycles), a local adaptive breeding program will achieve a cumulative yield advantage ranging from 20 to 60 kg/t as observed in the analysis of ISWYN trial data (Table 8.1). Given the time pattern of research benefits (Figure 8.3), we calculate that in order to achieve a 60 kg/t cumulative yield advantage for an adaptive program that adds 10 kg/t every year (after the year n_2), the genetic progress of imported varieties from a

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4 The costs of the breeding and testing program in the first breeding and testing cycle were adjusted using the cost per generation estimates of Brennan. For a breeding program, we assume that generations 1 and 7 (imported lines) are planted in year 1; that two additional generations are added in year 2, etc. until all 10 generations become active in year 6. Therefore year 1 costs for a breeding program are 27% of the cost of the mature program (with all 10 generations), year 2 costs are 42%, year 3 are 63%, year 4 are 68%, and year 5 are 77%. Similarly, for a testing program, we assume that generation 7 (from imported lines) is planted in year 1, and one additional generation is planted in year 2, etc., until generation 10 materials are planted in year 4, when a testing program becomes active. The year 1 costs of a testing program are 74% of a mature testing program, year 2 costs are 87%, and year 3 costs are 94%.

5 See Appendix 8A for a detailed illustration.

testing program would be 4.0 kg/t/yr less than for an adaptive breeding program (or g_1 = 6.0 kg/t/yr). Similarly, to achieve a 20 kg/t cumulative yield advantage, the progress in imported varieties from a testing program would be 1.4 kg/t/yr less then for an adaptive breeding program (or g_1 = 8.6 kg/t/yr).

Ex-ante Analyses of Investments in Wheat Improvement Research

Threshold Production Levels for Different Types of Research Programs

In order to develop general guidelines and explore their sensitivity to model parameters, we first develop a baseline for an "average" adaptive breeding program in developing countries using median parameter values across countries. For the median parameter values, the threshold wheat production level for both a testing and adaptive breeding program is established by setting the projected NPV at zero. The level of wheat production in the target area of the research program at which an adaptive breeding program (which includes the testing of foreign varieties) is more profitable than a testing program is established by equating the projected NPVs of the two programs.

Under the baseline scenario where only other NARS are the potential sources of spillins, the results indicate that a testing program for imported varieties (employing 2 FTE scientists) becomes the most profitable research strategy starting at an affected production level (i.e., the level of production affected by the adoption of new varieties released by the research program) of 20,000 t. A full adaptive breeding program becomes more profitable than a testing program only after the affected production level reaches just over 100,000 t, when the internal rate of return (IRR) is about 22%. Thus, even though investments in an adaptive breeding program earn good rates of return (12–22%), they are less profitable than testing-program investments unless the varieties produced account for at least 100,000 t of wheat in the region.

If we consider the second scenario with CIMMYT as a potential source of research spillins, *ceteris paribus*, it becomes very difficult to justify a local adaptive breeding program based on yield benefits alone in the most important MEs of the developing world. The smallest observed g_1 was 8.6 kg/t/yr, which requires an affected production level[6] of at least 275,000 t and an IRR of 38% to justify investment in an adaptive breeding program. A testing program seems to be the most profitable alternative if CIMMYT is considered as a potential long-run source of direct technology transfer.

The decision about whether to test foreign varieties or develop new varieties from local crosses clearly depends on the level of potential research spillins. Figure 8.4 shows the effect of increasing direct spillins on the IRR and the threshold level of wheat production to make an adaptive breeding program more profitable than a testing program. Research spillins in the form of directly transferable technology have a substantial positive effect on the IRR and the threshold production level at which breeding is more profitable than testing. In other words, larger direct spillins require an increasingly larger mandate region (and a higher IRR) to justify investments in an adaptive breeding program. Along with the spillover analysis (Chapter 4), these findings help to clarify the following.

6 Affected production is measured here in ME units rather than political units.

Consider the scenario in which NARS are the only sources of direct spillins. In countries that have wheat growing environments similar to ME1 (irrigated, temperate) and ME2 (high rainfall), the average yield advantages of locally developed or "home varieties" indicate that research programs in these MEs need an IRR of at least 22% and affected production levels of 100,000 t for a local adaptive breeding program to be the most profitable alternative. On the other hand, research programs in the more marginal environments (ME3, ME4A, and ME4B) — which have experienced the greatest yield advantages from locally developed varieties — can justify a local adaptive breeding program at a lower IRR if the yield advantage of home varieties is maintained.

The threshold level of wheat production is also sensitive to the time pattern of varietal adoption (Figure 8.4). As average wheat varietal age increases from 5 years (in the base model) to 11 years (observed in developing countries), the threshold level of wheat production required to justify a testing and adaptive breeding program increases by 100%. The higher weighted age of wheat varieties observed in developing countries reflects the slower rates at which new varieties diffuse among farmers. The sensitivity of results to the speed and diffusion rate of new varieties suggests research evaluation efforts must carefully examine the adoption and diffusion patterns of varietal technology. In addition, the finding emphasizes the importance of an effective seed multiplication and marketing system and an effective extension service in increasing the profitability of breeding research.

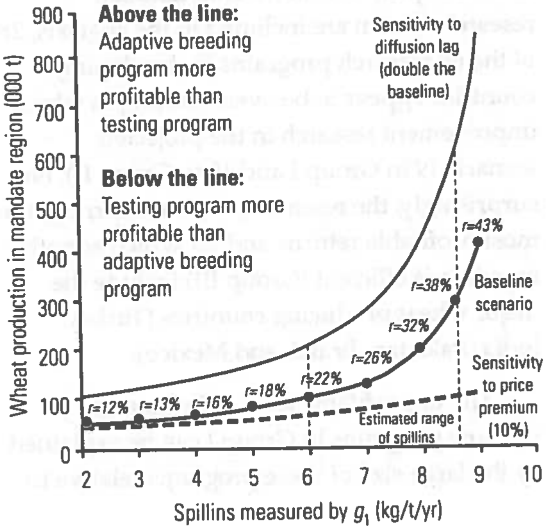

Figure 8.4. Sensitivity of implicit IRR and threshold level of wheat production for an adaptive breeding program to different levels of research spillins (measured by increasing g_1 for a given g_2=10 kg/t/yr), increased diffusion lag, and a 10% price premium for locally developed varieties.

The advantage of a local adaptive breeding program is measured above in terms of only one trait: yield. However, such a program may have an advantage in developing better varieties for other traits, especially traits that satisfy local consumers' preferences. To test the sensitivity of results to such quality differences, we assumed that the price of locally developed varieties was higher than that of varieties from a testing program. A 10% quality premium of locally developed varieties (within the range of commonly observed quality premiums) reduces the threshold levels of the most profitable alternative by more than 30%, indicating that the level of production at which an adaptive breeding program is most profitable is very sensitive to local quality premiums measured in terms of price differences (Figure 8.4). Such considerations are likely to be important in crops with location-specific consumer preferences, but they are relatively unimportant for wheat because similar consumer preferences prevail across countries for a given wheat type (i.e., bread and durum).

Analysis of Specific Wheat Improvement Programs in Developing Countries

The cost-benefit framework developed in the previous section is used to project ex ante the NPV of current levels of investment devoted to wheat improvement research by 69 spring wheat research programs in 35 developing countries. A research program is defined in terms of geographic area for all wheat types and may include one or more sub-environments based on other agroclimatic factors such as maturity, altitude, and moisture regimes.

We use program-specific information for the following parameter estimates based on the data collected in a 1992 survey of wheat research programs in developing countries (Chapter 5): Q (affected size of wheat production in the geographic region)[7] and S_f (number of FTE researchers in the program). For C_s (cost per researcher in US$ at the official exchange rate) we use country-specific estimates. The adoption parameter, w_i, was estimated based on country-specific information about the average age of varieties (Byerlee and Traxler 1995; Brennan and Byerlee 1991). For the other parameters — genetic yield gain in an adaptive breeding program (g_2), price (P_t), research lag (n_f), and discount rate (r) — we use the average values from the threshold analysis above. Since g_1, which measures research spillins, is the most important parameter in the model, we test the sensitivity of program-specific results at two levels of yield advantage: g_1 = 6.0 kg/t/yr (the average estimate without CIMMYT as a source of spillins) and the more realistic estimate of g_1 = 8.6 kg/t/yr (the maximum with CIMMYT as a source of spillins).

The ex-ante cost-benefit analysis in Table 8.2 divides the 69 research programs into three groups based on the NPV decision criterion. Under the assumption that g_1 = 6.0 kg/t/yr, Group I consists of 9 research programs that are projected to earn negative NPV on their current investments in wheat improvement research. For those adaptive breeding programs earning positive NPV, the NPV of an alternative investment in a testing program (assuming that such a research program employs one-third of the current number of FTE researchers)[8] was also projected. Group II consists of 9 programs whose NPV of current investments is less than the alternative investment in a testing program, and Group III includes 51 research programs earning maximum NPV (compared to the alternative of a testing program).

However, taking into account the empirical evidence of research spillins from the international research system, the number of inefficient programs (Group I and II) increases from 18 to 28. In other words, if potential research spillins from the international research system are included in the analysis, 28 of the 69 research programs in developing countries appear to be overinvesting in wheat improvement research in the projected scenario (9 in Group I and 19 in Group II). Not surprisingly, the research programs earning the most profitable returns and for which adaptive breeding is efficient (Group III) include the major wheat producing countries (Turkey, India, Pakistan, Brazil, and Mexico).

The unprofitable level of investment for research programs in Group I can be explained by the large size of these programs relative to

7 The affected size of wheat production in the mandate region was calculated by multiplying the total production in the mandate region as reported in the survey by the percentage production under modern wheat varieties (Byerlee and Moya 1993).

8 This ratio is based on the mean size of the testing and breeding programs estimated from the survey data of the research programs in developing countries (Chapter 3).

the small production levels in their target region. This discrepancy is reflected in the large number of scientists per million tons of wheat produced (Table 8.2), suggesting considerable economies of size in wheat breeding. The research programs in Group II, even though earning satisfactory rates of return (more than 12%), are inefficient because they are concentrating on adaptive research rather than screening imported varieties.

Our estimate of the number of inefficient programs is probably conservative. First, we have used a maximum estimate of the benefits that may be achieved from a local adaptive breeding program. The analysis of spillovers suggests that for many environments, the yield advantage of locally developed varieties relative to imported varieties is negligible or even negative. Second, we have assumed that varieties from a given program will diffuse to the entire mandate area (adjusted by the ceiling adoption), even though such diffusion in practice is incomplete because there are other breeding programs in the same mandate region. Third, the average CIF and FOB price of wheat that we have used overestimates the market clearing price in large countries close to self-sufficiency. We feel that these factors will generally outweigh any potential benefits of a local adaptive breeding program not considered in our analysis, including quality premiums for varieties developed for local tastes (not important for wheat), and risk considerations — uncertainty about the continuing supply of spillins and possible exposure to greater genetic uniformity if all neighboring countries plant varieties from the same spillin source.

Table 8.2. Wheat research programs in developing countries classified by the net present value (NPV) decision criterion for two levels of spillins

Group	Result of the analysis	Interpretation	Region	Level of research spillins (yield gains of imported varieties kg/t/yr) 6.0	8.6	FTE /M t wheat[a]
				Number of research programs		
I	NPV < 0	**Inefficient:** Cannot justify investment in wheat research (testing or breeding)	Sub-Saharan Africa	3	3	90.5
			West Asia /North Africa	3	3	
			South Asia and China	0	0	
			Latin America	3	3	
			Total	9	9	
II	0 < NPV < NPV of testing program	**Inefficient:** Investments in breeding are earning positive NPV, but less than testing	Sub-Saharan Africa	3	4	8.1
			West Asia/North Africa	1	7	
			South Asia and China	1	2	
			Latin America	4	6	
			Total	9	19	
III	NPV > NPV of testing program	**Efficient:** Current investments in breeding more profitable than testing	Sub-Saharan Africa	3	2	1.9
			West Asia/North Africa	16	10	
			South Asia and China	21	20	
			Latin America	11	9	
			Total	51	41	
			Grand total	**69**	**69**	**3.4**

[a] Average across all programs under higher level of spillins.

Analysis of Investments by the CIMMYT-NARS International Research System in Wheat Improvement by Megaenvironments

The international research system (CIMMYT plus the NARS testing component) is estimated to spend more than US$ 26 million (1990 US$ PPP) annually on spring wheat improvement research in developing countries (excluding China) to generate direct research spillins. Of this, approximately 25% is expended by CIMMYT in Mexico on crossing and early generation (F_1 to F_7) selection and testing, and 75% by developing country NARS in testing and screening (Chapter 7).

The cost-benefit model developed in this chapter is used to analyze the efficiency of this global and joint investment by the CIMMYT-NARS system, grouped by spring wheat MEs. CIMMYT costs by ME were based on the estimated percentage resources devoted by the CIMMYT Wheat Program to different MEs.[9] For each NARS, the costs of realizing direct transfers from CIMMYT in each of its MEs were obtained by taking the total costs by NARS for testing CIMMYT-developed varieties (as estimated in Chapter 7) and multiplying that figure by the percentage share of production in a given ME in that country. The costs were then aggregated across all NARS to obtain global NARS investments in the international research system for each ME. Similarly, wheat production under varieties developed by the international research system was estimated based on production in an ME relative to total wheat production in a country, aggregated over all the countries in a given ME.

Given the division of labor and cost between CIMMYT and NARS in this research model, the cost stream is estimated as follows: (1) In the first 4 years of the joint CIMMYT-NARS research system, only the CIMMYT costs are accounted for, on the assumption that it will take 4 years for CIMMYT to develop F_7 lines;[10] (2) NARS costs are phased in from year 5, when testing starts on the advanced lines generated by CIMMYT; and (3) the whole CIMMYT-NARS international research system starts operating at full cost (US$ 26 M) by year 8 and releasing varieties in year 11. The rate of yield gains for varieties released from the CIMMYT-NARS system was set at 8.6 kg/t/yr, consistent with the rate of yield gains used in previous models for a testing program (under the scenario in which CIMMYT is a potential source of spillins).

Table 8.3 presents threshold production levels required to justify continued investment at the current level by CIMMYT and NARS to generate and utilize direct spillins. The threshold production levels are below the actual production under CIMMYT-NARS varieties in all but one ME (ME4A — low rainfall, winter rain), providing an economic justification for current investments by CIMMYT and NARS in generating directly transferable varieties in these MEs. The projected internal rate of return to current levels of investment by the international system and actual production under CIMMYT-NARS varieties in spring wheat environments is projected to be about 24%.[11] Of course, there are other benefits, such as indirect spillovers to the NARS system, which

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9 R.A. Fischer (personal communication).

10 Based on two generations per year in the CIMMYT program.

11 Note that this projected rate of return for the international research system is lower than the projected 48% IRR in Chapter 6, which included both the direct and indirect transfers and encompassed the international and national research on spring wheats. The lower projected IRR in this chapter also stems from the different parameter values for price and adoption. The ex-ante analysis in this chapter is based on a declining price trend (as versus constant 1990 prices used in the Chapter 6 analysis) and an adoption lag of 10 years (as against 7 years in Chapter 6).

are not considered in this analysis. Hence, the projected IRR underestimates the true returns to the investment by the international research system.

The threshold level of wheat production for all 12 spring wheat MEs is 12 M t. In other words, to justify a global joint CIMMYT-NARS aggregated effort on wheat improvement requires an average global market size of 1.0 M t in a given ME. This is quite high, but it is consistent with and provides empirical evidence for CIMMYT's strategic plan, which advocates CIMMYT's involvement in an ME that has at least 1.0 M t of aggregated wheat production across countries.

Conclusions and Implications

The results of this chapter have important implications both at the conceptual level in methods used for research evaluation and at the policy level for research-investment decisions in developing countries. At the conceptual level, spillovers and spillins in crop research (research externalities) have usually been assumed to be indirect (e.g., exchange of germplasm for parent materials, exchange of breeding methods, and exchange of scientific information). The externalities created by research are therefore modeled to affect only the research production function of other research programs. The theoretical argument for underinvestment in

Table 8.3. Estimated internal rate of return (IRR) and threshold levels of wheat production to justify CIMMYT-NARS investments in different spring wheat megaenvironments (MEs) in developing countries[a]

Wheat type and ME	Total wheat production (1990) (M t)	Expenditures by CIMMYT-NARS research system: Total (M 1990 US$ PPP)	Share of CIMMYT (%)	Share of NARS (%)	Wheat production under CIMMYT-NARS varieties[b] (1990) (M t) *Q*	Threshold level of wheat production to justify given expenditures (M t) *Q**	IRR at actual level of *Q* (%) *r**
Spring bread wheat							
ME 1 Irrigated, low rainfall	79.5	7.07	17	83	25.5	3.1	32
ME 2 High rainfall	18.0	4.79	27	73	5.7	2.1	20
ME 3 Acid soils	4.6	1.00	57	43	1.4	0.4	22
ME 4A Low rainfall, winter rain	3.5	3.18	25	75	0.7	1.4	7
ME 4B Low rainfall, winter drought	3.7	0.43	67	33	1.4	0.2	30
ME 4C Low rainfall, stored moisture	4.4	0.35	21	79	2.0	0.2	37
ME 5A High temperature, high rainfall	11.5	3.25	31	69	4.4	1.4	22
ME 5B High temperature, low rainfall	3.1	0.94	31	69	1.1	0.4	20
ME 6 High latitude	4.9	0.00	—	—	0.0	—	—
Spring durum wheat							
ME 1 Irrigated, low rainfall	2.4	0.94	43	57	1.0	0.4	19
ME 2 High rainfall	5.0	2.05	12	88	2.2	0.9	20
ME 4A Low rainfall, winter rain	4.1	2.36	16	84	1.9	1.0	17
ME 4C Low rainfall, stored moisture	1.3	0.05	49	51	0.4	0.02	43
All spring wheat	**163.6**	**26.40**	**25**	**75**	**47.7**	**11.5**	**24**

[a] Excluding China.
[b] Varieties released between 1965 and 1990.

agricultural research is based on this basic premise (Ruttan 1982). However, as shown by this study, research spillins will not only affect research *productivity*, but also the choice of the research *strategy* for a given sector. The study therefore underlines the importance of incorporating estimates of direct spillins (or the potential for direct spillins) in the economic evaluation of research programs.

In addition, the presence of direct spillins has important implications for the criteria used in research evaluation. In principle, research resources should be allocated to every product or sector in which the expected present value of research is positive, given the appropriate discount rate. Ex-post rate-of-return studies evaluate research investments as free-standing research projects based on this principle. The evidence of rates of return greater than the opportunity cost of capital is therefore interpreted to imply that research investments should be increased to drive down the rate of return. However, this study has shown that if research costs and benefits are characterized by a discrete production function (as in the case of a testing vs. a breeding program), then high rates of return do not necessarily imply that resources are being used efficiently if investment in an alternative research strategy is more profitable. To allocate resources efficiently, policy-makers must review a framework of research options and consider the forgone opportunity costs of each option.

By incorporating direct spillins into a cost-benefit framework, we have provided some generic guidelines to help developing countries increase the efficiency of investments in public-sector wheat research programs. Most strikingly, our analysis reveals that many countries or regions within a country are investing more than is economically justifiable on wheat improvement. This finding suggests that efficiency gains could be considerably increased at the margin by shifting research strategies, especially for wheat research programs with a small mandate area.

This "overinvestment" in wheat improvement research occurs because many wheat improvement programs in developing countries place too much emphasis on adaptive and comprehensive research and too little on importing and testing improved varieties from the CIMMYT-NARS international research system. Too often, the result is duplication of research effort and inflation of developing-country research programs.

This chapter does not undercut the finding that, overall, wheat research in developing countries has been highly successful, continuously releasing superior wheat varieties that farmers adopt and generating a high rate of return (Chapter 6). This study has shown, however, that the research programs earning the highest returns were located in large wheat producing countries (Argentina, Brazil, China, India, Pakistan, and Turkey), suggesting considerable economies of market size in wheat improvement research.

The research option framework used in this chapter is based on the assumption that potential research costs and payoffs can be determined ex ante fairly precisely. As a result, when a testing program seems most profitable ex ante, investments in an adaptive breeding program are considered inefficient. This conclusion may not hold when research payoffs are very uncertain ex ante due to a corresponding uncertainty in the parameter values or continuation of research spillins.

The risks of depending on spillins have to be carefully assessed. These risks may be political (depending on a hostile or uncooperative country). Institutional risks must be considered as well. For example, can countries depend on CIMMYT forever? Will the donor community adequately fund CIMMYT for the next 5, 25, or 50 years? How will laws that protect intellectual property affect the cost of acquiring spillins? Economic instability also presents risks. For example, by depending on Argentina, Uruguay risks a discontinuity of research spillins if the Argentinean NARS undergoes an economic crisis. In addition, policy-makers must assess the risk of reducing genetic diversity and increasing the vulnerability to biotic stresses if neighboring countries grow the same varieties. Theoretically, this limitation can be corrected by calculating the probability distribution of parameters to assess the riskiness of each alternative and calculating the NPV based on the weighted parameters. Alternatively, a differential risk premium can be added to the discount factor to take into account the risks associated with pursuing one alternative as against the other.

Our emphasis on the importance of using direct spillins is based on the assumption that the CIMMYT-NARS international system will continue to generate them free of cost. The validity of this assumption will depend on political and institutional developments beyond the scope of this study. Nonetheless, an analysis of the joint CIMMYT-NARS investments in spring wheat megaenvironments justifies continued support for international wheat improvement research. This analysis indicates that current investments in the international research system generate profitable returns in almost all of the spring wheat megaenvironments. Increased investments will help CIMMYT generate spillovers and reduce the uncertainty NARS face in depending on those spillovers. And by building NARS capacity to use direct spillins, those investments will increase the efficiency of wheat improvement efforts worldwide.

Appendix 8A

Modeling the Adoption and Diffusion of New Varieties

We assume that a research program releases improved varieties every year ($T = 1, \ldots, i, \ldots N$), with a yield gain of ($g_f * I$). The cumulative diffusion of these varieties is represented by α_T, which follows a logistic curve beginning with a 5% diffusion in year 1 and reaching 100% by year 11 (i.e., $T_c = 11$) (Figure 8A.1). However, it is unlikely that a variety released in the i^{th} year with a yield gain of ($g_f * i$) is instantaneously adopted over the whole diffused region of a_T. Varieties released each year are assumed to follow a lifetime adoption pattern of w_i as depicted in Figure 8A.1. A variety released in i^{th} year is adopted in 5% of the production region in year 1 (i.e., $w^1_i = 0.05$) and 11% in year 2 ($w = 0.11$); it reaches a peak adoption level of 21% in year 5 ($w^5_i = 0.21$) and is disadopted thereafter until it is no longer planted in year 12 after its release.

As depicted in Figure 8A.1, in any given year T, α_T is composed of varieties released in that and preceding years (w^T_i). Hence attributing increased yield gains of ($g_f * i$) to all the production under improved varieties in the mandate region would overestimate the realized production gains due to research. The annual shift in production attributed to research, K_{fT}, is therefore defined as the sum of research-induced cumulative yield gains weighted by the percentage of production attributed to varieties released in current and preceding years:

$$K_{ft}=\sum_{i=1}^{T}(g_f i)w^T_i \qquad (8A.1)$$

such that, $\sum_{i=1}^{T} w^T_i=\alpha_T \quad w^T_i=0 \text{ for } o\leq T-11$

The model discussed in this chapter is based on the definition of K_{fT} as defined in Equation 8A.1, which analyzes varietal replacement on a continual basis (i.e., α_T is composed of varieties released in the past T years and new varieties with higher yield gains released each year and replacing older ones). This kind of adoption model now characterizes most wheat growing regions.

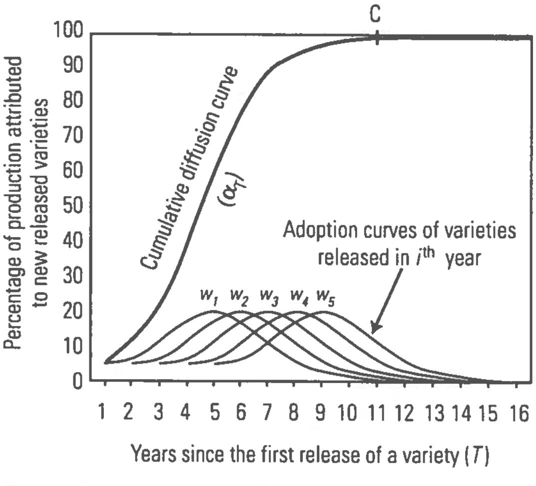

Figure 8A.1. Modeling the adoption and cumulative diffusion of new wheat varieties released by a research program.

Chapter 9

Investment Efficiency at the National Level: Wheat Improvement Research in India

K.B.L. Jain and Derek Byerlee

India has one of the largest and most successful wheat research programs in the world. Scientific wheat breeding in India began early in this century, and by the 1940s, improved varieties were sown on most of the irrigated area. Wheat research received another boost in the 1960s with the release of high-yielding semidwarf varieties that quickly spread to most of the wheat producing areas of India.

Considerable resources have been invested to achieve these results. For wheat improvement alone, some 450 scientists spread across 50 research centers were involved full or part time in 1992 (Directorate of Wheat Research 1992). A large number of other scientists are also engaged in crop and resource management related to wheat or wheat-based cropping systems. There is little doubt that in *aggregate* this research effort has paid high dividends (Evenson and McKinsey 1991; Khalon et al. 1997). Nonetheless public funding for agricultural research in India has leveled off in recent years, and there is increasing concern about research duplication and overstaffing (Mruthyunjaya and Ranjitha 1998). Given the climate of budget austerity in the 1990s, the following questions have become increasingly important.

1. What is the total cost of wheat improvement research in India, and how are resources being allocated across different environments?
2. Is allocation of research resources across environments consistent with the importance of wheat in each environment? Is there underinvestment in marginal areas?
3. What have been the outputs of and payoffs to wheat improvement efforts in each environment?
4. How extensive are technology spillovers across zones and environments, and what are the implications of these spillovers?

This case study of Indian system from 1970 to the early 1990s will address these questions.[1] It will also illustrate how the concepts of *research spillovers* and *research efficiency* can be incorporated in an empirical examination of a national research program for a single commodity. The results provide valuable insights into the success and impacts of one of the largest national wheat improvement systems. First, we describe the wheat improvement research effort and analyze the allocation of wheat research

1 This chapter is based on work completed in 1992 and does not necessarily represent the situation of the Indian wheat research program today. However, the chapter does show how research efficiency can be analyzed across a large number of sub-national research programs. The section on economic impacts was prepared by Gregory Traxler.

resources across environments (questions 1 and 2 above). Second, we analyze wheat varietal releases and estimate spillovers across environments (questions 3 and 4 above). Finally, we use formal economic methods to evaluate impacts of research investments in different environments, with and without incorporating spillover effects.

Structure of Wheat Improvement Research in India

Most research on wheat improvement in India is coordinated through the All India Coordinated Wheat Improvement Directorate (AICWID) of the Indian Council of Agricultural Research (ICAR). The states provide a considerable proportion of the resources to wheat improvement research, but most wheat breeders and related disciplines are affiliated with the national network of wheat breeders as part of the coordinated wheat research program established under the AICWID, now based in Karnal. Many of these scientists receive direct financial support from the AICWID. Others voluntarily associate with the AICWID in order to exchange germplasm and information and to test their materials at multiple locations. About 50 centers collaborate with the research and testing activities of the Directorate.[2] Some of these are main centers with a multidisciplinary team of scientists. Others are smaller centers with one or two disciplines and largely function as testing centers. Most centers are under the control of state agricultural universities and other autonomous bodies, some are under the control of ICAR, and a few are under the control of state departments of agriculture. In addition, about 120 centers of the state departments of agriculture help conduct the coordinated variety evaluation trials.

The underlying approach to wheat improvement research is to exploit genotype-by-environment (GxE) interactions through a multidisciplinary team approach. The country has been divided into a number of zones (discussed below). Most research centers located in a particular zone aim to develop products for that zone only. Exceptions to this rule are the wheat research programs of the Indian Agricultural Research Institute (IARI), which are unique in having a national mandate.

Breeders located at the cooperating centers develop materials relevant to the specific environmental conditions in their zone. The promising bulks are tested in station trials and then evaluated in multilocation trials under the jurisdiction of the concerned breeders. The best lines then undergo coordinated testing in the zone where they have been developed, under the cultural conditions for which they have been found promising. The coordinated testing system consists of four stages; only the most promising lines advance into subsequent stages.

After an entry is identified at the AICWID annual workshop as a candidate for release, it undergoes wide-scale testing. If results are favorable, the entry is submitted to the Central Seed Committee, which formally releases the variety and notifies relevant parties.

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2 Two centers serve as summer nursery sites to accelerate the breeding programs by advancing generations, multiplying selected bulks, screening against diseases, and undertaking a limited crossing program. Two other centers are exclusively engaged in research on various aspects of wheat rusts.

Wheat Research Zones and Environments

Wheat improvement research in India is organized by geographic zones, defined by temperature and rainfall characteristics, which in turn define biotic and abiotic stresses. Six major zones have been delineated — the Northwest Plains Zone (NWPZ), the Northeast Plains Zone (NEZ), the Central Zone (CZ), the Peninsular Zone (PZ), the Northern Hills Zone (NHZ), and the Southern Hills Zone (SHZ). The SHZ is maintained separately because of its importance as a focal point for disease inoculum. Because commercial wheat production is negligible here, however, the zone is not included separately in the later analysis.

In addition to the six major geographic zones, various *production environments* are defined within each zone as the basis for organizing wheat breeding programs and formulating varietal recommendations. These environments are defined on the basis of the following criteria:

1. Wheat species:[3] *Triticum aestivum* (or bread wheat) and *Triticum durum* (or durum wheat).
2. Irrigation status: *Irrigated*[4] and *rainfed*.
3. Planting time: *Timely planted* (usually from November 10–20 — the period that optimizes wheat yields) and *late planted*[5] (usually from December 10–20).

The environmental diversity within each zone leads to a potentially large number of breeding environments (six zones by at least four possible environments in each zone by two species). Fortunately not all environments are commercially important for wheat production. Twenty major environments across five zones (excluding the SHZ) are shown in Table 9.1.[6] An average of five environments

Table 9.1. Major target environments[a] for Indian wheat breeding programs, 1992

	Northwest Plains[b]	Northeast Plains[b]	Central	Peninsular	Northern Hills[c]	Total no. of environments
Bread wheat						
Irrigated timely sown	*	*	*	*	*	5
Irrigated late sown	*	*	*	*		4
Rainfed timely sown	*	*	*	*	*	5
Rainfed late sown		*				1
Durum wheat						
Irrigated	*		*	*		3
Rainfed			*	*		2
Total no. of environments	4	4	5	5	2	20

[a] Target environment marked with an asterisk.
[b] Ignores irrigated environments with salinity problems and very late sown environments in the Northern Plains.
[c] Ignores high-altitude summer and winter sown, and rainfed early sown environments in the Northern Hills.

3 There is also a small area of *Triticum dicoccon* and some organized breeding effort has been started recently.
4 A special trial was also introduced in the NWPZ and NEZ for irrigated areas that are affected by *salinity and alkalinity* — over 10% of the irrigated area, most of it in the NWPZ (Directorate of Wheat Research 1988).
5 Late planting is especially common in irrigated areas where intensive cropping patterns (particularly rice-wheat, but also sugarcane-wheat, soybean-wheat, and cotton-wheat) have led to increasingly delayed wheat planting. In recent years over half of the irrigated wheat area has been planted late (Directorate of Wheat Research 1988). Delayed planting is estimated to result in yield losses of 25–35 kg/ha/day beyond the optimum date (Directorate of Wheat Research 1988).
6 The table ignores some minor environments for which wheat improvement research is conducted, but for which there was no information to estimate the size of the environment (e.g., high altitude and early planting in the Northern Hills and very late planting and salinity in the Northern Plains).

occur in each zone. The irrigated timely planted environment and the rainfed timely planted environment for bread wheat occur in all zones. Other environments occur only in a few zones.

The estimated wheat area, production, and yield (by environments) within each zone are given in Table 9.2. Clearly the NWPZ — consisting of Punjab, Haryana, western Uttar Pradesh, northern Rajasthan, and small parts of adjoining states — is the most important wheat production zone, accounting for just over half of all production. This is followed by the NEZ, mostly located in eastern Uttar Pradesh and Bihar, which accounts for 29% of production. The CZ (Madhya Pradesh, Gujarat, and parts of adjoining states) accounts for 15% of production; the remaining two zones provide less than 5% of national wheat production. Overall, rainfed wheat occupies 17% of the area but only 10% of production. Although wheat production is highly skewed to a few environments, our estimates suggest that breeding programs target at least 100,000 t of wheat in all environments, except rainfed bread wheat in the PZ. This 100,000 t production level is probably sufficient to justify allocating at least 5 FTE breeding researchers for each environment (Chapter 8).

Table 9.2 Estimated area (M ha), production (M t), and yield (t/ha) of wheat by zone and environment, India, 1990

	Northwest Plains	Northeast Plains	Central	Peninsular	Northern Hills	All India
Area						
Bread wheat						
Irrigated timely	4.91	2.02	1.81	0.20	0.07	8.00
Irrigated late	3.30	4.89	0.96	0.20	0	9.35
Rainfed timely	0.43	0.23	1.87	0.08	0.73[a]	3.34
Rainfed late	0.0	0.54	0	0	0	0.54
Durum wheat						
Irrigated timely[b]	0.38	0	0.05	0.07	0	0.49
Rainfed	0	0	0.75	0.58	0	1.33
Total	**9.02**	**7.68**	**5.43**	**1.13**	**0.80**	**24.05**
Production						
Bread wheat						
Irrigated timely	16.42	4.74	4.14	0.35	0.15	25.80
Irrigated late	09.47	9.72	1.83	0.32	0	21.35
Rainfed timely	.89	.29	1.43	0.05	1.08[a]	3.74
Rainfed late	0	.68	0	0	0	0.68
Durum wheat						
Irrigated timely[b]	1.27	0	0.11	0.11	0	1.50
Rainfed	0	0	0.57	0.38	0	0.95
Total	**28.05**	**15.44**	**8.09**	**1.22**	**1.22**	**54.02**
Yield[c]						
Irrigated timely	3.3	2.4	2.3	1.8	2.2	2.9
Irrigated late	2.9	2.0	1.9	1.6	na	2.1
Rainfed	2.1	1.3	0.8	0.6	1.5	1.0
Weighted average farm yield[d]	3.1	2.0	1.5	1.1	1.5	2.2
Weighted trial yield[d]	4.0	3.0	2.7	2.1	2.4	3.2
Percent yield gap	**23 %**	**32 %**	**45 %**	**47 %**	**36 %**	**31 %**

[a] Includes early and late sown.
[b] Includes small area late sown.
[c] Average for both bread and durum wheat.
[d] Weighted by area in each environment in each zone.

The final rows of Table 9.2 give estimated farm yields for each zone and environment as well as the weighted trial yield to provide an estimate of the yield gap. The most important zones have the highest yields, which varied from 3.1 t/ha in the NWPZ to only 1.1 t/ha in the PZ in 1990. Yields are closely associated with irrigation, which is available in 90% or more of the wheat area in the two northern plains zones but in 50% or less of the wheat area in other zones. The NHZ has the least irrigated area, but higher rainfall partly compensates for that lack. In all zones except the NHZ, irrigated wheat accounts for well over half of production. Yields of both irrigated and rainfed wheat decline from north to south, as moisture and heat stress become more frequent. The yield gap between irrigated and rainfed wheat and between experimental and farm yields is also highest in the center and south.[7]

Late planting is especially important in the NEZ, where the rice-wheat cropping pattern is prevalent and where heavy soils and lack of irrigation further compound the problem of late planting. In the PZ, practically all rainfed area is under durum wheat. However, in terms of national production, irrigated durum wheat in the NWPZ has become important during the past few years and now accounts for half of all durum production.

The adoption of semidwarf or modern varieties (MVs) closely follows the moisture status of the environment. Practically all the irrigated area is now sown to MVs; tall varieties are thus now found primarily in rainfed areas and some areas with very limited irrigation. Adoption of MVs in rainfed areas is highest in the NHZ and NWPZ, which receive adequate moisture in most years. In other zones, adoption of MVs varieties is negligible, although improved tall varieties have been widely adopted in much of this area (e.g., C306 in the CZ and NEZ, and improved durums in the PZ).

An Analysis of Resource Allocations and Wheat Improvement Research

In 1992, an estimated 450 researchers were participating in wheat improvement research at about 50 centers across 20 major wheat producing environments. This is equivalent to 203 full-time scientists (FTEs) (Directorate of Wheat Research 1992) and represents the world's largest wheat improvement research effort outside of China and the former Soviet Union (Bohn and Byerlee 1993).

The distribution of these researchers (in FTEs) is shown in Table 9.3 by zone and discipline. Note that these estimates include the IARI researchers working in a given zone. Of the 50 research centers (including IARI) working on wheat improvement, six centers had 10 or more FTE scientists, while 26 centers had two or fewer. The centers with the most FTEs were located in the NWPZ, where four centers have more than 10 FTEs.

The main disciplines included in a wheat breeding program are breeding, pathology, and agronomy — with a smaller number of entomologists, nematologists, physiologists, and cereal chemists. Clearly the major activity is the development of improved varieties for the different wheat production zones and

7 We also estimated the average yield in zonal varietal trials, weighted by the area in each type of environment and zone. Comparison of this yield with the zonal average yield computed from official statistics provides an alternative measure to the commonly quoted yield gap between farmers' yields and yields achieved in national demonstrations, which usually under-represent the more marginal environments. The estimated gap between breeders' yields and farmers' yields is only 23% in the NWPZ, which is considered low (Herdt 1988). The yield gap increases in more marginal production zones, however, reaching nearly 50% in the PZ. These yield gaps provide a crude measure of the potential to increase yields by applying available technology.

ecologies. Breeding comprises half of the total FTEs; most of the time of the other disciplines, including agronomy, is also allocated to support varietal improvement. Together these centers make some 11,500 crosses and conduct multilocation tests of 700 lines per year (Directorate of Wheat Research 1992). Overall, wheat researchers conducted over 1,300 separate trials and nurseries in 1992, some 6.7 trials per FTE.

There is no comprehensive estimate of total expenditures on wheat improvement research in India. We estimated expenditures by environment from various sources. The share of total research expenditures allocated to wheat improvement research was assumed to be the same as the share of wheat improvement scientists[8] in total agricultural research scientists in 1992. Wheat improvement expenditures were then allocated to each zone and environment based on the share of total wheat scientists located in that zone and the share of breeding trials conducted in a given environment in that zone in a given year. Total expenditures on wheat improvement research in India in 1991 were estimated at 1989 Rs 59 million or about US$ 3.5 million. If one assumes that breeding research represents about half of all wheat research expenditures, this estimate is consistent with a figure of

9.3. Distribution of wheat research activities, number of research centers, wheat scientists, and trials conducted by zone and discipline (percentages in parentheses), India, 1992

	Northwest Plains	Northeast Plains	Central	Peninsular	Northern Hills	All India[a]
Number of research centers						
	13	12	12	5	7	50
Number of FTE scientists						
Breeding	44	18	24	6	9	102
Pathology	14	10	4	3	4	36
Agronomy	11	10	12	3	4	39
Entomology	6	1	2	0	0	9
Nematology	5	0	0	0	0	5
Physiology	1	1	2	2	0	6
Quality	2	2	1	3	0	6
Total	**83**	**42**	**45**	**17**	**17**	**203**
Percent	**(41)**	**(21)**	**(22)**	**(8)**	**(8)**	**(100)**
Number of trials and nurseries						
Breeding	311	137	149	135	81	818
Pathology	90	34	19	25	45	220
Agronomy	49	49	43	20	32	193
Entomology	41	4	9	4	0	58
Nematology	35	0	0	0	0	35
Physiology	3	2	4	3	5	17
Total	**529**	**226**	**224**	**187**	**163**	**1,341**
Percent	**(34)**	**(20)**	**(18)**	**(15)**	**(12)**	**(100)**

Source: Based on Wheat Project Directorate (1992).
[a] All India includes Southern Hills Zone.

[8] Wheat improvement scientists were defined to include breeders as well as supporting disciplines of pathology, agronomy, entomology, physiology, nematology, and grain quality.

Rs 150 million for all wheat research in 1992 calculated from data in Mruthyunjaya et al. (1995).

Indicators of Resource Allocation for Wheat Improvement Research

A simple comparison of resource allocation by environment with the value of wheat production[9] in each environment is a crude indicator of where research may be over- or under-investing. This method is often called congruency analysis (Alston et al. 1995).

The resources allocated to the two major zones (NWPZ and NEZ) are clearly low relative to their share in value of production, 47% and 31%, respectively (Table 9.3). Correspondingly, the smaller zones have a higher share of research resources than their share in the value of production. To some extent, this discrepancy is expected since a critical mass of researchers is still needed to develop or test new varieties in a small zone, while a large zone may experience diminishing returns to further research investments. These economies of "market size" in agricultural research have also been observed in earlier chapters at a global level and elsewhere (Byerlee and Traxler 1996). Nonetheless, the low share of the NEZ in total wheat improvement research, relative to its importance in production, is cause for concern.

Similarly, within zones, the share of resources targeted to specific environments can be compared to the importance of those environments within the zone (Table 9.4). For example, the allocation of resources for late-planted wheat closely followed the importance of late-planted wheat in each zone. However, the NEZ may be underinvesting in the development of late-planted varieties given that this is the dominant environment in the zone. Similarly, the NWPZ and NEZ, where rainfed wheat is

Table 9.4. Percent of value of wheat production and percent of resources allocated (in parentheses) by environment, India, 1990

	Northwest Plains	Northeast Plains	Central	Peninsular	Northern Hills	All India
Bread wheat						
Irrigated timely sown	27.1 (14.3)	9.4 (6.9)	8.2 (5.5)	0.8 (2.2)	0.3 (2.1)	45.9 (31.0)
Irrigated late sown	15.7 (11.5)	19.3 (7.1)	3.6 (6.8)	0.8 (2.4)	0 (0.1)	39.3 (27.9)
Rainfed timely sown	1.5 (6.1)	0.6 (5.3)	3.3 (3.3)	0.1 (1.7)	2.2[a] (4.8)	7.7 (21.2)
Rainfed late sown	0 (0)	1.4 (1.4)	0 (0)	0 (0)	0 (1.4)	1.4 (2.8)
Durum wheat						
Irrigated	2.4 (9.0)	0 (0)	0.3 (3.0)	0.3 (0.9)	0 (0)	3.0 (12.9)
Rainfed	0 (0)	0 (0)	1.5 (3.0)	1.2 (1.3)	0 (0)	2.8 (4.3)
All India	**46.7** **(40.9)**	**30.6** **(20.7)**	**16.9** **(21.7)**	**3.2** **(8.4)**	**2.5** **(8.4)**	**100.0** **(100.0)**

[a] Includes rainfed early and late sown.

9 An estimation of wheat prices was needed to value production. Since wheat prices vary by wheat type (bread and durum), quality, and location, we estimated the value of production in each zone based on prices in each zone for each wheat species.

only a small share of production, tend to overinvest in the rainfed environment, while the other zones where rainfed wheat is important slightly underinvest.

An overall measure of the congruency between resource allocation (measured by percentage of research expenditures) and importance in value of production is the Congruency Index, *I*, defined as:

$$I = [1 - \Sigma_i (r_i - v_i)^2]^{0.5}$$

where r_i is the share of environment *i* in resource allocation and v_i is the share of *i* in value of production. The maximum value of *I* is 1, indicating perfect congruency — i.e., resources are allocated proportionally according to the value of production in each environment. The estimated Congruency Index for all India is 0.88, which indicates that resource allocations generally follow the importance of wheat production in each environment.[10] Shifting more resources to the NEZ would be an effective way to increase the index even further.

Overall, the intensity of wheat research is graphically demonstrated in Figure 9.1, which plots in logarithmic terms the intensity of the research effort in FTE scientists per million tons of wheat produced (*r*) against the size of the environment in terms of wheat production (*Q*). This can be expressed as:

$$r = 6.3 - 0.616 \ln(Q), \; R^2 = 0.83, \text{t-value} = 9.21$$

(i.e., for every 1% increase in the size of the environment, there is a 0.6% decrease in research intensity). In general terms, the size of the research team tends to be fixed regardless of the size of the environment. This may represent the relatively indivisible nature of crop improvement research (i.e., a crop improvement research effort has significant fixed costs that do not vary by environmental size), or it could suggest efforts to distribute resources equitably among programs.

Finally, Table 9.5 presents some indicators of research productivity. The number of trials conducted per FTE scientist per year varies substantially from a very high of 14.5 in the PZ to only 5.0 in the CZ. The number of varieties released in the 1980s averages 0.8 per FTE per year, but is again highest in the PZ and lowest in the CZ. Another output measure is the number of wheat publications, which average 1.0 per FTE per year, but only 0.3 in the CZ. Finally, there are large differences among zones in the area covered by varieties released in the 1980s. These areas range from 185,000 ha per FTE in NWPZ to only about 15,000 ha per FTE in the PZ and CZ. These indicators suggest substantial differences in research productivity that are further investigated by the disaggregated economic analysis below.

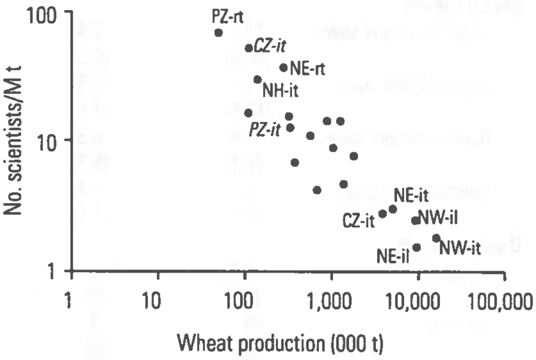

Figure 9.1. Number of scientists per million tons of wheat in relation to size of environment in India (logarithmic scale).
Note: First two letters for zone, i=irrigated, r=rainfed, t=timely planted, l=late planted, durum in italics.

[10] The index of congruency between wheat area in a given environment and resource allocation is very high at 0.98, indicating that resource allocation decisions are based more on area than on production.

Analysis of Wheat Varietal Releases in India

By far the most important activity of the AICWID is the development, evaluation, and release of improved cultivars for the varied ecological conditions under which wheat is grown in India. The AICWID has undoubtedly been one of the major successes of the Indian national agricultural research program. Although the success of the high-yielding varieties released by AICWID has been widely documented, there has been little discussion of the recent economic impacts of the wheat research program. Wheat researchers in India have continued to release a steady stream of new varieties, most of which have been based on local research efforts. From the time AICWID was established until 1992, over 120 varieties were approved for release. Another 80 varieties were released at the state level. In this section, we analyze the wheat varietal release data to estimate the impacts of wheat breeding research in India; spillovers across zones are taken into account.

Trends in the Composition of Varietal Releases

Tables 9.6 and 9.7 summarize trends for varieties released since 1965 (including both zonal and state releases). Table 9.6 shows that about two-thirds of the varieties have been released at the zonal level or for cultivation across zones. Most of the varieties released have been bread wheats. There has been a steady increase in the average number of releases per year up to the 1990s (Table 9.7), which reflects a strategy of developing varieties adapted to specific ecological niches. State-level institutions have developed over two- thirds of the varieties, and this share has in-creased over time. In the first period, 1965–69, many of the varieties, including the major Green Revolution varieties, Kalyansona and Sonalika, were recommended across all or most zones. After that period, most varieties have been recommended for a specific zone.

The largest number of releases has been targeted at the NWPZ, which is also the most important wheat production zone in India.

Table 9.5. Indicators of wheat research productivity by zone, India

	Northwest Plains	Northeast Plains	Central	Peninsular	Northern Hills	All India
Number of trials per FTE scientist	6.5	5.6	5.0	14.5	9.5	6.7
Number of varieties per FTE breeder, 1981-90[a]	0.82	0.94	0.54	1.50	1.00	0.84
Number of publications per FTE scientist per year, 1986-90[b]	1.3	1.6	0.3	1.1	na	1.0
Area (000 ha) planted to varieties released since 1980 per FTE	185	89	11	14	106	116
Number of FTE scientist per M t of wheat	2.7	3.2	4.8	7.3	13.6	3.6

[a] Excludes varieties released for more than one zone.
[b] Number of publications based on Kaur (1991).

Table 9.6. Wheat and triticale varieties released in India between 1965 and 1993, by recommended area and type

Recommended area	Bread wheat	Durum wheat	Emmer wheat	Triticale	Total
Across zones	11	—	—	—	11
State/zone	3	—	—	—	3
Zones	90	12	1	—	103
States	64	11	—	2	77
Total	**168**	**23**	**1**	**2**	**194**

However, only 27% of the varieties have been targeted to the NWPZ compared to its 50% share in the zone's wheat production. Over time, and especially in the 1980s, there has been a decline in the number of releases for the CZ and PZ and a corresponding increase in the share of releases for the NEZ. This shift follows the trends in research resource allocation discussed above. Likewise the trends in varietal releases for late planting and for rainfed areas follow the general trends in resource allocations as measured by the number of trials conducted (Table 9.7). Emphasis on varieties for late planting increased sharply in the 1980s as late planting of wheat became commonplace with intensification of irrigated cropping.

Overall resource allocations and release of varieties have shifted to accommodate emerging trends in wheat production. One exception appears to be rainfed wheat. There has been a substantial effort to develop varieties for rainfed areas, despite the decline in importance of rainfed wheat at the national level. Originally, no semidwarfs were recommended for rainfed areas, but this proportion has increased steadily over time, and now most of the releases for rainfed areas in the north of the country are semidwarfs.

Measuring Technology Spillovers: An Analysis of the Origin of Wheat Varieties

A total of 138 wheat varieties were released in India between 1976 and 1993, including 42 varieties originating at CIMMYT, based in Mexico.[11] The development of new varieties is highly concentrated. Two programs — IARI and the NWPZ program for irrigated timely planted wheat — account for 40% of all Indian releases and for the same share of successful varieties (defined as varieties which were sown on at least 25,000 ha in at least one growing season).

Since 1965, about one-third of the varieties have been developed by national institutions, especially the IARI stations at New Delhi, Indore, and Simla (Table 9.8).

Table 9.7. Characteristics of wheat varieties released in India, 1965-1993

	1965-69	1970-74	1975-79	1980-84	1985-89	1990-93	All
Number of varieties per year	5.6	6.2	6.8	7.8	8.4	7.0	7.0
Percent varieties							
Bread wheat	82	84	88	82	93	93	87
Durum wheat	14	16	12	15	5	7	11
Other[a]	4	–	–	3	2	2	2
Percent varieties semidwarf							
All	29	77	85	82	95	96	58
Rainfed only	0	43	44	14	82	86	49
Irrigated only	100	100	100	100	100	100	100
Percent varieties for rainfed areas[b]	21	23	27	18	26	25	23
Percent varieties for late planting[c]	11	13	15	17	33	29	17

[a] Includes emmer wheats and triticale.
[b] Includes varieties for both rainfed and irrigated areas.
[c] Includes varieties for both timely and late sowing.

[11] CIMMYT does not release wheat varieties. CIMMYT makes varieties available to national programs for testing. The national program may then decide to rename and release the variety.

These institutions are particularly important for the smaller zones, where they may account for half or more of variety releases. The national institutions also appear to have a broader mandate than the zone in which they are located. Of the varieties developed at the state level, a little less than one half have been approved by the Central Varietal Release Committee for release at the zonal level. The remainder of the varieties are released only by the state that developed them. Over time, the proportion of varieties developed by the states has increased, while the number of varieties released only at the state level has declined. This suggests that the state breeding programs are becoming more integrated with the AICWID.

The great majority of releases are from Indian crosses, usually with at least one Indian parent and one foreign parent, most of the latter from CIMMYT (Table 9.8). When the Mexican semidwarf wheats were introduced in 1965, introduced varieties made up nearly half the total releases. However, this proportion has steadily fallen since then, as semidwarfs were incorporated into the local crossing program. Originally, this program used foreign parents for crosses, but over time the proportion of crosses that involve only Indian parents has steadily risen (Table 9.8). In the 1990s, the proportion of introductions has again increased, reflecting the outbreak of a new race of leaf rust, for which the local materials had little resistance. The availability of widely adapted germplasm from international centers continues to be important even for a strong breeding program such as the Indian program.

Table 9.8. Origin and type of pedigree of wheat varieties released in India, 1965-93

	1965-69	1970-74	1975-79	1980-84	1985-89	1990-93	All
Percent varieties developed by:[a]							
State-level institutions	50	68	65	72	69	71	67
National institutions	50	32	35	38	31	29	33
Percent varieties released							
Zonal level	61	52	62	55	76	75	73
State level	39	48	38	45	24	25	27
Percent varieties developed from:							
Indian crosses	71	61	76	47	74	61	71
Selections/introductions from abroad[b]	25	39	24	26	26	39	29
Percent Indian crosses:							
Indian parent x Indian parent	16	12	23	26	40	31	26
Indian parent x foreign parent	79	77	39	56	53	63	59
Foreign parent x foreign parent	5	12	39	19	7	6	16

[a] Excludes a few varieties developed jointly.
[b] Mostly based on CIMMYT crosses.

Information on area planted to individual varieties is available only for the 1990–91 season (Table 9.9).[12] The table shows the percent of wheat area sown to varieties from each zone by environment. Spillovers were indeed prevalent. For example, the first line of the table indicates that 24% of the irrigated timely sown wheat area in the NWPZ was planted to varieties developed in that zone, while 51% of the area in that environment was sown to varieties developed by IARI, 4% to CZ varieties, 3% to CIMMYT varieties, and 14% to varieties released prior to 1976 (prior to the period used below for analysis of economic impacts). (Four percent of the area was sown to unidentified varieties.) Just 16% of total area and 6% of rainfed area are sown to "home developed" varieties (i.e., research institutions targeting that zone).

Table 9.9. Realized technology spillins: Percent of area in a given zone and environment sown to cultivars classified by origin, India, 1990-91

Wheat production zone and environment	Zone where cultivar developed							Cultivars released before 1976
	NWZP	NEZP	CZ	PZ	HZ	IARI	CIMMYT	
Northwest Plains Zone								
Irrigated timely bread wheat	24	—	4	—	—	51	3	14
Irrigaged late bread wheat	10	—	—	—	—	85	—	5
Rainfed bread wheat	20	—	—	—	—	—	33	47
Durum wheat	26	—	—	—	—	—	74	—
Sub-total	21	0	3	0	0	59	5	12
Northeast Plains Zone								
Irrigated timely bread wheat	41	—	—	—	—	—	59	—
Irrigaged late bread wheat	—	7	—	—	—	7	—	86
Rainfed timely bread wheat	—	—	—	—	—	—	—	100
Rainfed late bread wheat	—	—	—	—	—	—	—	100
Sub-total	13	4	0	0	0	4	19	62
Central Zone								
Irrigated timely bread wheat	65	—	20	—	—	3	—	12
Irrigaged late bread wheat	—	—	77	—	—	—	—	23
Rainfed bread wheat	—	—	—	—	—	14	—	86
Irrigated durum wheat	—	—	—	—	—	—	—	100
Rainfed durum wheat	16	—	52	—	—	—	—	26
Sub-total	16	0	26	0	0	8	0	50
Peninsular Zone								
Irrigated timely bread wheat	—	—	—	—	—	82	2	16
Irrigaged late bread wheat	—	—	—	—	—	—	—	100
Rainfed bread wheat	—	—	—	40	—	—	—	60
Irrigated durum wheat	—	—	—	—	—	—	—	100
Rainfed durum wheat	—	—	—	8	—	4	—	88
Sub-total	0	0	0	6	0	34	1	59
Hill Zones (both)	—	—	—	—	6	12	18	64
Total India	**16**	**1**	**7**	**0.3**	**0.2**	**30**	**9**	**37**

[12] The estimation of area planted is based on methods described in Byerlee (1993). Except for the Punjab, no official statistics on area planted to individual varieties are kept in India. Estimates are based on surveys of breeders in each state, extension surveys, and other survey information. Approximately 10% of total area was sown to unidentified varieties. Table totals are percent of identified area.

Varieties from the NWPZ research centers and IARI accounted for a combined 46% of area sown in India and more than 70% of the area sown to identified varieties released since 1976. Varieties from four zones (NEPZ, CZ, PZ, and NHZ) account for only 9% of sown area compared to the 61% of national research resources allocated to the 15 programs in these zones. Nine environments had 60% or more of their area planted to varieties released before 1976, indicating that much of the area in these environments is not being reached by any of the research programs.

Analysis of Genetic Contribution to Yield Gains

We estimated the rate of yield gains from annual yield evaluation trials conducted over 22 years both at the zonal and national level. These trials often include long-term checks, but the over years they become characterized by an unbalanced design in which some older or unsuccessful varieties are dropped from the trials each year and other varieties are added for evaluation. Given the unbalanced data set, the analysis employed the least squares approach discussed in Appendix 6A.

(1) $\ln Y_i = a + \Sigma_t b_t D_t + gV_i + e_i$

where Y is yield (t/ha), D is a set of dummy variables for year of trial, and V is vintage of variety i measured in years since official release.

The estimates of genetic gains from Equation 1 were disaggregated by zones, wheat types (bread and durum), and commercial success in terms of adoption (all varieties and only successful varieties) to better reflect gains made in different environments and in farmers' fields. The results are summarized in Table 9.10. The most rapid gains have been made in irrigated timely planted conditions in the main wheat producing zone, the NWPZ. The estimated rate of gain for all released varieties in this zone is about 0.6% per year. However, if only the commercially successful varieties (subjectively defined as occupying at least 25,000 ha in any one year) are considered, the rate of gain is 1.0% per year. These results indicate that farmers are selecting the better-yielding varieties from the total set of released varieties and confirm that yield is an important criterion for farmer selection of new varieties. The estimated 1% rate of gain in yield per year for important commercial varieties is comparable with other estimates of genetic gains in yields for irrigated spring wheat.[13] This rate of gain exceeds that measured for the pre-Green Revolution period, 1910–60 (0.53% per year) but it is below the gains experienced with the introduction of MVs (2.8% per year) over 1960–80 (Kulshresthra and Jain 1982).[14]

The summary results in Table 9.10 show the following:

1. Genetic gains are highest in the irrigated timely sown environment, lower in the irrigated late planted environment, and low or statistically insignificant in the rainfed areas, except in the two zones with relatively favorable growing conditions for rainfed wheat, the NWPZ and NHZ.
2. For irrigated wheat, gains are generally highest in the main wheat producing zone, the NWPZ.

13 See Appendix 6A, Table 6A.1, for a summary of other studies.

14 However, our results may measure gains in both yield potential as well as the effect of maintenance of disease resistance, whereas the above studies by Kulshresthra and Jain (1982) and most of those summarized in Appendix 6A are based on yields protected from disease losses.

3. Gains for commercially successful varieties are nearly always higher than the gains for all varieties.

4. Gains in irrigated durums may be lower than for bread wheat.

These estimated yield gains are based on experimental yields and may not represent the true gains in farmers' fields. However, the estimation of a varietal improvement index using more than 20 years of time-series data on varietal adoption in the Punjab showed that the rate of genetic gains observed in the trial data are probably representative of rates of gains in farmers' fields as long as there is evidence, as in the Punjab, that farmers are adopting released varieties.

Equation 1 (above) measures the average rate of gain in yields from all varieties included in the analysis. In order to compare the yields of individual varieties released in India, we estimated the following equation:

$$(2)\quad Y_{it} = a + \Sigma_t b_t D_t + \Sigma_i c_i D_i + e_{it}$$

where D_i is a dummy variable for variety i such that $D_i = 1$ for variety i and zero otherwise. One of the D_i is arbitrarily dropped from the estimation, usually the long-term check. The estimate of the coefficient c_i then measures the yield advantage of variety i over the long-term check (Kalyansona or Sonalika). Of the 173 varieties released since 1967 and evaluated in the trials for three or more years, we found that 46 (or 27%) of the total have significantly outyielded the check variety of the Green Revolution period at the 95% confidence level. The highest success rate has been for varieties developed for irrigated timely sown conditions where the number of varieties with higher yields than the check is 48% of the total releases. The proportion of varieties that significantly outyields the check declines somewhat for irrigated late-sown conditions and sharply for rainfed conditions, where only 13% of the releases outyield the check (usually a tall variety such as C306 in the drier areas or Kalyansona in the wetter areas). The lower success rate in rainfed conditions reflects the lower progress in breeding gains in these environments, as well as higher year-to-year variability.

Economic Assessment of Wheat Improvement Research

The analysis of the wheat improvement research so far suggests that the allocation of research resources, agroclimatic suitability,

Table 9.10. Summary of estimated genetic gains by environment, India, 1966-91

	Northwest Plains	Northeast Plains	Central	Peninsular	Northern Hills
Bread wheat					
Irrigated timely sown					
Successful	1.02***	0.44**	0.68***	0.46**	0.89
All	0.64***	0.41***	0.36***	0.41**	0.59***
Rainfed					
Successful	0.13[a]	na	0.27	−0.03[a]	0.13[a]
All	0.31***	0.14	0.25	−0.54	0.67***
Durum wheat					
Irrigated timely sown					
Successful	0.43[a]	—	na	—	—
All	0.38*	—	0.83***	—	—
Rainfed wheat					
Successful	—	—	0.67	-0.54	—
All	—	—	0.33	0.17	—

[a] No successful varieties in the category. Analysis based on varieties classified as limited commercial success.

research output (i.e., varieties released and their adoption), and the rate of yield gains vary substantially across environments in India. In this section, we estimate the internal rates of return (IRRs) to wheat improvement research in India, using information on yield gains, research costs, and research spillovers estimated above. Since the information is available by zone and environment within zone, the unit of analysis is the research program, defined as being made up of the one or more research centers that serve a given zone and environment as identified in Table 9.1.

Data and Basic Economic Framework

Returns to investment in wheat breeding research in India were estimated from benefits accruing for the period 1976–1991, selected to represent the post-Green Revolution period after MVs had been widely adopted in irrigated areas. The economic surplus generated by wheat improvement research was calculated using the model discussed in Chapter 6 and detailed in Appendix 9A. Two types of technical change resulting from the replacement of varieties were estimated (Morris et al. 1994). A yield gain of 35–50% from Type I technical change — which occurs when MVs replace traditional varieties (TVs) in irrigated areas — has been widely documented (Byerlee and Moya 1993). In rainfed areas of South Asía, yield gains of 15–25% over TVs have been observed in higher rainfall areas (Ahmad et al. 1991; Nagy 1984), falling to 10% or less in dry areas (Ahmad et al. 1991; Byerlee 1992). These estimates of observed yield gains were the basis for estimating the benefits of Type I varietal change.

The effect of Type II technical change (which occurs in post-Green Revolution areas where farmers periodically adopt newer MVs to replace older MVs) was estimated by the environment-specific trend in genetic gains in yield potential discussed in the previous section. Both Type I and Type II yield effects are assumed to be constant through time.

Incorporating Spillovers in the Economic Framework

Varietal diffusion data were used to calculate benefits for each program, defined by zone and environment, so that technology diffusion is directly linked to research program investments. Benefits in each production environment, j, were apportioned based on spillover share, w_{jm}, defined as the share of technology from program m in all environments (including home environment m), calculated as: $w_{jm} = A_{jm} / S(A_j)$, where A_{jm} is the area in environment j sown to varieties released by program m, and $S(A_j)$ is the total area sown to post-1976 varieties in environment j (Table 9.9).

The estimated overall IRR for wheat improvement research with and without research spillins and spillovers for 20 major sub-programs in India is given in Table 9.11.[15] The overall return to wheat improvement research for the whole country is 51%. This is high but consistent with other recent studies in India and South Asia (Evenson and McKinsey 1991; Byerlee and Traxler 1995). When spillovers are ignored, the estimated IRRs for the individual research programs range from negative to 74%. Fourteen programs generated an IRR greater than or equal to 19%. Only the environments that had no adoption of MVs, and therefore no technical change, experienced negative rates of return. Varietal turnover through adoption of successive generations of MVs (Type II technical change) was the dominant source of research benefits for the period, accounting for about 90% of all benefits. This represents a major shift from the previous

15 Note that the IARI is considered a separate research program and the two environments in the NHZ are merged into one program for the purposes of this analysis.

period, which was characterized by the advent of the Green Revolution and Type I adoption of MVs. These estimates, which ignore spillins or spillovers, are consistent with most previous applications of economic surplus models (i.e., the model assumes that the technical change in each environment is directly attributable to research conducted in that environment).

A strikingly different picture of program success emerges when spillins and spillovers are incorporated into the analysis (Table 9.11 and Figure 9.2). Eight programs now have

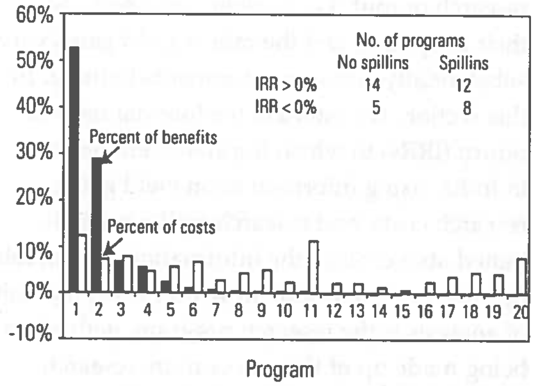

Figure 9.2. Percent distribution of costs and benefits, Indian wheat research program.

Table 9.11. Estimated internal rate of return (IRR) with and without accounting for within-country technology spillins by wheat breeding research environment in India

	IRR without spillins (%)	IRR with spillins (%)	Change in IRR (%)	Contribution to national research benefits (%)	Share in national research expenditure (%)
Northwest Plains Zone					
Irrigated timely bread wheat	71	61	-10	31.0	8.2
Irrigated late bread wheat	60	32	-28	1.0	7.2
Rainfed bread wheat	52	37	-15	0.3	4.6
Irrigated durum wheat	74	76	+2	0.6	5.4
Northeast Plains Zone					
Irrigated timely bread wheat	49	<0	-49	0.0	6.6
Irrigated late bread wheat	43	34	-9	0.8	6.9
Rainfed timely bread wheat	<0	<0	—	0.0	3.9
Rainfed late bread wheat	<0	<0	—	0.0	1.2
Central Zone					
Irrigated timely bread wheat	51	43	-8	5.8	5.0
Irrigate late bread wheat	51	51	0	3.6	6.1
Rain bread wheat	49	<0	-49	0.0	3.0
Irrigated durum wheat	<0	<0	—	0.0	2.4
Rainfed durum wheat	54	49	-5	0.5	2.4
Peninsular Zone					
Irrigated time bread wheat	19	<0	-19	0.0	3.5
Irrigated late bread wheat	<0	<0	—	0.0	3.0
Rainfed bread wheat	26	26	0	0.1	1.9
Irrigated durum wheat	<0	<0	—	0.0	0.6
Rainfed durum wheat	19	14	-5	0.0	1.7
Hills (all zones)	38	17	-21	0.4	12.8
IARI	—	66	—	45.2	13.6
CIMMYT	—	—	—	10.7	0.0
All India	**51**	**51**	**—**	**100**	**100**

negative IRRs. The two programs with the highest IRRs — IARI (including the AICWID) and the NWPZ program for irrigated timely planted wheat — generated more than 75% of all benefits from an expenditure of 22% of resources (the two programs on the left side of Figure 9.2). Only the NWPZ and CZ programs have been financially efficient at generating technologies for their mandate environments. Spillovers were clearly a dominant force in varietal technical change in India, accounting for more than 60% of all surplus produced. The national programs of IARI are responsible for 45% of the spillover benefits and CIMMYT for another 11%.

Conclusions

In this chapter, we examined the efficiency of investment in wheat improvement research across zones and environments, using India as a case study. With over 20 research programs (defined by agroecological zone, environment, and species) spread across 50 research institutes, the Indian wheat improvement research system in many respects resembles the international research system. Thus, many of the issues and concepts discussed and applied in previous chapters have also proved relevant in analyzing the efficiency of a national research system.

The large effort devoted to wheat improvement research in India has generated tremendous success. A large number of locally developed and successful varieties have been released by Indian research programs, continuous yield gains have followed genetic improvement, and rates of return are high (51%). However, most of the research output was concentrated in a few strong programs.

Important findings are reinforced by this case study. First, the nationally mandated research programs of IARI, like CIMMYT at the international level, appear to have a comparative advantage in generating successful technologies across many environments. In three of India's five zones, the varieties developed by IARI occupied more area than the varieties developed by centers targeting only that zone. The IARI research program generated almost half of all the benefits at the national level. Second, spillover benefits were dominant characteristics of technical change at the national level, similar to that observed at the international level.

The IARI research programs and those serving the NWPZ generated 75% of all benefits but absorbed only one-quarter of resources invested. The pattern of spillins appears to have been stable over time (i.e., over time few programs have switched from being "technology borrowers" to "technology generators"). The elimination or redesign of weak institutes in these programs would therefore appear to present relatively little risk of reducing the overall rate of technical change and at the same time would enhance efficiency.

The analysis presented in this chapter has two broad implications for studying rates of return to investment in agricultural research at a country level. First, high aggregate rates of return can hide considerable heterogeneity in the performance of research programs that make up the overall effort. Second, rates of return are quite sensitive to whether spillins from other programs are explicitly incorporated. Most studies in the past have ignored such spillins and have thus biased rates of return to research. Together these results imply that many previous evaluations of investment in agricultural research have underestimated the extent of investment inefficiencies at the sub-national level.

Appendix 9A

Estimation of Yield Gains for Type I and Type II Technical Change Arising from the Indian Wheat Research System

The annual increase in production due to Type I technical change generated in each agroecological environment was calculated as:

$$\text{Type I } \Delta Q_t = k^I Y_{TV} \bar{A}(MV_t - MV_0)$$

where k^I is the assumed percent yield increase due to adoption of MVs, $\bar{A}$ is the average wheat area in 1977–90, MV_t is the percent of wheat area planted to MVs in year t, MV_0 is the percent of wheat area planted to MVs in 1977, and Y_{TV} is the average TV yield in 1977.

The annual increase due to Type II technical change for each region and environment is:

$$\text{Type II } \Delta Q_t = (k^{II} - 1)\, Y_{MV} \bar{A}\, MV_0(s/7) \quad \text{for } t = 1978\text{–}1983$$

$$= (k^{II} - 1)\, Y_{MV} \bar{A}\, MV_0 \quad \text{for } t = 1984\text{–}1990$$

The research-induced yield advantage is assumed to grow at a compound rate, i.e., $k^{II}_t = (1 + g)^s$, where g is the environment-specific annual yield contribution (given in Table 9.10), $s = (t\text{–}1977)$, and d is the average varietal age. Y_{MV} is the average MV yield in 1977, and the s/d term is included to allow Type II impacts to diffuse linearly over the first d years of the benefit period beginning in 1977 before rising to a maximum area equal to the area planted to MVs in 1977.

The total economic surplus (ES) generated for each environment is:

$$ES_t = P_t Q_t K_t (1 + .5K_t/(n+e))$$

where K_t is the percentage increase in production ($\Delta Q_t / Q_t$) attributable to technical change (i.e., the combined supply shift of Type I and Type II technical change), P_t is the real wheat price, and n and e are demand and supply elasticities (assumed to be –0.35 and 0.40 respectively). Wheat prices vary by type (bread and durum), quality, and production location. To compute the IRR for each program, we assume a research lag of 10 years between the initiation of research investments and the initiation of benefit flows. Benefits were phased in linearly beginning in the eleventh year. The speed at which benefits accrued due to varietal adoption was based on the observed average of varieties age in each environment.[16]

[16] The frequency with which farmers replace varieties is approximated using the average age (in years since release) of varieties grown, weighted by the area sown to each variety. The weighted average age of varieties ranges from 4 years in the NWPZ to 23 years in some environments in the CZ and PZ.

Chapter 10

Efficiency in Wheat Improvement Research: A Case Study of Australia

John P. Brennan

This report has thus far focused on wheat breeding in developing countries. However, concerns about resource allocation, research spillovers, and research efficiency are increasingly being raised among industrialized countries as well. This chapter presents a case study of wheat improvement research in Australia, which is one of the most important wheat producing and exporting countries in the industrialized world.

Australia devotes considerable resources to wheat improvement research, employing more than 100 FTE researchers in several programs across the country (Chapter 5). Research spillovers from other countries and especially from CIMMYT have also been extremely important (Chapter 6). In recent years, as a result of funding pressures, wheat breeding programs in Australia have faced potentially important changes with implications for the structure and mix of public- and private-sector wheat breeding efforts.

This chapter provides insights into the workings of, and constraints faced by, one of the industrial world's largest wheat improvement programs. First, we examine the structure of Australian wheat breeding activities with an in-depth description of the resources allocated to wheat improvement research. We then assess the success and impacts of these research efforts, interstate and international research spillovers generated and utilized by Australian wheat improvement programs, and the future of the Australian wheat breeding industry.

Structure of Australian Wheat Breeding Activities

Wheat Breeding in Australia

Wheat is grown across Australia, mainly in low-rainfall areas, and it is grown almost entirely without irrigarion. The average growing-season rainfall for all wheat districts is 275 mm per year, ranging from 151 to 678 mm in the May to October growing season (Hamblin and Kyneur 1993). There have been some significant shifts in the location of wheat production over the past decades, with a move towards the lower-yielding areas, particularly in New South Wales and Western Australia (Brennan and Spohr 1985).

Most varieties grown in Australia are so-called spring wheats, even though they are grown through the winter (Simmonds 1989). Their growth is possible because of the, relatively mild winters in the Australian wheat-growing areas. Only in recent years have winter wheats (those with a vernalization requirement before flowering) begun to be important in the Australian wheat industry (Penrose et al. 1991).

Throughout its history, Australia has been importing wheat varieties and testing their performance in dry conditions. During the past 100 years, there have been continuous efforts to breed wheat varieties suitable for the low-rainfall, dryland production areas in the widely dispersed Australian wheat belt. Scientific wheat breeding was initiated in Australia in the late nineteenth century by William Farrer. He exerted a large influence on the development of the internationally important wheat industry; his is still a widely recognized name, and his achievements are well known across the country. Many of his varieties form the basis of varieties currently grown in Australia and internationally. One of Farrer's lasting achievements was to combine rust resistance and quality with higher yield (Simmonds 1989). From the start, then, Australian wheat breeders have emphasized improved quality.

Although the Australian industry long ago decided not to produce red-grained wheats, Australia has gained a firm place in international markets with its sound-quality, white-grained wheats (Simmonds 1989). As a result, breeders have had to develop white-grained varieties that incorporate the desired characteristics, even though many of those characteristics were first developed in red wheats overseas.

The responsibility for agricultural research in Australia has generally rested with the various state governments. Although the Commonwealth Scientific and Industrial Research Organization (CSIRO), a federal government organization, has played an important part in more fundamental research, the state governments have provided the bulk of the resources for wheat breeding. Consequently, each wheat-growing state has established its own (sometimes more than one) breeding program, focusing on its own production regions. Only in South Australia, where the breeding is now conducted under the auspices of the University of Adelaide, is the breeding not centered on the State Department of Agriculture/Primary Industry. In New South Wales, the State Department, the University of Sydney, and private breeding programs are all involved.

Clements et al. (1992) provided a comprehensive picture of Australian wheat breeding and identified 11 wheat breeding programs nationally. The location of these programs in relation to the areas of wheat production is illustrated in Figure 10.1. All but one of these are public programs, funded from the public purse and from growers' research levies.

Resources Used for Wheat Breeding

Clements et al. (1992) obtained information on the resources and staff used by each of these programs. While there are some concerns about the consistency and

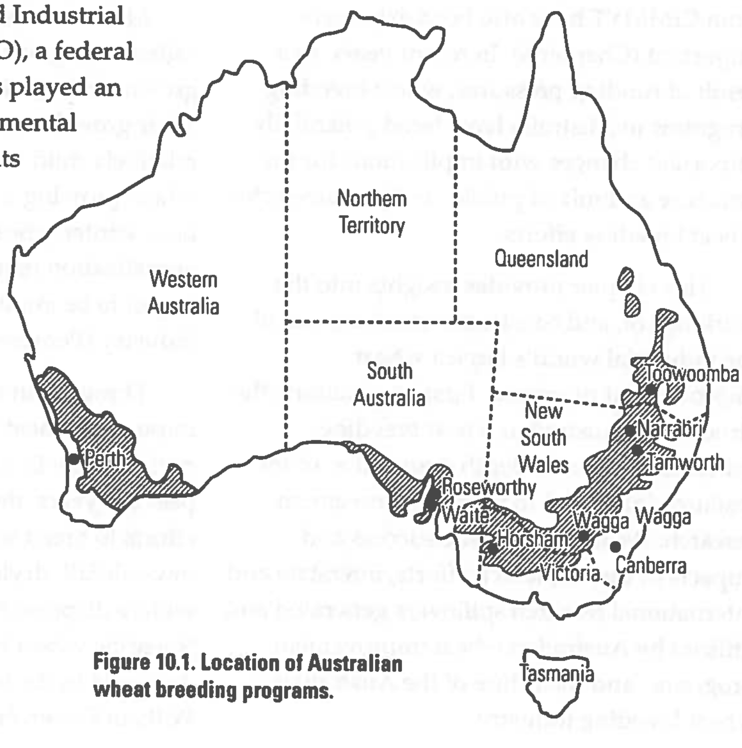

Figure 10.1. Location of Australian wheat breeding programs.

comparability of the information provided by the programs, these data provide some opportunity to identify the extent of the resources used by wheat breeding programs in Australia (Table 10.1).

A total of 131 person-years were devoted to wheat breeding in 1992. Of these, 17 were classified as breeders and 92 were other scientific or technical staff (including pathologists, cereal chemists, post-graduate students, and technical staff), all with the equivalent of a B.S. or higher degree. A further 22 person-years of non-degree staff time were devoted to the breeding programs.

On the basis of these data, Australia spends $5.5 million (in US$ 1992) on wheat breeding each year.[1] These data include some, but not all, the resources used for quality evaluation (since in some states quality testing is conducted outside the programs and is not included in the Clements data). The funds for wheat breeding represent half the total research funds for wheat (Clements et al. 1992, Table 34).

The mandate or target regions for each program are also indicated in Table 10.1. The mandate regions for several programs overlap, so the total of all the mandates exceeds the total Australian area and production. The data from Clements et al. (1992) enable comparisons between states concerning the intensity of wheat improvement research (Table 10.2). Inconsistencies in the coverage of the state data and the existence in some states of nationally focused programs mean that the data need to be interpreted with caution. However, they indicate that there are, on average, 7.7 scientists in crop improvement per million tons of wheat produced, or 0.063 scientists per million dollars of value of production. The research intensity (measured as research expenditures as a percentage of

Table 10.1. Staff and resources of Australian wheat breeding programs, 1992

Breeding program	Organization	Region	Mandate region[a] Area (M ha)	Mandate region[a] Prod. (M t)	Staff[b] (person-years) Breeders	Staff[b] (person-years) Other scientists	Staff[b] (person-years) Total[d]	Total funds (US$ 000)[c]
Agricultural Research Institute, Wagga Wagga	NSW Agriculture	Southern NSW	1.1	2.5	2.8	9.1	18.9	974
Agricultural Research Centre, Tamworth (bread)	NSW Agriculture	Northern NSW	0.8	1.1	0.5	4.6	5.1	221
Agricultural Research Centre, Tamworth (durum)	NSW Agriculture	National (durum)	0.1	0.1	0.5	2.9	3.4	164
I.A. Watson Wheat Research Centre, Narrabri	University of Sydney	Northern NSW	0.8	1.1	2.0	22.0	28.8	923
Queensland Wheat Research Institute, Toowoomba	Queensland Department of Primary Industries	Queensland	0.7	1.0	2.0	15.5	19.6	557
Victorian Institute for Dryland Agriculture, Horsham	Agriculture Victoria	Victoria	0.9	1.7	2.0	16.6	20.0	746
Roseworthy Campus, Roseworthy	University of Adelaide	South Australia	1.4	2.3	1.8	4.0	5.8	466
Waite Agricultural Research Institute, Adelaide	University of Adelaide	South Australia	1.4	2.3	0.5	5.0	5.5	202
WADA Division of Plant Industry, South Perth	WA Department of Agriculture	Western Australia	3.6	5.6	2.3	11.0	13.3	1,105
CSIRO Division of Plant Industry, Canberra	Commonwealth Scientific and Industrial Research Organization	High-rainfall zone	0.2	0.4	1.0	1.5	2.5	119
Cargill Seeds, Tamworth	Cargill Seeds	Northern NSW	0.8	1.1	2.0	3.0	8.0	na
Total wheat breeding/improvement			**8.6**	**14.3**	**17.3**	**92.1**	**130.8**	**5,476**

[a] Data based on average of 5 years to 1993-94. Mandate regions overlap, so the total of the mandates for all programs exceed the total area and production.
[b] In full-time equivalents. Breeders and other scientists have equivalent of B.S. qualification or better. Other (non-scientist) staff included in the total staff.
[c] Converted from Australian dollars at average 1992-93 exchange rate of A$ 1.0 = US$ 0.7.
[d] Includes non-degree staff.
Source: Clements et al. (1992), Table 11, and Australian Bureau of Statistics.

1 Note that this estimate differs from the estimated total research expenditure of US$ 8.8 million reported in Chapter 5 (Table 5.1) because the latter is based on the PPP exchange rate for 1990.

gross value of wheat production) varies from 0.16% in Western Australia to 0.51% in New South Wales (NSW). The overall research intensity for Australia is 0.31%.

Funding for Australian Wheat Breeding

As noted, Australian wheat breeding is funded predominantly from the public purse and a research levy. Indeed, of the breeding programs currently producing varieties for farmers, only one is a private breeding program, which aims to produce hybrid wheats. This program, however, made a major contribution through the development of a self-pollinated variety which was very widely grown in the early 1990s.

Other varieties have all been developed in the public breeding programs. The main support for these programs has come from the state governments, who have provided most of the infrastructure and the salaries of the senior breeding staff.

Since 1957, a research levy (paid by farmers) has been imposed on wheat production, the funds from which are then matched equally by a federal government grant. These funds are currently collected and distributed through the Grains Research and Development Corporation (GRDC). Clements et al. (1992) found that 42% of the total funds for breeding and varietal development were provided by the GRDC (Table 10.3). On that basis, 21% of the funds were from grower levies, a matching 21% from the federal government, and the remainder from state governments (45%), universities (11%), and CSIRO (2%).

Table 10.3. Source of funds for public wheat improvement research, Australia, 1992-93

Source of funds	Total public funding[a] (US$ 000)[b]	% of total
GRDC		
Grower levies	1,150	21
Federal government matching grants	1,150	21
Total	2,300	42
CSIRO (federal government)	119	2
State governments		
New South Wales	965	18
Victoria	451	8
Queensland	266	5
South Australia	0	0
Western Australia	782	14
Total state governments	2,464	45
Universities	593	11
Total	**5,476**	**100**

Source: Derived from data in Clements et al. (1992), Table 11.
[a] Excludes funding for the one private breeding program in Australia, for which data not available.
[b] Converted from Australian dollars at average 1992-93 exchange rate of A$ 1.0 = US$ 0.7.

Table 10.2. Intensity of wheat improvement research inputs, Australia

State	Production (M t)	GVP[a] (US$ M)	Scientists (FTE)	Intensity: FTE/Mt Production	Intensity: FTE/US$ M GVP	Research expenditure as percentage of GVP
New South Wales	3.7	451	51.9	14.0	0.115	0.50
Queensland	1.0	122	17.5	17.5	0.143	0.46
Victoria	1.7	207	18.6	10.9	0.090	0.36
South Australia	2.3	281	11.3	4.9	0.040	0.24
Western Australia	5.6	683	13.3	2.4	0.019	0.16
Australia	**14.3**	**1745**	**109.4**	**7.7**	**0.063**	**0.30**

Source: Derived from Table 10.1.
[a] Gross value of production; average production valued at US$ 122/t.

Structure of Australian Wheat Breeding Programs

A Representative Program

Wheat breeding programs vary based on the breeders who run them; individual programs also vary from year to year and from cross to cross, given different objectives and factor endowments. Brennan (1989a) examined a breeding program in detail to assess the costs and benefits of its different parts. The representative program assessed was an amalgam of two Australian programs. Both were single-breeder programs, aiming to produce varieties for the local dryland production environment. In the representative program, 50 crosses were made each year, 35,000 plants were evaluated in F_2 generation, and 2,000 lines entered the replicated field trials in F_5 generation. From trials and quality evaluation over the next five years, the best line was then identified (after the F_{10} generation). Only one of these from every four such breeding cycles was sufficiently superior to current varieties to warrant its release for commercial production (i.e., on average the program released a new variety every four years). Quality played a significant part in the selection process, with quality testing beginning at the F_2 stage. Bread-making quality was the major selection criterion in the later generations.

Costs of the Representative Program

Brennan (1988, 1989a) developed cost estimates for each operation and each generation in the program (Table 10.4). A complete breeding cycle from crossing through to the F_{10} generation cost a total of US$ 143,300, with F_6 the most costly stage of the program. The early generations (F_2 and F_3) are also relatively expensive, while the crossing stage and the later-generation stages cost relatively less.

Because four cycles are required for each commercially released variety, Brennan (1989a) calculated the total costs of breeding each variety at US$ 573,000 (Table 10.5). These costs are spread over 13 years from the initial crossing. At a discount rate of 5% per annum, the total discounted cost (discounted to the initial year of crossing) is US$ 446,000.

Table 10.4. Costs of wheat breeding cycle, Australia

Generation	Direct costs of operations (US$ 000)[a]			Percent of
	Breeder[b]	Quality	Total	total cost
Crossing/F_1	3.1	0.0	3.1	2.2
F_2	11.0	13.8	24.8	17.3
F_3	20.7	4.3	25.0	17.5
F_4	3.5	0.0	3.5	2.4
F_5	9.6	4.3	13.9	9.7
F_6	26.3	25.6	51.8	36.2
F_7	4.9	8.1	13.1	9.1
F_8	0.9	2.4	3.3	2.3
F_9	0.5	2.1	2.6	1.8
F_{10}	0.4	1.8	2.2	1.5
Total	**80.9**	**62.4**	**143.3**	**100.0**

Source: Brennan (1988).

[a] In 1988 US dollars, converted at average 1988-89 exchange rate of A$ 1.0 = US$ 0.81.

[b] Includes glasshouse and field evaluations and disease screening.

Table 10.5. Cost of variety produced after four cycles of breeding, Australia

Year	Breeding cycle number				Total
	1	2	3	4	
1	3.1	0.0	0.0	0.0	3.1
2	24.8	3.1	0.0	0.0	28.0
3	25.0	24.8	3.1	0.0	53.0
4	3.5	25.0	24.8	3.1	56.4
5	13.9	3.5	25.0	24.8	67.2
6	51.8	13.9	3.5	25.0	94.2
7	13.1	51.8	13.9	3.5	82.3
8	3.3	13.1	51.8	13.9	82.1
9	2.6	3.3	13.1	51.8	70.7
10	2.2	2.6	3.3	13.1	21.1
11	0.0	2.2	2.6	3.3	8.0
12	0.0	0.0	2.2	2.6	4.8
13	0.0	0.0	0.0	2.2	2.2
Total	**143.3**	**143.3**	**143.3**	**143.3**	**573.1**

Source: Brennan (1989a).

Returns from Wheat Breeding Programs

Brennan (1989a) estimated the returns from the representative wheat breeding program as follows:

- The expected genetic gains from selection were determined from the expected variability of the breeding population, the estimated heritability of the characters, and the selection intensity imposed by the selection program. From those data, the expected gains from each new variety compared to currently grown varieties were estimated as 2.25% for yield and 1.09% for quality (see Brennan 1988 for more details).
- The market value of each of the major selection characters was estimated as US$ 0.90/t for each 1% increase in yield and US$ 0.66/t for a 1% increase in the quality index. On that basis, the expected increase in yield and quality from each new variety was valued at US$ 2.74/t.
- The target or mandate region for the breeding program was defined as 1 million hectares of wheat, with average yields of 1.7 t/ha.
- The new variety was assumed to be released at the end of the F_{10} generation of every fourth cycle.
- From past data, the adoption pattern of a variety with a 2.25% yield advantage over current varieties was estimated to reach a maximum of 16.0% of the target area in the seventh year after release. Its adoption level by farmers then declined as the variety was gradually replaced over the following 13 years (i.e., it continued to be grown for 20 years after its release).

On the basis of these parameters, the expected returns from the breeding program were estimated. Annual returns reached a maximum of US$ 747,000 in the seventh year after release. When discounted to the initial year of crossing (13 years before release) at a real interest rate of 5%, the discounted value of total returns was US$ 3,091,000.

Analytical Model of Representative Program

Using these estimates of costs and returns, Brennan (1989a) carried out an economic analysis of the representative breeding program (Table 10.6). The benefit-cost ratio of the program was found to be 6.9 at a discount rate of 5%, and the internal rate of return was 19.2%. These results were sensitive to the size of the mandate region for the program. If the region had been half as large, the internal rate of return would have been 13.8%; if the region had been twice as large, the internal rate of return would increase to 25.2%.

The model developed by Brennan (1988, 1989a) was aimed at assessing changes in breeding strategies, rather than simply evaluating the current strategy. The model was subsequently used to evaluate changes that could be made to Australian breeding programs. The adoption of techniques and technologies that reduce the time that elapses between the initial crossing and the release of a commercial variety from the program (such as early release, off-season nurseries, and tissue culture) was shown to have high economic payoffs (Brennan 1989b). The increased emphasis on selection for quality,

Table 10.6. Analysis of costs and returns for a representative breeding program in Australia

Discounted[a] total costs (US$ 000)	446
Discounted[a] total returns (US$ 000)	3,091
Net present value[a] (US$ 000)	2,645
Benefit-cost ratio	6.9
Internal rate of return (%)	19.2

Source: Brennan (1989a).

[a] In 1988 US$, with a real discount rate of 5% per annum.

particularly when used in the early generations, does not increase the returns to the Australian economy unless the payment system recognizes the value of the improved quality (Brennan and O'Brien 1991). Recent changes in the payment system mean that payments to growers are more closely related to the quality of the wheat produced by the individual grower.

These analyses have provided Australian wheat breeders with more information than breeders in other parts of the world about the structure of their programs and the economic benefits and costs of the different components of their programs. The question now is whether there is any evidence that this information has helped Australian breeders become more efficient than their counterparts in other countries.

Impact of Australian Wheat Breeding Programs

Varieties Released from Wheat Breeding Programs and Their Impact

The output of the various breeding programs, in terms of the number of varieties released since 1970, is shown in Table 10.7. All the major wheat-producing states have had a regular flow of new varieties over that period. Between 1970 and 1994, on average, 0.63 varieties have been released each year for every million hectares of wheat planted, although the intensity of variety output per state has varied widely. The intensity of variety output appears to be closely related to the intensity of research input (Table 10.7).

One measure of an individual program's impact is the proportion of the wheat area sown to its varieties. Those data for selected years since 1980 are shown in Table 10.8. It is evident that the relative fortunes of the different programs can differ widely over time. Programs from each state have made a significant contribution to the national varieties since 1980. The programs tend to have a series of successful varieties, which are subsequently replaced by varieties from another program that are superior in some important characteristics. No single program has dominated the supply of varieties to farmers since 1980.

In 1993–94, 80 different varieties were sown on more than 1,000 ha each across Australia. Excluding minor varieties sown on less than 10,000 ha in that year, a total of 53 varieties were sown on a significant area, at an average area of approximately 177,000 ha each. Nineteen varieties were sown on more than 100,000 ha in 1993–94, with the leading variety, Spear, sown on 1.4 million hectares.

Table 10.7. Australian wheat varieties released since 1970, by state

State	1970-79	1980-89	1990-94	Total, 1970-94	Intensity[a]
New South Wales	12	27	14	53	1.12
Queensland	3	9	6	18	1.03
Victoria	4	10	6[a]	20[a]	0.89
South Australia	3	10	7[a]	20[a]	0.57
Western Australia	6	11	6	23	0.26
Other	1	0	1	2	–
Total	**29**	**67[a]**	**39[a]**	**135[a]**	**0.63**

Source: Information from Australian Winter Cereals Collection.
[a] Varieties released per year per million hectares of wheat planted, 1970-1994.
[b] Varieties released jointly by programs in two states are included in each state's releases, but only once in the overall total.

Trends in Australian Wheat Yields

Long-term trends in Australian wheat yields since 1870 are illustrated in Figure 10.2. After declining from nutrient exhaustion in the late 1800s, yields increased in the next 50 years to approximately the level they had been a century earlier. With the introduction of legume nitrogen (mainly subterranean clover), better rotations, and mechanization, yields began a relatively sharp increase in the 1950s. It appears that yields have moved onto a new curve in the past 20 years because of the use of semidwarf varieties, improved weed control, and improvements in alternative rotation crops such as lupins and canola.

Hamblin and Kyneur (1993) made a detailed study of various factors that have contributed to wheat yield changes in Australia. They presented a systematic analysis of wheat yield trends at the Local Government Area (LGA) level across Australia. They found enormous differences between regions in the trends in wheat yields from 1950 to 1991. Of the 208 shires or counties they examined, the mean annual rate of yield increase was 14 kg/ha, equivalent to approximately 1.1% of mean yields over the period. The frequency distribution of rates of yield increase in the LGAs examined is shown in Figure 10.3. Most LGAs had average yield

Table 10.8. Proportion of area sown to varieties released by breeding programs, Australia

Breeding program	Percentage of area sown to program's varieties 1980	1985	1990	1993
Agricultural Research Institute, Wagga Wagga	37	16	8	9
Agricultural Research Centre, Tamworth	1	1	1	1
I.A. Watson Wheat Research Centre, Narrabri	25	15	10	10
Queensland Wheat Research Institute, Toowoomba	7	21	16	18
Victorian Institute for Dryland Agriculture, Horsham	5	12	6	7
University of Adelaide, Roseworthy	11	12	26	31
University of Adelaide, Waite	1	6	8	5
WA Department of Agriculture, Perth	7	15	18	17
CSIRO Division of Plant Industry, Canberra	0	0	0	0
Cargill Seeds, Tamworth	0	0	6	2
Not specified	5	2	2	1

Source: Derived from data supplied by the Australian Wheat Board.

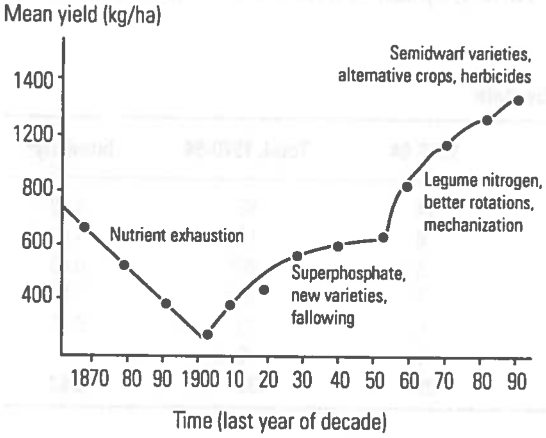

Figure 10.2. Long-term Australian wheat yield trends.
Source: Hamblin and Kyneur (1993).

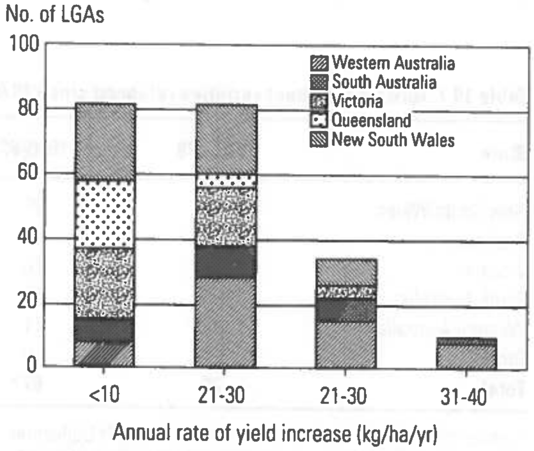

Figure 10.3. Frequency distribution of rates of yield increase, by local government area (LGA), 1950-91.

increases of less than 20 kg/ha/yr, but a significant number (especially in New South Wales) had larger average yield increases.

Contribution of Varieties to Wheat Yield Improvement

In any such analysis, it is difficult to identify precisely the contribution that new varieties have made to yield improvement. Using an Index of Varietal Improvement, Antony and Brennan (1988) found that varieties had made a significant, but fluctuating, contribution to yield improvement in New South Wales (NSW). They also identified a significant improvement in bread-making quality attributable to new varieties. Godden and Brennan (1994) compared the rate of yield improvement through varieties in southern NSW with that in the United Kingdom over the postwar period. They found no significant differences between the relative rate of yield increase in bread-making varieties. It is unclear what proportion of yield improvements in other states can be attributed to varieties, although O'Brien (1982) and Perry and D'Antuono (1989) found a significant contribution from varieties in Victoria and Western Australia, respectively. More recently, Brennan and Fox (1995) found that semidwarf wheats, in the 20 years since their first release, have contributed an upward shift in wheat yields of 5.3% on average over what they would have been.

Spillover Effects in Australian Wheat Breeding

International Spillins in Australia

Edwards and Freebairn (1984) and Davis et al. (1987) have analyzed the spillin and spillover effects of agricultural research, where technologies developed for one region are adopted in other regions. Brennan (1986, 1989c) and Brennan and Fox (1995) have estimated the spillin benefits flowing to Australia from CIMMYT's Wheat Program.

The wheat breeding program at CIMMYT in Mexico has succeeded in its aim of increasing wheat yields in developing countries throughout the world (Byerlee and Moya 1993). Even though CIMMYT's breeding program has been directed at developing countries, Australia has received considerable spillover benefits from it. While CIMMYT lines have been widely evaluated in Australian breeding programs, few of those imported lines have been suitable for direct release for commercial production in Australia. In most cases, the CIMMYT lines have been used as parent lines in Australian wheat breeding programs. The Australian breeders have combined those lines with other locally developed varieties to produce improved varieties adapted to the Australian environment.

Twenty years after the release in 1973 of the first semidwarf wheat in Australia, over 90% of Australia's wheat area was sown to semidwarf varieties. In 1993–94, Western Australia (77%) was the only state with less than 90% of the wheat area sown to semidwarf varieties incorporating CIMMYT material.

Semidwarf varieties have shown a significant advantage in yield per hectare over other varieties in most areas. As noted, Brennan and Fox (1995) estimated that CIMMYT-derived varieties had increased yields in Australia by an average of 5.3% by 1993, ranging from 2.1% in Western Australia to 8.8% in Queensland. Yield gains from CIMMYT-derived varieties reduced costs by an estimated average of US$ 101 million (in 1993–94 values) per year in the period 1974 to 1993.

However, only part of those benefits arise because of the contribution of the CIMMYT material; part also arises because of the efforts and inputs of the Australian wheat breeders in combining that material with other wheats with agronomic and other qualities appropriate to the Australian production environment and markets. Analysis aimed at identifying the relative contributions found that CIMMYT contributed 55% of those total benefits (on the basis of the direct contribution to pedigrees). In other words, Australia's wheat industry has received an average $56 million per year as a result of CIMMYT's work.

Clearly, the Australian wheat industry has received extremely valuable spillover benefits from the CIMMYT wheat breeding program in terms of direct yield increases. Brennan and Fox (1995) also identified several other benefits, particularly sources of disease resistance that have flowed to Australia from CIMMYT. However, a survey of Australian breeders reveals that they are currently making less use of CIMMYT's materials than in the past (Brennan and Fox 1995). The continuing emphasis of Australian breeding programs on quality for particular end uses means that the lower quality CIMMYT material based on the Veery lines has been used only sparingly in Australian breeding programs. However, it seems likely that Australian breeders will continue to obtain benefits from CIMMYT materials being targeted at environments in developing countries. The ability of breeders to use the recent developments in information technology to target particular characteristics in the CIMMYT material will ensure that the Australian wheat industry will continue to obtain spillover benefits.

There has been no study of the spillover effects from Australian breeding programs to other countries or the international agricultural research centers. There have been some limited spillovers from Australia to New Zealand (Burnett et al. 1990), but there are few other examples of Australian varieties being grown commercially in other parts of the world. Brennan and Fox (1995) have highlighted the genetic contribution of Australian varieties to the development of CIMMYT germplasm.

Interstate Spillovers from Breeding Programs in Australia

Each program has a target or mandate region at which its breeding activities are aimed (Table 10.1), generally the entire wheat belt of the state in question. In many cases, subprograms are aimed at specific parts of the region or at specialty wheat types within the region. Since the programs are established under the auspices of the state governments, the target regions have tended to be determined by state borders as much as by geographical environments.

There have been considerable spillovers of cultivars across state borders, however. For example, the most widely grown cultivar in New South Wales for much of the 1980s was Banks (released in Queensland), while the leading cultivar in Western Australia from the 1960s to the mid-1980s was Gamenya (released in New South Wales) and more recently Spear (released in South Australia). These spillovers are not merely to adjoining areas in adjacent states, but are often to environments far removed from the original target region of the breeding program.

The derivation of wheat cultivars grown in each state in 1993–94 is shown in Table 10.9. These data, however, are very sensitive to the choice of year (as indicated by the time-series data in Table 10.10). Of the total area of 2.47 million hectares sown in New South Wales, 972,000 ha (39%) was sown to varieties released by programs outside the state. The percentages for other states in 1993–94 were as follows: Victoria 42%, Queensland 22%, South Australia 21%, and Western Australia 62%. Overall, 4.403 million hectares (46% of the total area) were sown to a variety developed in another state. The most significant interstate flow of varieties was from South Australia to Western Australia and from Queensland to New South Wales.

In Table 10.10, the use of cultivars developed outside the state in which they were grown is shown for the period since 1980–81. Over the 14 years to 1993–94, an average of 44% of the total wheat area (equivalent to 4.6 million hectares) was sown to varieties developed interstate; the maximum occurred in 1983–84, when 55% of the total area (or 7.1 million ha) was sown to interstate varieties. While all states have significant spillover use of interstate varieties, Western Australia and Victoria have relied most on varieties developed in other states since 1980.

These figures show the importance of the interstate spillover of wheat cultivars. These interstate flows have been the result of a relatively free exchange of varieties and breeding materials between the public

Table 10.10. Percentage of wheat area sown to varieties developed in other states, 1980-81 to 1993-94, Australia

Year	New South Wales	Victoria	Queensland	South Australia	Western Australia	Total area
	(% of area sown)					
1980-81	9	70	40	51	74	49
1981-82	16	62	33	48	76	49
1982-83	29	53	31	47	77	54
1983-84	48	46	22	37	77	55
1984-85	53	39	19	41	71	54
1985-86	45	44	20	35	57	46
1986-87	41	55	26	25	51	43
1987-88	32	53	28	20	56	41
1988-89	26	44	27	15	49	34
1989-90	25	42	28	10	52	35
1990-91	24	44	22	8	52	34
1991-92	20	39	25	7	49	33
1992-93	27	39	14	9	58	38
1993-94	39	42	21	21	62	46
Mean	**31**	**48**	**26**	**27**	**61**	**44**

Source: Derived from data supplied by the Australian Wheat Board.

Table 10.9. Use of wheat varieties by program of origin, 1993-94, Australia

Program of release	Area (000 ha) sown in New South Wales	Victoria	Queensland	South Australia	Western Australia	Total area[a]
NSW Agriculture – Wagga Wagga	594	189	6	24	29	842
NSW Agriculture – Tamworth	27	0	1	17	4	49
Sydney University	627	27	113	11	147	925
Cargill	203	18	3	6	0	230
New South Wales, total	1,452	234	122	58	181	2,047
Victoria, total	0	604	0	11	21	636
Queensland, total	972	114	423	190	22	1,721
Adelaide University – Roseworthy	0	83	0	817	2092	2,992
Adelaide University – Waite	0	7	0	145	290	442
South Australia, total	0	90	0	963	2381	3,434
Western Australia, total	0	0	0	5	1588	1,593
Unknown/not identified	46	7	15	15	7	90
Total[a]	**2,470**	**1,050**	**560**	**1,242**	**4,200**	**9523**

Source: Derived from data supplied by the Australian Wheat Board.
[a] Figures are subject to rounding errors.

programs. There has been widespread promotion of the superior cultivars regardless of their origins. Thus, once one program achieves a cultivar superior in an important aspect, that cultivar is widely used in other programs as a parent (usually long before the final release of the cultivar), and closely related lines are also tested extensively. The Interstate Wheat Variety Trials help this process in a formalized way, although the major lines of communication between programs are the informal ones created by the breeders themselves. Pressures for greater levels of cost recovery for each program have placed this free exchange under some scrutiny in recent years, but a commendably high degree of cooperation remains between the breeding programs in the various states.

Implications of Spillovers for Breeding Programs

The spillover effects from the flow of varieties across state and regional borders have significant implications for breeding programs. One major implication is that any moves toward plant variety rights (PVR) for wheat could be costly for growers if the result restricts interstate movement of cultivars. If the breeding organizations receive royalties (or levies of some kind) for the use of their cultivars, there will be greater incentives for local state departments of agriculture to promote their own cultivars instead of those from other states. There will also be fewer incentives for breeders to share materials, retaining the advantage of any breeding advance for a longer period before competing programs also achieve that advance. If interstate cultivars are to be included in trials and promoted for farmers, each state may need to set up its own testing and marketing organizations in the states, which would add to the costs of the system.

Another implication is that analysis of the impact of any wheat breeding program must take interstate use into account, or a substantial portion of the total benefits will be overlooked. While breeders can continue to focus their efforts on the local regions, they must also consider the possible use of their cultivars in other states and regions in assessing their aims and objectives. Considerations of disease resistance are particularly important because the largest differences between states occur in this area.

The widespread use and promotion of interstate cultivars by breeders testify to their efforts to obtain the best cultivars for the farmers, rather than merely to promote their own cultivars.

Prospects for Australian Wheat Breeding

Pressures for Rationalization of Public Breeding Programs

Recently, public breeding programs have felt a lot of pressure to change. Improved efficiency is one part of that pressure, but by no means the overriding one. Initially, pressure has come directly from reductions in state government budget outlays on agricultural research. Government support for research is under increasing scrutiny. Because plant breeding was a major beneficiary of state government research funding, it has suffered from the reduction in such funds. Lloyd (1993) has suggested that data from sources including Lazenby (1986), Downes (1989), and Clements et al. (1992) indicate a 50% reduction in professional staffing in public-sector plant breeding programs since 1980.

In the past, state governments funded the basic breeding activities, supplemented by competitive funds from the GRDC. Gradually, over the past decade or so, breeding programs have come to rely on competitive GRDC funding for their continued operation.

The Industries Assistance Commission (1976, p. 66) argued that, because of the externalities and uncertainties associated with rural research, "if the level of research expenditure were much more heavily dependent on . . . [research] levies [than in 1976], there would be serious under-investment in rural research and a large loss to national income and social welfare would result." Research depends on producer levies considerably more now than when the Industries Assistance Commission made that judgement.

Accompanying the increased reliance on competitive funding has been strong pressure from GRDC for more coordinated wheat breeding programs (e.g., Clements et al. 1992). In recent years, the GRDC has worked strongly to get breeding programs to target production regions rather than state-based production areas. It has defined three major regions: (1) Northern Region (Queensland and northern New South Wales); (2) Southern Region (southern New South Wales, Victoria, South Australia); and (3) Western Region (Western Australia). The GRDC sees some substantial gains in breeding efficiency by a greater recognition of these production regions and reduced emphasis on state boundaries. As a result, coordination between breeding programs has been formalized, supplanting the earlier informal cooperation.

Role of Public and Private Breeding Programs

Australia introduced its first PVR scheme in 1988 to facilitate private-sector investment in plant breeding. Lloyd (1993, p. 292) found that PVR "has had no measurable effect on private-sector investment in breeding of principal grain crops." Publicly funded breeders have chosen to protect few of the public-sector varieties under PVR or to seek to obtain royalties from their seed sales. Lloyd (1993) argued that the provision for farmer-saved seed to be excluded from PVR provisions has been the most important disincentive to private-sector investment in breeding and commercialization of public-sector varieties in grain crops. Recent changes to the legislation have led to the enactment of the Plant Breeders Rights scheme, which is designed to overcome some of the perceived deficiencies of the previous PVR scheme.

The pressures on public breeding programs to generate more of their own funds have led to some increase in the numbers of varieties being protected and in the royalties collected in recent years. In addition, an increasing number of varieties are being released for smaller market niches, and these varieties are often produced under a contractual arrangement. Such arrangements represent a major departure from past practices in the Australian wheat industry.

Only one private breeding program currently develops varieties adapted to Australian conditions for commercial release: the hybrid wheat breeding program. Hybrids will likely become an increasingly important, though still small, feature of the Australian wheat industry in the near future. Any further reduction in public funds for wheat breeding will mean a fall in farm productivity unless other parts of the private sector can fill the void.

In the Australian system, the slow introduction of greater private incentives and the importance of public breeding programs in the intervening periods are important issues. The Australian experience exemplifies the earlier views of Ruttan (1982):

> There can be no question about the importance of maintaining viable public-sector crop-breeding programs until it is possible to monitor and to evaluate the effects of plant variety protection on the performance of private-sector varietal improvement efforts.

In the U.S., the experience has been that "breeding effort and time is sometimes extended to economically unimportant traits such as glume color or ligule length" (Ruttan 1982, p. 199) under a competitive PVR system. Producing crops for forage or hay is one area in which private companies could successfully become involved if there were PVRs because producers need to buy new seed each year.

Any further reduction of support for the public wheat breeding programs would lead to a reduced flow of new cultivars adapted to the various production environments. Ultimately yields and total output would decline to the extent that varieties imported from other states or overseas would be less productive in those environments than those developed locally. Murray and Brennan (1993) found that any reduction in the number of breeding programs would significantly increase the risk that disease resistance would not be adequate to prevent more frequent epidemics.

The remaining established programs could expand their focus if some public wheat breeding programs were closed down. However, private firms would have little incentive to establish programs unless there were adequate institutional mechanisms for cereal grains to allow suitable returns from varietal development. Even with such mechanisms in place, there is not likely to be sufficient incentive for other organizations to develop similar programs, particularly those for smaller market niches or the newer crops.

Conclusions

The Australian wheat breeding system has proven effective in the face of a harsh and unreliable production environment. A productive system has developed based on a number of cooperating public-sector breeding programs. As a result of the various funding pressures, wheat breeding programs are facing some potentially important changes.

While there is little scope for direct privatization of Australia's wheat breeding programs, there is considerable scope to increase the cost-recovery of the programs. The industry's efforts at breeding for minor crops or market niches for major crops also could perhaps be rationalized, so that adequate effort is made for important crops but breeding resources are not wasted by being dispersed too thinly over a large number of minor crops or end uses that may have limited potential (Brennan et al. 1993).

In Australia, a wheat breeder generally cannot obtain a direct economic return from each person who benefits from a variety, because for self-pollinated crops such as wheat it is possible to reproduce more seed (true to type and quality) from a small amount of the seed. With hybrid varieties, growers wishing to obtain the full benefits need to purchase new seed each year (and therefore are liable to be charged for the use of the technology). The only private breeding program in Australia is working on hybrids rather than self-pollinated varieties. Without public-sector wheat breeding, growers are likely to find a slower rate of productivity improvement.

Over the past 20 years, spillovers from CIMMYT to Australia have been significant. However, Brennan and Fox (1995) found that Australian breeders are currently making less use of CIMMYT material than in the past, largely because of perceived problems with the quality of food made from CIMMYT's more recent breeding materials. Nevertheless, it seems likely that Australian breeders will continue to obtain benefits from the CIMMYT material. Recent developments in information technology allow breeders to target particular characteristics in the wide range of CIMMYT material, and that should ensure that the Australian wheat industry will continue to obtain spillover benefits.

The funding pressures facing Australian wheat breeding programs mean that there could be some significant changes to the system, with a changed structure and mix of public and private breeding programs. If those pressures prove irresistible, a smaller, leaner, more competitive, and less cooperative wheat breeding system could emerge. Whether Australian wheat growers will be better off under a changed system is unclear. What seems clear is that a very effective system has served them in the past.

Chapter 11

Toward Efficient Allocation of Research Resources in the Presence of Spillovers: Lessons from Wheat Improvement Research

Mywish K. Maredia and Derek Byerlee

In the period following the Green Revolution, investment in agricultural research in the developing world increased rapidly and by 1990 exceed that in industrialized countries (Pardey et al. 1996). However, in recent years, investment in research has slowed in all regions—and in many cases it has declined. The emphasis in the 1990s has now shifted from the growth of international and national agricultural research systems (NARS) toward more efficient use of the existing research infrastructure. "Rationalization" of research investments, downsizing, and formal approaches to research priority setting are now the order of the day.

Investment in wheat improvement research over the past three decades has followed these general patterns. Today, more than 1,200 scientists work under widely varying conditions in NARS and CIMMYT to improve wheat varieties in the developing world. Those scientists are supported by a total investment of more than US$ 100 million (1990 $PPP). Without question, these efforts have generated substantial benefits. Most farmers in the major wheat growing areas now have access to a steady stream of improved wheat varieties, and these varieties are now being developed for more specialized agroecological niches. Moreover, wheat yields in developing countries have grown at a faster rate than yields of any other major food commodity. In the post-Green Revolution period, improvements in yield and disease resistance through wheat breeding efforts have generated an economic surplus in developing countries worth several billion dollars.

The remarkable success of wheat improvement research in developing countries is confirmed by the evidence assembled in this report: high output of wheat research programs, large *potential* and *actual* spillovers of wheat technologies across countries, and high rates of return to investments in wheat improvement research at both the international and national levels.

Despite the evidence of high productivity and profitable returns, however, international research centers and many NARS are facing reduced budgetary support. Such reductions suggest that research efficiency and resource allocation need to be re-examined if agricultural research is to remain effective in the twenty-first century. Responding to this challenge, this report has sought not just to document research successes, but to analyze the efficiency of research investments at a disaggregated level and to explore a range of options for restructuring wheat research programs to enhance efficiency.

Major Findings

Although this report covers only one crop, it provides an in-depth analysis of the global wheat improvement research system based on data from over 40 countries. More specifically, it presents a comprehensive overview of the major wheat production environments, the global resources devoted to wheat improvement research, the potential and actual spillovers, and wheat research outputs. The evidence assembled on research output and technology spillovers is based on three related sets of data—data on the release of varieties, on the performance of varieties in international trials, and on the diffusion of varieties. The release data are used as a general indicator of research output; the trial data measure the *potential* spillovers; and the diffusion data directly measure *actual* technology spillovers. Many important findings on research intensity, technology spillovers, the roles of national and international research, and research efficiency are reinforced across the data sets used in the global analysis and country case studies.

Research Intensity for Crop Improvement Is Relatively High in Developing Countries

Over the years, the resources devoted to crop improvement research (in numbers of research programs and researchers per program) have increased in developing countries. Many developing countries have established wheat research programs that are quite large in relation to the size of wheat production served by these programs. As indicated by the Indian case study, even large wheat-producing countries may support programs that have small mandate regions or overlapping mandate areas. Overall, the "average" wheat improvement program in developing countries employs six times more researchers per million tons of wheat and spends three times more (in US$ PPP) on wheat research per ton of wheat produced than comparable programs in developed countries.

Two inescapable conclusions emerge from these data: (1) developing countries invest considerable resources in wheat improvement research; and (2) research costs and intensities in developing countries (especially smaller wheat producing countries) by some measures are higher than (or at least comparable to) the levels in industrialized countries. The latter occurs because developing countries have a larger number of scientists per research program and a smaller average mandate area for each program. These findings also suggest that a minimum critical mass of researchers is needed to establish an effective crop improvement research program, independent of the size of the mandate area.

Technology Spillovers: Pervasive Rather than Limited

In the past, biological technologies have been assumed to be quite location specific. However, much of this conventional wisdom arose from attempts to transfer technologies from temperate areas in industrialized countries to subtropical and tropical areas in developing countries. This report has shown that there is considerable homogeneity of agroecological environments across developing countries; as a consequence, wheat producing regions in developing countries can be aggregated into wheat "megaenvironments" for the purpose of breeding research. Some of these megaenvironments (MEs) are concentrated in a few countries (e.g., ME3 — acid soils), and technology for these environments may have low potential for international spillovers. However, several wheat MEs are globally dispersed (e.g., ME1 — irrigated, and ME2 — high rainfall), indicating a high possibility for international spillovers and an important potential role for regional/international research.

Given the presence of relatively homogeneous but dispersed wheat growing environments in the developing world, the *potential* for wheat research spillovers within the developing world is larger than conventionally believed, as demonstrated by the superior performance of some wheat varieties over many locations in international trials (Chapters 5 and 9). Actual spillovers were also found to be dominant characteristics of technical change based on wheat varieties. Varieties with CIMMYT parentage dominate developing country wheat production: nearly twice as much area was sown to directly transferred CIMMYT wheat varieties in 1990 as at the height of the Green Revolution, and two-thirds of all spring wheat area is sown to either directly transferred or adaptively transferred varieties (Chapter 6). Realized spillovers are also widespread between regions within a country. In Australia, for example, more than 40% of the total area is sown to wheat varieties developed in other states (Chapter 10). Similarly, much of the wheat area in India was sown to varieties developed by IARI, which in many respects fulfills at the country level a role similar to that of an international research center at the global level.

The results of this analysis strongly support the concept of MEs as a basis for organizing international research efforts. The ME classification system, however, should not be used as a static tool, but must be refined periodically to reflect changes in the responses of evolving genotypes to differences in environmental characteristics (DeLacy et al. 1994). The growing ability through the new information technologies, such as geographic information systems, to describe like environments should greatly increase the precision with which spillovers can be targeted across countries (Pardey and Wood 1994). However, MEs will necessarily include much within-environment variation, especially in those environments characterized as marginal for wheat production.

International and National Research: Complements not Substitutes

The potential for international research spillovers, the cost efficiencies realized from research specialization, and the high returns to the international research system spearheaded by CIMMYT — all provide a strong rationale for international agricultural research. However, international research need not be synonymous with international agricultural research centers, but might be organized in various ways (e.g., through networks, regional associations, or even the private sector). Indeed, the emergence of large multinational private seed firms reflects the underlying efficiency of international agricultural research. A number of institutional factors will influence how international research is best organized and how fully the potential benefits of international research are actually realized. For plant breeding research, which has relatively few actors at the national and international level, the experience of wheat research suggests that these benefits can be best realized in a well-articulated system of international and national crop improvement research programs.

It is one thing to establish the rationale for international research and quite another to sort out the comparative advantage of international research programs versus national or sub-national research programs in generating technologies with potential international spillovers. In a world without political boundaries, an economic model could be developed to determine the optimum level of investment in research at different levels of centralization. In practice, research and funding decisions are conducted at multiple levels, and the situation is much more complex. For example, in the common case of one IARC focusing on a particular technology and many NARS, the NARS could take the IARC products as given for the purpose of making decisions on their research portfolio (e.g., Maredia and Byerlee 1999). Alternatively, the IARC could take the NARS products as given for the purpose of its decision making and focus on "filling the gaps" in NARS (i.e., serving a complementary role) (CGIAR/TAC 1992). These alternatives could lead to very different outcomes, and neither is likely to lead to anything close to an optimum allocation of resources from a global viewpoint. The marginal rate of return to additional research investments is likely to vary widely between the IARC and the NARS as a group, and among individual NARS, indicating suboptimal use of resources at the global level. Moreover, NARS are diverse both in size and maturity, and the vague notion that IARCs should "fill gaps" does not readily translate into practical options, since these gaps vary widely from country to country. Discussion between the IARC and the NARS to exploit complementarities can improve resource allocation. However, as long as resources are relatively immobile between the IARC and the NARS, and among individual NARS, it is unlikely that globally optimal resource allocation will be reached.

Clearly, IARCs are *relatively* more important to small NARS. However, the greatest *absolute* advantage is captured by large NARS (Chapter 7). This poses a dilemma for IARCs concerning which types of products to emphasize. Smaller and less mature NARS utilize finished research products, such as direct varietal transfers, while large mature NARS tend to make greater use of the products of strategic pre-breeding research.

NARS sometimes see the IARCs as *substitutes* for NARS research and as providing "unfair competition" (Chopra 1994). Implicit in this observation are the facts highlighted in this report: (1) IARCs may often be low-cost providers of products (Chapter 7), and (2) factors such as national prestige or risk impede countries from "borrowing" available technologies from other programs, even when they are apparently suitable for local conditions (Chapters 5 and 8).

The extreme assumption that NARS exploit IARCs and other imported technologies as fully as possible in order to minimize their own investments implies that imported technologies are free and without risk. The growing influence of private sector R&D and intellectual property rights implies that imported technologies might, in the future, incur costs that will need to be weighed against the cost of developing similar technologies locally. And the recent precarious funding situation of the IARCs implies that there is some risk in depending on them as the principal suppliers of new technologies.

This report suggests IARC research must *complement* NARS research, but must go well beyond the filling of research gaps. The results presented here show that CIMMYT's three main activities — conducting strategic pre-breeding research to produce useful parental materials, producing widely adapted varieties, and coordinating the global nursery network for testing and distributing germplasm,—• enhance the effectiveness of NARS crop improvement programs of all levels of sophistication. For example, the centralized activity of pre-breeding research at CIMMYT serves the needs of most NARS that do have sufficient wheat area or scientific resources to justify the expenses and risks involved in such strategic research. The prospects for technical change are similarly improved as various NARS expand their capacity to adapt or to efficiently screen CIMMYT varieties. Given the ability of the international system to serve a diverse range of NARS, it seems unlikely that research investments by NARS and CIMMYT will become substitutes in the foreseeable future.

Research Efficiency: Room for Improvement

Several measures of research output and benefits are presented in this report to estimate the efficiency of research investments at aggregate and disaggregate levels. Overall, wheat research in developing countries has been highly successful, continuously releasing superior varieties that farmers adopt and generating a high rate of return on the research investment. A striking finding of this report, however, is that many countries, or regions within a country, are investing more than is economically justifiable on wheat improvement research, either because of the small size of their mandate area or because they could capture research spillins at lower costs— or, more commonly, both (Chapters 8 and 9). In India, for example, two research programs generated 75% of all technical change benefits. Seven out of 20 programs were estimated to have earned a negative rate of return.

The fact that research programs have generally been established to conform to state or national political boundaries artificially truncates the natural target areas of many research institutions. The "small country problem" is one manifestation of this fracturing of natural agroclimatic zones. The evidence in this report suggests that small countries and programs with a small mandate area generally have higher costs per unit of output, and many of them are inefficient. Not surprisingly, the research programs projected to earn the highest returns are located in large wheat producing countries (Argentina, Brazil, China, India, Pakistan, and Turkey) or in large wheat producing regions within a country (e.g., the Northwest Plains Zone in India).

Two critical challenges for research administrators seeking to enhance system-wide efficiency are (1) to identify spillin opportunities for their small-market research institutions and (2) to devise institutional mechanisms for coordinating research responsibilities across traditional political boundaries. However, the resources and scientific capacity required for screening and testing of imported technologies should not be underestimated. As shown in Chapter 8, NARS spend at least as much in testing and releasing IARC-developed materials as IARCs spend in developing those materials.

Implications

This study has important implications at both the conceptual level, in methods used for research evaluation, and at the policy level, for decisions on investment in crop improvement research in developing countries.

Implications for Economic Analysis of Agricultural Research

While spillovers have been widely recognized in the literature on agricultural R&D, they have rarely been incorporated into the economic analysis of investment in agricultural research. Benefits of research occurring in a given area have usually been attributed to the research conducted in that area. Given that spillovers are pervasive in agricultural R&D, this has resulted in biased estimates of returns to investment in research. Because spillovers tend to flow from large regions and from central research programs, the failure to include spillovers and spillins has inflated estimates of returns to research in the smaller regions and underestimated returns in the larger programs.

It is important to account for spillovers in the ex ante assessment of the efficiency of research programs. The question asked is this: *Given the potential for spillins from the* *international system,* what is the value added from establishing a full breeding program locally as compared to a testing program to screen imported materials? On this basis, many of the 72 wheat breeding programs evaluated in this study are producing low or negative benefits *at the margin.* Most of the inefficient programs were serving relatively small mandate areas, so economies of market size were a key determinant of efficiency. A further important result of this analysis is that many of the inefficient programs had a relatively high *average* rate of return on investment; they were inefficient because they gave lower net present values than a smaller program that simply tests and screens technologies. In other words, the average rate of return for an individual program is an inappropriate guide for research investment decisions in the presence of spillins, because it does not measure the marginal return from changing the size of program.

These results are contrary to previous analyses of the effects of spillovers and spillins on returns to research. Research spillovers and spillins in crop research are usually assumed to be indirect (e.g., exchange of germplasm for parent materials and exchange of breeding methods and scientific information) and hence have been modeled to shift upward the research production function of other research programs. The theoretical argument for under-investment in agricultural research is based on this basic premise (Ruttan 1982). As shown by this study, however, research spillins will not only affect research productivity but will also affect the choice of research strategy. This fact underlines the importance of incorporating estimates of direct spillins (or the potential for direct spillins) in the economic evaluation of research programs.

Implications for the Design of National Research Programs

The conceptual and empirical analyses presented in this paper have important implications for the design of research programs. The efficient choice concerning the number and size of research programs is a function of the potential for spillovers and spillins, as well as economies of size and market size in research. Each of these is strongly conditioned by the type of research and technology, environmental diversity within the mandate of the research program, and the environmental similarity with other programs.

An assessment of spillin potential should be considered explicitly in the design of research programs. Exploiting economies of *market size* is also critical to enhancing the efficiency of research investments. Public research programs established on the basis of political rather then natural boundaries are likely to serve markets of less-than-optimal size.

Institutional mechanisms that facilitate both two-way and one-way flows of technology must be encouraged to facilitate spillins and spillovers. Formal and informal research networks are the most common means of facilitating two-way flows of knowledge and technology. In plant breeding, these networks usually involve some type of national or international varietal performance trials that allow varietal technologies from different origins to be tested in many locations, as well as providing breeders access to a wide range of new varieties for local screening. In some cases these networks are more formal, involving not only trials but joint decisions on trial entries and coordination of research. The national coordinated programs for major crops, which operate in many countries, are an example of this type of network.

Internationally, germplasm testing nurseries run by the IARCs as well as a variety of specialized research networks perform a similar function. With the growing complexity of science and the reduced cost of international cooperation due to the Internet, a variety of other formal collaborative research mechanisms—such as regional research consortia and biotechnology networks involving both the private and public sectors—are being established to facilitate spillins and share research costs.

One-way flows of spillovers result from the efforts of public research programs to solve the problem of market size and economies of size by creating centralized research facilities at the national, regional, or international level for the sole purpose of generating spillovers. Most large countries have a federal-state research system, in which the federal system is meant to conduct research with significant economies of size and potential for wide spillovers. However, in most of these systems, the roles of the federal and state research systems have not been well defined, a fact which leads to overlap and redundancy. In recent years, the trend has been toward regional research associations among neighboring countries, beginning in Latin America and now expanding strongly in Africa and Asia.

A number of risk considerations may influence the way research is organized. A region or country that designs a research program to exploit spillins assumes a continuing and costless supply of spillins and thus exposes itself to fluctuations in the productivity and priorities of the spillover-generating institutions. In addition, the free flow of technologies is at risk with the increasing use of intellectual property rights to protect research products, even in the public sector. The dependence on a few centralized research programs may expose society to technological risks, such as genetic uniformity.

Finally the success of the IARCs in varietal development indicates that they are low-cost producers of finished germplasm products and demonstrates their competitive advantage in applied plant breeding research. However, this does not establish their *comparative advantage* in this type of applied research. As for other central research organizations designed to produce one-way spillovers, the comparative advantage is likely to occur more in basic and strategic research that builds on their unique access to international germplasm collections and advances in science to provide intermediate research products that shift upward the research production function for national programs to produce finished varieties. In practice the IARCs tend to invest a relatively small share of their resources in this type of pre-breeding research even though the potential payoffs are high. The challenge is how to serve the needs of many small NARS for finished products while investing in strategic research to provide intermediate products. Since many large NARS were also shown in this study to be low-cost producers of finished products (in some cases lower than CIMMYT), some type of sub-contractual arrangement may be needed with these NARS to ensure a balanced supply of international public goods to NARS of all types—both finished products and intermediate products. To some extent, the various types of partnership, collaborative, and shuttle breeding programs used by CIMMYT reflect this orientation. The rise of regional networks should also provide an alternative source of research products.

Research Funding in the Presence of Spillovers

The pervasiveness of spillovers has been one of the major explanations for the widely observed under-funding of research, as shown by the high rate of return on research (Ruttan 1982). Theoretically, it is possible to estimate an optimal subsidy for research based on expected spillovers (Schweikhardt and Bonnen 1992), but in practice, it is difficult to administer such schemes. Federally funded programs that might be justified on the basis of spillovers are usually based on "political" criteria such as population and agricultural production rather than spillovers, actual or potential. The generation of spillovers is often concentrated in only a few programs that are underfunded, despite very high returns. At the same time, those programs that are—or potentially are—primarily spillin recipients appear to overinvest in technology development relative to adaptation and screening.

These anomalies reflect the political economy of research funding. Whereas spillovers are based primarily on agroclimatic similarity and technology characteristics, funding for public research is based on political constituencies defined by political boundaries. For this reason, it has proven difficult to fund regional and international research over the long term. This is manifested in the recent funding shortfalls to the IARCs, especially in germplasm improvement, even though the IARCs programs in some crops, especially rice and wheat, are probably the most successful research programs in history, when success is measured by the size of benefits generated.

Logic suggests that one solution to this dilemma would be to shift the burden of funding research at the regional and international level to the main beneficiaries. The recent establishment of a regional fund for research in Latin America through contributions of national governments represents a step in this direction. By carefully identifying research priorities on the basis of potential spillovers in the region, this fund will provide research grants on a competitive basis to NARS, IARCs, and other research organizations. Another example of innovative funding for regional research is provided by the Latin American Fund for Irrigated Rice, wherein farmers themselves contribute to the rice research program of the International Center for Tropical Agriculture (CIAT). Similarly, Australian farmers through the Grains Research and Development Corporation have provided small contributions to CIMMYT in recognition of the substantial spillover benefits to Australia. Finally, a healthy trend is that a growing number of developing countries are contributing to the budgets of the IARCs.

Looking beyond Wheat Improvement Research

The potential and realized spillovers for wheat improvement research are probably higher than for other commodities. Estimates of spillover coefficients for rice in India reveal a somewhat lower potential for spillovers (Evenson 1994). Likewise, Evenson and Gollin (1991) show that actual direct spillovers of rice varieties are somewhat lower than for wheat (see also Byerlee 1994). However, actual spillovers for maize have been estimated to be of an order of magnitude similar to those for wheat (López-Pereira and Morris 1994).

Spillovers and market size issues may be more important for wheat than other crops for a number of reasons. First, wheat is grown in relatively homogenous production environments. The irrigated and high rainfall environments together account for over 70%

of wheat production in the developing world. Higher-potential environments are likely to be more homogeneous and therefore more amenable to technology spillovers and spillins. Second, there is little variability in local tastes and preferences for wheat. Quality characteristics are similar whether the end product is bread or chapatis. On the other hand, quality characteristics for rice and maize are often quite location specific (Unnevehr 1986; Smale and Heisey 1994). For some commodities, tastes may be so location specific that even country-level programs cannot develop widely accepted varieties. Sperling et al. (1993) have demonstrated this problem for beans in Africa. Finally, because wheat is a highly political crop, many countries where it is a marginal crop, especially in the tropics, have established research programs to serve small wheat areas.

When one turns from *crop improvement* research to *crop management* research (CMR) and *natural resource management* research (NRMR), the story is likely to be quite different. Both CMR and NRMR provide location-specific recommendations on crop and resource management practices. These recommendations are conditioned by agroecological and socioeconomic considerations, and for this reason, research to develop these recommendations must be complemented by strong local institutions (e.g., extension) and appropriate policies (e.g., prices).

International and within-country spillovers of such research will thus be quite limited compared with crop breeding research. IARCs can do little of the actual research that is required in thousands of locations around the world. IARCs do not have a comparative advantage in producing finished CMR and NRMR technologies—as they do in producing finished varieties. There are also considerable transaction costs in ensuring close collaboration between IARCs and NARS and in integrating research with extension, policy-making, and institutional change. Consequently, the IARCs' work on crop and resource management problems must focus on generating strategic knowledge that can be used to solve specific problems through local applied and adaptive research.

Finally, we caution against using this study as a substitute for comprehensive quantitative studies of research programs at other international centers. The CIMMYT Wheat Program is focused on developing and distributing intermediate and finished germplasm for a major food crop grown in a relatively small number of homogeneous environments. Other IARC programs provide different services to NARS. Modeling the impact of other commodity research programs remains therefore another important area for future research.

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