Impacts of International Wheat Breeding Research in Developing Countries, 1966-97

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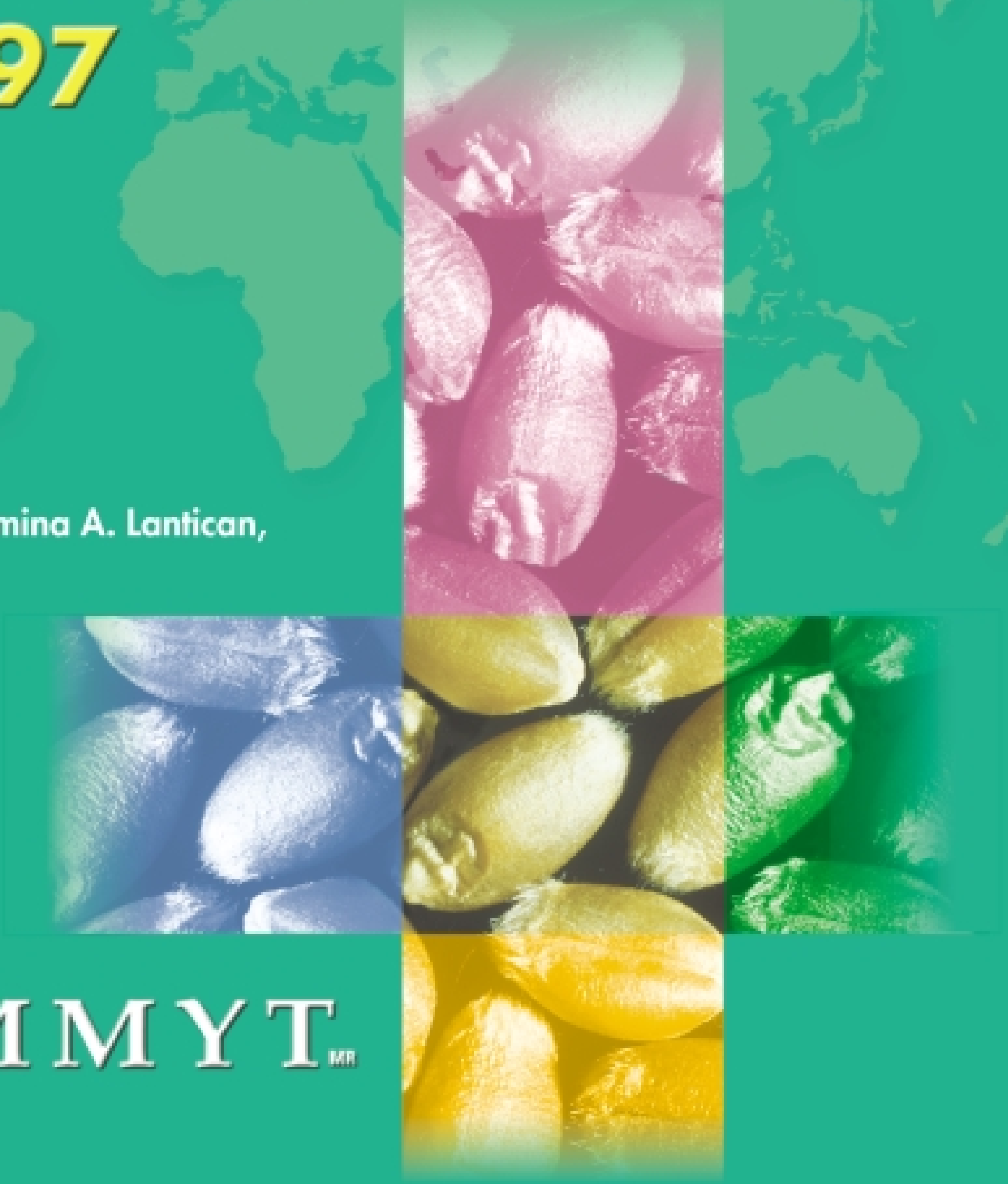

CIMMYT

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Paul W. Heisey, Maximina A. Lantican,

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ECONOMICS PROGRAM

INTERNATIONAL MAIZE AND WHEAT IMPROVEMENT CENTER (CIMMYT)

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Correct citation: Heisey P.W., M.A. Lantican, and H.J. Dubin. 2002. *Impacts of International Wheat Breeding Research in Developing Countries, 1966-97*. Mexico, D.F.:CIMMYT

Abstract: This report, which updates and extends the findings of an earlier CIMMYT study published in 1993, examines the impacts of international wheat breeding research in the developing world. Covering the period 1966-97, the report reviews investment in wheat breeding research by national and international breeding programs, documents the use of improved germplasm, estimates farm-level adoption of modern varieties (MVs), discusses factors that affect the adoption of MVs, and estimates the gross value of additional grain production attributable to international wheat breeding efforts. The area planted to wheat MVs in developing countries continues to expand. By 1997, slightly over 80% of the total area planted to wheat in developing countries was planted to MVs. During the past 10-15 years, the rate of wheat yield growth achieved in farmers' fields slowed in many favorable production environments, but spillovers from research conducted in favorable environments and continuing diffusion of MVs led to more rapid yield growth in many marginal production environments. Most wheat breeding research is carried out by public breeding programs, including international agricultural research centers and national research organizations. Within the international wheat breeding system, CIMMYT remains the dominant partner. During the late 1990s, about 62% of the area planted to wheat in the developing countries was planted to CIMMYT-related varieties, and about 20% was planted to CIMMYT crosses. Returns to international wheat breeding research continue to be high. For a total investment of US$ 100-150 million per year, the international wheat breeding system produces annual benefits of US$ 1.6 billion or more.

AGROVOC descriptors: Wheats; Development economics and policies; Food production; Food security; Economic development; Trends; Environmental policies; Small farms; Productivity; Research institutions; Systems analysis; Developing countries; Statistical data

AGRIS category codes: E14 Development Economics and Policies
A50 Agricultural Research

Dewey decimal classification: 633.11

ISBN: 970-648-090-0

Printed in Mexico.

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Acknowledgments

We owe a tremendous debt of gratitude to a large number of people who have contributed to this report. Wheat researchers from around the world provided the basic data for this study. We are grateful for their time and effort to provide the best information available, especially Ibrahim Umar Abubakar, Amri Ahmed, Azim Akbari, Muhammad Ramzan Akhtar, Julio Cesar Albrecht, Fernando Aldana, Antonio Maria Bolaños Alomia, Metin Arican, Mustafa Erkan Bayram, M.R. Bhatta, Efrem Bechere, Abderrezak Belaid, Egon Andres Bogado, Miguel Alfonso Camacho Casas, Ramesh Chand, Oswaldo Chicaiza, Mahmoud Deghaies, Abdalla Elahmadi, Regassa Ensermu, Kamel Feliachi, Joao Felicio, Mirihan Gamarra Flores, Francisco de Assis Franco, M. El-Ghouri, Mohammed Salah Gharbi, Bedada Girma, Rene Gomez Quintanilla, Edgar Guzman Arnez, Habib Halila, Ephrame Havazvidi, Hu Ruifa, J.S. Ijardar, B.S. Jadon, M.P. Jha, A.K. Joshi, Mesut Kanbertay, Lakshmi Kant, Mesut Keser, Fahed Saleh Khatib, Frank Kiriswa, Nafees Kisana, Gilberto Kraan, Benida Laubscher, Hassan Machlab, Luis Macagno, Elizabeth Maeda, Abdul Majid, E. Majidi, Demissie Mitiku, Raafat Abdel Hameed Mitkees, Ashok Mudwari, M.Y. Mujahid, Mary Mukwavi, S. Nagarajan, G.S. Nanda, Ali Reza Navabi, Hugo van Niekerk, Hassan Ozcan, D.R. Pokharel, Agromar Polidoro, Ignacio Ramírez A., V. Suryaprakasa Rao, Carlos Roberto Riede, Miguel Rivadeneira, S.M.A. Rizvi, Abelardo Rodriguez, E. Sadeghi, Soliman El Sebai, Jag Shoran, Cantidio N.A. de Sousa, Paulo Gervini Sousa, Jose Schvartzman, S.C. Sharma, G.S. Sethi, Ali Shehadeh, M.S. Shelembi, Oscar I. Silvero Sanz, R.P. Singh, T.B. Singh, Luis Hermes Svoboda, M. Taeb, B.R. Thapa, R.Y. Thete, Roque G.A. Tomasini, Gilberto Tomm, Ruben Verges, Jose Maria Vilela de Andrade, Nasrat Wassimi, and Mohammed Yunus.

Many CIMMYT colleagues also provided valuable support for this report, especially in questionnaire design, data collection, and review of the draft. We thank Osman Abdalla, Hans-Joachim Braun, Etienne Duvallier, Paul Fox, Man Mohan Kohli, Craig Meisner, Guillermo Ortiz Ferrara, He Zhonghu, Peter Hobbs, Mohamed Mergoum, Mulugetta Merkuria, Michael Morris, Wilfred Mwangi, M. Miloudi Nachit, Tom Payne, Wolfgang Pfeiffer, Prabhu Pingali, Sanjaya Rajaram, Bent Skovmand, Melinda Smale, Doug Tanner, Richard Trethowan, George Varughese, Maarten van Ginkel, Rey Villareal, Pat Wall, and Jeff White. Piedad Moya of the International Rice Research Institute (IRRI) also assisted with the design of the survey questionnaire for this study. Derek Byerlee of the World Bank, Greg Traxler of Auburn University, and George Norton of Virginia Tech provided useful guidance concerning economic analysis.

Finally, we are grateful to Satwant Kaur for editing this report, and to Eliot Sánchez Pineda, for its design, overall production, and printing.

Chapter 1

Introduction

Crop improvement research has had a record of spectacular success. The diffusion of "Green Revolution" wheat and rice varieties, accompanied by greater use of inputs such as fertilizer, has greatly improved national food security and enhanced the welfare of the poor, especially in developing countries.

As time goes on, however, the momentum favoring investments in crop breeding research has slackened. In both developing and industrialized countries, changes in the political economy of public finance, the introduction of new technologies, and privatization of agricultural research have undermined funding for public agricultural research organizations. The appearance of alternative development investments has also diverted resources away from agricultural research organizations. At the same time, these organizations have faced demands to broaden their research focus.

These changes have led to pressures on both national and international crop breeding programs. Is there still a role for these crop breeding programs? Are they still having a major impact on the economies and food security of developing countries? This report attempts to answer these and related questions. The short answer, at least in the case of wheat, is yes: the international wheat breeding effort undertaken by the International Maize and Wheat Improvement Center (CIMMYT) and its national program partners continues to generate tremendous benefits and to contribute significantly to social welfare.

In 1990, CIMMYT conducted a study to evaluate the impacts of international wheat breeding research in the developing world. The objectives of the study, which covered the period 1966-90, were to provide feedback to researchers on the acceptance or rejection of new technologies, explore the reasons behind farmers' responses, and to document the benefits of wheat research (Byerlee and Moya 1993).

In 1997, CIMMYT launched a follow-up study to update the 1990 data and analysis. The objectives were quite similar to those of the initial study:

- document the use of CIMMYT-related and other improved wheat germplasm;
- document farm-level adoption of improved wheat germplasm;
- identify factors that affect adoption of modern varieties (MVs);
- generate information for research priority setting; and
- provide information to raise awareness of the importance and benefits of international wheat research.

Questionnaires were sent to 41 developing countries that produced more than 20,000 tons of wheat annually (the Central Asian and Caucasus states, however, were not included in either the 1990 or 1997 study). Responses were received from 36 countries, representing just under 99% of all wheat production in the developing world. On a regional basis, coverage ranged from 94% of production in West Asia/North Africa (WANA) to nearly 100% in Latin America. The 1997 study differed from its predecessor in several respects. It included South Africa for the first time and had more complete coverage of China's wheat area.

Four other major sources of data were exploited to produce this report: information supplied by national agricultural research systems (NARS) and CIMMYT scientists, as well as some country-level secondary data available for larger countries; the comprehensive wheat pedigree database maintained by the CIMMYT Wheat Program; the CIMMYT wheat mega-environment database developed by CIMMYT's Wheat and Economics Programs; [1] and wheat area, production, and yield statistics maintained by the Food and Agriculture Organization of the United Nations (FAO).

This report is organized as follows. Chapter 2 describes the CIMMYT wheat breeding program and discusses CIMMYT's collaboration with the International Center for Agricultural Research in the Dry Areas (ICARDA) (also a member of the Consultative Group on International Agricultural Research or CGIAR) and with NARSs. It also includes a summary of wheat breeding costs incurred by these institutions and a description of major wheat breeding environments in the developing world. Chapter 3 analyzes patterns of wheat varietal releases in developing countries from 1966 to 1997 by origin, time period, wheat type, growing environment, and region. Chapter 4 investigates the adoption of wheat varieties in farmers' fields in developing countries, using many of the same variables for categorization. Chapter 5 outlines various methods of calculating the benefits of wheat improvement research and discusses the conceptual assumptions necessary to apply them. Chapter 6 provides estimates of actual yield gains attributable to wheat breeding programs and discusses how experimentally measured yield gains relate to yield gains measured in farmers' fields. Chapter 7 describes several different attempts to calculate the economic benefits of the international wheat breeding effort. Chapter 8 highlights some important conclusions of the report.

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[1] This source was perhaps the weakest link in the overall data collection effort as much of the data in the mega-environment database was over 15 years old.

Chapter 2

The International Wheat Improvement System and Wheat Breeding Research Investments

This chapter outlines the structure of the international wheat breeding system and presents information about current levels of wheat improvement investment in both CIMMYT and NARSs. Public sector research, of which the CIMMYT-NARS system is an extremely significant component, has been particularly important for wheat technology development worldwide, although private sector investment rose rapidly in Europe and other parts of the industrialized world in the last third of the 20th century. Investments in wheat improvement research in developing countries rose rapidly in real terms from the inception of the Green Revolution in the mid-1960s, but became mixed and fragmentary from the mid-1980s. Real resources invested in CIMMYT's wheat research program fell from that time. Some evidence suggests that NARS research investments have also decreased, but data are fragmentary, and in large producers such as China or India this may not have been the case. Our limited data indicate that the number of scientists involved in wheat improvement research in the 1990s increased in China, much of the WANA region, and in Brazil and Argentina.

Evolution of the International Wheat Breeding System

Geographical movement of wheat germplasm is not new. Like other domesticated crops, wheat spread from its ancient zones of origin in Mesopotamia at the dawn of agriculture. Wheat was cultivated in many parts of Eurasia and North Africa by 3000 B.C. and reached China by the second millennium B.C. (Harlan 1987). More recent diffusion of wheat can be described as "colonial" wheat germplasm flows, which began about 1500 A.D. (Smale and McBride 1996).

Modern scientific plant breeding can trace its development to cereal hybridization or planned cross-breeding which began in England in the 1790s and continued there through the work of Sherriff in the mid-19th century. The last decades of the 19th century were marked by greater interest in both cross-breeding and better methods of selection in Europe, North America, and Australia. Wheat improvement began to take the form of crossing locally adapted material with wheat from other areas to improve production characteristics or quality (Lupton 1987).

The rediscovery of Mendel's laws of heredity at the turn of the 20th century led to renewed interest in using genetics to improve crops. New approaches were developed to define the objectives of plant breeding, develop selection methodology, and choose parents for hybridization. Many scientists and statisticians who were involved in developing these methods were motivated by the desire to solve practical problems in plant breeding. Mendelian theory helped to make sense of successes and failures of practical breeding, to suggest new solutions to old problems, and to create new problems to be solved (Paul and Kimmelman 1988; Sprague 1975).

The advent of scientific plant breeding in areas of the world characterized as "developing" probably began in India in the first decade of the 20th century (Jain and Byerlee 1999). Research stations were founded with the aim of wheat improvement in Turkey in the 1920s and the 1930s, and planned crosses were made in Argentina and Brazil in the 1930s. Although some crossing was done in China as early as the 1920s, it was not until the 1950s that planned crossing began to replace selection from landraces as the primary means of wheat improvement. Introduction of foreign germplasm into China also became more prominent in the 1950s (Dalrymple 1986; Smale and McBride 1996; Yang and Smale 1996; He and Rajaram 1997).

In the developing world, the evolution of the modern system of wheat improvement has often been linked to the "Green Revolution" in wheat. The Green Revolution had its origins in the transfer of semidwarf wheat varieties developed by the Rockefeller Foundation research program in Mexico to India and Pakistan. This initial transfer was followed by the establishment of CIMMYT in Mexico in 1966 as successor to the Rockefeller Foundation program. Countries that already had wheat improvement programs reorganized and expanded them, and countries without wheat research programs began to develop them. The pace of interchange of wheat germplasm between NARSs and CIMMYT and among NARSs accelerated. International nursery activity became prominent, and visits of wheat scientists to CIMMYT and other countries also grew rapidly. The development and functioning of the international wheat improvement system is described and analyzed more comprehensively by Dalrymple (1986), Byerlee and Moya (1993), and Maredia and Byerlee (1999). Smale and McBride (1996), Skovmand et al. (1995), and Smale et al. (1996) document the flows of wheat germplasm within the global system.

In industrialized countries, wheat breeding has also remained within the public sector, especially in Australia, Canada, and the United States (U.S.), as well as in the countries of Eastern Europe and in the former Soviet Union. As in developing countries, the public wheat breeding system developed with an emphasis on germplasm exchange among different research institutions (Kronstad 1996). Wheat germplasm flows also continued between industrialized and developing countries. This is in contrast to maize, where the development of hybrid varieties led to the protection of inbred line development, encouraged widespread private sector investment in maize breeding, and discouraged direct germplasm exchanges among distinct breeding programs. In the case of wheat, factors such as plant varietal protection, the role of wheat within the cropping system, and level of wheat yields affected incentives for private companies to invest in wheat breeding. Private sector wheat breeding was practiced in Europe from the early 20th century and accelerated in the mid-1960s. Today 70% or more of European wheat area is planted to private varieties. Private varieties are less common in the U.S., Canada, and Australia, but institutional developments such as research funding through farmer check-offs, or the strengthening of intellectual property rights in plant breeding, continue to influence the organization of wheat breeding in these countries (Heisey, Srinivasan, and Thirtle 2001).

In developing countries, private sector wheat breeding has a long history in the Southern Cone of South America, particularly in Argentina.

Outside of the Southern Cone, the only countries where private sector wheat breeding is important are South Africa and Zimbabwe.

In summary, the global wheat improvement system consists of both national and international public sector wheat improvement programs, as well as private sector firms. Historically, public sector programs have provided the majority of wheat varieties grown, although private sector breeding programs have become increasingly important in Europe and, to a more limited extent, in the U.S.

IARC and NARS Investments in Wheat Genetic Improvement

In this section, we describe CIMMYT's wheat research program and analyze investments made by international agricultural research centers (IARCs) and NARSs in wheat genetic improvement. International wheat improvement research is collaborative and depends on international testing by a network formed by CIMMYT and national research systems worldwide (Maredia and Byerlee 1999). In the WANA region, CIMMYT also collaborates with ICARDA on wheat genetic improvement.

Evolution of the CIMMYT Wheat Breeding Program and Breeding Objectives[2]

Following its inception in the 1940s, CIMMYT and its predecessor organization, the Office of Special Studies, an agricultural research initiative by the Rockefeller Foundation and the Government of Mexico, initially focused breeding efforts on the development of semidwarf spring bread wheat varieties suitable for cultivation in irrigated areas. By the late 1960s, CIMMYT's breeding program began to address disease problems found in higher rainfall rainfed areas. In addition to spring bread wheat, by the end of the decade, CIMMYT also established spring durum wheat and triticale breeding programs.

During the 1970s, wheat breeding expanded in a number of directions: a program to inter-cross spring and winter wheat gene pools; a shuttle breeding program between CIMMYT and NARS in Brazil to develop aluminum-tolerant germplasm for acid soil areas; breeding for warmer environments; and greater emphasis on marginal rainfed environments of the WANA region following the establishment of the joint CIMMYT/ICARDA program in 1979.

During the 1980s, CIMMYT wheat breeders concentrated on incorporating new traits such as resistance to Karnal bunt (*Tilletia indica*) and head scab (*Fusarium* spp.) into material targeted primarily at irrigated and high-rainfall environments. Resistance to barley yellow dwarf virus (BYDV) and to Russian wheat aphids, which were more important in drier areas, was also targeted. The head scab effort, which was based primarily on a shuttle breeding partnership between CIMMYT and China, exemplified many germplasm development projects that featured cooperation between CIMMYT and other research programs. The spring x winter crossing program came to fruition with the release of a number of materials, including the extremely successful "Veery" lines. In 1986, a winter wheat program targeting some 26 million hectares of winter wheat grown primarily in Turkey, Iran, Afghanistan, and China, was established in Turkey. This program also has close ties with Eastern European countries and the newly independent Central Asian countries.

When characterizing wheat-growing environments, it is important to distinguish between the time of planting and growth habit.

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[2] The following discussion of CIMMYT's wheat breeding condenses earlier information found in Byerlee and Moya (1993) and adds additional material to cover the 1990s.

Time of planting information helps in determining stresses that wheat plants are likely to face during the growing season (e.g. drought, heat, frost) and also provides clues about where wheat fits into the larger crop rotation picture. Information about growth habit is arguably more important, especially for plant breeders. Winter habit wheats ("winter wheats" for short) have a vernalization requirement. This means that they will flower only after young seedlings have been exposed to cold temperatures for a number of weeks during the vegetative growth phase. Vernalization delays the onset of booting and flowering until the danger of frost has receded. In cold environments, winter wheats are planted during the fall and harvested the following summer.

Spring habit wheats ("spring wheats" for short) do not have a vernalization requirement and do not need to be exposed to cold temperatures to flower. In high-latitude regions (e.g., Central Asia, Russia, northern China, Canada, northern U.S.), spring wheats are sown in the spring (after the cold period has passed) and harvested during the late summer. By contrast, in the low-latitude regions (< 35 N and S) in which much wheat is grown in the developing world, winters are relatively mild and summers excessively hot, so spring habit wheats are often sown during the fall and harvested the following spring to avoid summer heat stress.

Facultative wheats are intermediate in growth habit between winter wheats and spring wheats. They possess fewer of the dominant genes for vernalization than true spring wheats and require less vernalization. The growing areas for facultative wheats tend to overlap with spring and especially winter wheats.[3]

Throughout the 1980s, much success was achieved in more traditional areas of breeding. During the 1990s, more emphasis was given to abiotic and biotic stresses and better management practices for increasing yields in a sustainable manner. In other words, emphasis was placed on conserving the environment and raising yields at the same time. The CIMMYT Wheat Program provided germplasm to NARSs that was increasingly efficient in its use of nitrogen, phosphorus, and water. Drought tolerance research was increased, and new germplasm with various types of drought tolerance is now available. Other abiotic stresses such as heat and soil toxicities were also emphasized, and the selection criteria for tolerance to these stresses were improved. The 1990s saw the production of germplasm with expanded genotypic diversity and increased efforts in genetic resource management (Smale et al. 2001), which should contribute to maintaining that diversity.

The incorporation of leaf and yellow rust resistance into CIMMYT germplasm was enhanced by greater understanding of the genetic basis of durable types of resistance. Increased efforts were made in the search for and application of molecular markers for selection, especially for disease resistance and quality characteristics. Results with markers for resistance to BYDV have been very promising.

The search for increased yields intensified in the 1990s. Several approaches are being explored including F_1 hybrids, synthetic hexaploids, and architectural changes in the wheat plant. The best prospects for hybrid wheat appear to be in high-yielding environments or environments in which the seeding rate can be greatly reduced. Methods of improving seed set in female plants and greater knowledge of heterotic groupings in wheat could improve the economic feasibility of hybrids by lowering seed costs and increasing hybrid yield advantage, respectively (Jordaan 1996; Lucken 1987). Changes in the architecture of the wheat

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[3] Many countries do not distinguish clearly betwen winter and facultative wheat. For simplicity, throughout this report "winter wheat" denotes winter wheat and facultative wheat, except in cases where the two are specifically disaggregated.

plant based on developing a plant with robust stem, long head, multiple spikelets and florets, large leaf area, and broad leaves, have been achieved. Advances based on this plant type depend on increasing seed set abilities (Rajaram and Borlaug 1997). Architectural changes may in time be coupled with hybrid development, but it is too early to determine which approaches to increased wheat yield potential will result in the highest payoffs.

International cooperation increased during the 1990s, as NARS scientists participated in several formal consultations with CIMMYT to set strategic research priorities. Additionally, regional programs were strengthened in key areas such as Kazakhstan, the Caucasus, and China, where the CIMMYT Wheat Program now has offices. The Kazakhstan office focuses on wheat in the Central Asian Republics. These are traditional wheat producing areas with limited resources for wheat breeding in the post-Soviet era. This effort has resulted in increased research into wheat for higher latitudes. Winter wheat research also received greater emphasis.

The challenge for the future will be to focus on the needs of developing countries and provide germplasm and technology for sustainable wheat production. Funding issues related to support for food production and agricultural research in the new millennium will be as important as the science, as will negotiating an increasingly complex research environment with greater private sector participation. We will return to these issues in later chapters.

DEFINITION OF WHEAT BREEDING ENVIRONMENTS

The mid-1980s witnessed a revision of definitions of environments where CIMMYT targets its wheat germplasm. "Mega-environments" (MEs) were defined as "large, not necessarily contiguous areas having similar requirements for wheat, such as time to maturity, resistance to particular diseases, and tolerance to various abiotic stresses" (Rajaram, van Ginkel, and Fischer 1993; Byerlee and Moya 1993). Cropping systems requirements, consumer preferences, and volume of production may also have contributed to ME definitions (Pingali and Rajaram 1999). Mega-environments are useful for defining breeding objectives because each ME comprises millions of hectares that are relatively homogeneous for wheat production (Dubin and Rajaram 1996).

The most recent ME classifications are described in Table 2.1. The most notable change in the present classification (van Ginkel, Trethowan, and Çukadar 2000) compared with the original classification (Rajaram, van Ginkel, and Fischer 1993; Rajaram and van Ginkel 1996; Pingali and Rajaram 1999; Byerlee and Moya 1993; Maredia and Ward 1999) has been the re-classification of the hot, irrigated, low humidity environments (old ME 5B) into a sub-environment of ME 1.

Table 2.2 indicates the division of wheat areas in developing countries into MEs. The first six columns are based on findings from the present study, other secondary information, and the old CIMMYT wheat ME database. They cover wheat in all developing countries producing over 20,000 tons annually in 1997, including countries that did not respond to our survey. They do not, however, include countries of the former Soviet Union.

Spring habit wheat covers about three-quarters of all wheat area in the developing world; winter wheat types cover the remaining area. Most wheat (92% of total area) is bread wheat. Durum wheat is planted on about 8% of total wheat area. Irrigated spring bread wheat is by far the most extensive wheat growing environment in the developing world.

Byerlee and Moya (1993) estimated the proportion of wheat production coming from different environments. Generally speaking, the proportion of production from a given environment is higher than the proportion of area in irrigated and high rainfall environments (MEs 1, 2, 5, 7, 8, 10, and 11), and the proportion of production is lower than the proportion of area in low rainfall environments (MEs 4A, 4B, 4C, 6, 9, and 12).[4]

The greatest uncertainty regarding the classification of wheat area into MEs lies in the division of area between MEs 1, 5, and 4C in the Indian sub-continent. The estimates here are based on data collected for this study, the old ME database, and estimates of India's irrigated wheat area reported by the Fertilizer Association of India. It is clear that irrigated wheat area in India has expanded greatly over the last half century, but it is not clear whether non-irrigated areas have shrunk to the levels estimated by van Ginkel, Trethowan, and Çukadar (2000), or whether these unirrigated areas should be classified as ME 4C. A second major uncertainty is the degree to which wheat area in China, particularly winter wheat area, is irrigated. During the preparation of this report, there were no direct sources to answer this question, and indirect evidence and expert opinion allow widely varying estimates. At present,

Table 2.1. Classification of mega-environments used by the CIMMYT Wheat Program.

Mega-environment (ME)	Latitude (degrees)	Moisture regime[a]	Temperature regime[a]	Growth habit	Sown[b]	Major breeding objectives[c]	Representative locations / regions	Year breeding began at CIMMYT
SPRING WHEAT								
1 Irrigated, low rainfall	35ºN-35ºS	Low rainfall irrigated	Temperate	Spring	A	Resistance to lodging; durable resistance to SR, LR, YR; resistance to KB (many locations); resistance to PM in China; tolerance of saline soils (some locations); preferred grain color is white	Gangetic Valley (India); Indus Valley (Pakistan); Nile Valley (Egypt); parts of Zimbabwe; irrigated river valleys in parts of China (e.g. Chengdu); Yaqui Valley (Mexico)	1945[d]
			Hot			In addition to above objectives, heat tolerance	Kano (Nigeria); Wad Medani (Sudan)	
2 High rainfall	35ºN-35ºS	High rainfall	Temperate	Spring	A, S	Resistance to SR, YR, LR; resitance to ST; resistance to pre-harvest sprouting. In many locations, resistance to SC, BYD, bacteria, PM, and root disease complex. In many locations, tolerance to soil micronutrient imbalances; preferred grain color is mostly red	High rainfall locations in West Asia and North Africa; high rainfall locations in Southern Cone and Andean Highlands, South America; East and Central African highlands; Izmir (Turkey): Toluca (Mexico)	1972
3 High rainfall, acid soil	35ºN-35ºS	High rainfall	Temperate	Spring	A	As for ME2, plus tolerance to aluminum and manganese toxicity; phosphorus deficiency another major constraint; preferred grain color is mostly red	Passo Fundo, Brazil; some locations in Central Africa and in the Himalayas	1974

Source: Adapted from van Ginkel, Trethowan, and Çukadar (2000) and Byerlee and Moya (1993), who based their descriptions on Rajaram, van Ginkel, and Fischer (1993).

[a] Moisture and temperature regimes refer to conditions during the growing season. For rainfall just before and during the crop cycle, High: $\geq$ 500 mm.; Low: < 500 mm.

[b] A = autumn; S = spring.

[c] These are factors additional to yield and industrial quality. SR = stem rust; LR = leaf rust; YR = yellow (stripe) rust; KB (Karnal bunt); SC = Scab (*Fusarium* spp.); ST = *Septoria tritici*; PM = powdery mildew; BYD = barley yellow dwarf virus.

[d] Rockefeller Foundation-Government of Mexico wheat improvement program in Mexico, precursor to CIMMYT wheat program.

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[4] Two MEs do not fit this general classification scheme based on relative yields. One is ME 3, where acid soils have historically reduced yields below those in other high rainfall environments. The other is ME 6, where yields are relatively high in northeastern China, the area most represented here, but relatively low in dry, high latitude spring wheat areas in countries of the former Soviet Union (FSU), which are not included in the current study.

Table 2.1. (continued) Classification of mega-environments used by the CIMMYT Wheat Program.

Mega-environment (ME)	Latitude (degrees)	Moisture regime[a]	Temperature regime[a]	Growth habit	Sown[b]	Major breeding objectives[c]	Representative locations / regions	Year breeding began at CIMMYT
4 Low rainfall, drought environments								
4A Winter rain or Mediterranean-type drought (moisture available <400mm)	35°N-35°S	Low rainfall; post-flowering moisture stress	Temperate	Spring	A	Drought tolerance; resistance to YR, LR, SR, root rots, nematodes, and bunts. Heat stress or late frosts may both be problems	Aleppo, Syria; Settat, Morocco; Cape Prov., South Africa	1970
4B Winter drought or Southern Cone-type drought (<400 mm)	35°N-35°S	Low rainfall; pre-flowering moisture stress	Temperate	Spring	A	Drought tolerance; resistance to LR, YR, and SR; resistance to ST and SC. Resistance to pre-harvest sprouting, many locations	Marcos Juárez, Argentina	1970
4C Residual moisture after monsoon rains; Indian subcontinent type drought (<400 mm)	35°N-35°S	Low rainfall; continuous drought under receding moisture	Hot	Spring	A	Resistance to drought; resistance to heat in seedling stage	Dharwar, India	1980
5 Warm area environment (< 1000 masl.)	23°N-23°S	High humidity; irrigated or high rainfall	Hot (mean minimum temperature in coolest month >17°C	Spring	A	Heat tolerance; resistance to *Bipolaris sorokinana, Drechslera tritici-repentis*, LR; tolerance to pre-harvest sprouting	Pusa, Bihar, India; Joydebpur, Bangladesh; Chiangmai, Thailand; Encarnación, Paraguay; Poza Rica, Mexico	1981
6 High latitude environments								
6A High latitude environment[e] (> 400 mm)	>45°N or S	High rainfall	Temperate	Spring	S	Yield potential; industrial quality; Resistance to SC, *Drechslera tritici-repentis*, YR, LR, SR; tolerance to sprouting; Photoperiod sensitivity also a consideration.[e]	Harbin, Heilongjiang, China	1989
6B High latitude environment (< 400 mm)	>45°N or S	Semiarid	Temperate	Spring	S	Drought tolerance; medium-tall stature; photoperiod sensitivity	Astana, Kazakstan	1998
WINTER WHEAT								
7 Favorable, irrigated, moderately cold	>30°N or S	Irrigated	Moderate cold (0°-5° coldest month)	Facultative	A	Resistance to YR, LR, and PM; cold tolerance; rapid grain fill	Zhenzhou, Henan, China	1986
8 High rainfall, moderately cold	>30°N or S	High rainfall	Moderate cold (0°-5° coldest month)	Facultative	A	Resistance to YR, LR, PM, eyespot; cold tolerance	Temuco, Chile; Corvallis, Oregon, U.S.A.	1986
9 Semi-arid, moderately cold	>30°N or S[g]	Low rainfall	Moderate cold (0°-5° coldest month)	Facultative	A	Resistance to YR and bunts; cold tolerance, drought tolerance	Diyarbakir, Turkey; Vernon, Texas, U.S.A.	1986
10 Favorable, irrigated, severely cold	>35°N or S[g]	Irrigated	Severe cold (-10°-0° coldest month)	Winter	A	Resistance to YR, LR, PM; resistance to winterkill	Beijing, China	1986
11 High rainfall, severely cold	>35°N or S	High rainfall	Severe cold (-10°-0° coldest month)	Winter	A	Resistance to LR, YR, PM, eyespot	Odessa, Ukraine; Krasnodar, Russia	1986
12 Semi-arid, severely cold	>35°N or S[g]	Low rainfall	Severe cold (-10°-0° coldest month)	Winter	A	Resistance to bunts; drought tolerance; resistance to winterkill	Ankara, Turkey; Kansas, U.S.A.	1986

Source: Adapted from van Ginkel, Trethowan, and Çukadar (2000) and Byerlee and Moya (1993), who based their descriptions on Rajaram, van Ginkel, and Fischer (1993).

[e] Description refers primarily to this environment as found in northeastern China.

[f] These 18 m. ha. of high latitude spring wheat grown primarily in Kazakhstan and southern Siberia are not considered in the remainder of this report.

[g] A few areas south of these latitudes in mountainous areas of Iran or Afghanistan may be classified in these environments.

Table 2.2. Distribution of wheat area in developing countries by mega-environment, 1997 with a comparison to 1990.

ME	Area (million ha)			Percentage (%)			Area[a] (million ha) (van Ginkel, Trethowan, Cukadar 2000; Braun et al. 2001)	1990 percentage (Byerlee and Moya 1993)	
	Bread	**Durum**	**Total**	**Bread**	**Durum**	**Total**	**Bread**	**Bread**	**Durum**
Spring									
1	38.4	0.6	39.0	36.3	0.6	36.9	36	32.3	0.4
2	7.1	2.1	9.2	6.7	2.0	8.7	>8	7.6	2.4
3	1.5	0	1.5	1.4	0	1.4	<2	1.7	0
4A	5.9	4.0	9.9	5.6	3.8	9.4	6	5.5	4.8
4B	3.2	0.1	3.3	3.0	0.1	3.1	3	3.2	0
4C	6.8	0.1	6.9	6.4	0.1	6.5	2 - 3	4.4	1.5
5	3.8	0	3.8	3.6	0	3.6	9	7.1	0
6	4.9	0	4.9	4.6	0	4.6	20[b]	4.9	0
Subtotal spring	71.7	6.8	78.5	67.7	6.5	74.3	85-90	66.8	9.1
Facultative									
7	9.9	0	9.9	9.4	0	9.4	2.8	5.6[c]	0[c]
8	0.2	0	0.2	0.2	0	0.2	1.4		
9	3.4	0	3.4	3.2	0	3.2	5.3	4.5	1.2
Subtotal facultative	13.6	0	13.6	12.8	0	12.8	9.5	10.1	1.4
Winter									
10	3.1	0	3.1	2.9	0	2.9	1.5	6.6[d]	0.2[d]
11	3.6	0.1	3.7	3.4	0.1	3.5	-		
12	5.7	1.1	6.8	5.4	1.0	6.4	6.9	6.0	1.2
Subtotal winter	12.4	1.2	13.6	11.7	1.1	12.9	8.4	12.6	1.4
Subtotal Facultative / Winter	26.0	1.2	27.2	24.6	1.1	25.7	17.9[e]	22.7	1.4
Total	**97.7**	**8.0**	**105.7**	**92.3**	**7.7**	**100.0**		**89.5**	**10.5**

[a] Source: van Ginkel, Trethowan, and Cukadar (2000); H.-J.Braun et al.;.(2001).

[b] Includes countries in the former Soviet Union (FSU).

[c] Includes ME's 7 and 8.

[d] Includes ME's 10 and 11.

[e] Includes only the facultative and winter wheat areas in WANA, and Central Asian and Caucasus Republics.

geographic information systems (GIS) techniques are being applied to refine the definition of MEs using various criteria, particularly irrigation, precipitation, temperature, soil acidity, and elevation (White et al. 2001). A better understanding of the economic importance of wheat production in different MEs will result if mapping based on physical characteristics can be combined with relatively high quality data on actual areas planted and amounts of wheat produced. Future classifications may also be modified as breeding objectives or technical factors change.[5]

Wheat Improvement Investment in CIMMYT

From its inception, CIMMYT's primary research focus has been on genetic improvement of wheat and maize. CIMMYT's entire budget could be considered devoted to genetic improvement of these two crops, although certain CIMMYT research activities, such as farming systems and natural resources research, and some economic analysis, may not appear to be directly related to crop genetic improvement.

In the following analysis, we use three approaches to measure investments in wheat genetic

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[5] For example, as basic constraints caused by soil acidity have been overcome, it might be possible to merge ME 3 into ME 2.

improvement research at CIMMYT. In two of the approaches, we assume that all Wheat Program staff, including representatives of disciplines such as pathology, agronomy, physiology, and plant breeding, are involved in genetic improvement. In the first of the two approaches, we assume that CIMMYT's entire budget can be charged to crop genetic improvement. Here, we allocate the total budget—including money spent on other programs[6] and administration—between wheat and maize according to the proportion that the Wheat Program budget comprises of the total budgets of the two crop programs. The second assumption is that the total CIMMYT budget is allocated to wheat genetic improvement according to the proportion of Wheat Program senior staff relative to all CIMMYT senior staff, including staff in programs other than the Maize Program, as well as administration. The set of figures from the first approach may be an overestimation of true investments in wheat genetic resource improvement; the figures from the second approach may be an underestimation. The third approach is similar but not identical to that of Byerlee and Moya (1993). In this approach, we assume that 65% of the Wheat Program budget is devoted to wheat improvement, along with a 26% overhead.[7]

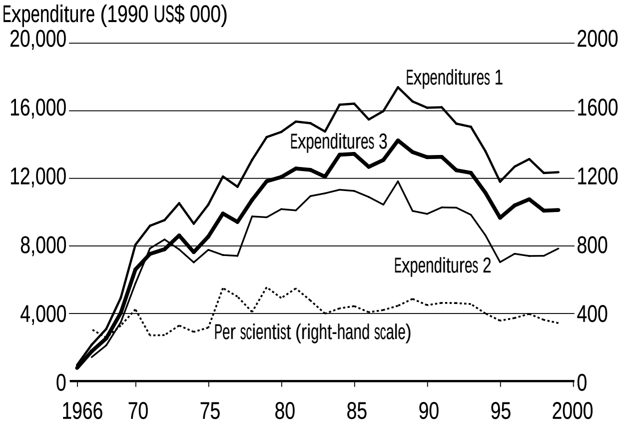

Figure 2.1. CIMMYT wheat research expenditures and expenditures per researcher, 1966-99

Total investments in wheat genetic improvement (in 1990 US dollars) at CIMMYT are presented in Figure 2.1. In addition, Figure 2.1 indicates cost per scientist as calculated from the first (high) assumption. Using the first assumption, real CIMMYT investment in wheat genetic improvement rose steadily until the late 1980s, after which it fell significantly. By the second measure, real investment began to fall slightly earlier, from the mid-1980s. The difference is the result of the second assumption's basis in staff numbers—numbers of non-crop program staff relative to crop program staff have risen since the mid-1980s. Using the third method, CIMMYT's investment in wheat improvement lies between the first two sets of assumptions. The estimated decline in real CIMMYT investment in wheat improvement may have been tempered in recent years, but by all three measures, this decline was substantial from the late 1980s through the 1990s.

By all assumptions, real CIMMYT investment in wheat genetic improvement in recent years is now roughly back at the 1970s level. By the high assumption, CIMMYT today invests about US$ 12 million annually in wheat genetic improvement; by the low assumption, the investment is about US$ 7-8 million per year; and by the intermediate assumption, it is about US$ 10 million per year.

Numbers of CIMMYT Wheat Program staff are shown in Figure 2.2. These can be combined with the first set of assumptions in Figure 2.1 to calculate expenditure per scientist.[8] The number of Wheat Program scientists peaked in

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[6] Currently there are five research programs at CIMMYT- Wheat, Maize, Economics, Applied Biotechnology, and Natural Resources.

[7] These proportions are identical to those used by Byerlee and Moya. However, we begin with actual Wheat Program budgets; Byerlee and Moya multiply 65% of the full time equivalent (FTE) scientists by estimated cost per scientist.

the mid-1980s and declined slightly thereafter. Real expenditure per scientist has fluctuated but also began to decline from about 1980.

Allocating ICARDA expenditures to wheat genetic improvement is more difficult, as ICARDA does not have a wheat breeding program but does allocate some resources to joint CIMMYT/ ICARDA efforts. Based on ICARDA reports of staffing and research programs, as well as estimates of joint CIMMYT/ICARDA investments in 1990 (Byerlee and Moya 1993), we estimate that in the 1990s, ICARDA may have invested up to US$ 1 million (1990 dollars) annually in wheat improvement research.

Wheat Improvement Investment in NARSs

Measures of NARS research investments in wheat improvement in developing countries can be constructed either by directly measuring research expenditure or by focusing on another input measure: numbers of scientists involved in wheat improvement. In the latter, monetary expenditures are sometimes estimated by multiplying numbers of scientists by assumed cost per scientist.[9] In practice, most of the estimates presented below are based on numbers of scientists in wheat improvement, since this information is more easy to obtain than total wheat improvement research expenditures.

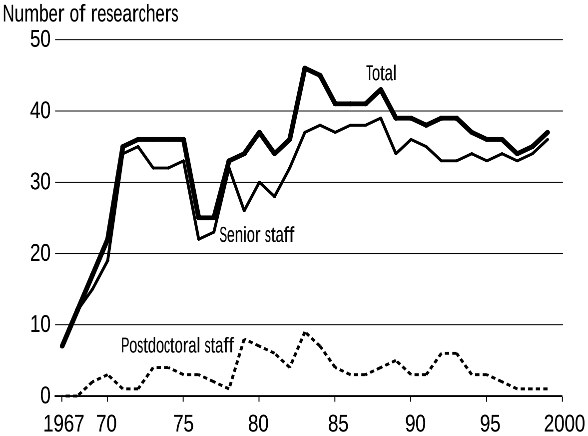

Figure 2.2. CIMMYT Wheat Program staff numbers, 1967-99

Analysis based on the actual number of scientists involved in wheat improvement research must still be treated with considerable caution, however, given the inherent constraints of an impersonal questionnaire and the difficulty of enumerating scientists outside of NARS who conduct research related to wheat improvement (e.g., researchers in universities). These factors could lead to an underestimate. On the other hand, both early 1990s surveys (Bohn and Byerlee 1993; Bohn, Byerlee, and Maredia 1999; Byerlee and Moya 1993) and 1997 surveys (the present one) asked respondents to identify the number of full-time equivalent scientists involved in wheat breeding, even when they represented disciplines other than plant breeding. In some instances, this could lead to an overestimate of the effort devoted to wheat improvement research, as opposed to, for example, wheat crop management.[10]

In terms of the number of scientists per million tons of wheat production, wheat research intensity appears to be slightly greater since the Bohn and Byerlee study (1993): 6.2 scientists per million tons across the developing world in 1997 compared to 5.3 scientists per million tons in 1992–93 (Figure

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[8] The second measure of investment is based on scientist numbers and therefore could not be used to calculate expenditures per scientist. The third measure is also based on the Wheat Program budget and would not yield information on expenditures per wheat improvement scientist much different than expenditures per Wheat Program scientist based on the first set of assumptions.

[9] Cost per scientist may be taken from some other data source, such as ISNAR's study of NARSs agricultural research investment in the mid-1980s (Pardey, Roseboom, and Anderson 1991).

[10] In a few cases information received on questionnaires was considered unreliable, for example large reported numbers of wheat improvement scientists in countries that produce very little wheat. In a few cases, we adjusted estimates based on the experience of international wheat scientists familiar with the wheat improvement program in the country in question.

2.3). This difference is caused largely by a greater number of wheat improvement scientists reported for China in 1997; when China is excluded, the 1992–93 and 1997 figures are nearly identical. Furthermore, research conducted by the International Food Policy Research Institute (IFPRI) and the International Service for National Agricultural Research (ISNAR) suggests that financial support for agricultural research in many NARSs has fallen in recent years. This trend has been masked at the aggregate level by continued support for research in strong NARSs such as China and India. Wheat improvement by NARSs may be polarizing, with large countries continuing their support, while funding in many smaller country NARS is declining in real terms. Hard evidence, however, is limited. We return to this question below.

Survey data confirm one empirical regularity in the number of wheat improvement scientists: research intensity measured by scientists per million tons of wheat production tends to fall with increasing wheat production (Figure 2.4). Because of the inverse relationship between production level and research intensity in the developing world, small wheat producing countries tend to have high wheat improvement research intensities. This pattern was observed in the early 1990s (Bohn and Byerlee 1993; Bohn, Byerlee, and Maredia 1999).[11]

Byerlee and Traxler (1995) estimated purchasing power parity (PPP) expenditures, in 1990 US dollars, by NARSs on spring bread wheat genetic improvement. Their estimates did not include China and were based on comparing numbers of scientists working on spring bread wheat genetic improvement to numbers of agricultural scientists in general, and then applying this percentage to PPP expenditures on all agricultural research. The latter data were taken from Pardey and Roseboom (1989). We extended these estimates to all wheat outside of China by using the ratio of "all wheat releases / spring bread wheat releases" for different periods to adjust investment figures upward.[12] For China, we applied the same methods used by Byerlee and Traxler to research data reported in Fan and Pardey (1992).

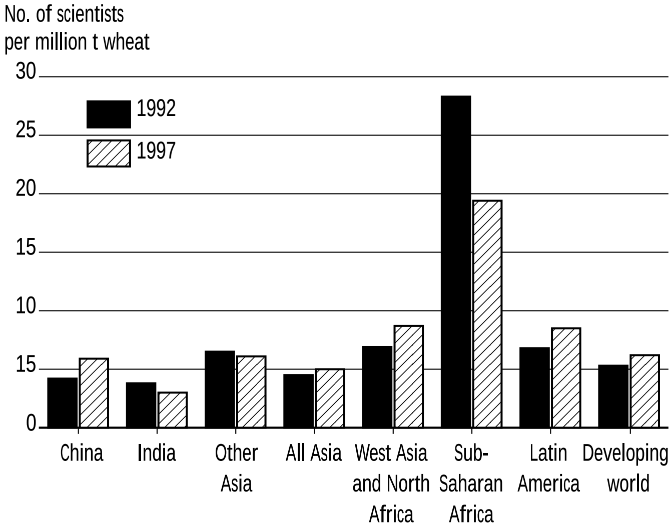

Figure 2.3. Wheat improvement scientists per million tons of wheat production, developing world, 1992 and 1997.

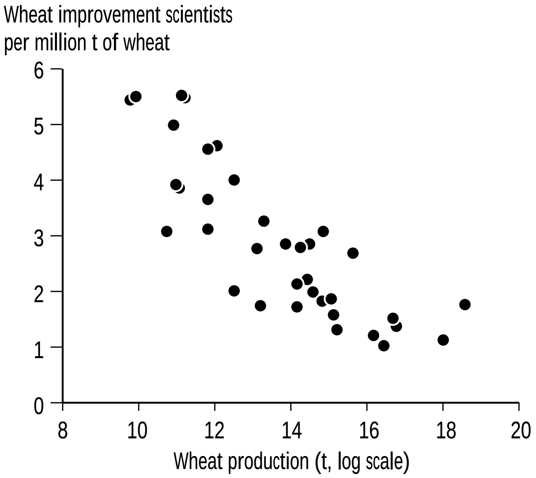

Figure 2.4. Wheat improvement scientists per million tons of wheat production.

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[11] Maredia and Byerlee (1999) consider the important issue of research efficiency, particularly for small programs.

[12] This measure was considered preferable to others, for example "total improved wheat area / total improved spring bread wheat area," because it could be applied in more time-specific fashion. Furthermore, we felt that the measure we used would be less likely to result in upward biases, particularly in the WANA region.

By these assumptions, real investments in NARS wheat genetic improvement research grew steadily from the mid-1960s to about 1990 (Table 2.3). In 1990, NARSs invested about US$ 100 million in genetic improvement research.[13] It is difficult to measure NARS investments in wheat genetic improvement past 1990. Most publicly available data on NARS agricultural research investments end in the late 1980s or early 1990s. The consensus is that worldwide, in both developing and industrialized countries, public investment in agricultural research stagnated or grew slowly during the 1990s. Certainly projections of 1980s trends in Latin America and sub-Saharan Africa support this view. Projections of 1980s trends in China (Fan and Pardey 1992) and India (Evenson, Pray, and Rosegrant 1999) suggest some continued growth in NARS investments.

It is hard to tell whether the apparent increases in NARS investments in wheat genetic improvement in the 1990s, based on numbers of wheat improvement scientists, were reflective of actual increases in real dollar investment, declining research support per scientist, or a combination of the two. Anecdotal evidence suggests that in some research programs, particularly in smaller wheat-producing countries, declining support per scientist combined with relatively stagnant wheat improvement budgets might have been the rule.[14] At the aggregate level, however, this might have been overcome by continued strong investments in wheat genetic improvement by large producers, particularly China and India. These contentions are largely speculative, however, with little hard data to support them. If wheat genetic improvement research budgets had increased over the 1990s consistent with late 1980s trends in aggregate research budgets, increased investments in the developing world would imply that total investments today exceed US$ 140 million (1990 dollars). To the extent that these increases are real, they would have for the most part bypassed Latin America and sub-Saharan Africa. At present, therefore, we estimate that NARS expenditures in wheat genetic improvement fall somewhere between US$ 100 and US$ 150 million (1990 dollars).

Table 2.3. Wheat genetic improvement research expenditures by NARSs, 1990 PPP US$[a].

	1965	1970	1975	1980	1985	1990
World	29.9	41.1	56.2	74.1	86.9	97.5
Asia	12.0	15.8	22.4	32.4	40.1	45.9
China	6.6	7.5	10.0	14.7	20.0	22.9
India	4.2	7.0	10.1	13.6	14.7	16.0
Other Asia	1.1	1.3	2.3	4.1	5.4	7.1
Latin America	5.4	8.8	12.4	16.2	16.3	16.6
Sub-Saharan Africa[b]	1.7	2.5	3.8	4.3	3.4	3.7
WANA	10.8	14.1	17.6	21.1	27.1	31.2

Source: Authors' calculations based on data in Byerlee and Traxler (1995); Bohn, Byerlee, and Maredia (1999); Fan and Pardey (1992); Evenson, Pray, and Rosegrant (1999); and CIMMYT wheat impacts database.

Note: [a] For countries excluding China, wheat improvement research expenditures were calculated from data provided by Byerlee and Traxler (1995) for spring bread wheat by adjusting by the proportion "total releases/spring bread wheat releases" for the relevant periods. For China, the same methods used by Byerlee and Traxler were applied to research expenditure data reported by Fan and Pardey (1992) and data on numbers of wheat genetic improvement researchers from the CIMMYT wheat impacts database.

[b] Excludes South Africa.

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[13] Recall that CIMMYT invested about US$ 16 million annually (high estimate) in wheat genetic improvement during the same period.

[14] Even in cases where the level of investment per wheat improvement scientist may have remained steady throughout the 1990s, in many programs a high percentage of this investment (80% or 90% or higher) has always gone to salaries, with little left over for operational budgets.

Chapter 3

Trends in Wheat Varietal Releases in Developing Countries, 1966-97

Rates of Varietal Release

National research systems of developing countries released about 2,200 wheat varieties between 1966 and 1997. Of these, one-fourth were released from 1991 to 1997, the most recent period for which data are available. The number of wheat varieties released annually by NARSs doubled between 1966 and the mid-1980s, when it leveled off at about 80 releases per year (Figure 3.1). Average annual releases for China and India reached their highest levels between 1981 and 1985. In Latin America, the number of average annual releases peaked between 1986 and 1990, and in the WANA region between 1991 and 1997. The number of average annual releases for sub-Saharan Africa showed little change between 1966 and 1997.

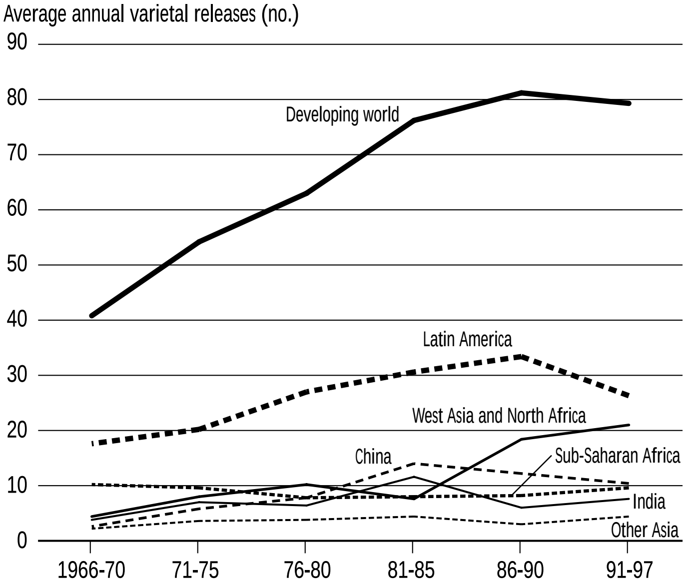

Figure 3.1. Average annual wheat varietal releases by region, 1966-97.

The number of releases is in general not congruent with the size of the wheat area in a country (Byerlee and Moya 1993). An alternative measure of the rate at which varieties are released is the number of varieties released each year per million hectares planted to wheat. For instance, Latin America and sub-Saharan Africa released far more varieties per unit of wheat area than the rest of the developing world (Byerlee and Moya 1993; Figure 3.2). Higher rates of release in these regions may be associated with smaller wheat areas, greater diversity in MEs (that is, in the target environments for wheat research), faster change in disease complexes, and greater private sector participation in wheat improvement.

Consistent with the pattern for numbers of releases, the average number of varieties released each year per million hectares in all developing countries increased until the mid-1980s and fluctuated thereafter. In the past 15 years, the greater number of releases in the WANA region somewhat counteracted lower rates of release in China and India (Figure 3.1; Figure 3.2). The lower rates of release in these two large producers with strong and mature wheat programs are probably indicative of more precise varietal targeting and not of declines in investment. Furthermore, as previously noted, large producers tend to release fewer wheat varieties per unit area than smaller producers.

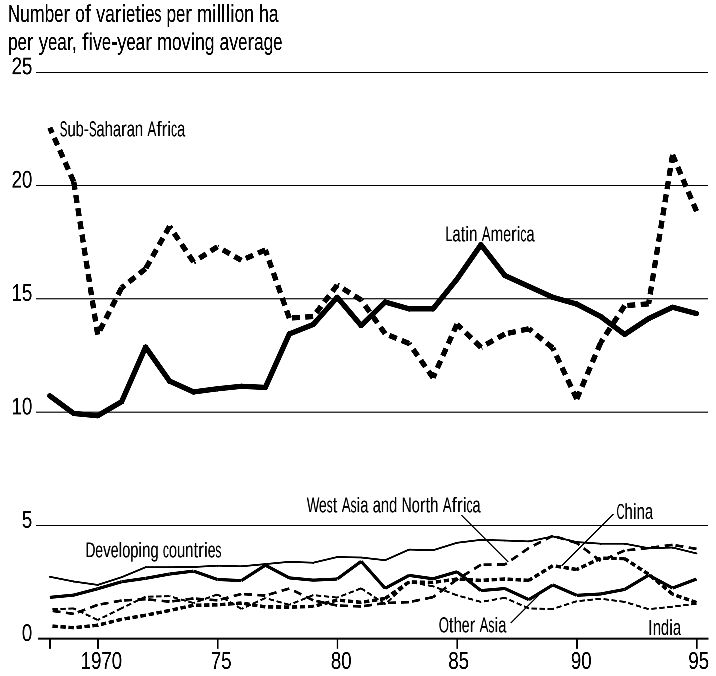

Figure 3.2. Rate of release of wheat varieties, normalized by wheat area, 1966-97.

Wheat Growth Habit, Production Environments, and Varietal Releases

Byerlee and Moya (1993) classified wheat varieties released in developing countries between 1966 and 1990 by wheat type or growth habit in each of three targeted ecological niches—irrigated/well-watered, dry, or both. In our analysis, we classified wheat varieties by growth habit and environmental classification.

Spring bread wheat releases dominate varieties released in the developing world. Though spring bread wheat releases as a percentage of total wheat releases has fallen from over 80% in 1970 to over 70% in the 1990s, this percentage is still higher than spring bread wheat's percentage of total wheat area. About two-thirds of all wheat area in developing countries consists of spring bread wheat (see Table 3.2). Spring durum wheat releases comprised about 6% of all releases in the 1960s, and made up about 10% in the 1990s. Spring durum wheat constitutes a little over 6% of all wheat area. Winter wheat releases reached their highest level (19%) in the 1990s, but this is still lower than the amount of total developing country wheat area covered by this wheat type.

Since many varieties are recommended for more than one moisture regime, we classified varietal releases between 1991 and 1997 into seven categories: irrigated; rainfed well-watered; rainfed dry; irrigated/well-watered; irrigated/rainfed dry; well-watered/rainfed dry; or all moisture regimes. Thirty-four percent of spring bread wheat releases, 25% of winter bread wheat releases, and 16% of spring durum wheat releases were recommended only for irrigated areas. In total, 53% of spring bread wheat releases, 49% of winter bread wheat releases, and 30% of spring durum wheat releases were recommended for irrigated areas. About one-third of winter bread and spring durum wheat releases were recommended only for rainfed dry areas. Over half of all winter bread and spring durum releases were recommended for dry areas (Table 3.1). These figures roughly confirm the importance of irrigated spring bread wheat areas and dry spring durum wheat areas. They also confirm the split in the importance of winter wheat areas between considerable irrigated land, particularly in China, and considerable dry land, particularly in the WANA region.

In South and East Asia, the emphasis in spring bread wheat releases has been on irrigated areas. In Latin America, the most frequently targeted moisture regime has been well-watered rainfed areas. In these large regions, therefore, the release pattern for 1991-97 has not changed much from earlier years (Byerlee and Moya 1993). In contrast, releases in WANA have shifted in favor of rainfed dry areas, indicating that the priority assigned to drier areas by NARSs in the region in recent years has paid off in increased releases. At the same time, spring bread wheat releases in sub-Saharan Africa were targeted more towards irrigated areas in 1991-97 than earlier years, despite the fact that irrigated wheat represents only one-sixth of wheat area in that region. This was probably the result of relatively high rates of releases in recent years in African countries that grow irrigated wheat, such as Zimbabwe, compared with those that do not.

Although some releases were targeted at more than one ME, our analysis by ME considered only the first-mentioned target ME as the basis for classification. On a global basis, the number of spring bread wheat releases by the first targeted ME is more or less congruent with the wheat area in a given ME for most smaller MEs (3-6), with the exception of ME 6, which is under-represented in releases. However, a larger proportion of spring bread wheat releases are targeted to high-rainfall areas (ME 2), and a lower proportion to favorable irrigated areas (ME 1), relative to the areas actually planted (Tables 3.2 and 2.2). This finding is related to the importance of releases for ME 2 in Latin America, which has a relatively high rate of releases (Figures 3.1 and 3.2). On a regional basis, the congruence between release proportions and actual areas planted is less apparent.[15]

Table 3.1. Distribution (%) of wheat varieties released in developing countries, by wheat type and moisture regime, 1991-97.

	Percentage recommended for:						
Wheat type / region	**Irrigated**	**Rainfed well-watered**	**Rainfed dry**	**Irrigated / Rainfed well-watered**	**Irrigated / Rainfed dry**	**Rainfed well-watered / Rainfed / dry**	**All three moisture regimes**
Spring bread wheat							
Sub-Saharan Africa	52	20	8	0	17	3	0
West Asia and North Africa	20	16	42	15	0	2	5
South and East Asia	53	6	8	0	33	0	0
Latin America	21	36	15	0	4	23	1
All spring bread wheat	34	20	18	3	14	9	2
Winter / facultative bread wheat	25	17	32	4	19	2	1
Spring durum wheat	16	25	31	0	14	14	0
All wheat	30	20	22	3	15	9	1

Table 3.2. Distribution (%) of spring wheat varieties released in developing countries, by wheat type and mega-environment, 1991-97.

	Mega-environment							
Wheat type	**ME 1**	**ME 2**	**ME 3**	**ME 4A**	**ME 4B**	**ME 4C**	**ME 5**	**ME 6**
Spring bread wheat								
Sub-Saharan Africa	62	21	3	3	-	-	12	-
West Asia and North Africa	49	18	-	28	-	1	1	2
South and East Asia	50	6	-	4	-	32	4	5
Latin America	20	43	11	-	18	1	6	-
All spring bread wheat	40	24	4	8	7	10	5	2
Spring durum wheat	19	37	-	27	12	-	6	-

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[15] There are some minor discrepancies between targeted MEs and estimates of area planted in that ME, especially on a regional basis. These discrepancies may be simply errors, or may be the result of a variety being released by a second country that was actually targeted at a different ME in its country of original release.

This breakdown by ME was very similar with our earlier findings using the moisture regime classification, with the exception of the WANA region. The reason for the contrasting results for WANA is that 28% of the spring bread wheat releases in the region were targeted not only to ME 1 but also to the low rainfall, winter rain environment, ME 4A. But since ME 4A was often the second-mentioned targeted ME, we classified the associated varieties as targeted to ME 1.[16] Had we considered ME 4A as the main target environment for WANA, then the results would be consistent with earlier findings based on moisture regime classification for this region.

In spring durum wheat, there was less congruence between releases and area planted. MEs 1, 2, and 4B were targeted more often, and ME 4A less often, than would be indicated by areas. This is partially the result of multiple targeting (ME 1 or ME 2 as well as ME 4A in WANA), or, again, the relatively high rate of varietal release in Latin America (ME 4B).

Area estimates reported in Table 2.2 for winter and facultative bread wheat releases were more ambiguous than spring bread and spring durum releases. In particular, the breakdown between irrigated and high rainfall winter bread wheat in China is not clear. As a result, targeted ME information is not presented here. Across both winter and facultative bread wheat releases, releases by ME were roughly similar to the pattern of release by irrigated or well-watered versus dry environments (Table 3.1). However the proportion of facultative wheat releases targeted at dry environments (ME 9) seems to be larger than the share of facultative wheat area, perhaps as a result of a relatively high rate of releases in South Africa.

RELEASES BY SEMIDWARF CHARACTER

In their study based on data collected in 1990, Byerlee and Moya (1993) calculated the percentage of varieties released by height (semidwarf or tall) and wheat type. Since South Africa and parts of China were not included in the 1990 study, we decided to re-estimate the percentage of semidwarf varieties released between 1966 and 1997. There was a rapid increase in the release of semidwarf varieties between 1966 and 1980, which is consistent with earlier findings of Byerlee and Moya (1993), particularly for spring bread and spring durum wheat (Figure 3.3). Since then, however, the rate of release of semidwarf varieties has slowed. The decrease in the numbers of semidwarf durum and winter wheat varieties released, as well as the slowdown in the rate of release of semidwarf spring bread wheat varieties between 1991 and 1997, seems to have resulted from continued release of some improved tall varieties for stressed environments. Most improved tall winter varieties released between 1991 and 1997 were released in South Africa or Turkey.

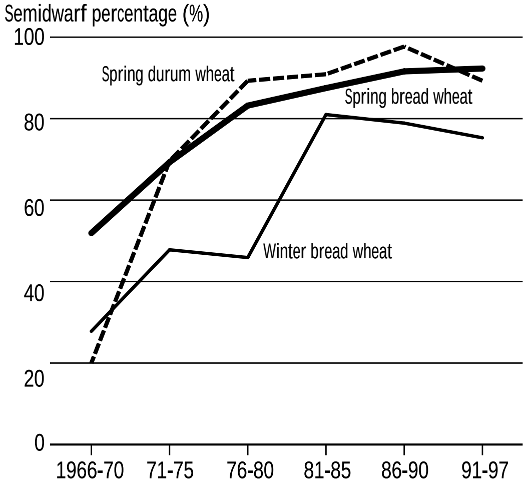

Figure 3.3. Percentage of all wheat releases that were semidwarfs, by wheat type, 1966-97.

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[16] In general, there might be a bias towards lower-numbered ME's simply because they might tend to be the first mentioned, even if another ME is really a more important target for a given variety.

Origins of Varieties Released in Developing Countries

For this analysis, we classified varieties according to whether they were derived from a cross made by a national research program (Groups 1 and 2) or by CIMMYT (Groups 3 and 4). Our classification is very similar to that used by Byerlee and Moya (1993) except that varieties derived from a CIMMYT cross were divided into two separate groups:

1) Variety derived from a cross made by a national research program:
    - Cross that did not involve an immediate CIMMYT parent and that was made in the country in which the variety was released. This includes semidwarfs that have only CIMMYT grandparents or earlier ancestry.
    - Cross that did not involve an immediate CIMMYT parent and that was made in a country other than the country in which the variety was released.
2) Some CIMMYT germplasm—at least one parent from CIMMYT:
    - Cross that involved at least one parent from CIMMYT and that was made in the country in which the variety was released.
    - Cross that involved at least one parent from CIMMYT and that was made in a country other than the country in which the variety was released.
3) Cross made by CIMMYT, reselection made by NARSs.
4) Cross and selection made by CIMMYT.

In practice, available selection histories suggest that when NARSs make selections from CIMMYT crosses, they tend to make them in later generations.[17] As a result, in our analysis we combined categories 3 and 4 into a single category, "CIMMYT cross."

All countries surveyed have made considerable use of CIMMYT wheat germplasm. China differs from other countries, however, by using its own material to a great extent. The extent to which the Indian and Brazilian wheat improvement programs have made their own crosses is also notable, although a substantial amount of the breeding material in their research programs is based on CIMMYT germplasm (Traxler and Pingali 1998). In most other countries, the importance of CIMMYT crosses and CIMMYT parents has not changed since the 1990 study.

In the late 1960s, about one-third of all wheat varieties released by developing countries were CIMMYT crosses, and an additional one-sixth had at least one CIMMYT parent. By the 1990s, these fractions had risen to about one-half CIMMYT crosses and another one-quarter that had a CIMMYT parent. Throughout the period covered in this study, an additional 7-8% of releases could be traced to at least one CIMMYT ancestor.

Just under two-thirds of the spring bread wheat varieties released by developing countries in the 1960s had some CIMMYT content. Over the last 15 years, around 90% of the spring bread wheat releases had CIMMYT content. In the late 1970s, CIMMYT crosses as a percentage of spring bread wheat releases fell because more NARS releases were crosses with at least one CIMMYT parent. Since 1980, the percentage of spring bread wheat releases that are CIMMYT crosses has fluctuated narrowly around 50%. An additional 30% consisted of NARS crosses with at least one CIMMYT parent (Figure 3.4).

More than 76% of all wheat varieties released by national programs (including China) between 1991 and 1997 were spring bread wheats.[18] Of the more than 350 spring bread wheat varieties

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[17] Byerlee and Moya (1993) did find some evidence that in an advanced program in Brazil, with which CIMMYT carried on a long-term shuttle breeding exchange, some selections were made from earlier generation, segregating material.

[18] Recall that nearly all spring bread wheats released today by NARSs in developing countries are semidwarfs.

released during this period, 53% were CIMMYT crosses, sometimes with reselection by NARS, 29% were NARS crosses with at least one CIMMYT parent, 8% were NARS crosses with CIMMYT ancestry, 7% were NARS semidwarfs with other ancestry, and 3% were tall varieties. The percentage of spring bread wheat releases that were CIMMYT crosses or had at least one CIMMYT parent was higher in 1991-97 (82%) than any other period, indicating that the use of CIMMYT germplasm has not declined in recent years (Figure 3.4).[19]

CIMMYT content in wheat releases differed by region. Over time, at least 80% of spring bread wheat releases in every major region had some CIMMYT ancestry. Asia (except for China and India) and the WANA region made particular use of CIMMYT crosses. China and India, the two largest wheat producers in the developing world, released proportionately more spring bread wheat varieties that were NARS crosses with at least one CIMMYT parent (Figure 3.5).

In the most recent period, 1991-97, virtually all spring bread wheat releases in Asia (not including China and India), WANA, and sub-Saharan Africa had some CIMMYT content. Moreover, CIMMYT crosses featured particularly heavily (62-73%) in releases in these regions. In India and Latin America, about 90% of spring bread wheat releases

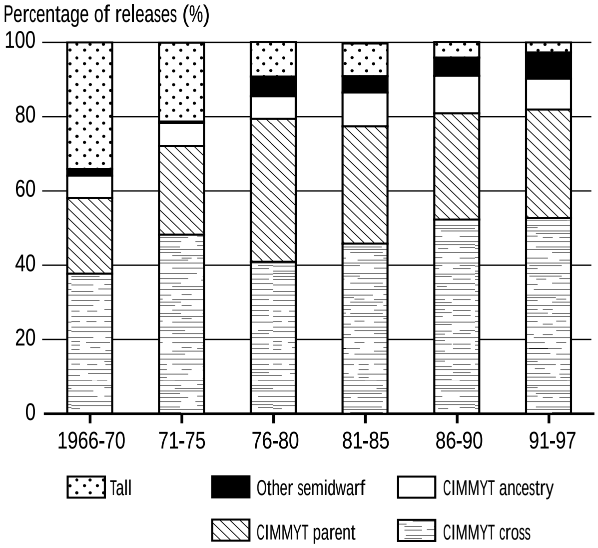

Figure 3.4. Spring bread wheat releases, developing world, 1966-97.

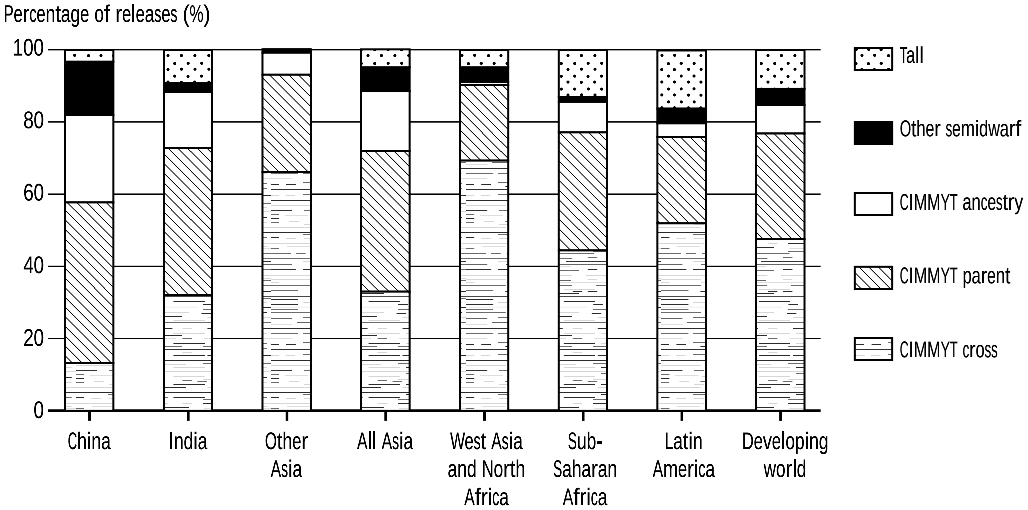

Figure 3.5. Spring bread wheat releases by region, 1966-97.

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[19] Apparent discrepancies between the percentage of releases that are semidwarfs (Figure 3.3) and the release data by origin (Figures 3.4, 3.6, and 3.8) are caused by the fact that some varieties with CIMMYT parentage or earlier ancestry are not semidwarfs. This seems to be the case particularly for durum and winter/facultative types.

had some CIMMYT content in the 1990s, and about 50% were CIMMYT crosses. In contrast, in China, although 60% of spring bread wheat releases had some CIMMYT content in the 1990s (and the percentage was even higher in some earlier periods), no direct CIMMYT spring bread wheat crosses have been released in recent years (Appendix A, Table A.1).

Compared with spring bread wheats, a higher percentage of spring durum wheats released by NARS contained CIMMYT germplasm. Since the early 1970s, two-thirds to three-quarters of spring durum wheats released by developing countries have been CIMMYT crosses. Use of CIMMYT lines as parents for NARS crosses did not become common until the 1980s. By the 1990s, nearly all spring durum wheat releases had a CIMMYT ancestor. Between 1991 and 1997, 77% of more than 50 spring durum releases were CIMMYT crosses, 20% were NARS crosses with at least one CIMMYT parent, 2% were NARS crosses with known CIMMYT ancestry, and 2% were tall varieties without CIMMYT ancestry (Figure 3.6).

Spring durum releases based on CIMMYT crosses were important in all regions, but they were particularly predominant in WANA and Latin America. Spring durum wheat releases based on at least one CIMMYT parent were relatively common in sub-Saharan Africa, followed by India. Nearly 30% of spring durum releases in India were tall varieties, as were about 17% in sub-Saharan Africa (Figure 3.7; see also Appendix A, Table A.2).

In contrast, no winter wheat releases were direct CIMMYT crosses over much of the period covered by this study. Winter wheat varieties with some CIMMYT ancestry (cross, parent, or any ancestor)

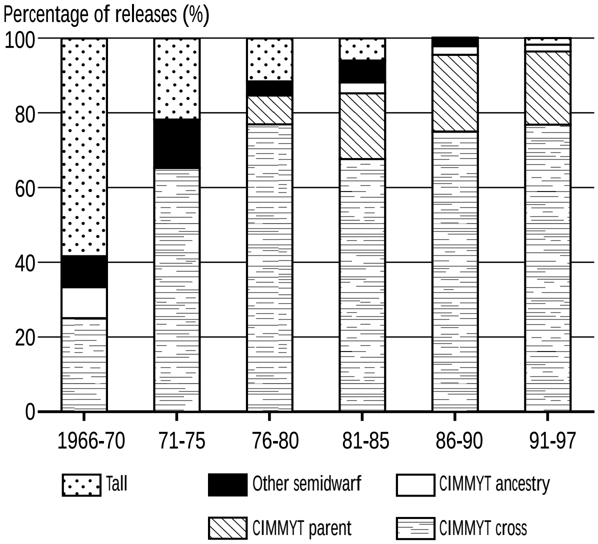

Figure 3.6. Spring durum wheat releases, developing world, 1966-97.

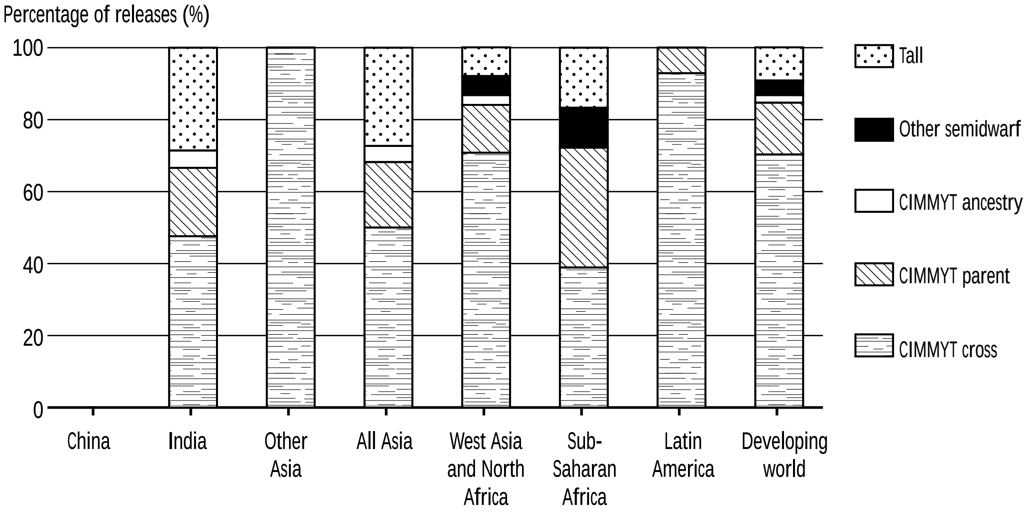

Figure 3.7. Spring durum wheat releases by region, 1966-97.

constituted about 35-40% of all releases since the 1970s. The number of winter bread wheat releases was considerably higher in 1991-97 (over 100) than earlier periods. The percentage of winter wheat releases that contained CIMMYT germplasm was also considerably higher in 1991-97 than previously. Following the opening of CIMMYT's collaborative winter wheat breeding program in Turkey in the mid-1980s, and the merging of this effort with ICARDA's highland wheat program in 1990, for the first time a notable percentage (15%) of winter wheat releases were based on direct CIMMYT crosses. Non-CIMMYT winter semidwarfs were mostly Chinese releases (Figure 3.8).

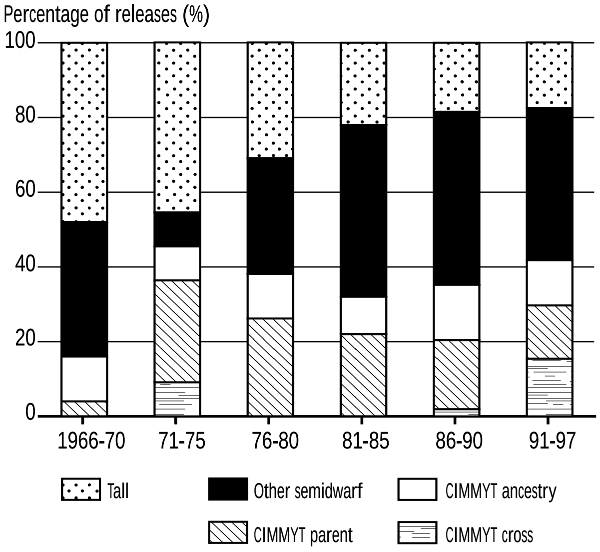

Figure 3.8. Winter bread wheat releases, developing world, 1966-97.

West Asia and North Africa had the highest percentage of winter wheat varieties with CIMMYT content between 1966 and 1997. Latin America, with relatively limited winter wheat area in the Southern Cone, also released a substantial proportion of varieties with CIMMYT content. As mentioned earlier, non-CIMMYT semidwarfs were predominant in China's winter wheat releases (Figure 3.9; see also Appendix A, Table A.3).

Private-Sector Wheat Releases and Wheat Varietal Protection in Developing Countries

Although the public sector dominates wheat improvement research in developing countries, there are some exceptions. Private-sector wheat improvement research has been strong in Argentina for some time. In 1935, Argentina was among the first countries in the world to institute some form of Plant Breeders' Rights (PBR) (Pray 1991). Argentina was also the first of the 36 study

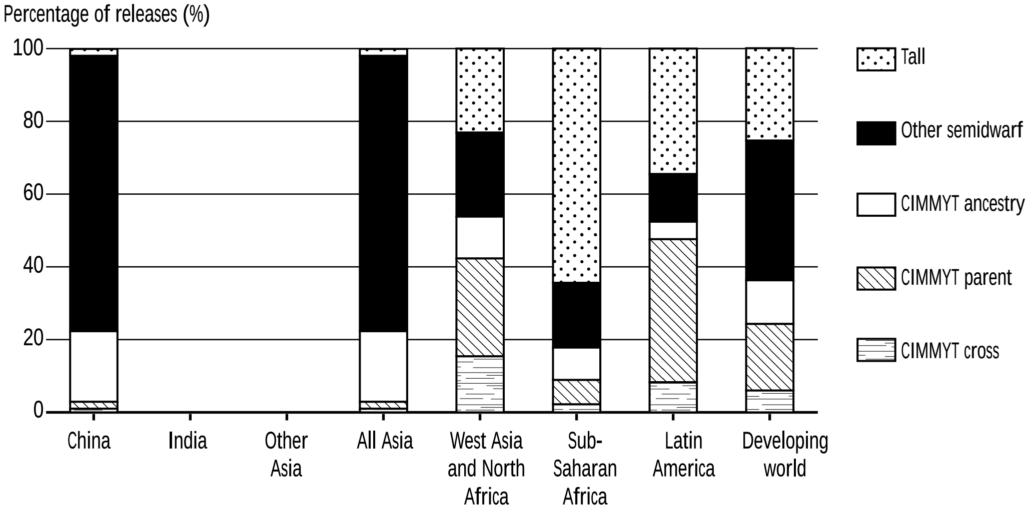

Figure 3.9. Winter bread wheat releases by region, 1966-97.

countries to become a member of the International Union for the Protection of New Varieties of Plants (UPOV). Varieties developed by the private sector in Argentina are sown in Brazil and Uruguay. Chile and Brazil have also conducted some private-sector wheat research. In Africa, the private sector currently appears to be important in South Africa and Zimbabwe (Heisey and Lantican 1999). Other African countries such as Kenya and Zambia, which had no private-sector wheat researchers in 1990, reported a modest level of private-sector research activity by 1997.

An increasing number of countries have joined the UPOV, an intergovernmental organization that was established by the International Convention for the Protection of New Varieties of Plants in 1961. The Convention aims to protect new plant varieties with intellectual property rights.[20]

As of September 1999, 12 of the 36 countries covered in this report were UPOV members: Argentina, Brazil, Bolivia, Chile, China, Colombia, Ecuador, Kenya, Mexico, Paraguay, South Africa, and Uruguay. Because most of these countries have only recently joined the UPOV, we were able to get the complete list of protected wheat varieties or varieties with PBRs for only five countries—Argentina, Brazil, Chile, South Africa, and Uruguay. To the extent possible, CIMMYT ancestry was traced for protected wheat varieties in these countries using CIMMYT's Wheat Pedigree Management System and our wheat impacts database. In general, pedigrees are less frequently available for private sector wheat varieties.

Figure 3.10 shows the percentage of protected wheat varieties with CIMMYT content in the five countries mentioned above. More than 60% of wheat varieties with PBRs in Argentina, Brazil, and Uruguay have CIMMYT content. Slightly less than 45% of Chile's protected wheat varieties are CIMMYT-related; varieties with unknown pedigrees account for more than 45%. Only 14% of protected wheat varieties in South Africa have known CIMMYT content; more than 50% have unknown pedigrees. Some of these unknown varieties may have CIMMYT ancestry, but because most of them are new varieties, it was not possible to get information on their pedigrees. Even though the figures presented come from only five countries, they indicate that protected or private-sector wheat varieties (these two categories are not always identical) in the developing world also make considerable use of CIMMYT germplasm.

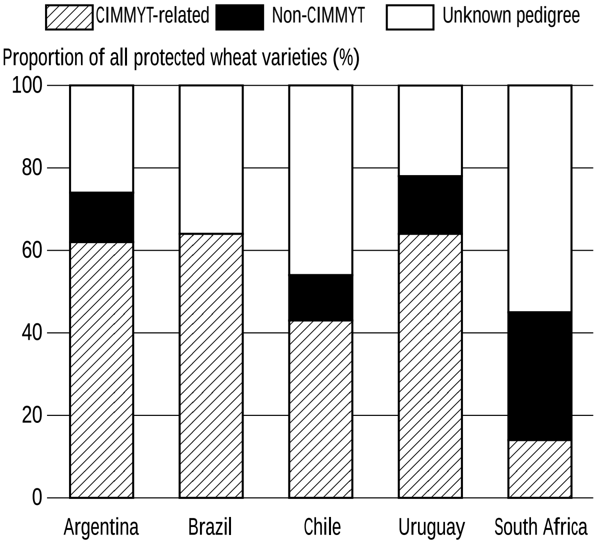

Figure 3.10. Parentage of protected wheat varieties, selected countries.

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[20] For more details on the protection of new varieties under the international Convention, refer to UPOV's website (http://www.upov.int/eng/protectn/exclusive.htm).

Chapter 4

Adoption of Improved Wheat Varieties in Developing Countries

In this chapter, we review the adoption of semidwarf varieties in developing countries between 1966 and 1997. We then assess CIMMYT's contribution to varieties planted in farmers' fields and present several alternative methods to measure these contributions. The chapter concludes with a brief assessment of the slow rates at which newer varieties have replaced older varieties in farmers' fields in many developing countries. Slow replacement rates dilute the impact of international and national wheat breeding programs.

Spread of Semidwarf Varieties

Since the introduction of semidwarf wheat varieties in the 1960s, adoption has grown steadily, although at different rates in different parts of the world. In 1970, semidwarf varieties covered a substantial percentage of the total wheat area only in South Asia. The rate of diffusion was particularly rapid in Latin America during the 1970s. By the late 1990s, semidwarfs covered over 80% of all developing country wheat area, with adoption rates of 90% or more in South Asia and Latin America. Adoption of semidwarfs in China initially lagged behind, but by 1997 stood at just under 80%. In 1997, more than 60% of the total wheat area in WANA and sub-Saharan Africa was planted to semidwarf wheat varieties. In the aggregate, adoption of semidwarf varieties in the developing world continued to increase during the 1990s (Figure 4.1).

Nearly 70% of the developing world's spring bread wheat area is found in Asia, so adoption there dominates the aggregate results. Adoption of semidwarfs is highest for spring bread wheat varieties (nearly 90% of total spring bread wheat area); there is little variation in adoption rates for this wheat type across all regions. As in 1990, in 1997 the adoption of semidwarf spring bread wheat was lowest in sub-Saharan Africa (Figure 4.2).

Spring durum wheat production is highly concentrated, with over 80% found in the WANA region. In that region, semidwarfs increased from about 60% of the area in 1990 to around 75% in 1997 (Figure 4.2). The proportion of durum wheat

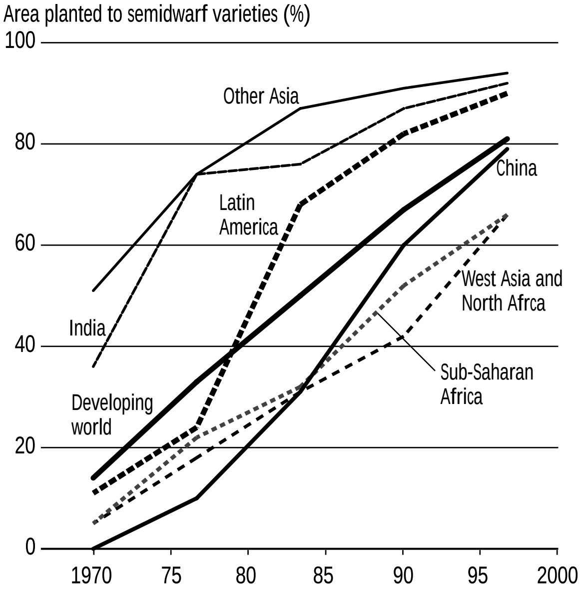

Figure 4.1. Percentage of wheat area planted to semidwarfs in developing countries, 1970-97.

area planted to semidwarfs in Latin America also increased substantially between 1990 and 1997, but adoption of semidwarfs in sub-Saharan Africa's durum region (found only in Ethiopia) remained low. Adoption of semidwarf spring durum wheat in Asia (found only in India) appears to have increased substantially between 1990 and 1997, but total durum area decreased notably (Figure 4.2). Asia has the smallest durum wheat area in the developing world (Byerlee and Moya 1993).

Over 60% of the developing world's winter bread wheat area is found in China, and another third is found in the WANA region. Adoption of semidwarfs appears to be higher for winter bread wheat in China than for spring bread wheat. In contrast, adoption of semidwarfs is low for winter bread wheat in WANA and South Africa. South Africa is the only country in sub-Saharan Africa where winter bread wheat is grown; all of the winter bread wheat in that country is planted to improved varieties. In Latin America, with limited winter area in the Southern Cone, adoption of semidwarfs is high. Turkey is the only country in which winter durum wheat is grown, and adoption of semidwarfs is very low (10%) for that wheat type and country (Figure 4.2).

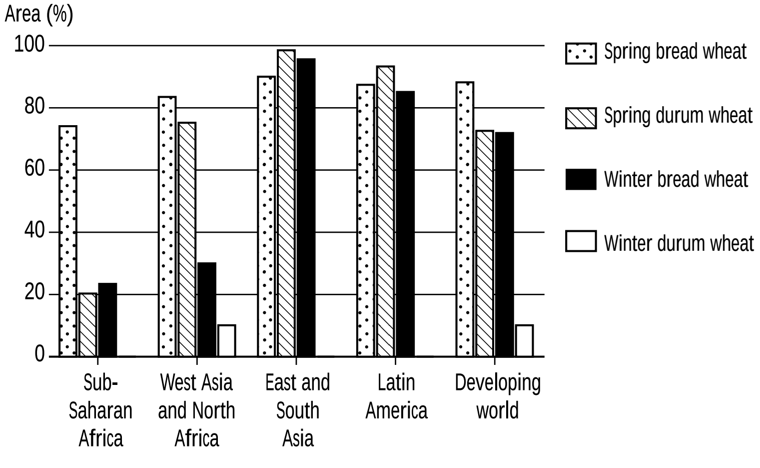

Figure 4.2. Percentage of wheat area planted to semidwarf varieties by wheat type and region, 1997.

Adoption of modern varieties (MVs) carrying dwarfing genes has been very high in irrigated areas and low in rainfed areas (Byerlee and Moya 1993). However, adoption of MVs increased rapidly in rainfed areas in the 1980s, despite modest yield gains there as compared with irrigated areas (Byerlee and Morris 1993). In more recent years, adoption of MVs has continued to increase in some rainfed areas. For example, semidwarfs now appear to be grown on nearly 100% of rainfed area of Argentina and Syria and around 85% of the rainfed area in Pakistan (Byerlee and Moya 1993).

Area Planted to CIMMYT-Related Germplasm

Table 4.1 summarizes the area planted in 1997 to varieties of different origins. As noted previously, spring bread wheat is the dominant type of wheat grown in the developing world, and spring bread wheat releases dominate all releases. In the countries surveyed for this report (including China), 69 million hectares were planted to spring bread wheat in 1997. Of this, about 60 million hectares were planted to semidwarfs, nearly 53 million hectares (88%) of which were sown to CIMMYT-related varieties. CIMMYT or NARS crosses with at least one CIMMYT parent covered about 40 million hectares, and another 12 million hectares were planted to varieties with some earlier CIMMYT ancestor.

In the countries surveyed, spring durum wheat covered about 6.5 million hectares. More than two-thirds of this area was planted to CIMMYT-related varieties and more than one-half to CIMMYT crosses. Landraces covered 1.5 million hectares, representing over 20% of the spring durum area.

Winter bread wheat covers considerably more area than spring durum wheat: in 1997, about 26 million hectares were sown to winter bread wheats. Of these, about 6 million hectares (24% of the total area planted) were planted to varieties related to CIMMYT, mainly varieties in which CIMMYT germplasm had been incorporated in earlier generations. Semidwarf varieties unrelated to CIMMYT covered about 12 million hectares, while landraces covered about 3 million hectares (Table 4.1).

The adoption of CIMMYT-related spring bread wheat in 1997 is disaggregated in greater regional detail in Figure 4.3. Excluding China, 80-90% of the spring bread wheat area in the developing world's major wheat-growing regions was planted to CIMMYT-related material. The use of CIMMYT crosses was greatest in WANA and Latin America, where about 50% of the spring bread wheat area was planted to CIMMYT crosses. In China, about one-third of the spring bread wheat area was planted to CIMMYT-related germplasm, and an additional 40% was planted to semidwarf wheats that did not contain CIMMYT germplasm.

Spring durum wheat area, which is relatively small compared to the area sown to other wheat types, is predominantly sown to CIMMYT-related semidwarf varieties. As is the case in adoption of spring bread wheats, Latin America and WANA have been major adopters of CIMMYT crosses in spring durum wheat (Figure 4.4). In WANA, where over 80% of the developing world's durum wheat is grown, more than 50% of spring durum wheat area was planted to CIMMYT crosses. In Latin America, the percentage of area planted to CIMMYT crosses was more than 90%.

Table 4.1. Area (million ha) sown to different wheat types, classified by origin of germplasm, 1997.

		NARS crosses						
Wheat type	**CIMMYT cross**	**CIMMYT parent**	**CIMMYT ancestor**	**Other semidwarf**	**Tall**	**Land races**	**Unknown cultivars**	**All**
Spring bread wheat	18.2	22.4	12.6	7.7	5.2	2.2	1.0	69.4
Spring durum wheat	3.4	1.2	<0.1	0.1	0.3	1.5	0.1	6.6
Winter bread wheat	0.2	1.8	4.2	11.6	2.3	3.2	2.6	25.9
Winter durum wheat	0.0	0.0	0.0	0.1	1.0	0.1	0.0	1.2
All	21.8	25.5	16.8	19.5	8.8	7.0	3.8	103.1

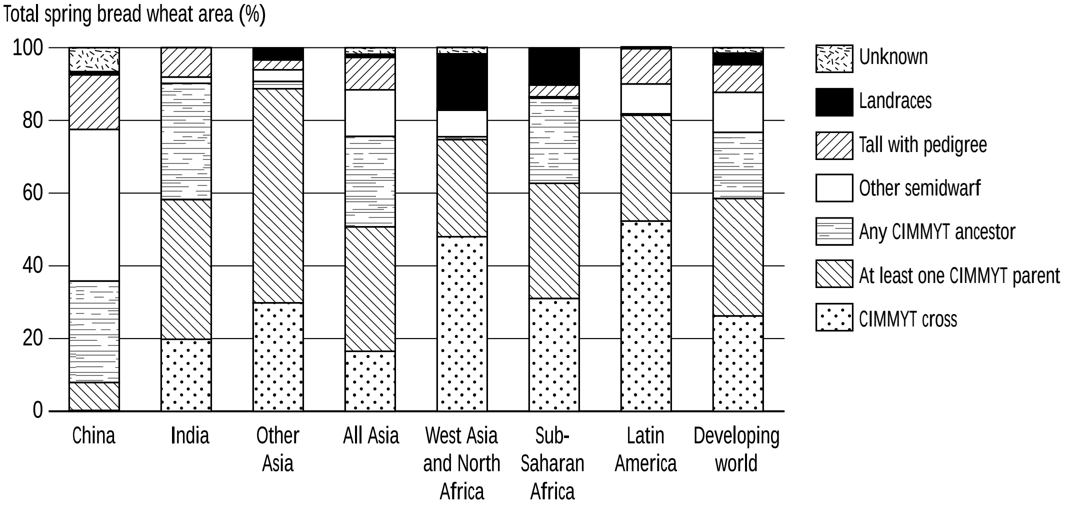

Figure 4.3. Area planted to spring bread wheat in developing countries, 1997.

In contrast to areas planted to spring bread and spring durum wheat, the area planted to winter bread wheat is dominated by semidwarf wheats that are unrelated to CIMMYT wheats. These are overwhelmingly Chinese winter wheat varieties. Among the regions where winter wheat is grown, Latin America was the only region where CIMMYT material was dominant (Figure 4.5). In China, nearly two-thirds of the winter bread wheat area (36% of the total wheat area) consisted of non-CIMMYT winter semidwarfs. In WANA, a region with a large winter wheat area, about 35% of the winter wheat area was planted to varieties with some CIMMYT ancestry. In South Africa, the only country in sub-Saharan Africa where winter wheat is grown, two-thirds of the wheat area was planted to tall varieties with pedigrees (i.e., tall varieties known to have originated with a scientific wheat breeding program).

Unlike spring bread wheat area, large proportions of both spring durum and winter bread wheat areas were still planted to landraces in 1997. Seven million hectares of the developing world's wheat area were sown to landraces, and 3.8 million

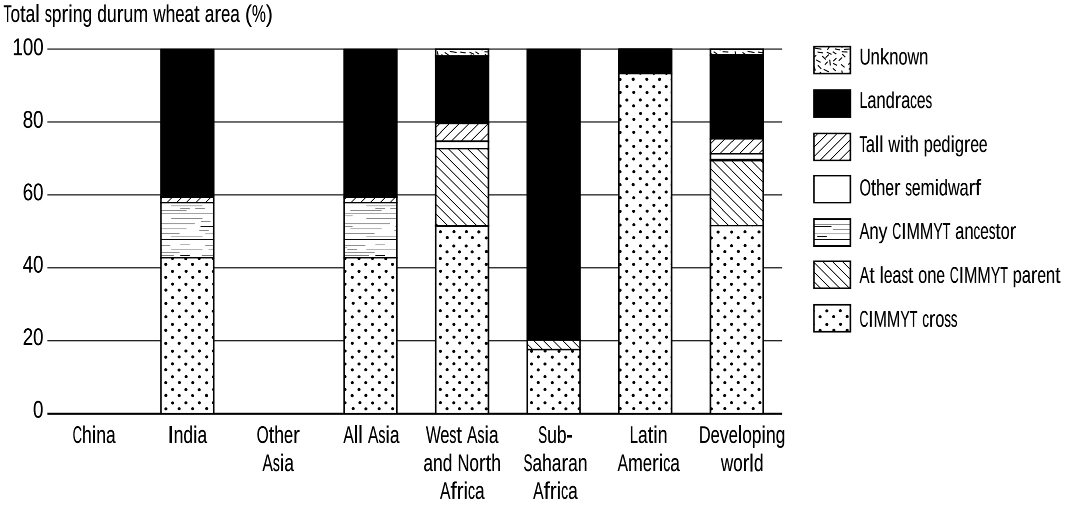

Figure 4.4. Area planted to spring durum wheat in developing countries, 1997.

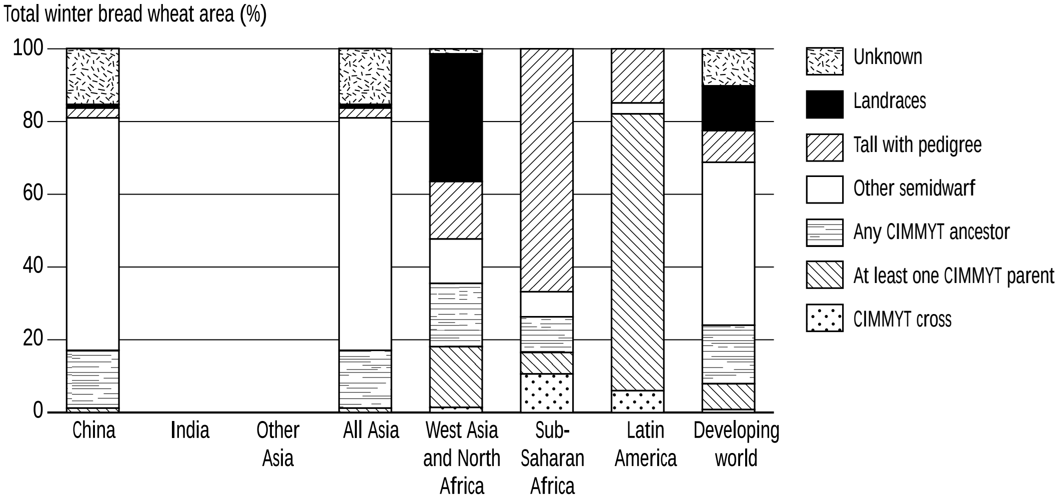

Figure 4.5. Area planted to winter bread wheat in developing countries, 1997.

hectares were planted to cultivars whose pedigrees and origin were unknown. It is possible that some of these unknown cultivars also had CIMMYT ancestry. Landraces tended to be concentrated in WANA, covering slightly less than 20% of the spring durum area and nearly 40% of the winter wheat area. In Ethiopia, the only country in sub-Saharan Africa where durum wheat is grown, landraces covered about 80% of wheat area (Figures 4.4 and 4.5).

Taking into account all wheat types, in 1997 62% of wheat area in the developing world was planted to wheat varieties with some CIMMYT content; without China, this figure rises to 75% (Figure 4.6). Slightly less than half of the wheat area in the developing world was planted to varieties produced from crosses made by CIMMYT or that had at least one CIMMYT parent. More than 80% of the wheat area planted in Asia (outside of China) and Latin America was sown to CIMMYT-related varieties.

Table 4.2 summarizes the total area sown in 1997 to varieties derived from popular CIMMYT spring wheat crosses. Sonalika remained the most popular CIMMYT cross released before 1980. Of the varieties released during the 1980s, Veery remained the most popular cross. About three million hectares were planted to Veery in 1997, similar to the area sown in 1990. The areas planted to both Bittern and Frigate (durum) crosses were about the same for 1990 and 1997. In contrast, the area sown to the Bobwhite cross in 1997 was significantly higher than in 1990. Kauz and Attila[21] crosses, which covered about one million hectare each in 1997, were the two most popular recent crosses. In both 1990 and 1997, the area sown to varieties based on recent CIMMYT crosses was much lower than the area sown to varieties released earlier. This was related to the rate of varietal replacement in developing countries, which will be discussed further at the end of this chapter.

Byerlee and Moya (1993) reported that in 1990 varieties from many crosses were grown on smaller areas. This was still the case in 1997. In addition to the specific crosses shown in Table 4.2, about 200 CIMMYT crosses were sown on more than 10 million hectares. Of this area, 6 million hectares were planted to 73 crosses (varieties)

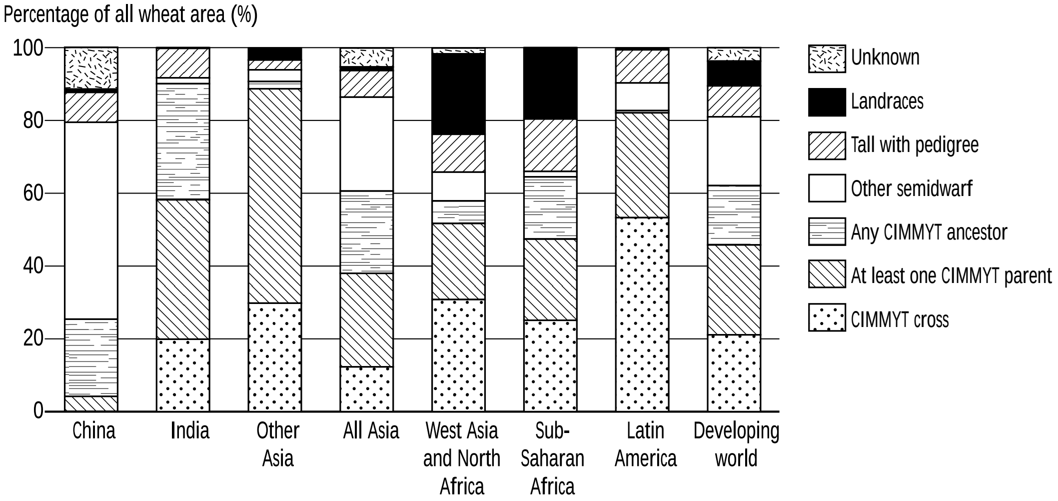

Figure 4.6. Area planted to all wheat in developing countries, 1997.

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[21] By 2001, Attila probably covered more than 5 million ha in India alone.

released since 1980, and about 3 million hectares were sown to 85 recent crosses (varieties) released since 1990. Although the total area sown to the most popular CIMMYT crosses declined in 1997, the use of CIMMYT germplasm as a parent in NARS crosses rose throughout the 1990s.

In both 1990 and 1997, India, Pakistan, Argentina, and Morocco had the largest wheat area sown to varieties developed from CIMMYT crosses (Table 4.3). The wheat area grown to varieties developed from CIMMYT crosses decreased between 1990 and 1997 in some countries (e.g. India, Pakistan, Brazil, and Mexico). However, in most of these countries, a substantial area was sown to varieties with considerable CIMMYT content, though they resulted from several generations of crossing and selection by NARS or private-sector scientists. In India and Pakistan, for example, farmers planted large areas to varieties with at least one CIMMYT parent. In Brazil and Mexico, the area planted to CIMMYT-related varieties declined because the total wheat area declined.

For the countries listed in Table 4.3, we also estimated the percentage of area covered by varieties derived from CIMMYT crosses, relative to the total wheat area planted (Figure 4.7). This shows how shifts in area planted to varieties derived from CIMMYT crosses can be offset by changes in total wheat area. As an example, even though the area planted to CIMMYT-derived varieties declined in Brazil in absolute terms, about 35% of the total wheat area in Brazil was planted to CIMMYT crosses in both 1990 and 1997.

In a number of countries (notably those in the WANA region as well as Argentina), the proportion of total wheat area sown to varieties

Table 4.2 Area sown to varieties derived from popular CIMMYT spring wheat crosses, 1997.

Cross	Average year of varieties from cross released	Area sown (000 ha)	Main country of release
Released before 1980			
Sonalika	1972	1224	Bangladesh, India, Nepal, Yemen
II8156	1972	293	Afghanistan, Morocco, Nigeria, Syria, Yemen Rep.
Other (30 crosses)		1,275	
Subtotal		2,791	
Released 1980-89			
Veery	1988	3,351	Afghanistan, Bolivia, Brazil Chile, Egypt, Ethiopia, India, Iran, Morocco, Nepal, Nigeria, Pakistan, Paraguay, South Africa, Tanzania, Turkey, Uruguay, Yemen, Zambia, Zimbabwe
Bobwhite	1988	1,643	Argentina, Ethiopia, Paraguay, Turkey, Uruguay
Bittern (durum)	1984	963	Chile, Egypt, Morocco, Tunisia, Turkey
Frigate (durum)	1988	584	Algeria, Lebanon, Syria
Buckbuck	1989	421	Kenya, Pakistan
Pavon	1982	323	Bolivia, Ethiopia, Mexico, Nigeria, Pakistan, Peru Tanzania, Yemen
Gallareta (durum)	1984	361	Mexico
Other (73 crosses)		5,905	
Subtotal		13,551	
Released since 1990			
Kauz	1994	1,092	Afghanistan, Chile, India, Iran, Pakistan , Turkey
Attila	1996	1,006	India, Iran
Loxia	1992	416	Argentina, Paraguay
Other (85 crosses)		2,993	
Subtotal		5,508	
Total		**21,851**	

Table 4.3. Countries having the largest wheat area (million ha) sown to varieties developed from CIMMYT crosses, 1990 and 1997.

Country	Area sown to wheat varieties developed from CIMMYT crosses 1990	1997
India	6.8	5.1
Pakistan	5.5	2.5
Argentina	1.9	3.1
Morocco	1.4	1.9
Turkey	0.9	0.5
Brazil	0.9	0.5
Mexico	0.9	0.7
Iran	0.8	1.4
Syria	0.7	1.4
Egypt	0.6	0.9
Algeria	0.4	0.7

Source: Byerlee and Moya (1993); CIMMYT Wheat Impacts database.

released from CIMMYT crosses was larger in 1997 compared to 1990. In another instance, the large decline in the percentage area planted to CIMMYT crosses in Pakistan was due largely to a single shift in varieties grown. In the mid-1990s, following a change in stripe rust virulence, farmers switched from a CIMMYT cross that dominated Pakistan's wheat area during the late 1980s and throughout much of the 1990s to a cross with a CIMMYT parent (and considerable CIMMYT germplasm on both sides of the pedigree) (Figure 4.7).

Alternative Measures of CIMMYT Contribution to Wheat Varieties Planted in the Developing World

The methods of analyzing the origin of cultivars released and planted in the developing world were not discussed in the preceding and current chapter. In this section, we look more explicitly at ways of measuring the contributions of different wheat breeding programs, and more specifically at CIMMYT's contribution to wheat varieties planted in 1997.

The broadest way to define CIMMYT's contribution is to use an "any ancestor" rule. More restrictive definitions can be used, such as "varieties with CIMMYT parents" and "crosses made by CIMMYT." The last category, "crosses made by CIMMYT," constitutes the narrowest definition. Pardey et al. (1996) summarized these and other measures that have been used by researchers to apportion contributions of different breeding programs to pedigree-bred crops and proposed several new measures.

In the following discussion and Figures 4.8-4.11, we apply four rules to our database on wheat planted in developing countries.

1. The "geometric" rule developed by Pardey et al. (1996).
2. The "any ancestor" rule.
3. A "CIMMYT cross or parent" rule similar to the one used by Byerlee and Moya (1993).
4. The "CIMMYT cross" rule.

These rules are applied to individual varieties, and then aggregate measures of CIMMYT's contribution are determined by calculating area-weighted proportions.[22]

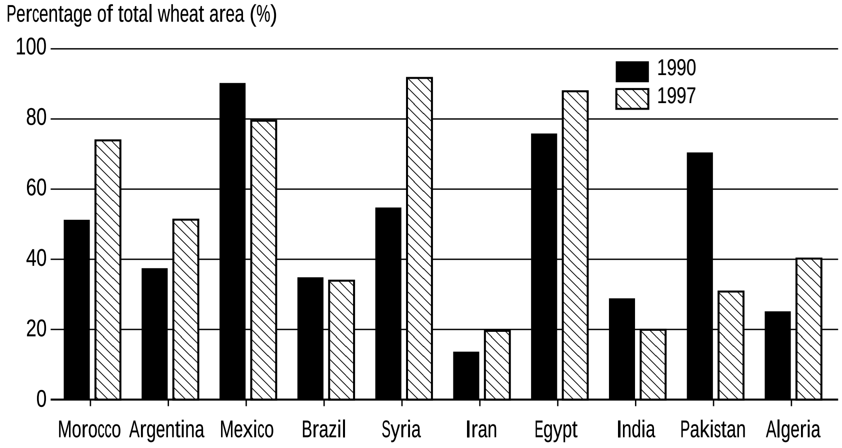

Figure 4.7. Percentage of wheat area sown to CIMMYT crosses in selected countries, 1990 and 1997.

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[22] This was the implicit methodology of the simple measures applied earlier in this chapter.

The geometric rule analyzes a variety's pedigree by applying geometrically declining weights to each level of crossing for as many generations as desired. Hence, it gives a weight of 1/2 to the cross itself, 1/8 to each of the two crosses used as parents, 1/32 to each of the four crosses used as grandparents, and so on back. In the earliest generation considered, weights are doubled to make all weights sum to 1. In our calculations, we included five generations. In addition, wheat areas planted to landraces and unknown varieties were included in the calculations. For these areas, the CIMMYT contribution was set to zero. For the 1997 data, we report results with and without China, primarily for the purpose of allowing comparison with 1990. This is because only a few spring bread wheat zones in China were covered in the 1990 survey.

During the 1990s, the area planted to spring bread wheat varieties with some CIMMYT content increased at the same time that the area planted to CIMMYT crosses decreased. Combining these effects, apportionment of CIMMYT content by the geometric rule declined slightly between 1990 and 1997 when China was excluded (Figure 4.8).

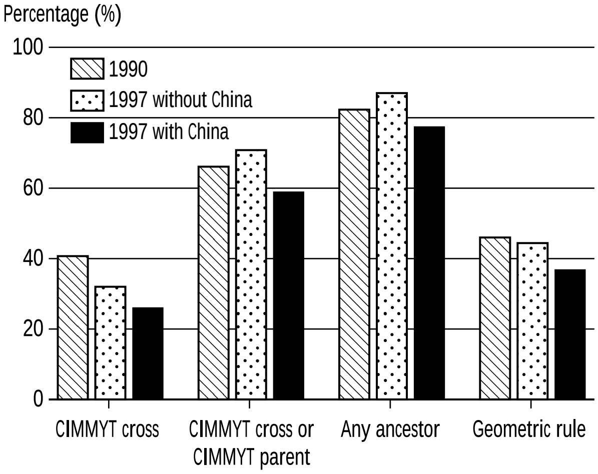

Figure 4.8. Percentage of CIMMYT contribution to spring bread wheat planted in developing countries, 1990 and 1997.

These results conceal a number of regional differences, some of which are not evident in Figure 4.8. Outside of China, all four indicators of CIMMYT content presented here—geometric rule, any ancestor rule, CIMMYT cross or parent, or CIMMYT cross—increased between 1990 and 1997 in the spring bread wheat areas of WANA, Latin America, and sub-Saharan Africa. In South Asia, although the area planted to wheat with some CIMMYT content increased between 1990 and 1997, areas apportioned according to the geometric rule or CIMMYT cross rule fell significantly. This change was enough to drive the aggregate estimates down for the developing world (excluding China) (Figure 4.8). At the same time, the percentage area planted to wheat varieties with some CIMMYT ancestry is higher in South Asia (as discussed earlier) than in any other region of the developing world. In other words, CIMMYT germplasm is present in nearly all spring bread wheat grown in South Asia today, particularly in India, where substantial areas are sown to varieties from several generations of crossing and selection by local scientists in wheats with a large amount of CIMMYT germplasm. Wheat scientists in Asia have also incorporated improved tall varieties into their germplasm base.

As expected, when China is included, CIMMYT's contribution to improved wheat released in developing countries declines by all measures. The decline is proportionately lowest when using the any ancestor rule (compare the two 1997 indicators in Figure 4.8). As the figures indicate, China's wheat genetic improvement program has made less use of CIMMYT germplasm than other programs in the developing world, both for historical reasons and because China's wheat growing environments differ substantially from those found elsewhere in the developing world.[23]

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[23] These include large areas sown to winter habit area, some area sown to high-latitude spring wheat, and special disease problems even in the areas sown to low-latitude spring wheat (Byerlee and Moya 1993).

Even so, a significant amount of Chinese spring bread wheat area (around 4.7 million hectares in 1997) is sown to wheat varieties with some CIMMYT ancestry, and about a million hectare of this area is sown to spring bread wheat varieties that have a CIMMYT parent rather than a more distant CIMMYT ancestor.

Figure 4.9 shows CIMMYT's contribution to spring durum wheat planted in developing countries. Little spring durum wheat is grown in China, so the analysis focuses only on CIMMYT's contribution in major developing country spring durum wheat producers in 1990 and 1997. Regardless of the measure used, CIMMYT's contribution to spring durum wheat planted in the developing world was higher in 1997 than in 1990. Using the CIMMYT parent or the any ancestor rule, over two-thirds of spring durum wheat planted in the developing world in 1997 could be attributed to CIMMYT. Using the CIMMYT cross or the geometric rule, CIMMYT's contribution to spring durum wheat planted in 1997 was slightly more than 50%.

The data on releases and area planted show that CIMMYT has made a smaller contribution to winter wheat breeding in developing countries compared to spring bread or spring durum wheat breeding. This can be attributed both to the late start of winter wheat breeding by CIMMYT (Chapter 2) and to China's dominance of the total winter wheat area. Even so, CIMMYT's contribution to winter wheat has grown substantially since 1990. No CIMMYT winter crosses were planted in 1990; in 1997, a small area was planted to such crosses (Figure 4.10). Excluding China, the proportion of winter wheat planted to varieties with some CIMMYT content tripled between 1990 and 1997. Within China, a little more than 10% of the winter wheat area was planted to varieties with some CIMMYT ancestry in 1997. By the geometric rule, CIMMYT contribution to winter wheat planted in developing countries increased from 2% to 5% between 1990 and 1997. Including China, the aggregate figure would again be slightly greater than 2% in 1997.

To a large extent, the pattern of CIMMYT's contribution to all wheat planted follows that of spring bread. As with spring bread wheat, the aggregate area planted to CIMMYT crosses for all wheat types declined between 1990 and 1997, while the area planted to NARS crosses with at

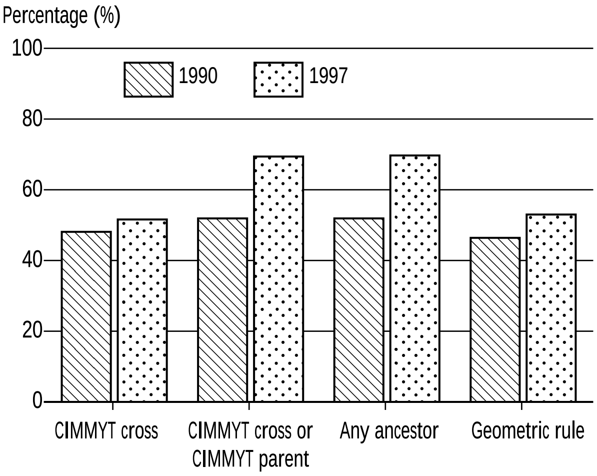

Figure 4.9. Percentage of CIMMYT contribution to spring durum wheat planted in developing countries, 1990 and 1997.

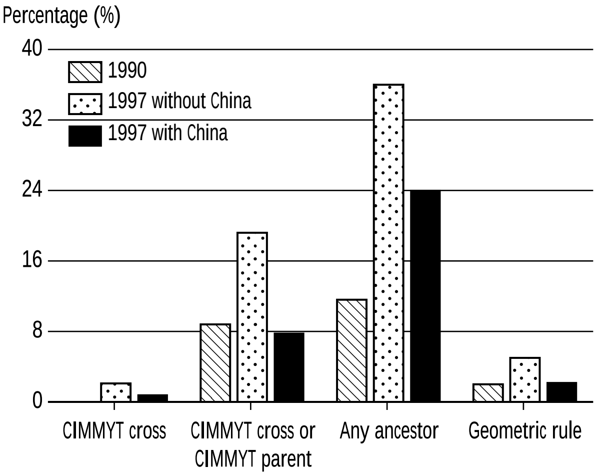

Figure 4.10. Percentage of CIMMYT contribution to winter bread wheat planted in developing countries, 1990 and 1997.

least one CIMMYT parent and NARS varieties with some CIMMYT ancestry increased. By the geometric rule, however, the increased contributions in spring durum and winter wheat offset the decline for spring bread wheat, and so the aggregate estimate for CIMMYT contributions for all wheat types increased slightly between 1990 and 1997. Again, by the geometric rule, CIMMYT accounted for nearly 40% of genetic contribution to all wheat planted in the developing world (excluding China) in 1990 and 1997. When China was included, CIMMYT's contribution to all wheat planted in 1997 was slightly less than 30% (Figure 4.11).

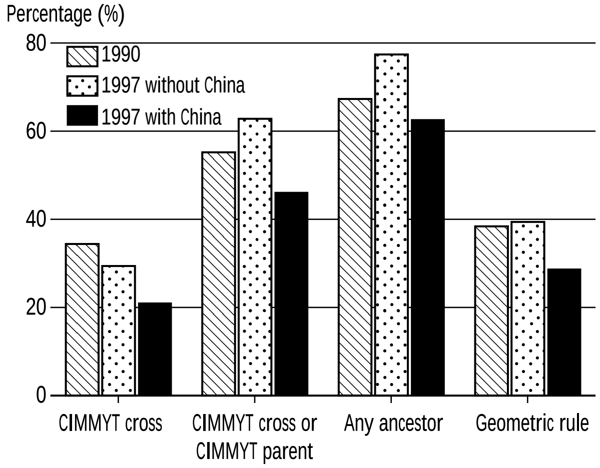

Figure 4.11. Percentage of CIMMYT contribution to all wheat planted in developing countries, 1990 and 1997.

Lags in Adoption of MVs

A significant proportion of total wheat area was still planted to older improved varieties in 1997. This is consistent with the results reported in 1990 study by Byerlee and Moya (1993). Despite the fact that farmers in developing countries have widely adopted improved varieties, the rate at which older varieties are replaced by newer varieties remains unacceptably slow. As long as they continue to grow old varieties, farmers benefit neither from the improved yield potential of newer varieties nor from their superior disease resistance. Although many economic studies of returns to agricultural research make assumptions about adoption lags, such lags have not been given a great deal of analytical attention. Nonetheless, long adoption lags are important factors that reduce returns to wheat breeding research.

A measure of the rate at which varieties are being replaced is the age of varieties in farmers' fields. This is measured in years since release and weighted by the area planted to each variety (Brennan and Byerlee 1991). Based on this indicator, varietal replacement accelerated between 1990 and 1997 in only 12 of the 31 countries for which comparisons could be made.

The weighted average age of improved varieties planted in farmers' fields in 1997 is given in Table 4.4. Note that only improved wheat varieties (semidwarfs and improved tall varieties) are included in these calculations. Zimbabwe and Afghanistan were the only two developing countries where the average age of varieties in farmers' fields was less than six years. This length of time is notable because it is roughly equivalent to the longevity of rust resistance derived from a single resistance gene (Kilpatrick 1975). Rust is the most important disease of wheat worldwide. In Zimbabwe, the private sector's involvement in wheat research may have played a role in the rapid turnover of wheat varieties. In Afghanistan, external aid following the Russian withdrawal

Table 4.4. Weighted average age (years) of improved varieties in farmers' fields, 1997.

Age	Country
< 6	Zimbabwe, Afghanistan
6 - 8	China, Pakistan, Guatemala, Chile, Argentina, Brazil
8 - 10	Zambia, Nigeria, Iran, Colombia, Bolivia, Uruguay
10 - 12	Paraguay, Ecuador, South Africa, Morocco, Tanzania
12 - 14	Syria, Yemen, Lebanon, India, Kenya, Mexico
> 14	Sudan, Ethiopia, Egypt, Algeria, Tunisia, Jordan, Bangladesh, Nepal, Peru, Turkey

included widespread distribution of wheat seed; otherwise wheat varietal turnover in Afghanistan would undoubtedly have been much slower.

With the exception of Peru and Mexico, farmers in most Latin American countries replace their varieties more rapidly than farmers in other developing countries. This is consistent with earlier findings (Byerlee and Moya 1993). In Mexico, varietal replacement seems to be decelerating (Brennan and Byerlee 1991). This deceleration in the rate of varietal turnover resulted primarily from a shift from bread wheat to older improved durum wheat varieties in major wheat-growing areas of northwestern Mexico. In addition, Mexican policy has increasingly focused on high industrial quality and protein levels, as well as high and stable yields. This shift has led to incentives for the substitution of durum varieties for bread wheat varieties.

In contrast to Latin America, the weighted average ages of varieties in most nations of the WANA region exceeds 12 years. Interestingly, even large wheat-producing countries such as India have weighted varietal ages exceeding 12 years, although wheat varieties are replaced much more rapidly in some regions, particularly northwestern India (Byerlee and Moya 1993). Factors affecting the rate of varietal replacement in wheat are discussed from a theoretical perspective by Heisey and Brennan (1991). Empirical evidence on varietal replacement is presented by Heisey (1990) and Mwangi and colleagues (see, for example, Alemu Hailye et al. 1998; Regassa E. et al. 1998; and Hailu B., Verkuijl, and Mwangi 1998).

Chapter 5

Measuring Costs, Benefits, and Economic Impacts of Wheat Breeding Research

How can the success of a wheat breeding program be evaluated? Wheat scientists, economists, and research policy makers all recognize that the benefits of a wheat improvement program must be measured against the costs incurred in operating that program. They may, however, take different approaches to identifying and measuring these costs and benefits, particularly the benefits.

In principle, the costs of a wheat breeding program are relatively straightforward to define and measure. In Chapter 2, we presented some measures of costs associated with international wheat breeding targeted at developing countries. Even when measuring the costs of a single international organization such as CIMMYT, we saw that different assumptions can lead to different, though related estimates. Computing the costs of all international wheat breeding research, or assessing the expenditures of NARS wheat breeding programs is more difficult. However, the difficulty is usually due to lack of data, rather than lack of a conceptual framework.

In contrast, measuring the benefits of wheat breeding research is fraught with conceptual problems. Byerlee and Moya (1993) divide the process by which wheat breeding research generates benefits into three stages:

1. New varieties are developed, released, and adopted. This part of the process has been analyzed in Chapters 3 and 4.
2. Adopted varieties generate benefits through gains in yield, improved stability, and other desirable characteristics.
3. These benefits are transmitted via prices and distributed to society through the effects on producers' and consumers' incomes.

This chapter, along with Chapters 6 and 7, will analyze the second and third steps of this process.

A number of definitional and practical problems complicate the measurement of benefits of a wheat improvement program. For example, wheat scientists tend to concentrate on yield gains, whereas economists are generally interested in increases in output or shifts in supply. Although it is theoretically possible to relate the concept of yield gains to the concept of supply shifts, the relationship is not always easy to measure empirically. Furthermore, if quality improvements are an important goal of a wheat breeding effort, measurements of benefits may be further complicated.

In this chapter, we begin by examining the ways in which the superiority of new varieties developed by wheat breeding programs can be measured. We then look at the ways in which improvements in yield or other characteristics can be translated into shifts in wheat supply. Next, we consider the economic benefits associated with a supply shift and discuss how these benefits are distributed among different groups of consumers and producers. Following this, we review how cost and benefit estimates can be combined to derive an estimate of economic impacts. Finally, we note some special issues related to the measurement of the economic benefits of wheat breeding programs.

Gains in Yield and Other Characteristics

Over time, a successful wheat breeding program is likely to generate genetic gains in yield. One component of yield gain is a gain in yield potential. Starting at time 0, each subsequent variety released at time *t* may yield more (Y_t) compared to a variety released at time 0 (Y_0). Although the gains in yield from varieties released over time will not follow a smooth trajectory, for our purposes they can be considered to follow the pattern outlined in Figure 5.1. It is important to remember that gains in yield potential are assumed to be measured with potential stresses (such as soil fertility and disease pressure) set at non-limiting levels. In reality, it is somewhat difficult to disentangle gains in yield potential alone from gains in stress tolerance or resistance.

If we consider a single important stress affecting wheat grown in a particular target region, it is possible that wheat varieties released over time may yield more when subject to the stress ($Y_t[+S]$) or free of it ($Y_t[-S]$). In Figure 5.2a, yield gains in the presence and absence of the stress are depicted as occurring at the same rate. That assumption can be relaxed, however. Alternatively, gains may be made in yield potential in the absence of the stress, but no gains may be made in the presence of the stress (Figure 5.2b). In the first case, total gains in yield may be divided into gains in yield potential and gains in stress resistance; in the second case, all yield gains may be attributed only to increases in yield potential. Gains in expected yield at time *t*, compared with time 0, in both cases would be $(1-p)\{ Y_t[-S] - Y_0[-S] \} + p\{ Y_t[+S] - Y_0[+S]\}$, where *p* is the probability that the stress occurs.

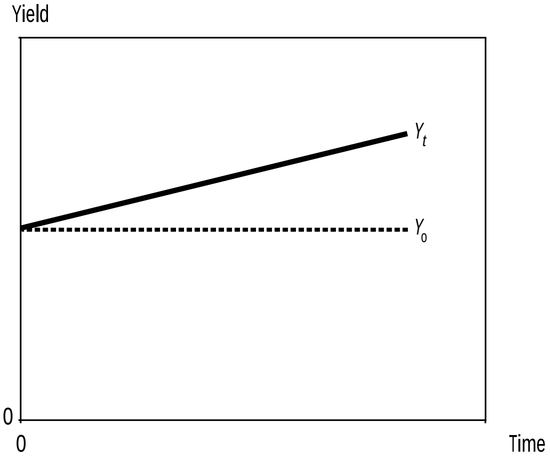

Figure 5.1. Gains in yield potential over time.

To further complicate matters, a variety's tolerance or resistance to some stresses may deteriorate over time. This is often the case for disease resistance, because over time pathogens frequently mutate to overcome genetically based resistance in the plant. Wheat rust pathogens (stem rust, or *Puccinia graminis*; leaf rust, or *P. recondita*; and stripe or yellow rust, *P. striiformis*) continually evolve and break down genetic resistance in wheat varieties.

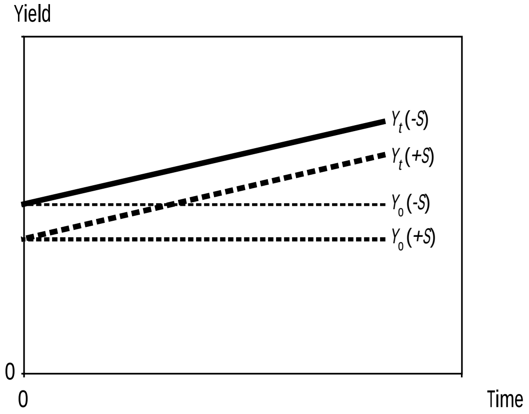

Figure 5.2a. Gains in yield with and without stress.

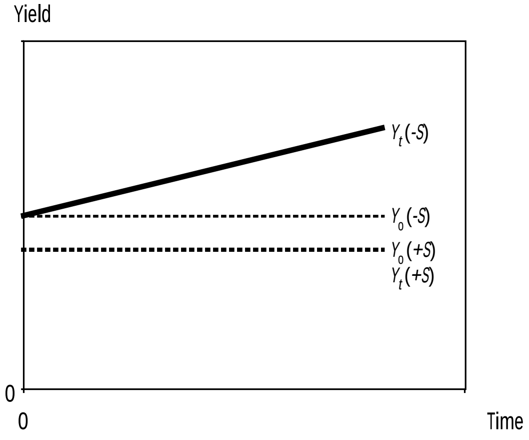

Figure 5.2b. Gains in yield only without stress.

A considerable amount of modern scientific wheat breeding has focused on securing new and more durable sources of disease resistance, particularly to rusts. Figures 5.3a and 5.3b depict two possible yield gain scenarios in which disease resistance breaks down over time. In such situations, it is conceptually possible to distinguish between gains in disease resistance resulting in an improvement in resistance, and gains in disease resistance resulting in the maintenance of resistance at the levels present in previously released varieties at the time of their release.

Byerlee and Moya (1993) argue that genetic gains in wheat yield can be classified into gains in yield potential, improvements in disease resistance, and maintenance of disease resistance. They describe the types of trials and statistical analysis necessary to measure these different types of genetic gains.

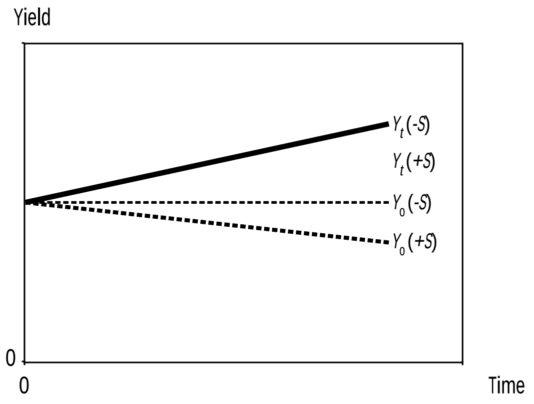

Figure 5.3a. Perfect disease resistance in new varieties and loss of resistance in old varieties.

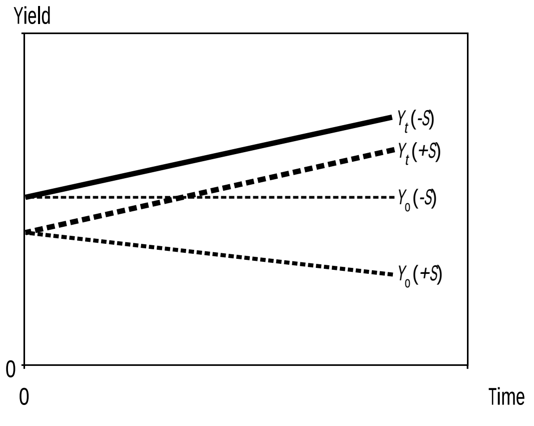

Figure 5.3b. Improvements in disease resistance in new varieties and loss of resistance in old varieties.

In practice, often gains from improving and maintaining disease resistance are not measured separately. Furthermore, gains measured in yield potential may actually be the result of gains in tolerance to other stresses, such as nutrient deficiencies and moisture stress, or heat stress. Evans and Fischer (1999) and Tollenaar and Wu (1999) present alternative approaches for conceptualizing gains in yield potential and gains in stress resistance/tolerance. At an extreme, all yield gains could be considered gains in stress resistance. At a practical level, however, breeders are often comfortable distinguishing between gains in yield potential and gains in resistance or tolerance to major stresses in their targeted environments.

For simplicity, in this report we concentrate on benefits from wheat breeding that show up in the form of yield gains. However, the process through which new varieties are developed and diffused may also bring other benefits (or losses). Earlier maturity, or the ability to plant and harvest more rapidly, may allow farmers to increase cropping intensity. This is a clear production-related benefit resulting from wheat improvement, but because it is felt at the level of the cropping system, it is less readily measured when the focus is on wheat alone. Also, wheat breeders may alter the market value of wheat by changing its quality. Measuring the effects of quality improvements requires some means of measuring quality and a way of valuing changes in quality. If byproducts such as straw are valuable, changes in the quality and quantity of byproducts will also be important determinants of the net benefits from wheat breeding (Traxler and Byerlee 1993). Environmental effects of new varieties, such as reduced chemical use for disease control when new varieties have host-plant resistance, or greater problems in the maintenance of soil quality given the management practices associated with new varieties, are particularly hard to measure. Nonetheless they, too, can be important economic impacts of wheat breeding.

Translating Yield Gains Into Economic Benefits

YIELD GAINS AT THE FARM LEVEL

Yield gains estimated from data generated through varietal evaluation trials may not be equivalent to yield gains realized in farmers' fields. Varietal evaluation trials conducted in farmers' fields are usually conducted with a package of technology that the farmer would not normally use. Furthermore, trials on experiment stations may not be carried out under environmental conditions representative of conditions in farmers' fields. Absolute yields of varieties grown in farmers' fields under farmers' conditions will usually be lower than yields in variety trials, as will the absolute size of gains in yield.

It is empirically uncertain, however, whether the relative yield gains realized in farmers' fields are lower than the relative yield gains observed in variety trials (Byerlee and Moya 1993). If yields increase in farmers' fields at the same rate that they increase in experiments, the relative rate of gain in farmers' fields would be the same as in the trials, even though the absolute gain would be less.

FARMER MANAGEMENT AND FARM-LEVEL YIELD GAINS

There are several reasons to believe that relative yield gains in farmers' fields will not be identical to experimental yield gains, even if farmers' management is equivalent to management levels in experiments. First, in farmers' fields, the supply and demand of production factors depend on economic considerations. Second, production factors may be readily substituted for one another in wheat production, or, alternatively, substitution possibilities may be limited (Alston, Norton, and Pardey 1995).

Varietal changes in farmers' fields may also induce changes in management practices as farmers choose economically optimal levels of inputs. Changes in management practices in turn imply changes in costs at the farm level. All these things must be considered if there is to be a complete accounting of economic net benefits. As we have seen, it is unlikely that yield gains measured in trials have been evaluated at a management level equal to the equilibrium level of inputs that would have prevailed in farmers' fields before the change in variety.[24] Even if they had been, the changes in net economic benefits must take into account not only changes in the value of production, but changes in costs between the old and new equilibrium levels of input use. In the language of economics, the magnitude of the supply shift is related to the yield gains resulting from research, but there may not be a simple correspondence between the measure of gains in yield resulting from breeding, the measure of yield gains in farmers' fields, and the measure of economic benefits resulting from these yield gains.

TECHNICAL AND ALLOCATIVE EFFICIENCY

The preceding discussion assumes that differences between farmers' yields and experimental yields result from conscious economic choices made by farmers. However, it is possible that farmers are also "inefficient" in their use of resources. Microeconomic theory usually distinguishes between allocative efficiency and technical efficiency. Allocative efficiency refers to the use of economically optimal combinations of inputs, given input and output prices. Technical efficiency means obtaining the greatest possible output for any given combination of inputs. Inefficiencies in input use are often associated with inadequate information (Ali and Byerlee 1991). It is sometimes

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[24] Or, for that matter, at the equilibrium level of inputs that would have been used in farmers' fields *after* the change in variety.

hypothesized that inefficiencies are greater in periods of rapid technological change, such as the Green Revolution, than in other periods such as the years following the Green Revolution (Byerlee 1992).

Most empirical studies, including those that focus on wheat production, seem to show that farmers are allocatively and technically inefficient (Rejesus, Heisey, and Smale 1999). The evidence on whether inefficiency is greater in periods of Green Revolution-like technical change is limited and mixed (Pingali and Heisey 2001). Numerous conceptual and methodological problems are associated with estimating allocative and technical efficiency. Partitioning inefficiency into these two components is sensitive to the level of input aggregation used in the modeling process (Ali and Byerlee 1991). Furthermore, it is possible to argue that apparent inefficiency is really due to unmeasured inputs, which are very likely unpriced as well. The conceptual and empirical difficulties in attributing differences between experimental and farmer yields and yield gains to farmer inefficiency are economic counterparts to agronomic difficulties in attributing experimental yield gains to gains in yield potential or gains in stress resistance.

CHANGES IN WHEAT PRICES

Changes in wheat technology that result in increased wheat yields and increased wheat supply may result in changes in wheat output prices. The degree to which demand for wheat is sensitive to the price of wheat will influence the relationship between experimental and "industry" yields (the latter refers to yields in farmers' fields). If the country or region served by the breeding program is neither a net exporter nor a net importer of wheat, increases in wheat supply will drive down the real price of wheat. For net exporters, shifts in supply will leave the price of wheat at the export price, and for net importers, shifts in supply will leave the price of wheat at the import price. In the long run, the likely result of increased wheat supply attributable to wheat improvement research is lower real world wheat prices. This will also affect benefits generated from wheat research, although the primary effect may be on the distribution of benefits between producers and consumers, rather than on the total size of benefits.

TRANSLATING YIELD GAINS INTO SUPPLY SHIFTS

In this section, we apply the model originally proposed by Muth (1964) and further developed by Alston (1991) and Alston, Norton, and Pardey (1995) to illustrate potential changes in wheat yield in farmers' fields, as well as changes in economic benefits that may be associated with an increase in experimental wheat yields. In the simplest version of the model, it is assumed that wheat is produced using two factors, land and labor, which substitute for one another in a constant elasticity of substitution production function, with elasticity of substitution σ.[25] Land and labor are supplied with elasticities of ε_1 and ε_2, respectively. A land elasticity of 0.1, for example, would imply that a 10% increase in the price of land would increase land supply by 1%. In this model, s_1 and s_2, the cost shares of land and labor respectively, also influence the relationship between experimental yield gains on the one hand, and industry yield gains and economic benefits on the other. The cost share of land s_1 is the rental price of land times the

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[25] The elasticity of factor substitution measures the degree to which land and labor substitute for one another. A low value indicates limited substitution possibilities. A value of 1 means the CES production function simplifies to the commonly used Cobb-Douglas form, and a high value means land and labor substitute readily for one another in production.

amount of land used; in this simple model $s_1 + s_2 = 1$. In situations in which shifts in wheat supply affect the price of wheat, the final important parameter is η, the price elasticity of demand for wheat. A price elasticity of demand $\eta = -0.3$, for example, would imply that a 10% reduction in wheat price would lead to a 3% increase in the amount of wheat demanded.

For this analysis, we allowed the elasticity of land supply, ε_1, to take on the values 0, 0.2, and 0.4. A "perfectly inelastic" supply of land, $\varepsilon_1 = 0$, would characterize the case in which no more land would become available for wheat production, even if the rental rate of land rose. Although in general opportunities for land expansion are rather limited, the supply of land for a particular use, such as wheat production, might be somewhat more elastic than the overall supply of agricultural land, which is why we considered non-zero values. The elasticity of labor supply, ε_2, took several values from 0.2 to 1 in the analysis. We even considered the case where labor supply would become perfectly elastic, i.e., $\varepsilon_2 \to \infty$. In the old debate over development and growth, it was often assumed that labor was in essence infinitely elastic, particularly in densely populated countries with large, underemployed populations. In post-Green Revolution Asia, however, it has become apparent that there are significant opportunity costs for labor in agriculture and that a smaller, finite elasticity of labor supply is most realistic.

In our analysis, we let the land share, s_1, take on values of 0.25, 0.5, and 0.75, and the price elasticitity of demand, η, take on values -0.2, -0.3, and -0.4. The price elasticity of demand for wheat is often assumed to be around –0.3 in developing countries. We assumed that varietal improvement represents a biased, land-saving technological change[26] and analyzed the effects of a 1% increase in experimental yields. Not all combinations of parameters are reported here. Tables 5.1 and 5.2 report the percentage change in farm-level yields associated with a 1% increase in experimental yields in a closed economy and a small open economy. In a closed economy, the wheat price is determined by domestic wheat supply and demand. In a small open economy, the wheat price is set at the export price if the country is a net exporter, or the import price if it is a net importer.

These results illustrate the point made by Alston, Norton, and Pardey (1995) that, in general, increases in experimental yields will not lead to identical increases in farm-level yields. Over the range of parameters used in our simple model, farm-level yields appear to increase by a greater amount in a small open economy than in a closed economy. An increasing supply elasticity of land is associated with a greater increase in industry

Table 5.1. Percentage change in industry yields when experimental yields increase by 1%, land-saving technological change, closed economy.

σ = 0.1 (elasticity of factor substitution—limited factor substitution)		
ε_2 (elasticity of supply of labor)	ε_1 (elasticity of supply of land)	
	0	0.2
0.2	1.29%	1.67%
1	1.43%	1.72%
∞	1.50%	1.75%
σ = 1 (elasticity of factor substitution—Cobb-Douglas production function)		
ε_2 (elasticity of supply of labor)	ε_1 (elasticity of supply of land)	
	0	0.2
0.2	0.84%	1.17%
1	0.63%	0.98%
∞	0.46%	0.82%
σ = 9 (elasticity of factor substitution—high degree of substitutability)		
ε_2 (elasticity of supply of labor)	ε_1 (elasticity of supply of land)	
	0	0.2
0.2	0.76%	1.02%
1	0.41%	0.62%
∞	0.06%	0.14%

Note: For all estimates, $s_1 = s_2 = 0.5$, or land and labor cost shares are assumed equal; for all estimates, $\eta = -0.3$ (elasticity of demand for wheat = -0.3).

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[26] Other possibilities would be a biased, labor-saving technological change and a neutral technological change that would not be biased towards either factor.

yields. The effects of an increasingly elastic supply of labor, however, differ between a closed and small open economy. They also differ according to the degree of substitutability between land and labor. For the most part, farm-level yield gains are higher if there is little substitution between land and labor in wheat production and lower if there is a greater substitution between the two.

Tables 5.3 and 5.4 show net changes in total economic benefits (combined consumers' and producers' surplus in the closed economy, producers' surplus in the small open economy) associated with a 1% increase in experimental yields. These changes do not differ much between the closed economy and small open economy. Increasing supply elasticities for both land and labor reduces the change in total benefits. Increasing the substitutability between land and labor also reduces the change in total benefits.

Table 5.3. Percentage change in total economic benefits when experimental yields increase by 1%, land-saving technological change, closed economy.

$\sigma = 0.1$ (elasticity of factor substitution—limited factor substitution)		
ε_2 (elasticity of supply of labor)	ε_1 (elasticity of supply of land)	
	0	0.2
0.2	29.81%	4.98%
1	21.84%	4.22%
∞	19.85%	3.98%
$\sigma = 1$ (elasticity of factor substitution—Cobb-Douglas production function)		
ε_2 (elasticity of supply of labor)	ε_1 (elasticity of supply of land)	
	0	0.2
0.2	11.95%	4.98%
1	3.99%	2.49%
∞	2.00%	1.43%
$\sigma = 9$ (elasticity of factor substitution—high degree of substitutability)		
ε_2 (elasticity of supply of labor)	ε_1 (elasticity of supply of land)	
	0	0.2
0.2	10.18%	4.98%
1	3.99%	1.78%
∞	0.22%	0.21%

Note: For all estimates, $s_1 = s_2 = 0.5$, or land and labor cost shares are assumed equal; for all estimates, $h = -0.3$ (elasticity of demand for wheat = -0.3).

Table 5.2. Percentage change in industry yields when experimental yields increase by 1%, land-saving technological change, small open economy.

$\sigma = 0.1$ (elasticity of factor substitution—limited factor substitution)		
ε_2 (elasticity of supply of labor)	ε_1 (elasticity of supply of land)	
	0	0.2
0.2	1.50%	1.67%
1	1.83%	1.86%
∞	2.00%	2.00%
$\sigma = 1$ (elasticity of factor substitution—Cobb-Douglas production function)		
ε_2 (elasticity of supply of labor)	ε_1 (elasticity of supply of land)	
	0	0.2
0.2	1.09%	1.17%
1	1.33%	1.38%
∞	2.00%	2.00%
$\sigma = 9$ (elasticity of factor substitution—high degree of substitutability)		
ε_2 (elasticity of supply of labor)	ε_1 (elasticity of supply of land)	
	0	0.2
0.2	1.01%	1.02%
1	1.05%	1.06%
∞	2.00%	2.00%

Note: For all estimates, $s_1 = s_2 = 0.5$, or land and labor cost shares are assumed equal.

Table 5.4. Percentage change in total economic benefits when experimental yields increase by 1%, land-saving technological change, small open economy.

$\sigma = 0.1$ (elasticity of factor substitution—limited factor substitution)		
ε_2 (elasticity of supply of labor)	ε_1 (elasticity of supply of land)	
	0	0.2
0.2	30.22%	5.02%
1	22.20%	4.26%
∞	20.20%	4.04%
$\sigma = 1$ (elasticity of factor substitution—Cobb-Douglas production function)		
ε_2 (elasticity of supply of labor)	ε_1 (elasticity of supply of land)	
	0	0.2
0.2	12.07%	5.02%
1	4.03%	2.52%
∞	2.02%	1.44%
$\sigma = 9$ (elasticity of factor substitution—high degree of substitutability)		
ε_2 (elasticity of supply of labor)	ε_1 (elasticity of supply of land)	
	0	0.2
0.2	10.27%	5.02%
1	4.04%	1.80%
∞	0.22%	0.21%

Note: For all estimates, $s_1 = s_2 = 0.5$, or land and labor cost shares are assumed equal.

Interestingly, over the range of parameter values examined here, only a high degree of substitutability between land and labor, along with a very high elasticity of labor supply, produces increases in total benefits that are smaller in percentage terms than the initial increase in experimental yields. In some analyses, benefits at time *t*, B_t, are calculated as $B_t = gY_tX_{1t}P_t$, where *g* is the percentage gain in yield attributable to the breeding program, Y_t is yield at time *t*, X_{1t} is land area affected by the breeding program, and P_t is price. This simplification assumes a perfectly elastic demand function for wheat (equivalent to the small open economy assumption) and a perfectly inelastic supply function (Morris, Dubin, and Pokhrel, 1992, 1994). In addition, it might be assumed that *g* (yield gains in farmers' fields) is equal to experimental yield gains.[27] This simplification ignores regional or international price effects that may arise from the research, as well as distributional effects (Alston, Norton, and Pardey 1995). However, over a plausible range of parameters, it does not appear that such a simplification systematically overstates total research benefits; in this formulation, at least, it often understates them.

Distributional Issues in Measuring Agricultural Research Benefits

In general, agricultural research institutions are supported because their work is viewed as beneficial to farmers. Indeed, one of the justifications for public-sector agricultural research is that individual farmers are unlikely to have the incentives, capital, or knowledge to perform agricultural research and development (Alston and Pardey 1996). Over much of the last century, however, agricultural research has often improved agricultural productivity and driven down commodity prices, thus benefiting consumers. For many purposes, it may be desirable to estimate the distribution of research benefits between consumers and producers. The most common method of doing this is to use the economic surplus method in a supply and demand framework (Alston, Norton, and Pardey 1995). The basic framework is subject to many possible modifications, but all may be understood in the context of supply and demand. One example of a more complex analysis is the division of benefits among different groups of consumers (e.g., rural and urban, rich and poor). Benefits to producers can also be attributed to different factors of production (e.g., land, labor, or capital) (Alston, Norton, and Pardey 1995). In many developing countries, small-scale farmers may be significant consumers as well as producers of a commodity such as wheat. In principle, this poses few problems for economic surplus analysis (Renkow 1994).

For research programs that have impacts in more than one region or country, such as CIMMYT's wheat breeding program, market models may include the impacts of research in different countries or groups of countries. As noted above, an important consideration is whether or not the research is expected to change the price of wheat in a given country. In the international trade context, it may be useful to analyze whether the impact of the research is felt in an exporting country, an importing country, or both.

Price policy instruments, such as input or output subsidies or tariffs, will also affect the distribution of benefits of agricultural research. As with other modifications of the simple economic surplus model, there is little in principle to preclude analysis of the distribution of research benefits when such policies are in effect (Alston, Norton,

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[27] In the context of the Muth model, one way that experimental yield gains would equal actual yield gains at the same time that the elasticity of supply of wheat would be 0, would be if land and labor supply elasticities, ε_1 and ε_2, were both equal to 0.

and Pardey 1995). The main difficulty is likely to be empirical. Obviously it is harder to obtain the data to estimate supply and demand functions for wheat in many countries or regions, or data to estimate the effects of policies in many countries, than in a smaller geographical area.

Putting Costs and Benefits Together

An analysis of the economic impact of a crop breeding program requires an examination of research costs and benefits within the same framework. Several issues are important in this regard: the time pattern of costs and benefits, the association of “correct” costs with “correct” benefits, and consideration of what would have happened had the research not occurred.

TIME PATTERN OF COSTS AND BENEFITS

Agricultural research is a long-term proposition. Research on any given subject takes years, and the outcome is uncertain. When the research result is obtained, there is usually an additional development lag as a product is refined for farmers’ fields. Adoption is not instantaneous. Significant use of a product in farmers’ fields may begin several years after the release of the technology. Further time will pass before the use of the technology reaches its peak. Eventually, the technology will be replaced by a newer technology. Studies that have specifically analyzed lag times for agricultural research have concluded that a 30-year lag may be necessary to capture all the effects (Pardey and Craig 1989; Chavas and Cox 1992). Since economic returns occurring at different points in time must be discounted to make them comparable, the issue of lags between when costs are incurred and when benefits are experienced is very important in the analysis of research impacts.

Recently, some economists have claimed that the nature of knowledge itself makes research lags essentially infinite, and that considering these infinite lags in the context of an empirically tractable model will reduce estimated rates of return (Alston, Craig, and Pardey 1998). The economics profession has not as a whole embraced this viewpoint (Huffman 1999), and reported rates of return have in general been quite high (Evenson 2001). It is clear, however, that the assumed time pattern of research costs and benefits can have a major effect on the estimated economic benefits from the research.

Whatever the outcome of the debate over the best way to model and empirically estimate research lags, the major outlines of a wheat breeding program provide several clear reference points in time. Costs of a breeding program incurred during years 1 through *n* result in the release of one or more varieties in year *n* (Morris, Dubin, and Pokhrel, 1992, 1994). Even before a cross eventually results in a variety, considerable research may be necessary to ensure the success of the plant breeding effort. This might include basic research on plant molecular biology, research on the genetics of plants and methods of plant breeding, and germplasm enhancement, such as “gene transfer via sexual and asexual means from germplasm accessions” or “increasing the frequencies of desirable genes in crop gene pools that will be used for developing parents or cultivars” (Frey 1996). These costs may be incurred by other institutions. Since they tend to be hard to measure and are associated with a given breeding program, they may often remain unanalyzed.

Only a few of the many crosses made by a breeding program in a given year result in finished varieties. After a cross is made, there may be as many as ten generations of sowing different numbers of lines and selection of the best resulting lines for planting in the next cycle (Brennan 1989).

If the breeding program plants only one cycle per year, this could mean ten years before a finished variety is available from a given cross. Many breeding programs, including the CIMMYT Wheat Program, use shuttle breeding to plant two cycles per year, thereby reducing the time between the initial cross and the release of a variety.

After a variety is released, seed must be multiplied and made available to farmers. Even for popular varieties, there may be a two- or three-year lag between increases in seed production and significant varietal adoption. On the other hand, the area under a variety may continue to expand even after seed production begins to decline as farmers multiply their own seed or as the variety is diffused through farmer-to-farmer seed transfer (Heisey 1990). Many released varieties will never be adopted; others will be somewhat successful over a wide area or important within a significant ecological or market niche; and others will be very successful over a very wide area (Byerlee and Moya 1993). Eventually, some maximum adoption level will be reached, after which the variety will be replaced by other varieties (Brennan and Cullis 1987).

Some of these lags can be illustrated by referring to the experiences of selected CIMMYT crosses. Table 5.5 and data presented by Byerlee and Moya (1993) suggests that for popular CIMMYT crosses, there is on average a 6-year lag between the year the cross is made and the first release by a NARS, usually in Mexico. The mean lag between the date of the cross and the average NARS release date is a little over 12 years. The mean lag between the date of the cross and the peak area covered by the variety ranges from 15 to 20 years, and in the case of Sonalika was probably even longer.

ASSOCIATING COSTS WITH BENEFITS

Increases in wheat yields and productivity can be attributed not only to varietal change but also to improved management. As noted earlier, disentangling the effects of changes in input use and/or changes in efficiency of input use from the effects of varietal change may require careful measurement and attribution. This is particularly important in the case of semidwarf wheat varieties, one of whose features was greater responsiveness to inputs such as fertilizer. Here, it may be necessary to analyze the extent to which research benefits are attributable to genetic improvement and the extent to which they resulted from other research, for example, crop management research.

Agricultural research in general is characterized by spillovers, in which research done in one location produces benefits in another. Furthermore, plant breeding is cumulative in nature. New releases are

Table 5.5. Time patterns for major crosses made by the CIMMYT Wheat Program.

Cross	Year cross made	Year released in Mexico (or first developing country release)	Average year of release in NARS	Area planted, 1990 (million ha)	Area planted, 1997 (million ha)
II8156 [a]	1957	1966	1972	1.14	0.29
Sonalika	1961	1967 [b]	1972	6.29	1.22
Bluebird [c]	1965	1970	1975	0.94	0.11
Veery	1974	1981	1988	3.39	3.35
Kauz	1980	1988	1994	—	1.09
Attila	1984	1995 [d]	1996	—	1.00

[a] This cross was the base for the most important Green Revolution varieties. In the early 1970s, II8156 was grown on about 13 million hectares, primarily in South Asia (Byerlee and Moya 1993).

[b] Not released in Mexico; first released in India.

[c] Planted on more than 3 million hectares in the early 1980s.

[d] Not released in Mexico; first released in India and Ethiopia.

produced using older cultivars and breeding materials developed by a number of different research programs, including the breeding program that releases the cultivar. Chapter 2 described the many actors in the international wheat breeding system. Under these circumstances, apportioning the credit of growth in wheat productivity to the different institutions involved may require careful accounting (Alston and Pardey 2000).

The general topic of agricultural research spillovers is analyzed by Byerlee and Traxler (2001), and the specific case of allocating wheat improvement research resources in the presence of spillovers is studied by Maredia and Byerlee (1999). One approach to partitioning benefits among cooperating wheat breeding institutions is to estimate the total impacts of international crop genetic improvement research and partition those impacts to IARCs and NARSs, perhaps using the methods developed by Pardey et al. (1996). This approach does not, however, consider the catalytic contribution IARC crop germplasm improvement may have made to NARSs' research, a possibility explored by Evenson (2000).

COUNTERFACTUAL SCENARIOS

A related question is the development of an appropriate counterfactual scenario. If a given research program had not existed, would an alternative program have come into existence? It is likely, for example, that in the absence of CIMMYT, a more limited form of international exchange of wheat germplasm would have developed, and genes for plant height, disease resistance, and other important traits would have eventually been used in wheat in the developing world. To the best of our knowledge, Evenson's recent attempt (2000) to estimate NARS varietal production in the absence of IARC crop germplasm improvement investment is the only effort to delineate the counterfactual empirically.

Special Issues in Measuring the Economic Impacts of Wheat Breeding Programs

A successful wheat breeding program does not, of course, incur costs over a fixed period of time only to release a single variety (or set of varieties) in year *n*. A successful program will release a stream of varieties over time, with later superior releases replacing earlier releases. Costs will also be spread over a longer period of time. When modelling the benefits of a wheat breeding program that releases a stream of varieties, it is important to recognize that not all varieties perform equally well. If the benefits associated with the best variety are attributed to all varieties (i.e., if the benefits associated with the best variety are assumed to have occured over the entire area planted to MVs), then the total benefits attributed to the breeding program will be overestimated (Morris, Dubin, and Pokhrel, 1992, 1994; Maredia and Byerlee 1999).

Maredia and Byerlee provide a stylized adoption model of successive releases of varieties over a period of years. Analyses of economic benefits of international wheat improvement research now usually divide benefits into Stage I gains associated with the initial adoption of semidwarf wheat and Stage II gains associated with the replacement of earlier semidwarf varieties with higher yielding cultivars (Byerlee and Moya 1993; Byerlee and Traxler 1995).

We have already discussed some questions related to attributing gains from research: for example, dividing yield gains into gains attributable to crop improvement research and gains attributable to crop management research, or dividing credit for gains attributable to breeding among different research institutions. Few authors have attempted to analyze the impacts of individual components of a breeding program (i.e. breeding sub-programs), although this kind of analysis has been more common for wheat than for other crops. In large part, this may be due to the importance that maintenance research plays in wheat.

As noted previously, maintenance research is research that is necessary to maintain current levels of productivity. In the U.S., for example, it has been estimated that anywhere from one-third to two-thirds of agricultural research expenditure is necessary simply to maintain previous research gains (Heim and Blakeslee 1986; Adusei 1988; Adusei and Norton 1990). In the context of maintenance research, delineating the appropriate counterfactual scenario becomes particularly important. What is important is not a comparison "between current and previous yields but rather between current yields and what yields otherwise would have been" in the absence of research (Alston, Norton, and Pardey 1995).

Several studies have specifically attempted to look at the expenditures and economic importance of maintenance research in wheat. Heim and Blakeslee (1986) estimated that in Washington state in the U.S., over 70% of public expenditure on production-oriented research for wheat is required for yield maintenance, and any significant prolonged reduction in real research expenditures would soon result in a decline in wheat yields. Collins (1995) studied the impact of leaf rust resistance research in Pakistan. Smale et al. (1998) analyzed the economic benefits of breeding specifically for race-nonspecific resistance to leaf rust. These studies have found a positive rate of return to maintenance research in wheat breeding.

In the disaggregation cases discussed earlier, the analytical approach was primarily to look at the overall benefits to wheat research and then distribute the benefits among component research programs. Studies of maintenance research, however, have tended to analyze the economic benefits of such research directly, rather than looking at the total benefits from wheat improvement research and partitioning them among components of the breeding program, such as yield improvement and yield maintenance. The next important step would be to compare the "top-down" and "bottom-up" approaches to evaluating maintenance research for consistency.

In summary, there are a number of key issues in evaluating the economic impact of a wheat breeding program. First, how can yield gains be characterized? Second, how can yield gains be related to shifts in wheat supply, and what are the economic benefits to consumers and producers associated with such a supply shift? Third, how can costs and benefits be combined into a measure of economic impact? In our opinion, three areas need further consideration before estimates of the economic benefits of international wheat breeding research can be made more precise. Though all these areas are noted in the literature, there is very little in the way of a standard and accepted methodology to address them. The main issue is an accurate assessment of what would have happened in the absence of the breeding program under analysis. The second and third issues are related to the first. What is the correct characterization of the time pattern of costs and benefits? And when and by how much would yields decline, particularly due to changes in disease pressure in the absence of maintenance research? The answers to all of these questions must be constructed in such a way that they are consistent with the empirically observed aggregate supply and demand for wheat, in the case of *ex post* analysis, or with plausible future aggregate supply and demand, in the case of *ex ante* analysis.

Chapter 6

Empirical Evidence of Gains in Yields and Other Characteristics

In this chapter we review empirical evidence of tangible outcomes of CIMMYT and NARS wheat breeding programs, with additional relevant evidence from wheat breeding programs in other institutions. We begin by assessing empirical experimental evidence of gains in wheat yield and wheat yield potential. This evaluation is followed by a brief summary of selected components of gains in wheat yield. The final section of the chapter reviews actual wheat yields in developing countries and asks to what extent experimental gains have translated into gains in farmers' fields.

Considerable evidence suggests that wheat yields and wheat yield potential both increased from the introduction of semidwarf wheat varieties at the beginning of the Green Revolution to the late 1990s. At the same time, gains in worldwide industry wheat yields have decelerated over the past 15 years or so. As a result, direct use of experimental yield gains to model industry yield gains is less justifiable today than was in the past. In order to refine our understanding of how gains made by wheat improvement scientists are being transferred to developing country wheat fields, a greater effort will be needed to collect and interpret data, classified according to major wheat-growing environments in the developing world, rather than political boundaries. Nonetheless, advances made by wheat breeders in yield potential, disease resistance and other characteristics demonstrate that wheat supply is considerably greater than it would have been without an international breeding effort. Furthermore, wheat supply with only NARSs' breeding efforts would have been greater than what it would have been with no wheat breeding at all.

Experimental Gains in Wheat Yields

Crop scientists often distinguish between gains in yield potential and gains in yield. Yield potential has been defined as "the yield of a cultivar when grown in environments to which it is adapted; with nutrients and water non-limiting; and with pests, diseases, weeds, lodging, and other stresses effectively controlled" (Evans 1993). In the previous chapter, we outlined conceptual approaches to measuring gains in yield and yield potential. But as Evans and Fischer (1999) noted, it is not easy to verify that nutrients and water are non-limiting and that stresses are effectively controlled, because of the possibility of emerging or unrecognized stresses and side-effects of control. In many experimental studies of the type summarized below, attempts were made to supply nutrients and water at non-limiting levels. In some trials, efforts were also made to control for the effects of foliar diseases and lodging.[28]

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[28] Lodging control may be particularly relevant when comparing semidwarf and tall varieties in the same trial because one major advantage of semidwarf varieties has been their resistance to lodging.

Scientific Reviews of Gains in Wheat Yield Potential and Wheat Yield

The recent deceleration in the growth of world wheat yields has led some observers to infer that breeding gains in wheat yield potential may also be slowing. However, a major scientific review of yield gains in several different crops concludes that the best available data support the view that wheat yield potential has continued to increase since the Green Revolution (Evans and Fischer 1999). Reynolds, Rajaram, and Sayre (1999) focus more specifically on irrigated wheat and some factors responsible for this gain in yield potential. They also argue that there was no observable slowing in the rate of growth in wheat yield potential up through the mid-1990s.

Genetic Gains in Yield from Successive Release of New Wheat Varieties

Byerlee and Moya (1993) summarized data on genetic gains in yield resulting from the release of new wheat varieties over time. Many of these data were obtained from trials in which varieties with different years of release were grown under the same environment and management. Rejesus, Heisey, and Smale (1999) reviewed the results of other trials. In Table 6.1, we combine these summaries and add the results of other trials. A few results are presented from industrialized countries, particularly for Mediterranean-type (winter rainfall) environments such as drought spring wheat, high latitude spring wheat, and winter wheat. These results are included to give some idea of yield gains in environments that also exist in some developing countries.

Though yield gains are used here because they give clear evidence of impacts of past research, it is important to bear in mind that yield gains expressed in percentage terms may not be independent from base yield levels, and the time periods for which yield gains or base yields are measured may also be significant. Yield gains over time as reported in Table 6.1 are estimated using

Table 6.1. Evidence on rates of genetic gain in bread wheat in developing and industrialized countries, 1962-1997.

Developing Countries			
Environment / location	**Period**	**Rate of gain (% / yr)**	**Data source**
Spring habit wheat			
Irrigated			
Sonora, Mexico	1962-75[a]	1.1	Fischer and Wall (1976)
	1962-83[a]	1.1	Waddington et al.(1986)
	1962-81[a]	0.9	P. Wall CIMMYT[b]
	1962-85[a]	0.6	Ortiz-Monasterio et al. (1990)
	1962-88[a]	0.9	Sayre, Rajaram, and Fischer (1997)
	1988-96[a]	0.8	H.J. Dubin, CIMMYT[b,c]
Nepal	1978-88	1.3	Morris, Dubin, and Pokhrel (1992)
India	1911-54	0.6	Kulshrestha and Jain (1982)
	1967-79	1.2	
Northwest India	1966-90[a]	1.0	Jain and Byerlee (1999)
	1985-95[a]	0.9	H.J. Dubin, CIMMYT[b,c]
Pakistan	1965-82[a]	0.8	Byerlee (1993)
Zimbabwe	1967-85[a]	1.0	Mashiringwani (1987)
Hot (irrigated)			
Sudan	1967-87	0.9	Byerlee and Moya (1993)
Rainfed			
Ethiopia	1967-94	1.2-1.7	Amsal et al. (1996)
Uruguay	1966-95[a]	1.4 (high fertility)	M. Kohli, CIMMYT[b]
	1966-95[b]	0.9 (low fertility)	M. Kohli, CIMMYT[b]
Paraná, Brazil (non-acid)	1978-94	0.9	M. Kohli, CIMMYT[b]
Argentina	1912-80	0.4	Slafer and Andrade (1989)
	1966-89	1.9	Byerlee and Moya (1993)
	1971-89[a]	3.6 (unprotected)	M. Kohli, CIMMYT[b]
	1971-89[a]	2.1 (unprotected)	M. Kohli, CIMMYT[b]
	1988-97[a]	3.7	M. Kohli, CIMMYT[b]
Paraguay	1972-90	1.3	M. Kohli, CIMMYT[b]
	1979-92[a]	1.6	M. Kohli, CIMMYT[b]
Bolivia	1986-96[a]	1.0	M. Kohli, CIMMYT[b]
Central India	1965-90	0.0	Jain and Byerlee (1999)
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)
	1970-96[a]	0.2 (ns)	M. Kohli, CIMMYT[b]
Facultative / winter (rainfed)			
South Africa	1930-90	1.4	Van Lill and Purchase (1995)

[a] Semidwarfs only.
[b] Unpublished data.
[c] Two-variety comparison only.

semi-logarithmic regression (gains are expressed as the average percentage change per year). An alternative method often used by crop scientists to measure genetic gains is linear regression (gains are expressed as the increase in kilograms per hectare per year).

For a number of reasons, yield gains are imperfect measures of research performance. On the output side, yield data may not reflect differences in market classes and value. On the input side, yield data across different ecologies usually represent different levels of input use and thus different levels of production costs. Yield gains may be lower when calculated over longer periods, making comparisons across studies problematic. Furthermore, for both types of yield gains, individual studies may happen to straddle a quantum leap in yield potential, such as the one that occurred following the introduction of semidwarf wheat, whereas others may refer only to periods before or after large shifts in yield potential.

Table 6.1. (continued) Evidence on rates of genetic gain in bread wheat in developing and industrialized countries, 1962-1997.

Industrialized Countries			
Environment / location	**Period**	**Rate of gain (% / yr)**	**Data source**
Spring habit wheat			
Rainfed			
Victoria, Australia	1850-1940	0.3	O'Brien (1982)
	1940-81	0.8	
New South Wales, Australia	1956-84	0.9	Antony and Brennan (1987)
Western Australia	1884-1982	0.4 (low rainfall)	Perry and D'Antuono (1989)
High latitude (rainfed)			
North Dakota,	1934-69	0.3	Feyerherm and Paulsen (1981)
U.S.	1970-78	2.4	Feyerherm, Paulsen, and Sebaugh (1984)
Western Canada	1893-1980	0.0	Hucl and Baker (1987)
	1926-80	0.4	
	1934-80	0.2	
Western Canada	1900-90	0.2	McCaig and DePauw (1995)
Winter wheat			
Rainfed			
Kansas (hard red winter)	1932-69	0.6	Feyerherm and Paulsen (1981)
	1971-77	0.8	Feyerherm, Paulsen, and Sebaugh (1984)
	1874-1970	0.4	Cox et al. (1988)
	1976-87	1.2	
Oklahoma/Texas (hard red winter)	1932-74	0.8	Feyerherm and Paulsen (1981) Feyerherm, Paulsen, and Sebaugh (1984)
U.S. Corn Belt winter	1934-67	0.4	Feyerherm and Paulsen (1981)
(soft/hard)	1968-76	1.7	Feyerherm, Paulsen, and Sebaugh (1984)
U.S. winter (various regional performance nurseries)	1958-78	0.7-1.4	Schmidt (1984)
U.K.	1908-78	0.5 (low fertility)	Austin et al. (1980)
U.K.	1908-78	0.4 (high fertility)	Austin et al. (1980)
U.K.	1947-77	1.5	Silvey (1978)
Sweden	1900-76	0.2	Ledent and Stoy (1988)

Nearly all of the studies whose results are reported in Table 6.1 showed significant gains in yield potential even when the data were restricted to MVs, giving further credence to the argument that MV turnover in wheat as well initial MV adoption can lead to significant yield gains. Although it is not always possible to characterize the environments in which these trials were conducted, about 30 trials were reported from irrigated environments or environments with more reliable rainfall, and about 15 were reported from drier, less reliable environments. It is important to remember that these environments differ by factors other than rainfall and that previously mentioned complications such as the time period covered by the trials also hamper comparisons. Nonetheless, the median yield gain in better-watered environments was about 1% per year; the median gain in drier environments was about 0.4% per year.

Wheat breeders clearly have been successful in raising wheat yields in a wide variety of different environments and time periods. The most rapid increases in yields have often been associated with the switch to semidwarf varieties. However, in some locations genetic gains in yield were observed before semidwarf cultivars were widely used. Furthermore, in nearly all cases breeders have continued to increase wheat yields in semidwarf varieties. In some cases, progress in raising yields may have been slowed because of emphasis on other varietal characteristics, such as grain quality.

Results from International Yield Trials

International yield trials—trials of wheat varieties grown in many locations around the world in a number of seasons—can also provide perspective on yield gains resulting from plant breeding. Using data from CIMMYT's International Spring Wheat Yield Nursery (ISWYN) from 1980 to 1988, Maredia, Ward, and Byerlee (1999) considered spillover potential across breeding programs. They showed that across most major spring wheat growing environments in the developing world, yields of CIMMYT crosses were greater than or equal to yields of locally bred varieties originating from within each environment. Weighting by relative areas in the different environments, and adjusting trial yields to yields under farmers' conditions, the yield advantages averaged about 200 kg/ha in farmers' fields. Note that this is a yield advantage of CIMMYT crosses over other improved wheat varieties, some of which may also have some CIMMYT content.

Recently Lantican, Pingali, and Rajaram (2001) looked at yield gains both in the ISWYN from 1964 to 1995 and in the CIMMYT Elite Spring Wheat Yield Trial (ESWYT) from 1979 to 1999. In contrast to Maredia, Ward, and Byerlee, their analysis focused on yield gains over time rather than spillover potential, although Lantican, Pingali, and Rajaram's work also demonstrated the importance of spillovers across spring wheat growing environments in the developing world. Indeed, one of their most important objectives was to compare and contrast yield gains through time achieved in different environments. In another interesting contrast with the trial-based analysis reported in Table 6.1, Lantican, Pingali, and Rajaram used extreme values, basing their regressions on the top three yields in each location.

In the ISWYN, yield gains for four types of environment—irrigated, high rainfall, drought prone, and high temperature—ranged between 1.22% and 1.72% annually between 1964 and 1978. Since base yields were higher in irrigated and high rainfall environments, gains expressed in absolute terms (kilograms per hectare per year) were less than half in drought-prone and high temperature environments than they were in irrigated and high rainfall environments. From 1979 to 1995, yield gains in irrigated and high rainfall environments were about the same in percentage terms and in absolute terms as they had been in the earlier period. In less favorable environments, percentage yield gains increased between 2.53% and 2.75% annually, and gains in kilograms per hectare per year, although still lower, were now more similar across all four environments (Table 6.2). It should be noted that despite the increase in rates of yield growth in marginal environments relative to favored environments in the latter period, these results still imply maximum trial yields in dry or hot environments of about 3.5-4 t/ha at the end of the sample period, compared with yields of about 7-8 t/ha in favorable environments at the end of the sample period.

In the ESWYT trials, yield gains expressed both in percentage terms and in absolute terms were greatest in dry environments (Table 6.3). Despite the high rates of growth in these environments, the maximum experimental ESWYT yields were

Table 6.2. Trends in developing country wheat yield potential by environment, International Spring Wheat Yield Nursery (ISWYN), 1964-95.

		Environment			
Period		Irrigated (ME 1)	High Rainfall (ME 2)	Dry (ME 4)	Hot (ME 5)
1964-78	Growth rate (%/yr)	1.22	1.72	1.54	1.41
	Growth (kg/yr)	71.6	81.5	32.4	34.9
1979-95	Growth rate (%/yr)	1.32	1.71	2.75	2.53
	Growth (kg/yr)	84.6	92.8	70.5	72.3

Source: Lantican, Pingali, and Rajaram 2001.

only around 3.5 t/ha by the late 1990s, compared with yields of 6-7 t/ha in high rainfall and irrigated environments. Yields in hot environments were even lower than those in dry environments at the end of the 1990s.

Much of the yield gains in hot and dry environments, however, represent spillovers from wheat research for irrigated environments. Moving from experimental to farmers' field data, Lantican, Pingali, and Rajaram (2001) show that in both 1990 and 1997 over 60% of the wheat area in dry and hot environments (excluding the area planted to landraces) was planted to varieties with one parent from an irrigated environment, and another one-eighth to one-sixth was planted to varieties for which both parents were varieties originating in irrigated environments. Only one-fifth to one-quarter of the area was planted to varieties directly targeted to either dry or hot environments.[29]

Components of Wheat Yield Gains

Improved yield performance has been associated with higher yield potential. In a survey of more than 70 wheat breeders in developing countries, Rejesus, Smale, and van Ginkel (1996) found that yield potential was one major reason for the use of CIMMYT wheats by these programs. Superior stress resistance is another important characteristic associated with CIMMYT wheat. Smale et al. (2001) summarize much of the known research about components of yield gains related to stress resistance.

Table 6.3. Trends in developing country wheat yield potential by environment, Elite Spring Wheat Yield Trial (ESWYT), 1979-99.

	Environment			
	Irrigated (ME 1)	High Rainfall (ME 2)	Dry (ME 4)	Hot (ME 5)
Growth rate (%/year)	0.82	1.16	3.48	2.10
Growth (kg/year)	53.5	62.5	87.7	46.1

Source: Lantican, Pingali, and Rajaram 2001.

A major goal of most wheat breeding programs is to develop resistance to diseases, particularly rusts. Over the period 1966-88, much of the increase in yields in CIMMYT-derived cultivars may have been due to superior leaf rust resistance, rather than increases in physiological yield potential (see Figure 6.1, taken from Sayre et al. 1998). Respondents to the survey of breeding programs indicated that disease resistance was another major reason for incorporating CIMMYT germplasm (Rejesus, Smale, and van Ginkel 1996). Improving race-nonspecific rust resistance has been a major strategy in the breeding effort to confer superior rust tolerance (Smale et al 1998; Marasas, Smale, and Singh, forthcoming).

Over time, successive generations of CIMMYT wheat have shown steady improvement in their ability to respond to abiotic stress. Although high yielding wheat is often thought to require more nitrogen, over time CIMMYT wheat cultivars have improved their nitrogen-use efficiency

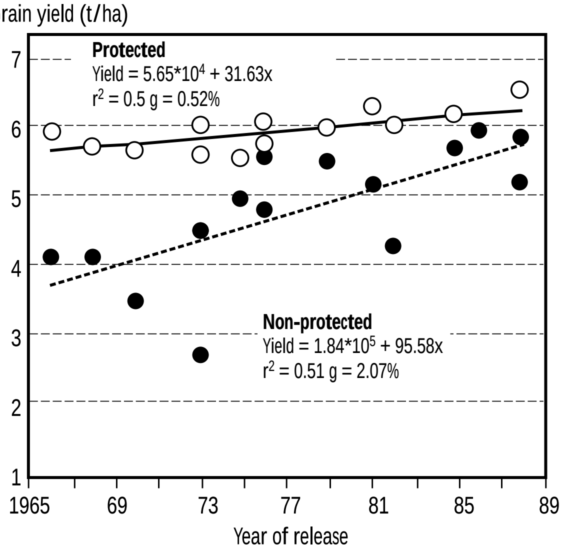

Figure 6.1. Grain yields for spring bread wheat varieties under fungicide-protected and non-protected conditions for normal plantings.
Source: Sayre et al. (1998).

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[29] Some of these varieties may have had ancestors that originated in more favorable environments.

(Ortiz-Monasterio et al. 1997). Waggoner (1994) has taken the data reported by Ortiz-Monasterio et al. and demonstrated an inward shift in unit yield isoquants defined over nitrogen and land (Figure 6.2). Over time, CIMMYT wheat lines have also shown increased tolerance to heat (Reynolds et al. 1998) and better tolerance to drought (Trethowan et al. 2001).

Wheat Yields in Farmers' Fields by Environment in Developing Countries

How have experimental yield gains translated into industry yield gains? As noted previously, this question is difficult to answer in ways that are useful for guiding wheat breeding programs or for evaluating the impacts of past research. Difficulties often result from the fact that experimental wheat yield data are classified by wheat growing environment, while industry yield data are classified by political units such as countries. Industry yield data can often be used to estimate returns to research for programs focused on particular political units, but they may not be suitable for addressing subtle questions about returns to research in different environments, or optimal future allocation of breeding effort across these environments.

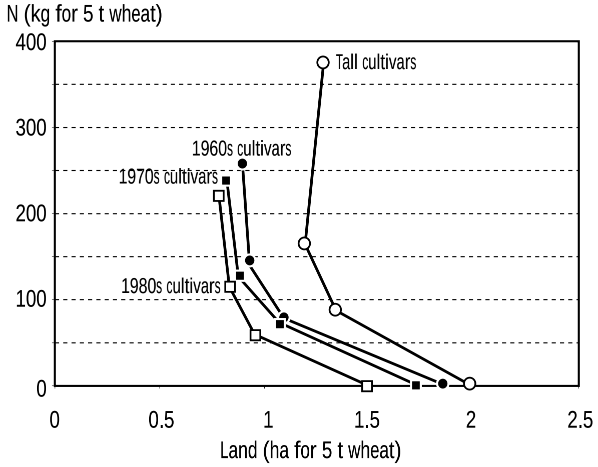

Figure 6.2. Land and nitrogen required to grow 5 tons of wheat.

Source: Waggoner (1994) and Ortiz-Monasterio et al. (1997).

In an effort to bridge the gap, we attempted to summarize developing country wheat yields in 1997 according to environment. For this exercise, the FAO country wheat production data were taken for five-year periods, centered on 1997, and averaged. This information was combined with data from the CIMMYT wheat ME database on yields in different production zones in each country.[30] The yields for different production zones for each country were then adjusted to make them consistent in relative terms with information from the ME database, and in absolute terms with country-level yields as reported by FAO. Area-weighted yields were subsequently aggregated across regions and environments.[31] Results for durum wheat were kept separate from those for bread wheat.

Tables 6.4 through 6.7 indicate the results of this exercise. As expected, ME 1 (irrigated spring bread wheat) is not only the most extensive environment in the developing world (Table 2.2), but it is also the highest yielding. Dry environments (ME 4) have the lowest yields. Overall spring bread wheat yields are highest in Asia and lowest in WANA and sub-Saharan Africa (Tables 6.4 and 6.5). Spring durum wheat yields tend to be lower in the aggregate than spring bread wheat yields, but they are slightly higher than spring bread wheat yields in ME 4A, where durum wheat is most widely grown (Table 6.6).

Yields of winter bread wheat in the developing world are higher than yields of spring bread wheat. This is entirely due, however, to high yields

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[30] Updated information for sub-Saharan Africa was obtained from Payne, Tanner, and Abdalla (1996).

[31] Because of the difficulty in separating irrigated from high rainfall winter wheat in the data, these environments (ME 7 and ME 8 for facultative wheat, and ME 10 and ME 11 for winter wheat) were not distinguished in our calculations.

Table 6.4. Yields of spring bread wheat by mega-environment, 1997, including China and other East Asia.

Region	ME 1 Irrigated	ME 2 High rainfall	ME 3 Acid soils	ME 4A Drought (winter rain)	ME 4B Drought (winter drought)	ME 4C Drought residual moisture	ME 5 Hot	ME 6 High latitude	All Spring bread wheat MEs
Sub-Saharan Africa	4.71	1.53	1.68	1.93			1.74		2.02
West Asia and North Africa	3.01	2.50		0.87					1.98
Asia	2.97	2.08				1.16	2.17	2.66	2.63
Latin America	4.90	3.04	1.71		1.56		1.56		2.31
All regions	**3.01**	**2.54**	**1.71**	**1.00**	**1.56**	**1.16**	**2.10**	**2.66**	**2.46**

Table 6.5. Yields of spring bread wheat by mega-environment, 1997, excluding China and other East Asia.

Region	ME 1 Irrigated	ME 2 High rainfall	ME 3 Acid soils	ME 4A Drought (winter rain)	ME 4B Drought (winter drought)	ME 4C Drought residual moisture	ME 5 Hot	ME 6 High latitude	All Spring bread wheat MEs
Sub-Saharan Africa	4.71	1.53	1.68	1.93			1.74		2.02
West Asia and North Africa	3.01	2.50		0.87					1.98
Asia	2.74					1.14	2.15		2.43
Latin America	4.90	3.04	1.71		1.56		1.56		2.31
All regions	**2.82**	**2.64**	**1.71**	**1.00**	**1.56**	**1.14**	**2.08**		**2.30**

Table 6.6. Yields of spring durum wheat by mega-environment, 1997 (including or excluding China).

Region	ME 1 Irrigated	ME 2 High rainfall	ME 3 Acid soils	ME 4A Drought (winter rain)	ME 4B Drought (winter drought)	ME 4C Drought residual moisture	ME 5 Hot	ME 6 High latitude	All Spring durum wheat MEs
Sub-Saharan Africa		0.97							0.97
West Asia and North Africa	3.12	2.36		1.19					1.56
Asia	2.17					0.97			1.00
Latin America	4.68	0.95			2.06				4.17
All regions	**4.15**	**1.99**		**1.19**	**2.06**	**0.97**			**1.69**

for this wheat type in China[32]. In WANA, another region in which winter wheats are widely grown, yields of winter bread wheat are lower than yields for spring bread wheat and slightly higher than yields for spring durum wheat (Tables 6.7 and 6.8). Only a small amount of winter durum wheat is grown in Turkey, and there yields are generally comparable to yields of winter bread wheat (Table 6.9).

Figures for spring habit wheat yields can be combined with adoption figures reported in Appendix B and Table 32 (taken from Byerlee and Moya 1993) to derive a rough estimate of yield gains by environment between 1990 and 1997. These comparisons can be made for four environments: irrigated (ME 1), high rainfall (ME 2), acid soils (ME 3), and drought (MEs 4A, 4B, and 4C). Calculations based on these assumptions suggest that in the 1990s, yield growth was high in drought environments not only because of Stage I effects caused by further adoption of MV wheat, but also because of Stage II yield growth for MV wheat planted in these environments (Tables 6.10 and 6.11). In contrast, ME 1 (irrigated) yield growth in the 1990s was almost entirely driven by MV (Stage II) yield growth, as adoption of MVs in

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[32] These wheats have long crop cycles, sometimes up to ten months. In contrast, spring wheats mature in four to six months, allowing a second and sometimes a third non-wheat crop in a year.

Table 6.7. Yields of winter bread wheat by mega-environment, 1997, including China.

Region	ME 7/8 Irrigated/high rainfall/facultative	ME 9 Drought/facultative	ME 10/11 Irrigated/high rainfall/winter	ME 12 Drought/winter	All facultative/winter bread wheat MEs
Sub-Saharan Africa		1.38			1.38
West Asia and North Africa	6.21	1.14	2.09	1.51	1.79
Asia	4.71	2.66	4.97	2.57	4.23
Latin America	3.26	2.40	4.00	2.40	3.33
All regions	**4.70**	**2.02**	**3.18**	**1.93**	**3.35**

Table 6.8. Yields of winter bread wheat by mega-environment, 1997, excluding China.

Region	ME 7/8 Irrigated/high rainfall/facultative	ME 9 Drought/facultative	ME 10/11 Irrigated/high rainfall/winter	ME 12 Drought/winter	All facultative/winter bread wheat MEs
Sub-Saharan Africa		1.38			1.38
West Asia and North Africa	6.21	1.14	2.09	1.51	1.79
Asia					
Latin America	3.26	2.40	4.00	2.40	3.33
All regions	**4.45**	**1.25**	**2.12**	**1.52**	**1.80**

Table 6.9. Yields of winter durum wheat by mega-environment, 1997 (including or excluding China).

Region	ME 7/8 Irrigated/high rainfall/facultative	ME 9 Drought/facultative	ME 10/11 Irrigated/high rainfall/winter	ME 12 Drought/winter	All facultative/winter durum wheat MEs
Sub-Saharan Africa					
West Asia and North Africa			4.80	1.45	1.85
Asia					
Latin America					
All regions			4.80	1.45	1.85

Table 6.10. Implied rate of yield gain for spring habit wheat MVs by mega-environment, 1990-1997, excluding China and other East Asia.

Region	ME 1 Irrigated	ME 2 High rainfall	ME 3 Acid soils	ME 4A Drought (winter rain)	ME 4B Drought (winter drought)	ME 4C Drought (residual moisture)
Sub-Saharan Africa		High				
West Asia and North Africa	Low	≤ 0		High		
Asia	Intermediate					High
Latin America	≤ 0	Intermediate	High		High	

Note: Low: 0.1-0.5 % annually; intermediate: 0.6-1.5 % annually; high: > 1.5% annually.

Table 6.11. Implied rate of yield gain for all spring habit wheat by mega-environment, 1990-1997, excluding China and other East Asia.

Region	ME 1 Irrigated	ME 2 High rainfall	ME 3 Acid soils	ME 4A Drought (winter rain)	ME 4B Drought (winter drought)	ME 4C Drought (residual moisture)
Sub-Saharan Africa		Low				
WANA	Low	High		High		
Asia	Intermediate					High
Latin America	≤ 0	Intermediate	High		High	

Note: Low: 0.1-0.5 % annually; intermediate: 0.6-1.5 % annually; high: > 1.5% annually.

ME 1 was essentially complete by 1990. Under these assumptions, MV yields in farmers' fields in ME 1 in South Asia grew at a little over 1% per year in the 1990s. This is consistent with the yield growth rate often assumed for irrigated wheat in farmers' fields on the basis of experimental yield gains (Byerlee and Moya 1993). Irrigated spring wheat yields appeared to have grown more slowly in WANA, however, and they actually decreased in Latin America.[33] Rates of yield growth in ME 2 (high rainfall) appear to have varied widely.

Varying rates of yield growth by environment and region partially result from inaccurate estimates of area, production, and yield by environment. As we have noted, it is difficult to estimate these parameters for wheat-growing environments when available data refer to political units, rather than MEs. In an alternative approach, we estimated yield growth for five environments based solely on country data. For ME 1 (irrigated), ME 2 (high rainfall), ME 4A (Mediterranean-type drought), and ME 5 (hot), we aggregated data from countries that have 50% or more of their wheat area in these environments. Most other MEs do not constitute a sufficiently large proportion of any individual country to make this a reasonable procedure. However, the fact that most acid soil wheat area is in Brazil and most Brazilian wheat area is acid soil allowed us to estimate yield growth for ME 3 based on Brazilian data.

Using this approach, we can see that in the early 1960s, yields were slightly higher in countries dominated by irrigated environments and slightly lower in countries dominated by acid soils and/or dry, hot environments. In the early Green Revolution years (mid-1960s to mid-1970s), wheat yields in both irrigated and hot environments grew very rapidly as semidwarf varieties diffused widely. In the immediate post-Green Revolution period (mid-1970s to mid-1980s), wheat yields grew very rapidly in all environments. Further diffusion of semidwarf wheats, newer varieties, and more efficient input management probably all contributed to yield growth in areas where semidwarfs had already spread. Initial diffusion of semidwarf wheats (Stage I yield gains) probably played a substantial role in boosting industry yields in dry areas (CIMMYT 1989). Since the mid-1980s, wheat yield gains appear to have slowed in all environments, but they have continued to increase at a substantial rate in countries with large areas of irrigated wheat. Yield growth has been less consistent in other environments and may even have turned negative in countries in which a great deal of wheat is grown under early drought conditions (Table 6.12). However, in some of these countries, it is possible that the results of our earlier analysis—that yield growth continued in less favored areas and decelerated in more favored areas—still hold.

Research spillovers from irrigated environments thus seem to have contributed to wheat yield gains in less favorable environments. Over longer periods of time, it appears to have been easier to sustain rapid yield growth in irrigated environments than other environments. The slower rates of yield gain in high rainfall environments compared to irrigated wheat environments may have resulted from more complex disease pressure in high rainfall areas.

Summary

Experimental data strongly support the contention that wheat breeders have continued to improve wheat yields in the post-Green Revolution period. Even abstracting from the semidwarfing characteristic, it appears likely that improvements in disease and lodging resistance and increases in yield potential have been the most important

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[33] In an example from Mexico's Yaqui Valley, Sayre (1996) and Bell et al. (1995) show a slowdown in yield growth rate in farmers' fields over a similar period in which Sayre, Rajaram, and Fischer (1997), and Reynolds, Rajaram, and Sayre (1999) indicate no deceleration in experimental wheat yield growth.

sources of genetic gains in wheat yield. Other things being equal, rates of genetic gains in yield have tended to be higher in more favorable and better-watered environments than in drier areas. However, during certain periods, intelligently designed, spillover-based research has brought rapid experimental yield gains to less favorable environments, starting in most cases from a much lower base yield.

Although the evidence is not conclusive, aggregate industry-level wheat yield data categorized by environment and region suggest that over a long period of time, yield gains have been most consistent in irrigated wheat environments. In recent years, these yield gains may have slowed[34] in these environments, while spillovers have brought both Stage I and Stage II benefits to less favorable environments. This result, particularly the decelerating yield growth in irrigated areas, is similar to the less aggregated analysis of Bell et al. (1995), Sayre (1996), and Byerlee (1992). Yield levels in less favorable environments nevertheless remain considerably lower than those in irrigated or higher rainfall areas.

Several caveats need to be applied to the analysis. First, it would be useful to have better individual country production and yield data by major environment. Geographic information system (GIS) efforts (which are already in process) combined with thorough investigation of available country-level data will play an important role in improving the reliability of environment-specific analysis.[35]

Second, calculations of additional yield and production in different environments will need to become more sophisticated. Direct translation of experimental yield gains into industry yield gains no longer tracks yields very well in a variety of wheat growing environments. Researchers who wish to estimate the benefits of wheat improvement research will increasingly need to formulate careful scenarios of what has happened where research has taken place and what would have happened had that research not taken place. The recent revival of interest in evaluating the benefits of maintenance research is welcome.

Third, it would also be good to begin analyzing non-yield benefits due to improvements in industrial quality.

Table 6.12. Wheat yield gains in developing countries, 1966-2000.

	Environment				
	Irrigated[a] (ME 1)	High rainfall[b] (ME 2)	Acid soils[c]	Dry[d] (ME 4A)	Hot[e] (ME 5)
Yield, 1961-65 (t/ha)	0.94	0.84	0.71	0.73	0.74
Yield gains, 1966-77 (%/yr)	3.90	1.92	-1.20	1.06	3.62
Yield gains, 1977-85 (%/yr)	3.59	3.48	7.87	4.62	6.31
Yield gains, 1985-2000 (%/yr)	2.16	0.95	0.99	-0.73	0.80
Yield gains, 1990-97 (%/yr)	2.04	0.07	4.74	0.51	2.34

Source: Calculated from FAO production statistics. Environments defined using CIMMYT mega-environment database.

[a] Eight countries with 50% or more wheat area planted to irrigated spring habit wheat. India and Pakistan account for 94% of total area. Does not include countries such as Bangladesh or Sudan where higher growing season temperatures prevail.

[b] Seven countries with 50% or more wheat area planted to high rainfall spring habit wheat. Ethiopia accounts for 75% of total area.

[c] Brazil only.

[d] Nine countries with 50% or more wheat area planted to low rainfall, pre-flowering moisture stress spring habit wheat. Morocco, Syria, Algeria, Iraq, and Tunisia account for 96% of total area. Does not include two other sub-categories of drought environment.

[e] Four countries with 50% or more wheat area planted to hot environment spring habit wheat. Includes Bangladesh, Myanmar, Sudan, and Paraguay. In recent years Bangladesh wheat area has risen from about 50% to about 70% of total.

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[34] In recent years, end-use quality of wheat varieties has increased, which may have also contributed to lesser yield increases than otherwise possible.

[35] In the interim, updates to the CIMMYT ME database, which is now more than 15 years old, such as the one performed for sub-Saharan Africa by Payne, Tanner, and Abdalla (1996), have proven quite helpful.

Chapter 7

Economic Benefits of Wheat Improvement Research

In this chapter we present several estimates of economic benefits from international wheat improvement research. We begin with simple calculations of gross annual research benefits based on alternate assumptions about yield gains in farmers' fields resulting from wheat improvement research. Following that, we review the most thorough economic study of international wheat improvement research by Byerlee and Traxler (1995), as well as a more recent study by Evenson (2000) that focused on international crop germplasm improvement efforts for wheat and other major crops. We conclude with a discussion of several areas in which the economic evaluation of wheat breeding research could be improved.

Gross Annual Research Benefits from CIMMYT/NARS Wheat Improvement Research[36]

We began this exercise by assuming that annual yield gains attributable to germplasm alone might range from 0.2 to 0.4 t/ha. These yield gains are assumed to result from the use of new varieties developed by wheat breeding programs. A yield gain of 0.2 t/ha is similar to the weighted average yield gain Maredia and Byerlee (1999) estimated for CIMMYT crosses over other ISWYN entries. Another way of looking at a yield gain of 0.2 t/ha is that it implies that over the past 35 years, yields in developing country wheat reached current levels 4 or 5 years earlier than they would have in the absence of CIMMYT/NARS wheat improvement research. This appears to be a fairly conservative assumption. A yield gain of 0.3 t/ha is close to the yield gain implied by Byerlee and Traxler's (1995) more complex analysis for spring bread wheat, considered in further detail below. A yield gain of 0.4 t/ha is similar to Evenson's (2000) "conservative" estimate of yield gains due to CIMMYT alone. It would correspond to the assumption that yields in developing country wheat production would have lagged in their actual values by 8 to 10 years in the absence of the CIMMYT/NARS program.

Additional assumptions in the calculation of gross annual research benefits are that MV wheats cover nearly 84 million hectares in the developing world and that the world wheat price is $120/t. To make the current price US$ 120/t consistent with earlier cost estimates, which were expressed in 1990 dollars, this price was converted to US$ 97/t.

Based on these assumptions, the additional wheat production directly attributable to the CIMMYT/NARS wheat improvement effort each year is estimated to range from 17 to 33 million tons, and the total annual value of extra production is estimated to range from US$ 1.6 to US$ 3.2 billion (1990 dollars) (Table 7.1).

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[36] The CIMMYT/NARS international wheat improvement program includes CIMMYT research efforts, the joint CIMMYT/ICARDA program, as well as NARSs wheat improvement programs.

How much of this extra annual production can be attributed to CIMMYT? Table 7.2 applies several of the attribution rules discussed in Chapter 4 to the total value of annual extra production reported in Table 7.1. The CIMMYT cross rule underestimates CIMMYT's contribution, since it assumes that CIMMYT's contribution is confined only to CIMMYT crosses planted in farmers' fields; the any ancestor rule overstates CIMMYT's contribution, since it assumes that all yield gains from any variety with CIMMYT ancestry are credited entirely to CIMMYT. The geometric rule attempts to account for contributions at different stages of the breeding process. It, too, may understate CIMMYT's contribution, if one wants to take into account the catalytic effect CIMMYT research may have had on NARS research (as Evenson does).

This brings up an interesting consideration. There is probably some kind of interaction between the yield gain figure and the proportion of CIMMYT contribution. This interaction is ignored in Table 7.2. If one wants to look at overall benefits over time, then the catalytic role of CIMMYT is particularly important. Furthermore, yield gains (Stage I gains) depend on the counterfactual; they will be smaller if the counterfactual accommodates semidwarf MVs, and they will be larger if the counterfactual includes only tall varieties. Therefore a higher figure (probably even higher than 0.4 t/ha) should be chosen. On the other hand, the very real Stage II gains, which have accounted for two-thirds or more of total benefits achieved since the 1960s (Byerlee and Traxler 1995), should probably be calculated using a smaller yield gain. Smaller yield gains may come closer to estimating the annual marginal benefits that might be expected from future CIMMYT research.

Economic Surplus Studies of Economic Benefits from Wheat MVs

Byerlee and Traxler (1995) provide the most comprehensive attempt to date to evaluate the economic impact of the joint CIMMYT/NARS wheat genetic improvement effort. Focusing on spring bread wheat, they estimate an *ex post* rate of return for wheat breeding research for developing countries. They report the highest returns in South Asia and in irrigated and high rainfall environments. They argue that by 1990 more than two-thirds of the benefits from wheat improvement research were coming from varietal turnover (Stage II) rather than initial MV adoption (Stage I). They project future rates of return would be 35% if all future research were only maintenance research, and greater than 35% if additional gains in yield potential are achieved. In monetary terms, Byerlee and Traxler estimate that total economic surplus in developing countries is about US$ 2.5 billion annually (1990 US$), for a

Table 7.1. Annual benefits from wheat improvement research in the developing world attributable to the CIMMYT/NARS system, simple gross annual research benefits assumption.

Assumed yield gain from MVs (t/ha)	Additional annual production (million/t)	Value of additional production (billion 1990 U.S.$)
0.2	16.7	1.6
0.3	25.1	2.4
0.4	33.4	3.2

Note: Area planted to MV's is 83.6 million hectares; the assumed price of wheat is US$ 97/t (1990 dollars, equivalent to US$ 120/t 2000 dollars).

Table 7.2. Annual benefits attributable to CIMMYT wheat breeding research (billion 1990 US$).

Assumed yield gain from MVs (t/ha)	CIMMYT contribution			
	0.21	0.29	0.46	0.63
	CIMMYT cross rule	Geometric rule	Cross plus parent rule	Any ancestor rule
0.2	0.3	0.5	0.7	1.0
0.3	0.5	0.7	1.1	1.5
0.4	0.7	0.9	1.5	2.0

Note: Total benefits taken from Table 7.1.

total research cost that has never exceeded US$ 70 million annually.[37] They assume a lag of 17 years from initial investment to peak benefits.

In an alternative approach, Evenson (2000) estimates the direct contribution of IARC crop improvement research to NARS varietal releases (Evenson considers a number of crops, including wheat). He analyzes econometrically the indirect impacts of IARC germplasm improvement efforts on NARSs' varietal releases and then presents the results of another model estimating the net impacts of IARC breeding programs on NARSs' crop genetic improvement investments. The results are combined to determine a counterfactual scenario of NARS varietal releases in the absence of the IARC system and fed into the IMPACT general equilibrium model developed by IFPRI.

Evenson estimates that the number of wheat varieties released would have been between 32% and 45% lower in the absence of the IARC system. Evenson's estimates from the IMPACT model suggest that wheat imports by developing countries would have been 15-20% higher had there been no IARC wheat genetic improvement research. The IMPACT model also suggests that real wheat prices would have been 26-34% higher, and the area planted to wheat 3-4% greater, had there been no international wheat research.

It is difficult to compare the estimates made by Byerlee and Traxler of the economic benefits of IARC wheat research with those made by Evenson, because the summary statements focus on different indicators. It is possible, however, to make some rough comparisons by coupling straightforward projections of major indicators used by Byerlee and Traxler on the one hand and by Evenson on the other with simple assumptions about supply and demand elasticities. The Byerlee-Traxler assumptions suggest that by the late 1990s, without the CIMMYT-NARS wheat improvement research, developing country wheat yields would have been 8% or 9% lower, developing country wheat production would have been around 24 million tons less, and international wheat prices would have been around 7% higher. The Evenson assumptions suggest that without IARC wheat improvement research, developing country yields would have been 13-20% lower, developing country production 35-65 million tons less, and international wheat prices 26-34% higher.

In terms of methodology, Byerlee and Traxler use relatively simple price assumptions to capture the effects of large regions' positions as net wheat importers or self-sufficient producers. They do not consider the price effects of changing levels of wheat supply. They estimate benefits from all international wheat crop improvement research, not benefits attributable to CIMMYT alone. Furthermore, as indicated in Chapter 6, it is possible that the yield assumptions they use no longer track wheat yield changes in farmers' fields, especially since aggregate statistics show that country wheat yields are no longer growing at the phenomenal rates seen from the Green Revolution through the mid-1980s. On the other hand, Byerlee and Traxler focus exclusively on research in spring bread wheat for four major environments in which this type of wheat is grown. Adding all spring bread wheat area, spring durum wheat area, and winter wheat area to the analysis would have resulted in larger yield, output, and price effects than they reported.[38, 39]

Evenson, too, may have overestimated the economic benefits of international wheat genetic improvement research. While the IMPACT model disaggregates wheat production and consumption

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[37] As noted, Byerlee and Traxler were estimating the costs of spring bread wheat genetic research only.

[38] It should be remembered, however, that the four spring bread wheat environments chosen were those in which CIMMYT wheat improvement research had had the largest impacts.

[39] Spillover benefits to industrialized countries are also ignored.

into a number of different regions, Evenson's model does not allow for the possibility that supply effects resulting from IARC research (including numbers of varieties released and production advantages from IARC-related varieties) might differ significantly from region to region. Furthermore, one key component of Evenson's counterfactual scenario for wheat, ln(*SC*), or the natural logarithm of the number of wheat improvement scientists in NARSs, is a publications-based estimate and seems considerably larger (almost by a factor of 10) than the count-based estimates used as the basis of our calculations of numbers of wheat scientists reported in Chapter 2.

Using different attribution rules comparable to those used in Table 7.2, estimates of annual benefits attributable to wheat improvement research by Byerlee and Traxler (1995) and Evenson (2000) are shown in Table 7.3. Evenson implies that all estimated benefits (first column of Table 7.3) are attributable to IARC wheat research, which in turn suggest that the IARC/NARS total would be even larger. Tables 7.2 and 7.3 indicate that annual benefits currently attributable to CIMMYT research could range anywhere from US$ 300 million up to nearly US$ 6 billion (1990 dollars). The larger estimates derive from what amounts to the assumption that had CIMMYT never existed, wheat yields in developing countries would have remained near their pre-Green Revolution levels. The figures based on Byerlee and Traxler (1995), adjusted upward to account for CIMMYT's impact outside of the main spring bread wheat environments, are probably the most reliable. Using these figures or, alternatively, the middle two columns of Table 7.2, a plausible estimate of the expected marginal benefits from CIMMYT research might range between US$ 500 million and US$ 1.6 billion annually (1990 dollars).

Despite differences in assumptions and estimation procedures, it is quite clear that without IARC wheat genetic improvement research:

- annual wheat production in developing countries would today be significantly lower;
- total wheat production in developing countries over the past 30 or more years would have been much lower;
- wheat imports by developing countries would today be notably larger;
- real world wheat prices would today be significantly higher; and
- the area planted to wheat in developing countries would today be slightly higher.

Table 7.3. Estimates of annual benefits from IARC/NARS wheat improvement research based on previous economic surplus studies.

Basis of calculation	Total annual benefits (billion 1990 US$)	CIMMYT contribution 0.21 CIMMYT cross rule	 0.29 Geometric rule	 0.46 Cross plus parent rule	 0.63 Any ancestor rule
Byerlee and Traxler (1995)	2.5	0.5	0.7	1.2	1.6
Evenson (2000) I	3.4	0.7	1.0	1.6	2.1
Evenson (2000) II	6.3	1.3	1.8	2.9	3.9

Note: Assumed price of wheat: $97/t (1990 dollars, equivalent to $120/t 2000 dollars).

Chapter 8

Conclusion

At the beginning of the 1990s, Byerlee and Moya (1993) reached three main conclusions in their study of the impacts of international wheat breeding research in the developing world. “First, the adoption of modern wheat varieties has maintained its momentum in the post-Green Revolution period. Second, CIMMYT germplasm continues to be used extensively as source material for the varieties that have diffused in the post-Green Revolution period. Third, investment in international wheat breeding research has continued to provide high rates of return.”

Our study, which updates Byerlee and Moya’s work and extends its coverage to include all of China as well as South Africa, provides strong support for these conclusions. In this concluding section, we briefly recap the evidence. We also review the ways in which the international wheat breeding effort has changed during the 1990s and identify two research areas that deserve further attention.

During the 1990s, the area planted to wheat modern varieties (MVs) in developing countries continued to expand, rising from just under 70% in 1990 to just over 80% in 1997. Adoption of MVs varied by region, wheat type, and growing environment. In South Asia and Latin America, 90% or more of wheat area was planted to MVs; China’s percentage was just under the aggregate figure of 80%; and two-thirds of the wheat area in WANA and sub-Saharan Africa was planted to MVs. Across the developing world, adoption of spring bread wheat MVs, the most commonly grown wheat type, stood at just under 90% of wheat area. Adoption of spring durum wheat MVs and winter bread wheat MVs was just over 70% of the area planted to each of these wheat types. Adoption of MV wheat ranged from 80% to 100% in nearly all irrigated or high rainfall environments, varied between 50% and 60% in dry spring wheat environments, and stood at around 30% to 40% in dry winter wheat environments. In areas where MV wheat has been planted for some time, older MVs are continuously replaced by newer MVs, although lengthy adoption lags continue to reduce research impacts below what they would be were new MVs to reach farmers faster.

In developing countries, the average rate of wheat varietal releases and the rate of varietal releases per million hectares planted to wheat have leveled off since the mid-1980s. Wheat breeding programs in large wheat-producing countries today are releasing fewer varieties, perhaps because they target their releases more precisely. Meanwhile, releases have increased in smaller wheat-producing countries.

CIMMYT is clearly the leading organization working in wheat breeding for the developing world. CIMMYT’s wheat breeding program, which collaborates extensively with NARSs and ICARDA, can claim credit for more than one-half of the spring bread wheat crosses released in the developing world since the mid-1980s. Another

30% of spring bread wheat crosses have one or two CIMMYT parents, and when crosses with CIMMYT ancestry further back in the pedigree are included, about 90% of all spring bread wheat releases have some CIMMYT ancestry. Spring durum wheat releases feature CIMMYT material even more prominently, with about three-quarters coming from CIMMYT crosses and nearly all having some CIMMYT ancestry. On the other hand, although the use of CIMMYT material in winter bread wheat releases increased during the 1990s, particularly in Latin America and WANA, only about 15% of these were CIMMYT crosses, and about 40% percent had some CIMMYT ancestry.

The importance of CIMMYT-related varieties is evident in farmers' fields. Even including China, where CIMMYT-related materials have been used less extensively, about 62% of the total wheat area in developing countries is planted to CIMMYT-related varieties. About 20% of the total wheat area in developing countries is planted to CIMMYT crosses. These figures take into account all wheat varieties, so they include landraces and unidentified varieties that are still planted widely in durum wheat and winter bread wheat areas. Using a geometric rule that attempts to weigh contributions made by different breeding institutions to a given wheat variety, CIMMYT germplasm accounts for just under 30% of all wheat germplasm planted in the developing world. This figure is much higher when only scientifically bred wheat varieties are considered, when China is excluded, or when the focus is only on spring habit wheat.

Returns to international wheat breeding research continue to be high. For a total annual investment of US$ 100 to US$ 150 million, the international wheat breeding system produces annual benefits ranging between US$ 1.6 and US$ 6 billion or more (1990 dollars). The large difference between the "high end" estimate and the "low end" estimate results partly from assumptions made concerning the "without research" scenario. The "high end" estimate is derived by comparing post-Green Revolution yields and production with pre-Green Revolution yields and production, and the "low end" estimate is derived by comparing the results of wheat improvement research that has actually been done with wheat improvement research that presumably would have been done in the absence of the current international system. Very loosely speaking, the "high end" estimate was derived by summing average annual returns, and the "low end"estimate was derived by summing marginal returns that might be expected from continued investment in wheat improvement research. Excluding China, Byerlee and Traxler (1995) estimated a future rate of return of 37% for spring bread wheat alone even if research only maintained yields and did not increase them. Since wheat improvement research has affected all wheat types, has been very successful in China, and has increased yields at the same time that it has provided superior stress resistance, it is clear that the conditions for a high rate of return to wheat improvement research have been met.

What has changed in international wheat improvement research since 1990 when the first study was undertaken? First, there have been notable changes in research funding. These changes have been exemplified by the decline since the late 1980s in real resources committed to wheat improvement research at CIMMYT. CIMMYT wheat improvement research constitutes a relatively small part of the international breeding effort in expenditure terms, but its influence nonetheless is large.

It is often claimed that resources devoted to wheat breeding research in developing countries have declined in real terms. At the level of the NARSs, there is relatively little evidence to support this view. Declines in NARS public-sector investments in wheat breeding research may be easiest to document in sub-Saharan Africa and possibly parts of Latin America, with anecdotal evidence from other developing countries. Increases in wheat breeding investment in large producers such as China may have masked declines in smaller producers, but this remains conjecture rather than demonstrable fact. For many countries, even those in which real resources allocated to wheat research have not declined, two additional features may be important. First, a very high proportion of the investment often goes to salaries, with limited funds left over for operational budgets crucial to conducting research. Second, it might be possible to increase breeding efficiency by relying more heavily on the international system or by reallocating resources within larger countries (Maredia and Byerlee 1999).

It is too soon to say how the real decline in breeding resources at CIMMYT will affect the international wheat breeding system. In recent years, the pivotal role of CIMMYT in many developing country wheat releases has been maintained, and the influence of CIMMYT in winter wheat breeding has actually increased (it should be recalled, however, that CIMMYT began targeting winter wheat only in the mid-1980s). Since lag times in agricultural research tend to be long, however, it is possible that the real decline in CIMMYT funding may in the future have an adverse effect on the number of wheat varieties that NARSs will release.

A second significant feature of developing country wheat production over the past 10 or 15 years has been the slow rate of growth of wheat yields. On the one hand, there is little hard evidence that breeders are making slower progress in increasing wheat yield potential than they have over the entire post-Green Revolution period. Furthermore, breeders have been making gains both in wheat yield potential and particularly in disease resistance while increasing, not decreasing, the genetic diversity of released varieties (Smale et al. 2001). There is also evidence that although yield growth has slowed in favored wheat production environments, it has grown faster over some periods in some marginal environments due to increased MV adoption and faster MV yield growth. Increased adoption and faster yield growth in marginal environments have resulted in large part from spillovers from research conducted in more favored areas. Evidence to support these conclusions comes from experimental trials, yields observed in farmers' fields, and a few micro-level studies in favorable wheat-growing areas that have been characterized by early MV adoption and relatively high yields. Because it is hard to estimate aggregate yields based on environments rather than political units, the evidence is not completely conclusive, but it does deserve further scrutiny.

The fact that yield growth has varied by environment raises several important methodological issues that will have to be addressed in future studies of impacts of wheat breeding research. In the first place, it will become harder to assume that experimental yield gains translate directly to industry supply shifts in every environment. To sort out how research affects different environments, several thing will be required—better data on wheat areas, wheat yields, and wheat production in major wheat-growing environments in the developing world; consistent experimental data such as the ISWYN and ESWYT data; and the combination of the secondary data with GIS data. In the interim, updating the CIMMYT ME database using expert opinion appears a worthwhile first step.

Next, impacts assessment research will have to make more explicit assumptions about the "with research" and "without research" scenarios. In distinguishing between the two, it will be necessary to consider the research lags that exist in the international wheat breeding system. It will also be necessary to determine what proportion of current and future benefits of wheat breeding research results from increases in yield potential and what proportion results from maintaining or improving resistance to disease or other stresses. It will be important eventually to integrate the evaluation of components of breeding strategies, such as those directed at disease resistance, nitrogen-use efficiency, or improved end-use quality, into the overall evaluation of impacts of wheat breeding research. In addition, the assumptions and results of impact assessment models will have to be continually evaluated to ensure that they are consistent with observed patterns of wheat supply and demand in the countries, environments, or regions to which they are applied.

Finally, research managers will have to continue to scrutinize breeding priorities within the international wheat breeding community, particularly within the CIMMYT/NARS agenda. The evidence to date suggests that the strategy should be continued of directing more breeding research efforts toward favorable wheat-growing environments, at the same time that some resources are devoted to maximizing spillovers into less favorable environments. Furthermore, payoffs to investments in disease resistance are likely to continue to be high. What is less clear is what combination of tactics will be most successful in continuing to advance yield potential in wheat—conventional breeding, hybrid wheat, wide crossing, biotechnology (including functional genomics), and the like. It will also be useful to further analyze the apparent slowdown in wheat yield gains in highly productive environments to determine possible environmental factors in this slowdown. Last but not least, it will be important to consider what combination of breeding research, crop management research, and policy research will best advance wheat yields, wheat production, and wheat productivity worldwide.

Appendix A

CIMMYT Content in Released Wheat Varieties by Wheat Type, Region, and Period

Table A.1. CIMMYT content in released spring bread wheat varieties by region and period (proportions).

	1966-70			1971-75			1976-80			1981-85			1986-90			1991-97		
	Cross	Parent	Ancestor	Cross	Parent	Ancestor	Cross	Parent	Ancestor	Cross	Parent	Ancestor	Cross	Parent	Ancestor	Cross	Parent	Ancestor
World	0.38	0.20	0.06	0.48	0.24	0.06	0.41	0.38	0.06	0.46	0.32	0.09	0.52	0.29	0.10	0.53	0.29	0.08
Asia	0.44	0.25	0.03	0.46	0.27	0.11	0.23	0.61	0.08	0.30	0.45	0.18	0.24	0.38	0.36	0.38	0.31	0.14
China	0.00	0.00	0.00	0.38	0.15	0.27	0.08	0.58	0.15	0.17	0.63	0.15	0.10	0.44	0.44	0.00	0.38	0.20
India	0.39	0.22	0.06	0.37	0.40	0.00	0.24	0.69	0.03	0.25	0.40	0.23	0.14	0.46	0.36	0.49	0.29	0.16
Other Asia	0.64	0.36	0.00	0.72	0.22	0.06	0.42	0.53	0.05	0.71	0.19	0.10	0.80	0.07	0.13	0.68	0.26	0.03
Latin America	0.39	0.14	0.09	0.54	0.17	0.00	0.50	0.22	0.05	0.60	0.20	0.01	0.55	0.31	0.00	0.50	0.31	0.08
Sub-Saharan Africa	0.27	0.32	0.04	0.32	0.39	0.11	0.38	0.47	0.09	0.46	0.30	0.12	0.70	0.23	0.03	0.62	0.25	0.10
West Asia and North Africa	0.54	0.09	0.00	0.67	0.12	0.04	0.57	0.36	0.00	0.52	0.29	0.05	0.81	0.10	0.00	0.73	0.25	0.00

Table A.2. CIMMYT content in released spring durum wheat varieties by region and period (proportions).

	1966-70			1971-75			1976-80			1981-85			1986-90			1991-97		
	Cross	Parent	Ancestor	Cross	Parent	Ancestor	Cross	Parent	Ancestor	Cross	Parent	Ancestor	Cross	Parent	Ancestor	Cross	Parent	Ancestor
World	0.25	0.00	0.08	0.65	0.00	0.00	0.77	0.08	0.00	0.68	0.18	0.03	0.75	0.20	0.02	0.77	0.20	0.02
Asia	0.00	0.00	0.00	0.40	0.00	0.00	0.67	0.00	0.00	0.57	0.29	0.00	0.00	0.50	0.50	0.75	0.25	0.00
China	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
India	0.00	0.00	0.00	0.40	0.00	0.00	0.67	0.00	0.00	0.50	0.33	0.00	0.00	0.50	0.50	0.75	0.25	0.00
Other Asia	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.00	0.00	0.00	NA	NA	NA	NA	NA	NA
Latin America	1.00	0.00	0.00	1.00	0.00	0.00	0.75	0.25	0.00	0.875	0.125	0.00	1.00	0.00	0.00	0.93	0.07	0.00
Sub-Saharan Africa	0.00	0.00	0.00	NA	NA	NA	0.33	0.33	0.00	0.40	0.20	0.00	1.00	0.00	0.00	0.43	0.57	0.00
West Asia and North Africa	0.00	0.00	0.17	0.64	0.00	0.00	0.88	0.00	0.00	0.71	0.14	0.07	0.73	0.24	0.00	0.77	0.17	0.03

Table A.3. CIMMYT content in released winter wheat varieties by region and period (proportions).

	1966-70			1971-75			1976-80			1981-85			1986-90			1991-97		
	Cross	**Parent**	**Ancestor**	**Cross**	**Parent**	**Ancestor**	**Cross**	**Parent**	**Ancestor**	**Cross**	**Parent**	**Ancestor**	**Cross**	**Parent**	**Ancestor**	**Cross**	**Parent**	**Ancestor**
World	0.00	0.04	0.12	0.09	0.27	0.09	0.00	0.26	0.12	0.00	0.22	0.10	0.02	0.18	0.15	0.15	0.14	0.12
Asia	0.00	0.00	0.10	0.00	0.00	0.33	0.00	0.00	0.15	0.00	0.00	0.17	0.00	0.00	0.25	0.00	0.03	0.21
China	0.00	0.00	0.10	0.00	0.00	0.33	0.00	0.00	0.15	0.00	0.00	0.17	0.00	0.00	0.25	0.00	0.03	0.21
India	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Asia	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Latin America	0.00	0.00	0.20	0.15	0.31	0.00	0.00	0.44	0.00	0.00	0.48	0.05	0.00	0.41	0.06	0.50	0.40	0.10
Sub-Saharan Africa	0.00	0.00	0.20	0.00	0.00	0.25	0.00	0.00	0.25	0.00	0.00	0.00	0.10	0.10	0.10	0.00	0.10	0.00
West Asia and North Africa	0.00	0.20	0.00	0.00	1.00	0.00	0.00	0.43	0.29	0.00	0.33	0.00	0.00	0.29	0.14	0.29	0.18	0.11

Appendix B

Adoption of MV Wheat by Mega-Environment

In this appendix we present our attempts to break down adoption of modern varieties (MVs) by mega-environment (ME). These data are based primarily on results of the 1997 wheat impacts study, although for Iraq, Saudi Arabia, and Libya we used earlier estimates from Dalrymple (1986) and Byerlee and Moya (1993). The results are probably more accurate for spring habit wheat (especially for MEs 1-4) than winter habit wheat. In fact, for both facultative and winter habit wheat we combined irrigated with high rainfall environments because of limited data that distinguishes between these two environments.

The ME 1-4 estimates, excluding China, can be compared almost directly with Table 32 in Byerlee and Moya (1993: 45), with the caveat that Table 32 combines bread and durum varieties. We can briefly summarize that comparison to characterize the environmental pattern of MV adoption between 1990 and 1997 for much of the spring wheat area in the developing world. Another caveat to bear in mind is that we define MVs as semidwarf. In a few cases (notably Brazil and Ethiopia), tall varieties, some of which have CIMMYT ancestry, continue to be widely used by farmers. In Brazil some of these tall varieties are of fairly recent origin. Although in these exceptional cases tall varieties may perform as well as semidwarfs, they are excluded as MVs for clarity of definition.

Adoption of MVs is almost universal in ME 1, the irrigated spring wheat environment. Adoption reached 100% in ME 1 in South Asia and Latin America and was almost universal in WANA by 1990. During the 1990s, adoption increased slightly in ME 1 in WANA, with higher adoption in bread wheat than durum wheat.[40] The almost universal adoption of MV wheat in ME 1 means that yields and production gains in this environment are almost all Stage II (varietal replacement by later MV generations) rather than Stage I (replacement of tall varieties by MVs) (Byerlee and Moya 1993).

By 1990 adoption of MVs was relatively high in ME 2 (high rainfall spring wheat environment) and increased between 1990 and 1997, although it has not reached 100%. Adoption was almost universal in Latin America's ME 2 by 1990 and increased to just under 100% in WANA during the 1990s. A comparison of Tables B.2 and B.3 with Table 32 (Byerlee and Moya 1993:45) reveals an apparent disadoption of MV wheat in ME 2 in sub-Saharan Africa between 1990 and 1997. This is probably an erroneous conclusion; rather, it is the result of the fact that MEs for sub-Saharan Africa have been more rigorously defined in the intervening period (Payne, Tanner, and Abdalla 1996). Over all spring wheat areas in sub-Sahara Africa, adoption of MVs did indeed increase between 1990 and 1997.[41] The percentage of MV adoption attributed to ME 2 in

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[40] Adoption of MV wheat was also 100% in small irrigated spring wheat areas of sub-Saharan Africa.

[41] This is true even if South Africa, which was not part of the 1990 survey, were excluded.

sub-Sahara Africa by Byerlee and Moya (1993) was probably in reality the overall MV adoption percentage for 1990.[42]

Although some acid soil (ME 3) areas have been identified outside of Brazil, most of this ME is located in this country. Adoption of MVs actually appears to have fallen in this ME between 1990 and 1997. As noted, this is probably because wheat breeding programs in Brazil continue to release both semidwarfs and new tall varieties that are competitive in this environment.[43]

Drought-prone spring wheat areas have tended to have the lowest adoption rates among the four environmental types considered here. From 1990 to 1997, adoption in drought-prone areas of Latin America increased from just under 70% to just over 90%. In drought-prone areas of both WANA and South Asia, adoption appears to have more than doubled, from about one-fourth to just over one-half of all drought-prone area. In South Asia, some problems in defining MEs may affect this conclusion. In general, however, for drought-prone areas, yield and production gains from MV adoption are from both Stage I and Stage II adoption in the 1990 to 1997 period.

Table B.1. Adoption of spring bread wheat MVs, by mega-environment, 1997, including China.

Region	ME 1 Irrigated	ME 2 High rainfall	ME 3 Acid soils	ME 4A Drought (winter rain)	ME 4B Drought (winter drought)	ME 4C Drought residual moisture	ME 5 Hot	ME 6 High latitude	All spring bread wheat MEs
Sub-Saharan Africa	100^-	49	100	100^-			78		74
West Asia and North Africa	94	99		53					84
Asia	100	24				50	96	70	90
Latin America	100	100^-	46		91		100		87
All regions	99	81	48	59	91	50	95	70	88

Note: 100^-: very small amounts reported planted to tall varieties.

Table B.2. Adoption of spring bread wheat MVs, by mega-environment, 1997, excluding China.

Region	ME 1 Irrigated	ME 2 High rainfall	ME 3 Acid soils	ME 4A Drought (winter rain)	ME 4B Drought (winter drought)	ME 4C Drought residual moisture	ME 5 Hot	ME 6 High latitude	All spring bread wheat MEs
Sub-Saharan Africa	100^-	49	100	100^-			78		74
West Asia and North Africa	94	99		53					84
Asia	100					52	98		95
Latin America	100	100^-	46		91		100		87
All regions	99	93	48	59	91	52	97		91

Note: 100^-: very small amounts reported planted to tall varieties.

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[43] Some of the older tall spring bread wheat varieties released in Ethiopia (ME 2) had some CIMMYT ancestry.

[44] Some of these new tall releases in Brazil had CIMMYT ancestry.

Table B.3. Adoption of MV spring durum wheat by mega-environment, 1997 (including or excluding China).

Region	ME 1 Irrigated	ME 2 High rainfall	ME 3 Acid soils	ME 4A Drought (winter rain)	ME 4B Drought (winter drought)	ME 4C Drought residual moisture	ME 5 Hot	ME 6 High latitude	All durum bread wheat MEs
Sub-Saharan Africa		20							20
West Asia and North Africa	82	99		66					75
Asia	100					56			58
Latin America		100	0		80				93
All regions	94	78		66	80	56			72

Table B.4. Adoption of MV winter bread wheat by mega-environment, 1997, including China.

Region	ME 7/8 Irrigated/ high rainfall/ facultative	ME 9 Drought/ facultative	ME 10/11 Irrigated/ high rainfall/winter	ME 12 Drought/ winter	All facultative/ winter bread wheat MEs
Sub-Saharan Africa		23			23
West Asia and North Africa	100	19	52	49	30
Asia	100	59	93	0	81
Latin America	72	100	100	100	85
All regions	100^{-}	42	68	30	63

Note:100^{-}: Very small amounts reported planted to tall varieties.

Table B.5. Adoption of MV winter bread wheat, by mega-environment, 1997, excluding China.

Region	ME 7/8 Irrigated/ high rainfall/ facultative	ME 9 Drought/ facultative	ME 10/11 Irrigated/ high rainfall/winter	ME 12 Drought/ winter	All facultative/ winter bread wheat MEs
Sub-Saharan Africa		23			23
West Asia and North Africa	100	19	52	49	30
Asia					
Latin America	72	100	100	100	85
All regions	83	22	53	49	31

Table B.6. Adoption of MV winter durum wheat by mega-environment, 1997 (including or excluding China).

Region	ME 7/8 Irrigated/ high rainfall/ facultative	ME 9 Drought/ facultative	ME 10/11 Irrigated/ high rainfall/winter	ME 12 Drought/ winter	All facultative/ winter durum wheat MEs
Sub-Saharan Africa					
West Asia and North Africa			84	0	10
Asia					
Latin America					
All regions			84	0	10

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ISBN: 970-648-090-0

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