

Impacts of International Wheat Breeding Research in the Developing World, 1988-2002

M.A. Lantican, H.J. Dubin, and M.L. Morris



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Abstract: The third in a series of global studies, this report (covering 1988-2002) documents the adoption and diffusion of modern wheat varieties in the developing world and assesses the benefits generated by international wheat breeding efforts. It updates the findings and confirms the three major conclusions of the two earlier studies, and extends the coverage to include many countries in Eastern Europe and the former Soviet Union. In the post-Green Revolution era, CIMMYT's improved germplasm continues to be used extensively by breeding programs in developing countries, and public investment in international wheat breeding research continues to generate high rates of return. Measured in terms of varietal releases, wheat breeding programs in developing countries continue to be very productive. Between 1988 and 2002, public national research organizations and private seed companies in the developing world released nearly 1,700 wheat varieties. The international wheat breeding system continues to be dominated by public breeding programs, but private companies also engage in wheat breeding in a number of developing countries. More than 75% of protected cultivars (those with plant breeding rights) in South America have CIMMYT ancestry. Of the area planted to wheat in the surveyed countries, 64% was sown to varieties containing CIMMYT-related germplasm, and 24% of varieties in those countries were derived from CIMMYT crosses. A simple economic surplus model was used to estimate the value of additional grain production attributable to the adoption of modern wheat varieties in developing countries. Depending on the stringency of the method used, the value of additional grain ranges from US\$ 2.0 to 6.1 billion per year (2002 dollars). The extensive use of CIMMYT germplasm by public and private breeding programs, combined with the widespread adoption of CIMMYT-derived varieties, generates significant benefits. Using the most conservative rule for attributing credit to CIMMYT (CIMMYT cross), the annual benefits associated with the use of CIMMYT-derived germplasm range from US\$ 0.5 to 1.5 billion (2002 dollars), a huge return on CIMMYT's annual investment (US\$ 9-11 million in 2002 dollars) in wheat improvement research.

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Executive Summary

In 1990, CIMMYT launched the first in a series of global studies designed to document the adoption and diffusion of modern wheat varieties in the developing world and to assess the benefits generated by international wheat breeding efforts. The purpose of these global wheat impact studies is not only to evaluate the performance of the international wheat breeding system in general, but also to monitor the use of improved germplasm coming out of CIMMYT's own wheat breeding program, with the idea of generating information that can be used by CIMMYT scientists and research managers to assess progress and set priorities for future research investment. CIMMYT's first global wheat impact study (1966-1990) was followed by a second one, which covered 1966 to 1997, with the objective of updating and extending the earlier results.

The first two global wheat impact studies reached three main conclusions:

1. The adoption and diffusion of modern wheat varieties have continued in the post-Green Revolution era.
2. Improved germplasm developed by CIMMYT's wheat breeding programs continues to be used extensively by breeding programs in developing countries.
3. Public investment in international wheat breeding research generates high rates of return.

This report (1988-2002), which updates the findings of the two earlier studies and extends the coverage to include many countries in Eastern Europe and the former Soviet Union, provides additional strong support for these three conclusions.

Measured in terms of varietal releases, wheat breeding programs in developing countries continue to be very productive. Between 1988 and 2002, public national research organizations and private seed companies in the developing world released nearly 1,700 wheat varieties. Of these, approximately one-third were released after 1997, the date when CIMMYT conducted the last global survey. Rates of varietal release have varied somewhat between countries and regions, but on the whole they do not appear to have slowed down. However, there has been a noticeable increase in the proportion of tall varieties released and a corresponding decrease in the proportion of semidwarf varieties.

Varietal release data suggest that wheat breeding programs in developing countries have directed their efforts in a way that is compatible with wheat production patterns. The proportion of wheat varietal releases representing different types of wheat (spring versus winter, bread versus durum) and the proportion targeted for a particular environment have been roughly congruent with the area planted to each type of wheat in each environment.

CIMMYT germplasm continues to be used extensively by wheat breeding programs in developing countries. This report presents quantitative estimates of the proportion of CIMMYT germplasm contained in wheat varieties planted in those countries. Although the proportion varies depending on the attribution rule used to assign credit for breeding, CIMMYT germplasm content is especially high in spring bread wheats and spring durum wheats, which have been the main focus of CIMMYT's efforts. When data for the just recently targeted regions of Eastern Europe and the former Soviet Union are excluded, the content is higher.

Including data from Eastern Europe and the former Soviet Union, the proportion of CIMMYT germplasm present in all wheat types is 24% using the CIMMYT cross rule, 38% using the CIMMYT cross or parent rule, 29% using the geometric rule, and 64% using the "any ancestor" rule. If data from Eastern Europe and the former Soviet Union are excluded, the proportions increase to 27% using the CIMMYT cross rule, 42% using the CIMMYT cross or parent rule, 32% using the geometric rule, and 70% using the any ancestor rule.

The international wheat breeding system continues to be dominated by public breeding programs, but private companies also engage in wheat breeding research in a number of developing countries. Private companies are usually interested in exerting ownership rights over their released varieties to generate income from seed sales. While some have predicted that private companies would be reluctant to use public germplasm out of concern that ownership rights might be difficult to claim on varieties developed with such germplasm, evidence from a sample of five countries suggests otherwise. More than 75% of the protected wheat varieties in Argentina, Brazil, Chile, and Uruguay have CIMMYT ancestry. In South Africa, the lower proportion (45%) of protected wheat varieties that contain CIMMYT germplasm does not reflect private companies' reluctance to use it, but rather its limited suitability for some production environments there.

Widespread adoption of CIMMYT-derived wheat varieties reflects the extensive use of CIMMYT germplasm by public and private wheat breeding programs. Since CIMMYT's wheat breeding efforts have focused on certain types of wheat and certain geographic regions, the pattern of adoption of CIMMYT-derived varieties varies by wheat type and by the sample of countries considered. Nevertheless, 64% of the area planted to wheat in countries surveyed in 2002 was covered by varieties containing CIMMYT-related germplasm. This figure increases to 70% if data from Eastern Europe and the former Soviet Union are excluded, given that these regions contain large areas planted to non-CIMMYT-related winter wheat varieties. The proportion of the total wheat area planted to varieties containing CIMMYT-related germplasm

totaled 97% in Other Asia,¹ 83% in Latin America, 74% in East and South Asia (including 90% in India and 37% in China), 63% in Eastern and Southern Africa, 57% in West Asia/North Africa (WANA), and 3% in Eastern Europe and the former Soviet Union.

A simple economic surplus approach was used to estimate the value of the additional grain production attributable to the adoption of modern wheat varieties under four assumed levels of cumulative yield increase (0.15, 0.25, 0.35, and 0.45 t/ha). Using 2002 adoption data, the additional amount of wheat produced in developing countries that is attributable to international wheat breeding research is estimated to range from 14 million tons per year under the most conservative assumed yield increase of 0.15 t/ha to 41 million tons per year under the most liberal assumed yield increase of 0.45 t/ha. In monetary terms, the total value of additional wheat grain produced in developing countries that can be attributed to international wheat improvement research ranges from US\$ 2.0 to 6.1 billion per year (2002 dollars).

The extensive use of CIMMYT germplasm by public and private breeding programs, combined with the widespread adoption of CIMMYT-derived varieties, generates enormous benefits. Using the most conservative rule for attributing credit to CIMMYT (CIMMYT cross), the annual benefits associated with the use of CIMMYT-derived germplasm range from US\$ 0.5 to 1.5 billion (2002 dollars). Based on the most liberal rule for attributing credit to CIMMYT (any CIMMYT ancestor), the annual benefits associated with the use of CIMMYT-derived germplasm range from US\$ 1.3 to 3.9 billion (2002 dollars). These figures confirm that returns to investment in international wheat breeding research in general and in CIMMYT's wheat breeding program in particular are huge. CIMMYT invests about US\$ 9-11 million (2002 dollars) each year in wheat improvement research, so clearly the economic benefits generated each year far exceed the investments made. The results of this most recent global wheat impacts study thus support the findings of the two earlier studies and provide strong evidence that investment in international wheat breeding research remains extremely attractive.

¹ The category "Other Asia" includes Bangladesh, Korea DPR, Nepal, and Pakistan.

CHAPTER 1. Introduction

In 1990, CIMMYT researchers conducted a major study to document the global impacts of wheat breeding research.

Results of this study were published in 1993 in *Impacts of International Wheat Breeding Research in the Developing World, 1966-90* (Byerlee and Moya 1993). The authors of the report concluded that returns to investment in international wheat breeding research had been high, but they stressed the need for continued monitoring of research investment costs and benefits to ensure that high returns were maintained in the future.

In 1997, a second study was conducted to update and extend the findings of the first study. Results of the second study, which for the first time included South Africa and all of China, were published in 2002 in *Impacts of International Wheat Breeding Research in the Developing World, 1966-97* (Heisey, Lantican, and Dubin 2002). Generally speaking, the findings of the second study were consistent with those of the first. The authors concluded that returns to investment in international wheat breeding

research remained high, although they again stressed the importance of continued monitoring and evaluation.

This report presents the findings of a third study, launched in 2002 and harking back to 1988. In addition to updating the findings of the earlier studies, the 2002 study also extended the coverage by including, for the first time, selected countries from Eastern Europe and the former Soviet Union, as well as Korea DPR (Democratic People's Republic of Korea, or North Korea).

Objectives of the Study

Similar to those of the two earlier studies, the objectives of the 2002 global wheat impacts study were to:

- document the investment in wheat breeding research in developing countries;
- document the use of improved wheat germplasm in developing countries;
- document farm-level adoption of modern wheat varieties in developing countries;
- document the contribution made by national agricultural research systems (NARSs) and by CIMMYT to international wheat breeding research;
- estimate the benefits generated by international wheat breeding research;
- generate information for use in research priority setting; and
- increase awareness of the importance of international wheat breeding research.

Sources of Information

Data were collected through a global survey of public wheat breeding programs, complemented by interviews with a representative sample of private wheat breeding programs. Questionnaires were sent to public wheat breeding organizations in nearly 60 countries producing more than 20,000 tons of wheat annually. Responses were received from 43 countries that account for more than 96% of the wheat produced in the developing world. Countries that participated in the study are shown in Table 1.1.

As in the 1997 study, all major wheat producers in East Asia, South Asia, and Latin America were included. In West Asia and North Africa (WANA), several countries that participated in the 1997 survey did not respond in 2002;² even so, all major wheat producers were included. Korea DPR and selected countries from Eastern Europe and the former Soviet Union were also included.

However, Central Asia does not have a separate regional grouping because not all countries in that region responded, and data sent were in general incomplete. Because data for Central Asia were incomplete, the data available were included as part of a larger category called the former Soviet Union.

Primary data collected through the survey were complemented by data from the FAOSTAT website and from the comprehensive wheat pedigree database maintained by CIMMYT.

Organization of the Report

Counting this introduction, the report includes seven chapters. Chapter 2 describes wheat breeding environments, reviews wheat types and growth habits, summarizes wheat cropping systems in the developing world, and describes the mega-environments used by CIMMYT breeders. Chapter 3 describes the evolution of CIMMYT's wheat breeding programs and summarizes investments made by international agricultural research centers (IARCs) and NARSs in wheat genetic improvement. Chapter 4 analyzes patterns of wheat varietal releases in the developing world, including Eastern Europe and the former Soviet Union, from 1988 to 2002. Chapter 5 presents data on the adoption of modern wheat varieties in farmers' fields. Chapter 6 discusses the economic impacts of

Table 1.1. Coverage of the wheat improvement research impacts study.

Region	Country	Country
Eastern and Southern Africa	Ethiopia	Zambia
	Kenya	Zimbabwe
	South Africa	
East and South Asia	Bangladesh	Korea DPR
	China	Nepal
	India	Pakistan
West Asia and North Africa	Afghanistan	Morocco
	Egypt	Turkey
	Iran	
Latin America	Argentina	Ecuador
	Bolivia	Mexico
	Brazil	Paraguay
	Colombia	Peru
	Chile	Uruguay
Eastern Europe and the former Soviet Union	Armenia	Lithuania
	Azerbaijan	Macedonia
	Czech Republic	Poland
	Estonia	Romania
	Georgia	Russia ^b
	Hungary	Slovakia
	Kazakhstan ^a	Tajikistan
	Kyrgyzstan	Ukraine ^c
	Latvia	

^a Only the northern part of the country's wheat area (33%) was covered in the study.

^b Only 13% of the country's wheat area was covered in the study.

^c Only 12% of the country's wheat area was covered in the study.

² Nine countries that participated in the 1997 study did not respond to the 2002 survey: Algeria, Jordan, Lebanon, Nigeria, Sudan, Syria, Tunisia, Tanzania, and Yemen.

wheat breeding research and presents estimates of gross annual research benefits that can be attributed to the international wheat breeding system in general and to CIMMYT's wheat breeding program in particular. Chapter 7 highlights key conclusions and describes future challenges facing the international wheat breeding system.

Estimating Costs and Benefits

Since plant breeding is an ongoing process, with both costs and benefits occurring over time, in reality the best way to estimate the returns to investment in plant breeding is to make an analysis in terms of dynamic flows. However, using such an approach generates performance measures, such as internal rates of return, that are difficult to interpret and understand. Thus CIMMYT in its global impacts studies has traditionally presented an annual cost and a concomitant annual benefit, on the theory that most readers will have an easier time understanding the relationship.

Benefits realized in any given year actually represent the cumulative returns to investments made over an extended period. By the same token, the investment made in any given year generates benefits over an extended period. Rather than commencing with a complicated discussion about, for example, the economics of valuing cost and benefit flows through time, research lags, and time rates of discounting, in this study we have chosen to present one year's worth of investment costs and one year's worth of benefits gained.

CHAPTER 2. Wheat Breeding Environments

R.M. Trethowan, D. Hodson, H.-J. Braun, W.H. Pfeiffer, and M. van Ginkel

Wheat Types and Growth Habits

Most commercially cultivated wheat comes in two basic types that differ in genetic complexity, adaptation, and uses: durum wheat (*Triticum turgidum*) and bread wheat (*Triticum aestivum*). Durum wheat was derived from the fusion of two grass species some 10,000 years ago, while bread wheat was derived from a cross between durum wheat and a third grass species about 8,000 years ago.

Today bread and durum wheats are used to make a range of widely consumed food products. Bread wheat is processed into leavened and unleavened breads, biscuits, cookies, and noodles. Durum wheat is used to manufacture pasta (mainly in industrialized countries), bread, couscous, and bulgur (mainly in the developing world).

Wheat production is widely distributed around the world (Figure 2.1). Bread wheat, which accounts for nearly 90% of the total area sown to wheat worldwide, is grown on all five continents. Durum wheat, which

comprises the remaining 10% of global wheat area, is grown in a more limited set of countries. More than one-half the area sown to durum wheat in developing countries is located in North Africa and West Asia, with the remainder distributed throughout north-central Asia, central India, Ethiopia, and Latin America. Production of durum wheat, which is not as widely adapted as bread wheat, is limited by the crop's greater susceptibility to soil-borne diseases, its greater sensitivity to soil micronutrient imbalances, and its lack of cold tolerance. Demand-side factors also affect wheat distribution patterns. A high demand for products made from bread wheat (bread and soft noodles), instead of products made out of durum wheat, tends to limit durum wheat production in developing countries.

Wheat has two different growth habits. Winter-habit wheat (commonly known as winter wheat) is sown in the autumn, and the growing plant must experience a period of cold temperatures (vernalization)

before flowering can be initiated the following spring.

Vernalization, a temperature-control mechanism found throughout the plant kingdom, ensures that plants do not enter the reproductive stage before winter. In contrast, spring-habit wheat (commonly known as spring wheat) does not have to experience vernalizing temperatures before flowering.

Sometimes the distinction between winter and spring wheats is not clear, for two main reasons. First, winter wheats differ in their vernalization requirements, so there is no abrupt distinction between spring and winter growth habits. Furthermore, an intermediate group of wheats known as facultative wheats, which have lower vernalization requirements and good tolerance to low temperatures, are grown in many transitional areas. Second, farmers and researchers often define spring or winter wheats based on what time of year they are sown, but this can be misleading, since most of the wheat area in less developed countries is sown in autumn or winter. Hence, not all wheats

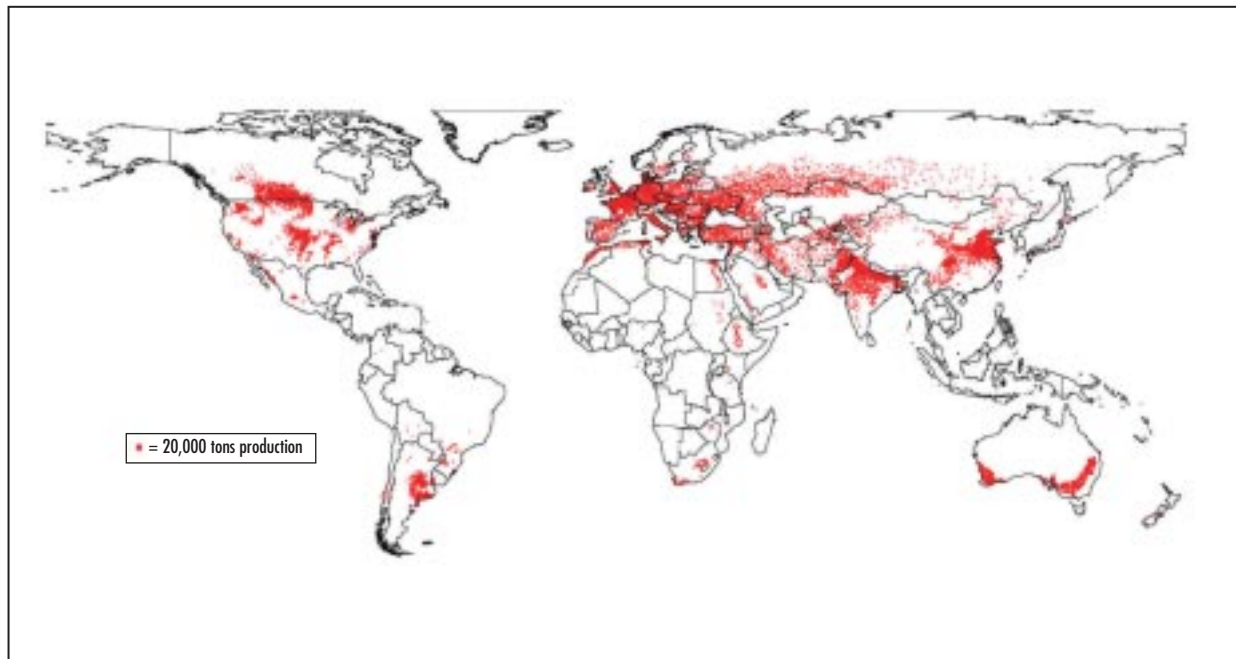


Figure 2.1. Distribution of global wheat production.

planted in the autumn are winter wheats. In regions where rainfall is plentiful during the winter and spring months, and winter temperatures are mild, spring wheat may be sown in autumn or winter, causing some to think that it is winter wheat.

At higher latitudes (exceeding 40° N), both winter and spring wheats may show photoperiod sensitivity (day length response). This means that a certain minimum day length must occur before flowering is triggered. Regulation of flowering time through photoperiod response confers an adaptive advantage at higher latitudes by reducing the risk of frost damage during the reproductive phase of the plant's growth cycle.

Photoperiod insensitive spring wheats are distributed in a belt around the equator between latitudes 45° N and 45° S. Since growing season temperatures and water availability are the primary determinants of adaptation for these wheats, they can be sown in either autumn or spring. Photoperiod sensitive spring wheats are grown between latitudes 40° N and 65° N, the northern limit of wheat adaptation. Since temperatures are too extreme for these wheats to survive the winter months, they are nearly always sown in spring and harvested in autumn.

Winter wheats are grown mainly between latitudes 35° N and 55° N, in areas where minimum winter temperatures are low enough to vernalize—but not kill—the growing wheat plant. In other words, the young winter wheat plant cannot survive the extremely low temperatures that are common in regions between latitudes 55 and 65° N, where spring-planted, photoperiod sensitive spring wheats are grown instead (see above). Small amounts of winter wheat are also grown closer to the equator in high-altitude areas where temperatures during the cropping season are cool enough to meet vernalization requirements.

Global wheat distribution is also affected by the incidence and severity of diseases, which in turn are influenced by factors such as temperature, rainfall, geographic isolation, and farming practices. In warmer wheat-growing areas such as eastern India and Bangladesh, the incidence of spot blotch (*Bipolaris sorokiniana*), stem rust (*Puccinia graminis*), and leaf rust (*P. triticina*) is much higher than in cooler wheat-growing areas such as the Punjab of India and Pakistan, where stripe rust (*P. striiformis*) is more frequent. Root diseases may also severely constrain wheat production, especially in the presence of drought stress. In some cases, even though an environment may favor a particular disease, its incidence and severity may be controlled by careful management practices. For example, quarantine regulations may prevent the introduction of susceptible varieties, or the promotion of certain farming practices may eliminate alternative hosts.

Wheat Cropping Systems and Farmers' Management Practices

Management practices used by wheat farmers vary greatly between locations and are influenced by a wide range of agro-climatic factors (temperature, rainfall, day length,

soil type, and topography), biotic factors (pests and diseases), and socio-economic factors (cropping patterns, technology, institutions, and policies). Wheat is grown in many types of farming systems and on many different scales. In rainfed areas of North America, the Southern Cone of South America, and Australia, wheat is grown using extensive cultivation methods, and farms may be several thousand hectares in size. In irrigated areas of South Asia and East Asia, it is grown using intensive cultivation methods on small plots of less than one hectare. Wheat is grown on flat land and on steep hillsides, under irrigated and rainfed conditions, in continuous wheat systems and in rotations, as a monocrop or in association with other crops.

Of all the cereals consumed as primary staples, wheat requires the least amount of water. Depending on the temperature, 600-1,000 liters of water are needed to produce 1 kilogram of wheat grain, compared to 1,100 liters of water needed to produce 1 kilogram of sorghum, 1,400 liters of water needed to produce 1 kilogram of maize, and 1,900 liters of water needed to produce 1 kilogram of rice.

Water source and reliability tend to be determinants of wheat production. In areas where rainfall is abundant and reliable during the growing season,

moisture stress rarely constrains wheat production. In locations where rainfall during the growing season may be deficient, wheat can be grown successfully on residual moisture available in the soil at the time of planting. In places where rainfall is scarce and residual soil moisture levels are low, wheat-fallow systems may be practiced in which wheat is grown every second year; this allows soil moisture to be replenished during the fallow year. In the many areas where none of these three options is feasible, irrigation is needed for successful wheat production.

Rainfed wheat production systems are found in Europe, Africa (with the exception of Egypt and Sudan), West and Central Asia, central and northeastern China, Australia, and North and South America. Cropping season rainfall and temperature vary greatly across these diverse environments, as do farming practices.

Irrigated wheat production is found in the Nile Valley, northwestern Mexico, and across a wide belt spanning large parts of Iraq, Iran, Afghanistan, Pakistan, India, Bangladesh, and China. These areas are characterized by low rainfall during the cropping season, and irrigation is essential for agriculture to succeed. However, since the amount of water

available for irrigation is often variable, even irrigated crops can suffer significant water stress. Cropping season temperatures vary greatly across these regions, as do farming practices.

Whether rainfed or irrigated, wheat production systems are characterized by a wide range of tillage practices. In the extensive, highly mechanized wheat production systems of the developed world (and in the Southern Cone of South America), conservation tillage methods are widely practiced to reduce input costs and better conserve soil and water resources. Adoption of conservation tillage methods is less common in the intensive, small-scale wheat production systems of East and South Asia, although recently the technology has started to spread within these systems as well.

Residue management practices in wheat production systems vary widely, reflecting the overall needs of local farming systems. In some areas, crop residues are retained to reduce soil erosion, improve soil organic matter content, and increase water infiltration. Elsewhere, especially in areas where livestock form an important part of the farming system, crop residues are removed and fed to animals.

CIMMYT Mega-Environment Definitions

CIMMYT's mandate is to develop improved wheat germplasm for use in emerging countries. Given the breadth of this mandate, there is a need to classify the developing world's wheat-growing regions into a set of discrete environments that can be targeted individually by plant breeders. In 1988, the CIMMYT Wheat Program formalized the concept of breeding for areas with similar adaptation patterns (Rajaram et al. 1994). These regions, which are not always geographically contiguous, are called *mega-environments* (MEs). Germplasm developed for a particular ME must show good adaptation to the major biotic and abiotic stresses found throughout that ME, although it does not necessarily show good adaptation to all significant secondary stresses.

Mega-environment definitions have evolved over the years. The latest appear in Braun et al. (1996) and are summarized in Table 2.1. These ME definitions are based primarily on the following parameters: wheat type (bread wheat versus durum wheat), growth habit (spring versus winter), and moisture regime (irrigated versus rainfed). Since every ME corresponds to a unique combination of these three parameters, each one tends to be associated with a characteristic set of abiotic and biotic stresses.

The ME definitions included in Table 2.1 can be associated with specific physical locations (countries or regions). While this helps to provide a general idea of the distribution of each ME, the representation is static and does not reflect the fact that MEs tend to shift from year to year and have fluctuations in weather patterns. For example, depending on cropping season temperature and rainfall, many locations classified as ME2/ME4 shift back and forth between ME2 (rainfed spring wheat, high rainfall) and ME4 (rainfed spring wheat, low rainfall). The frequency with which ME2 or ME4 conditions are experienced varies between locations. Constantine, Algeria (long-term average 560 mm cropping season rainfall) is classified as ME2, whereas Bordenave, Argentina (long-term average 260 mm cropping season rainfall) is classified as ME4. Despite the difference in classification, dry ME4-type years do occur in Constantine, although at a much lower frequency than in Bordenave. The opposite is true for Bordenave, where wet ME2-type years sometimes occur. Since the physical incidence of MEs is thus basically stochastic in nature, a better way to relate MEs to specific physical locations would be in terms of the probability or frequency of occurrence.

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

Mega-environment	Latitude	Moisture regime	Temperature regime	Growth habit	Season sown	Major constraints	Representative locations
1	Low	Low rainfall, irrigated	Temperate	Spring	Autumn	Rust, lodging	Indo Gangetic Plains, Nile Valley, NW Mexico
2	Low	High rainfall	Temperate	Spring	Autumn	Rust, septoria, head scab, tan spot	North African coast, East African Highlands
3	Low	High rainfall	Temperate	Spring	Autumn	Rust, septoria, head scab, tan spot, acid soil	Southern Brazil
4	Low	Low rainfall	Temperate	Spring	Autumn	Rust, septoria, tan spot, root diseases	North Africa, rainfed areas of South Asia
5	Low	High rainfall and/or irrigated	Hot	Spring	Autumn	Heat, spot blotch, leaf & stem rust	Eastern India, areas in southern Brazil
6	High	Moderate to low rainfall	Temperate	Spring	Spring	Rust, root diseases, tan spot	Northeastern China, north-central Asia
7	High	Irrigated	Moderate cold	Facultative	Autumn	Cold, stripe rust, mildew	Central China, Iran, Turkey, Central Asia, Afghanistan
8	High	High rainfall/irrigated	Moderate cold	Facultative	Autumn	Cold, stripe rust, mildew, Septoria, root rots	Central Chile, Turkey,
9	High	Low rainfall	Moderate cold	Facultative	Autumn	Cold, drought, stripe rust, root rots	Turkey, Iran, Afghanistan; North Africa, Central Asia
10	High	Irrigated	Severe cold	Winter	Autumn	Winter kill, rust, mildew	Beijing, China Turkey, Iran, Central Asia
11	High	High rainfall/irrigated	Moderate to severe cold	Winter	Autumn	Winter kill, rust, septoria, mildew	Southern Chile, Eastern Europe
12	High	Low rainfall	Severe cold	Winter	Autumn	Winter kill, drought, stripe rust, bunts, root rots	Anatolian Plateau, Turkey, NW Iran, NW China, Central Asia

Source: Adapted from Braun et al. (1996).

Another more empirical approach for targeting germplasm is based on analysis of yield trial data. By analyzing the performance of many different cultivars in environmentally diverse locations, CIMMYT breeders have been able to define zones of adaptation and identify key testing sites (Braun et al. 1992; Abdalla et al. 1996; Trethowan et al. 2001; Braun et al. 2002; Trethowan et al. 2002; Trethowan et al. 2003). Analysis of yield trial data has also helped to determine the magnitude of genotype x environment interactions (GEI), although it has shed very little light on their underlying causes. In an attempt to identify those causes, CIMMYT has recently begun to deploy an adaptation trial containing pairs of lines

that respond differently to defined biotic and abiotic stresses (Matthews et al. 2003). Data generated through this trial are being used to explain the portion of GEI that results from specific stresses in the environment.

Use of agro-climatic criteria to refine ME definitions

Given the importance of GEI and the wide range of environments in which wheat production occurs, there is a need to further refine traditional ME definitions. Historically, key components of ME definitions—for example, moisture regimes and temperature ranges—have been defined very broadly in generic terms (e.g., “high rainfall” vs. “low rainfall,” “moderate cold” vs. “severe cold”). However, with the increasing availability of

spatially-referenced global datasets for agro-climatic parameters, and of geographical information systems (GIS) tools that allow for efficient analysis of these datasets, new opportunities have arisen to define and map wheat MEs in a more rigorous manner.

Data generated through CIMMYT’s extensive network of international wheat testing sites, combined with information provided by knowledgeable wheat scientists who collaborate with CIMMYT, have been used to develop ME profiles for over 400 locations around the world (Figure 2.2). Site-specific information about wheat varietal performance, wheat production systems, and wheat management practices can be combined with climatic, topographic, edaphic,

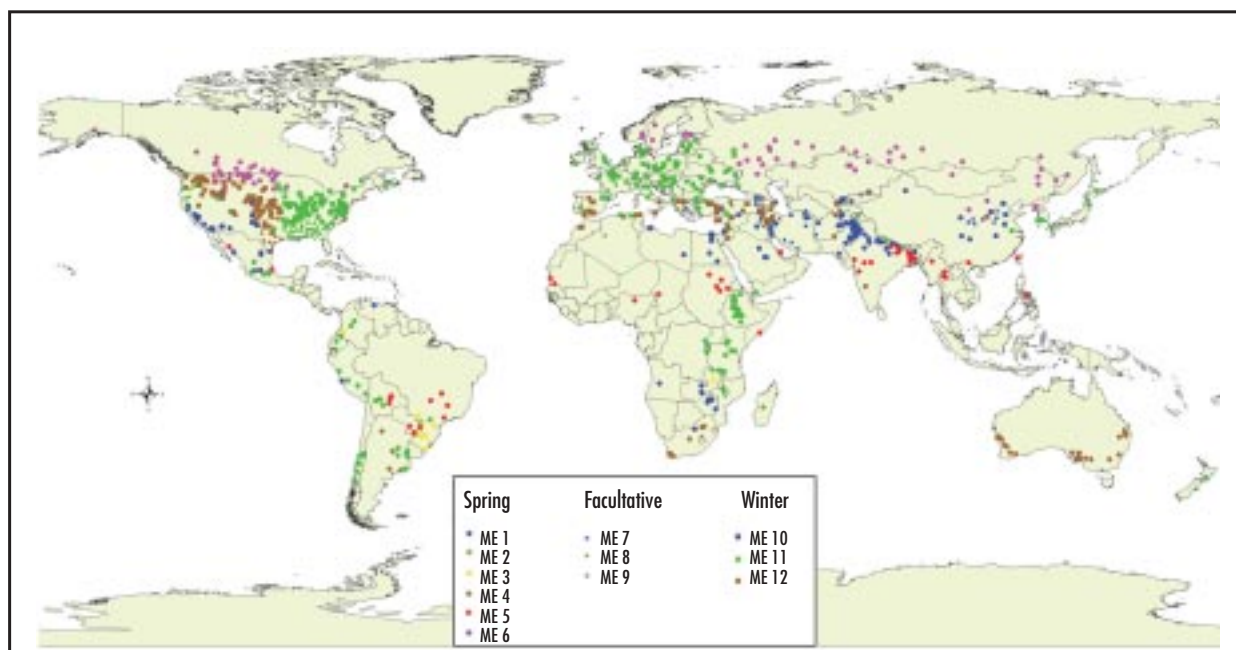


Figure 2.2. Distribution of CIMMYT and NARS wheat trial sites by mega-environment.

and other secondary data using GIS tools. Through this approach, agro-climatic information relating to each location can be used to delineate MEs, and the physical and temporal distribution of these MEs can be defined with precision.

In a practical application of this methodology, White et al. (2001) used data on long-term average minimum temperature in the coolest quarter of the year (T_{\min}) to more precisely define the relationship between temperature and wheat growth habit. Their analysis led to the following classification:

Autumn-sown spring wheat

(MEs 1-5):

$$T_{\min} \geq 3^{\circ}\text{C}$$

Facultative wheat (MEs 7-9):

$$3^{\circ}\text{C} > T_{\min} \geq -2^{\circ}\text{C}$$

Winter wheat (MEs 10-12):

$$-2^{\circ}\text{C} > T_{\min} \geq -13^{\circ}\text{C}$$

Spring-sown spring wheat (ME 6):

$$T_{\min} < -13^{\circ}\text{C}$$

White et al. (2001) also used temperature-based criteria to distinguish between favorable irrigated environments (ME1) and environments in which heat tolerance is required (ME5), with the upper limit for ME1 effectively falling at $T_{\min} = 10^{\circ}\text{C}$ (Figure 2.3).

Temperature obviously is only one of many factors that can be used to delineate wheat MEs.

Other agro-climatic factors can be used in a similar manner, alone or in combination. In fact, the great advantage of using GIS-based approaches to define MEs is that many different types of data can easily be combined. The only requirement is that all of the data must be spatially referenced.

Due to data limitations, it is not yet possible to develop new, more refined ME definitions at the global level and to generate probability distributions for their occurrence. Using data from sites where CIMMYT yield trials have been conducted, combined with information provided by knowledgeable wheat scientists, however, it has been possible to assign one of the existing ME definitions to each yield trial site. With the help of GIS, it has also

been possible to obtain long-term normal agro-climatic data for each site, which via extrapolation can be used to map potential zones for each ME. Further improvements could be made by factoring in temporal variability in climatic parameters to determine fluctuations in environment types around the mean. Agricultural researchers are starting to deploy such techniques in order to construct “target populations of environments” (Chapman and Barreto 1996).

In the future, probability bands for key agro-climatic variables will be merged with trial data and with information about the incidence of pests and diseases, farmers’ management practices (including irrigation), and consumer preferences to more accurately

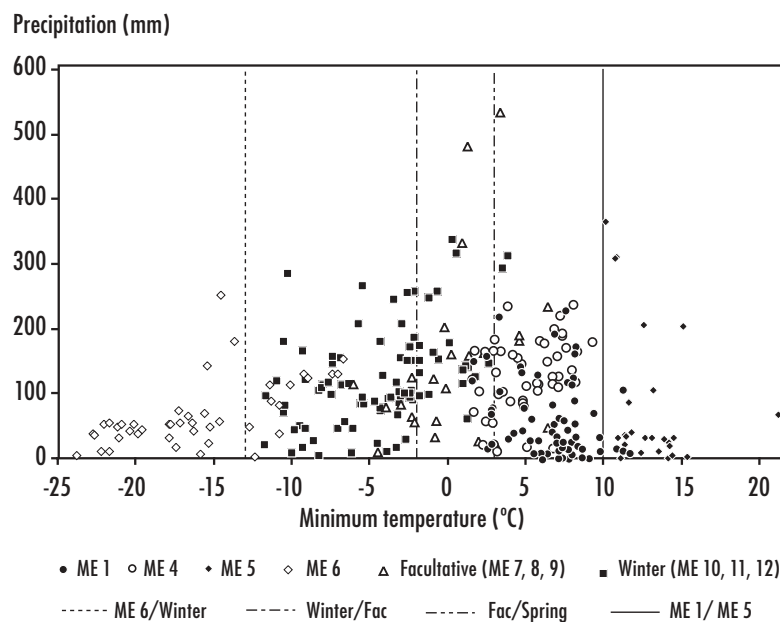


Figure 2.3. Use of temperature criteria to further define wheat mega-environments.

define MEs for wheat production. Clearly, germplasm to be deployed in a particular region should be chosen based on the probability of occurrence of particular environment types. For example, if the probability of experiencing water deficit during the critical vegetative phase of the crop growth cycle is 40%, then germplasm should be selected that combines high yield potential with drought tolerance

or improved water use efficiency. If the probability of drought stress is low, then drought tolerance or improved water use efficiency will be less essential.

While complete global ME maps are not yet available, progress is being made in regions where more data are available. For example, climatically derived MEs have been developed for the Indo-Gangetic Plains of

South Asia. Figure 2.4 shows the distribution of two wheat MEs (ME1 and ME5), indicates major irrigated areas, and depicts how these relate to actual wheat production and CIMMYT trial sites. With the help of this map, wheat breeders in South Asia can better define needed plant traits and identify optimal locations in which to select and test germplasm.

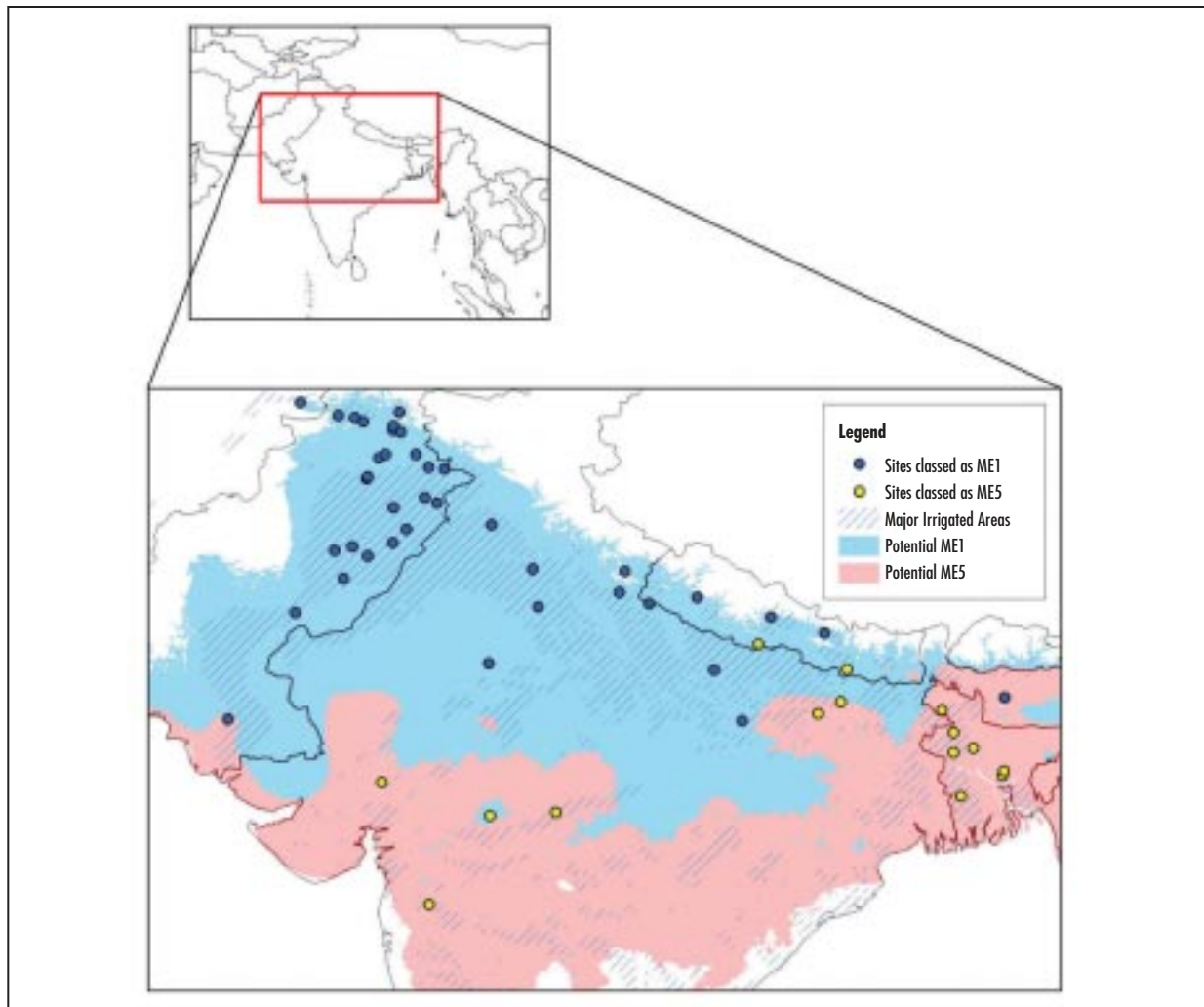


Figure 2.4. Climatically derived wheat mega-environments, Indo-Gangetic Plains, South Asia.

CHAPTER 3. Investment in Wheat Breeding Research

Research carried out by the international wheat breeding system made up of IARCs and NARSs is very important to wheat technology development worldwide. Although private companies also engage in wheat breeding research, private sector involvement is not very significant. This chapter describes the evolution of the international wheat breeding system and gives current levels of public investment in wheat improvement research.

Evolution of the CIMMYT Wheat Breeding Program³

Prior to World War II, wheat breeding research was carried out mainly by scientists working for national agricultural research organizations and universities in a handful of countries in which wheat was an economically important crop.

The roots of today's international wheat breeding system trace back to the late 1940s, when CIMMYT's predecessor, the

Mexico-based Office of Special Studies, began to develop semidwarf spring bread wheats with improved levels of disease resistance. Nearly two decades later, in 1966, when it had become apparent that the Mexican wheats could be introduced successfully into other countries, the Office of Special Studies was formally internationalized with the creation of CIMMYT.

Consistent with its new global mandate, CIMMYT's wheat breeding program soon expanded its scope and diversified its priorities. During the late 1960s, the original narrow focus on spring bread wheat was broadened to include work on spring durum wheat, triticale, and barley. In the 1970s, several new areas of research were opened up, many of which involved close collaboration with NARSs: a spring x winter wheat crossing program designed to diversify the wheat gene pool (which eventually led to the development of the phenomenally successful "Veery" lines); a shuttle breeding program with Brazil designed to introduce

varieties tolerant to aluminum toxicity in acid soils; a collaborative breeding effort with several NARSs targeting warmer production environments; and increased efforts to develop materials suitable for the marginal rainfed environments of WANA region (the latter was launched in collaboration with the International Center for Agricultural Research in the Dry Areas, ICARDA).

During the 1980s, CIMMYT's wheat breeding program continued to evolve and diversify. The focus of wheat improvement efforts shifted away from increasing yield potential to improving resistance or tolerance to important biotic and abiotic stresses. Pathology work was strengthened in order to tackle diseases such as *Fusarium* head blight (FHB), barley yellow dwarf (BYD), and Karnal bunt, and an entomology program was initiated focusing on major wheat insect pests, particularly Russian wheat aphid and Hessian fly. Screening was initiated for drought and heat tolerance.

³ This section draws heavily on Byerlee and Moya (1993) and Heisey, Lantican, and Dubin (2002).

An important milestone for CIMMYT came in 1986 with the founding of a winter wheat breeding program in partnership with the Government of Turkey. The joint TURKEY/CIMMYT/ICARDA International Winter Wheat Improvement Program targets the 26 million hectares that are sown to winter wheat in Turkey, Iran, Afghanistan, China, and surrounding countries. The original focus on a small number of developing countries has expanded over the years, and the program now has strong ties to breeding programs throughout East, Central, and West Asia, Eastern Europe, South Africa, and the former Soviet Union.

During the 1990s, CIMMYT wheat breeders built on past successes in traditional areas of breeding while continuing to tackle new biotic and abiotic stresses. The genetic basis for durable resistance to the rusts was elucidated, selection criteria were improved, and efficient breeding strategies were developed to maintain effective rust resistance for longer periods. Notable progress was achieved in developing materials capable of making more efficient use of nitrogen, phosphorus, and water. Drought and heat tolerance were improved.

Today, CIMMYT wheat breeders continue to focus on the basic goals of any plant breeding program: improved yield potential, sustainable resistance to important diseases and pests, and tolerance to drought and heat stress. In addition, new goals are finding their way into the research agenda in response to emerging needs. For example, the persistence of malnutrition in many wheat-consuming countries and regions has led to an increased emphasis on biofortification, i.e., breeding crops that are rich in key micronutrients such as iron and zinc. Similarly, changes in crop management practices—particularly the rapid diffusion of conservation tillage technologies—have led to an increased appreciation of the complementarities between improved germplasm and improved management practices, and generated emphasis on developing varieties that perform well in low-till and no-till systems.

The evolution of the wheat breeding research agenda has been accompanied by changes in breeding techniques and methods. As knowledge of genetics has evolved and as the ability to manage and analyze large amounts of data has improved with the advent of more powerful computing systems, earlier qualitative

breeding methods that relied heavily on empirical experience have gradually given way to more quantitative approaches that rely more on knowledge of genetics, molecular data, and powerful statistical analysis procedures. The rise of biotechnology, which has generated techniques such as DNA fingerprinting and marker-assisted selection, has enabled breeders to increase the efficiency of their selection strategies by allowing them to make smarter crosses and track the progress of their efforts at the molecular level.

An additional benefit of biotechnology is that it has made possible more rigorous monitoring and analysis of the genetic diversity in CIMMYT wheats. An important finding coming out of recent studies is that the gains realized in recent years were achieved even as the genetic diversity of these wheats was increasing (Smale et al. 2001). This information has helped to expose as unfounded the concerns expressed by some that the international breeding system has contributed to a decline in genetic diversity at the global level. While these concerns are understandable, all evidence suggests that genetic diversity in modern wheats continues to increase as breeders tap increasingly diverse sources of germplasm in their quest for new traits.

In summary, the international wheat breeding system spearheaded by CIMMYT has evolved significantly since its inception in response to changing needs of wheat farmers worldwide. The evolutionary process continues even today, as national and international wheat breeding programs respond to changing demands for germplasm and associated technologies needed to ensure sustainable wheat production. Despite these changes, some basic breeding goals have remained constant and will likely endure for the foreseeable future. The global survey of national wheat breeding programs carried out as part of the present study identified the following objectives as likely to be the most important 10 years from today: (1) improved yield potential, (2) resistance/tolerance to biotic and abiotic stresses, and (3) improved nutritional and processing quality.

Public Investment in Wheat Improvement Research

International wheat improvement research is a collaborative undertaking that depends on a global testing network managed by CIMMYT and involving the participation of NARSs worldwide (Maredia and Byerlee 1999). Another important collaborator is ICARDA, an international agricultural research

center based in Aleppo, Syria. ICARDA, which, like CIMMYT, is a member of the CGIAR, has a mandate to conduct wheat improvement research in the WANA region.

Many NARS scientists who participate in the global testing network receive training at CIMMYT. The strong *esprit de corps* resulting from this shared experience helps to ensure that trials distributed from CIMMYT are managed well and produce high quality data. Strong and successful partnerships between CIMMYT, ICARDA, and many NARSs underpin wheat improvement efforts worldwide and are critical to the success of the international testing network.

CIMMYT investment in wheat improvement research

Because CIMMYT is widely known for its success in maize and wheat improvement, it is sometimes assumed that it is exclusively a plant breeding organization. This is not correct. Although wheat and maize improvement have always been primary research foci, CIMMYT engages in many other activities that are not directly related to plant breeding. These include crop and resource management research, social science research, training and capacity building, networking, and knowledge management.

Given the diverse range of CIMMYT's activities, it is not a trivial matter to isolate the portion of CIMMYT's overall budget that is spent on wheat improvement research. Following Heisey, Lantican, and Dubin (2002), the discussion that follows is based on two measures of CIMMYT's investment in wheat breeding research, referred to as *Expenditures 1* and *Expenditures 2*.

Expenditures 1 was generated by assuming that all Wheat Program staff engage in wheat improvement research—not only plant breeders, but also scientists in other disciplines. Based on this assumption, CIMMYT's investment in wheat improvement research was calculated by multiplying the overall budget by the proportion of Wheat Program senior staff relative to all CIMMYT senior staff, including staff in other research programs and administrative staff. *Expenditures 2* was generated by taking the Wheat Program budget and then breaking out the proportion that was likely spent on wheat improvement research plus associated overhead (estimated to be 65% plus 26%).

Expenditures 1 is a very conservative estimate for use in analyzing the returns to CIMMYT's investment in wheat breeding research because it almost certainly overstates CIMMYT's true investment by including expenditures on activities not directly related to wheat breeding. This approach is conservative in the

sense that overstating the level of investment will drive down calculated measures of research payoff. Expenditures 2 is arguably a more accurate measure of CIMMYT's investment in wheat improvement research. However, some might say it understates the investment, because even non-breeding activities indirectly contribute to CIMMYT's crop improvement mandate.

As noted above, CIMMYT's sister center ICARDA conducts wheat improvement work targeted at the WANA region. Because ICARDA until recently has not had a separate wheat breeding program, it is difficult to precisely estimate its investment in wheat improvement research. However, based on earlier estimates by Heisey, Lantican, and Dubin (2002), and taking into account recent increases in the number of wheat breeders working at ICARDA, it is likely that ICARDA currently invests US\$ 1.5-2.0 million (2002 dollars) in wheat improvement research.

CIMMYT's investment in wheat breeding research is shown in Figure 3.1. Using Expenditures 1, CIMMYT currently invests US\$ 9-11 million per year (2002 dollars) in wheat genetic improvement. The true amount may be somewhat lower, since CIMMYT budget data include funds that flow through to collaborators and are not spent by CIMMYT. Using Expenditures 2, investment in wheat genetic

improvement ranges between US\$ 6 and 8 million per year (2002 dollars). Using both measures of expenditures, investment measured in real terms gradually declined in the early 1980s and fell sharply thereafter. By both measures, CIMMYT's real investment in wheat breeding research is lower today than it was two decades ago.

The number of CIMMYT wheat scientists, shown in Figure 3.2,⁴ peaked during the mid-1980s and declined slightly thereafter. Despite the slight increase in the number of CIMMYT Wheat Program staff in 2001, today the number of scientists remains lower compared with the 1988 level.

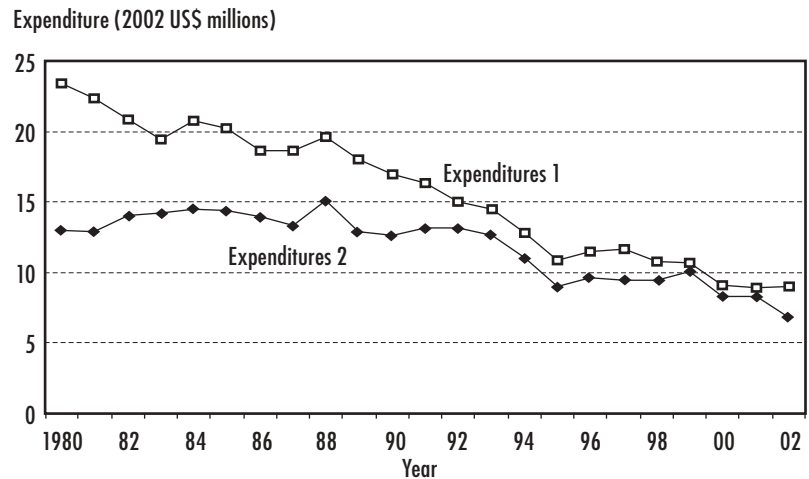


Figure 3.1. CIMMYT wheat research expenditures, 1980-2002.

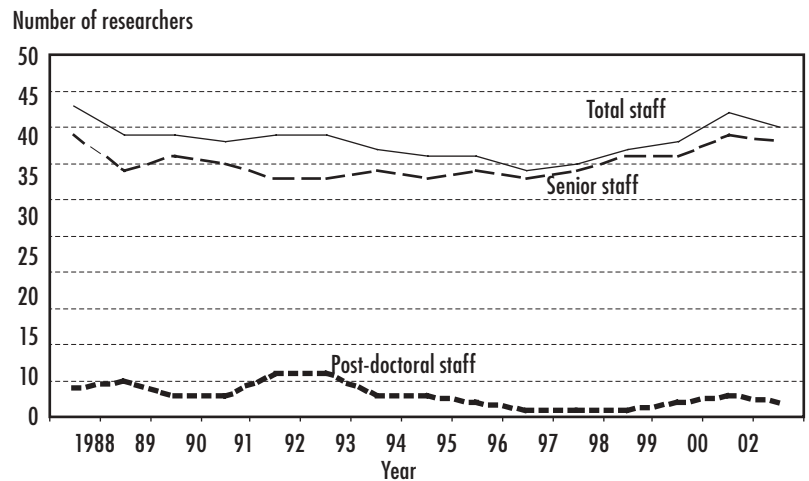


Figure 3.2. CIMMYT Wheat Program staff numbers, 1988-2002.

⁴ Until 2003, all CIMMYT wheat scientists were members of the Wheat Program. Following the reorganization of CIMMYT, beginning in 2004 wheat scientists are distributed among several global and eoregional programs.

NARS investment in wheat improvement research

NARS investment in wheat improvement research is best estimated by examining research expenditure data. Complete and accurate NARS research expenditure data are not available, however, so we must use indirect intensity indicators. These include absolute measures such as the number of full-time equivalent (FTE) scientists involved in wheat improvement research and the associated direct support costs (salary and benefits), as well as research intensity measures such as the number of scientists per million tons of wheat produced and the number of scientists per million hectares planted to wheat.

Any analysis based on numbers of scientists involved in wheat improvement research is subject to potential problems. Since it is difficult to account for all scientists involved in wheat improvement research (especially researchers working in universities), the approach can lead to underestimation of the level of investment. At the same time, since some researchers identified as wheat breeders may actually work on crop management issues, the approach can also lead to overestimation of the level of investment. Despite these

difficulties, indirect approaches based on numbers of scientists have been used in a number of widely recognized studies (Bohn and Byerlee 1993; Bohn, Byerlee, and Maredia 1999; Byerlee and Moya 1993; and Heisey, Lantican, and Dubin 2002).

Wheat research intensity measures calculated from the 2002 survey results are shown in Table 3.1 and Figure 3.3. For purposes of comparison, equivalent measures calculated from the 1997 survey results are also shown in Figure 3.3.

Table 3.1. Regional analysis of national wheat improvement research, early 2000s.

Region	Total wheat improvement scientists	Direct support costs (2002 US \$ 000)	Wheat scientists per million ha	Wheat scientists per million t	Wheat area (million ha)	Wheat production (million t)
East and South Africa	67	0.4	29.9	18.0	2.2	3.7
West Asia and North Africa	305	2.0	14.6	8.5	20.9	35.9
East and South Asia	1038	3.7	16.6	5.7	62.4	183.7
Latin America	172	2.8	17.8	6.3	9.7	27.3
Eastern Europe and Former Soviet Union	417	1.0	31.3	6.8	13.3	61.4

No. of scientists per million t wheat

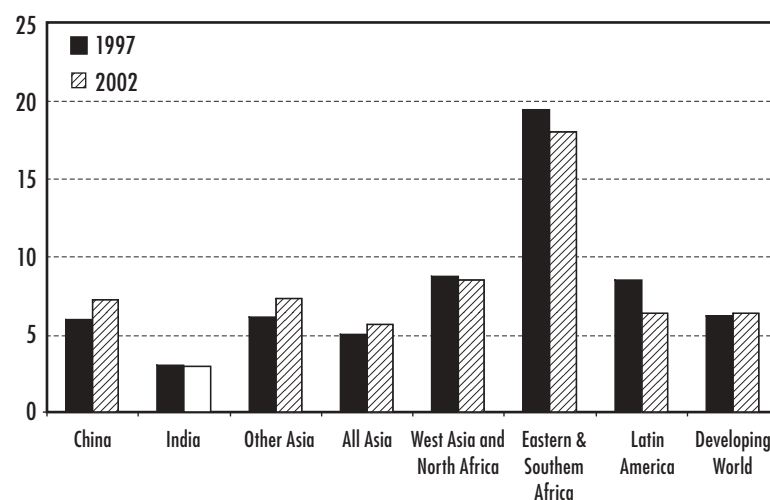


Figure 3.3. Wheat improvement scientists per million tons of wheat production, developing world, 1997 and 2002.

For the developing world as a whole, investment in wheat research measured by the number of scientists per million tons of wheat production was about the same in 2002 (6.3 scientists/million tons) and as it was in 1997 (6.2 scientists/million tons).⁵ Despite a slight increase in the total number of wheat scientists working in Latin America, research intensity decreased in that region due to a sharp increase in wheat production. In contrast, wheat area and production decreased in China while the number of scientists remained roughly unchanged, leading to a rise in the research intensity measure. In India, the WANA region, and Eastern and Southern Africa, research intensity in 2002 was similar to 1997 levels.⁶

Previous work done at CIMMYT and elsewhere has shown that because of input non-divisibilities and economies of scope and scale, measures of plant breeding research intensity are often inversely correlated with production or area planted (Lopez-Pereira and Morris 1994; Byerlee and Moya 1993). The existence of this inverse relationship is once again borne out by the results of the 2002 survey, which shows high wheat improvement research intensities in small wheat-producing countries and regions (Table 3.1). In Eastern and Southern Africa,

both measures of research intensity are nearly double those found in the other regions. In Eastern Europe and the former Soviet Union, the number of scientists per million hectares of wheat was also unusually high. Elsewhere, research intensity measures were similar, ranging from 14.6 to 17.8 scientists per million hectares of wheat and from 5.7 to 8.5 scientists per million tons of wheat production.

Crop specific estimates of public research expenditures are extremely scarce, especially in developing countries. In the case of wheat, the last such estimate was made in 1990, when it was estimated that NARSs in developing countries were investing about US\$ 100 million per year in wheat breeding research. Of this amount, about US\$ 46 million was being spent by NARSs in Asia, and about US\$ 31 million was being spent by NARSs in the WANA region. Asia and the WANA region are the two largest wheat producing regions in the developing world, which explains the high level of NARS expenditures on wheat

improvement research in those regions (Bohn, Byerlee, and Maredia 1999; Heisey, Lantican, and Dubin 2002). Data for other regions are very incomplete and, when available, tend to refer to specific countries or even regions within countries. For example, Tomasini (2002) reports that annual wheat research investments made by EMBRAPA Trigo in the Brazilian states of Rio Grande Do Sul (1990) and Paraná (1991) amounted to about US\$ 2.4 and US\$ 1 million, respectively.

In the absence of reliable data on capital investments in wheat research, we can report only the direct support cost of NARS wheat improvement research, defined as the cost of supporting the salaries and benefits of wheat researchers. Given the low amount of private sector wheat research in most developing countries, the estimates are based mainly on data collected from public wheat breeding programs⁷. However, information from private companies was included when it was available.

⁵ To facilitate comparisons, the 2002 results shown in Figure 3.3 do not include data for Eastern Europe and the former Soviet Union, which were not surveyed in 1997. As reported in Table 3.1, the research intensity measure for these two groups of countries was 6.8 in 2002.

⁶ The lower reported number of wheat improvement scientists in the WANA region and Eastern and Southern Africa does not indicate that investment in wheat breeding declined in those two regions; rather it simply reflects the fact that fewer countries participated in the survey in 2002 compared to 1997.

⁷ It should be noted that the national agricultural research systems (NARS) in developing countries include the private as well as the public sector; thus this study also attempted to gather data on private sector wheat breeding research.

Direct support costs for wheat improvement research vary considerably between regions (Table 3.1). In East and South Asia, the largest wheat producing regions in the developing world, direct support costs totaled US\$ 3.7 million in 2002. This was followed by Latin America (US\$ 2.8 million) and WANA (US\$ 2.0 million).

Regional figures mask considerable differences in the structure of support costs, which vary from country to country, often within the same region.

The direct cost of supporting a senior wheat improvement scientist (salary and benefits only) in some Latin American countries is high compared with other regions. The cost is four times higher than in WANA and East and South Asia, and seven times higher than in Eastern Europe and the former Soviet Union. There does not seem to be an obvious relationship between the level of support costs per scientist and the size of a country's national wheat area or level of wheat production.

It is frequently argued—usually without evidence—that support for agricultural research in many NARS has declined in recent years. Data collected during the 2002 survey do not support this claim, at least with regard to wheat improvement research. Heisey, Lantican, and Dubin (2002) note that investment in wheat research may indeed have declined in many smaller developing countries, but evidence of any such decline would be masked at the aggregate level by continued strong investment in wheat research by extremely large countries such as China and India.

CHAPTER 4. Wheat Varietal Releases

Rates of Varietal Release

Public national research organizations and private seed companies in the developing world released nearly 1,700 wheat varieties between 1988 and 2002. Of these, approximately one-third were released after 1997, the year CIMMYT conducted the previous global survey. Rates of varietal release have fluctuated between countries and regions. During the most recent period of analysis, 1998-2002, the average number of varietal releases per year ranged from a low of 6 in Eastern and Southern Africa to a high of 33 in Eastern Europe and the former Soviet Union (Figure 4.1).

Because of the unpredictable nature of the plant breeding process, varietal release rates are often not regular, particularly in small countries. Snapshots of varietal release rates taken over short periods may therefore be misleading. Thus it is worthwhile to examine how rates of varietal releases may have changed over more extended periods. In addition to providing a better indication of the long-term average varietal release rate, this

may also provide clues as to whether the productivity of a breeding program is increasing, decreasing, or remaining constant.

Varietal release rates for India, Latin America, Eastern Europe, and the former Soviet Union peaked between 1997 and 1999. In Eastern and Southern Africa, as well as in the WANA region, varietal release rates reached their highest levels between 1994 and 1996. In China, varietal release rates peaked even earlier, between 1991 and 1993. For the developing world as a whole, varietal release rates decreased between the late 1990s and the

early 2000s. However, current release rates remain higher than they were in the late 1980s (Figure 4.1).

One would expect that the total number of wheat varieties released in a particular country or region might be related to the size of the area planted to wheat in that country or region, in which case it would not be a very good measure of research productivity. A more meaningful measure of research productivity might be the number of varieties released per year per million hectares planted to wheat (Heisey, Lantican, and Dubin 2002). Using this measure, and focusing on the most recent

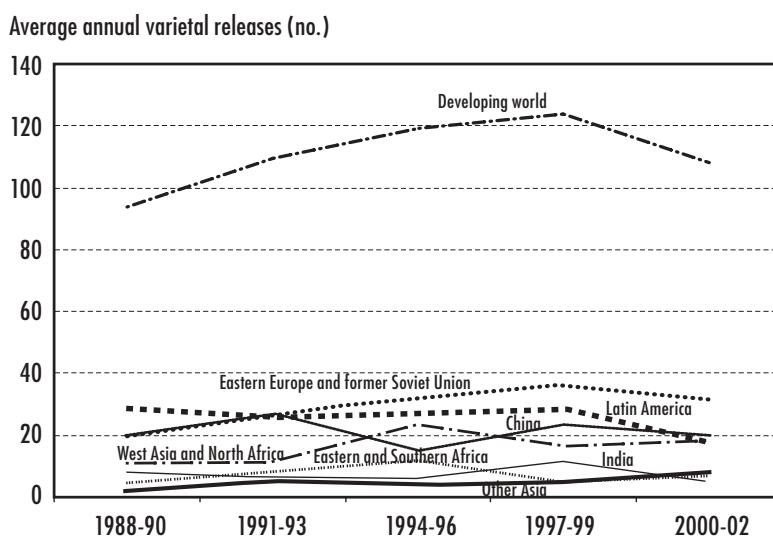


Figure 4.1. Average annual wheat varietal releases by region, 1988-2002.

period (1998-2002), more wheat varieties were released in Latin America and Eastern and Southern Africa than in other regions of the developing world (Figure 4.2). This finding is similar to the earlier findings of Byerlee and Moya (1993) and Heisey, Lantican, and Dubin (2002).

The higher area-adjusted varietal release rates in these two regions can be explained in terms of the large diversity in target environments, the small size of national wheat areas, the enormous variability in disease complexes, and, possibly, the active involvement of the private sector in wheat improvement. In contrast, area-adjusted varietal release rates were lowest in India and China, the two largest wheat producers in the developing

world. The relatively low rates in these two countries, which have strong, mature breeding programs, do not indicate low levels of research investment. Rather, for reasons referred to in the previous section (having to do with non-divisible inputs and economies of scope and scale), large wheat producing countries tend to release fewer wheat varieties per unit area than smaller producers (Heisey, Lantican, and Dubin 2002).

Varietal Releases by Growth Habit and Production Environment

How have patterns of wheat varietal releases varied by growth habit and production environment? Have patterns of

varietal releases been congruent with the area planted to different types of wheat? If not, what does this tell us about the priorities of national wheat breeding programs?

Wheat growth habit

Summarizing across all developing countries, spring bread wheats have dominated varietal releases. This is as expected, since most of the wheat area in the developing world is planted to spring bread wheat. During the period 1998-2002, spring bread wheats accounted for about 66% of all wheat varietal releases, consistent with the fact that about 63% of all the wheat area was planted to spring bread wheat in 2002. During the same period, spring durum releases accounted for slightly more than 6% of all wheat releases, and spring durums covered 5% of world's total wheat area.⁸ Meanwhile, winter and facultative wheat releases accounted for about 28% of all wheat varietal releases, and nearly 32% of the total wheat area was planted to winter and facultative wheats.

Number of wheat varieties per million hectares per year, five-year moving average

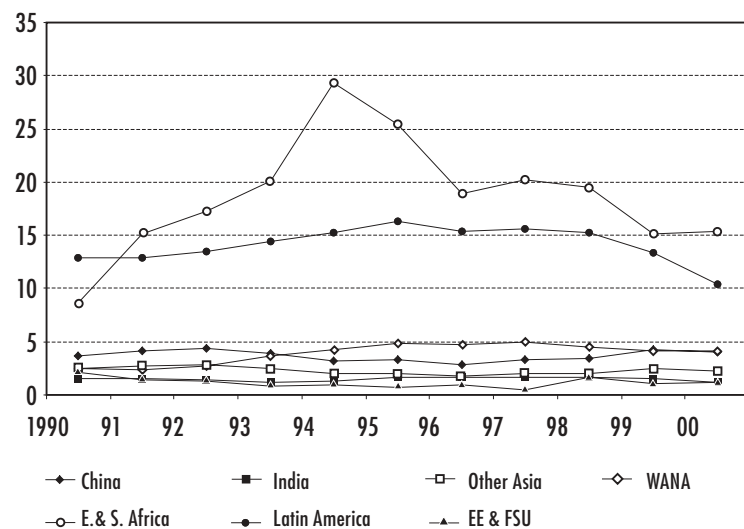


Figure 4.2. Rate of release of wheat varieties, normalized by wheat area, 1988-2002.

⁸ The slight decline, compared to the 1997 report, in number of durum releases and the area planted to durum reported here is probably due to differences in the sample, since a number of durum producing countries did not respond to the 2002 survey (Algeria, Syria, Tunisia, Lebanon, and Jordan).

Wheat production environment

Classifying wheat varietal releases by MEs is difficult, because outside of CIMMYT, few breeding programs work with the ME classifications. However, since MEs are somewhat correlated with moisture regimes, an alternative approach is to use moisture regimes as proxies for MEs.

Generally speaking, most breeding programs characterize wheat varieties as being suited to one or more of three basic moisture regimes: irrigated, well-watered rainfed, and dry rainfed. For this report, wheat varieties released between 1998 and 2002 were classified into seven categories: (1) irrigated, (2) well-watered rainfed, (3) dry rainfed, (4) irrigated and well-watered rainfed, (5) irrigated

and dry rainfed, (6) well-watered rainfed and dry rainfed, and (7) irrigated, well-watered rainfed, and dry rainfed. The results of this classification exercise appear in Table 4.1. Thirty-one percent of spring bread wheat releases and 24% of spring durum releases were recommended mainly for irrigated areas (Category 1). More than 50% of winter bread wheat releases were recommended for well-watered rainfed areas (Category 2), while 44% of spring durum releases were recommended for both irrigated and dry rainfed areas (Category 5). In the case of spring bread wheat and winter bread wheat, breeders appear to have been targeting more favorable environments. By contrast, in the case of spring durum wheat, breeders

appear to have been focusing on both irrigated and dry rainfed environments. Disaggregating these data by region reveals some interesting patterns, also evident in Table 4.1.

Classifications based on moisture regime were re-mapped into CIMMYT MEs. Just as many varieties are considered suitable for more than one moisture regime (i.e., all varieties in Categories 4-7), many are considered suitable for more than one ME. In the following analysis, classifications were based only on the primary target ME.⁹ As discussed in Chapter 2, ME1 through 6 are spring wheat environments, ME7 through 9 are facultative wheat environments, and ME10 through 12 are winter wheat environments.

Table 4.1. Wheat varietal distribution (%) by water regime production environment, region, and wheat type, 1998-2002.

Region/Wheat type	Irrigated only	Well-watered rainfed only	Dry rainfed only	Irrigated and well-watered rainfed	Irrigated and dry rainfed	Well-watered rainfed and dry rainfed	All three moisture regimes	Total
East and South Africa	38	44	9			9		100
West Asia/North Africa	22	3	28	31	13		3	100
South and East Asia	50	8	18	1	23			100
Latin America	11	41	6		11	31		100
Eastern Europe and the former Soviet Union	32	54	14					100
Spring bread wheat	31	26	14	4	13	11	1	100
Spring durum wheat	24	4	4	4	44	8	12	100
Winter bread wheat	23	52	13	4	3	2	3	100
All wheat	26	38	13	4	10	7	2	100

⁹ In general, there might be a bias toward lower-numbered MEs because they tend to be mentioned first, even when another ME is really the more important target for a variety.

Worldwide, most bread wheat varietal releases have been targeted for favorable environments, both irrigated (ME1 and ME7) and high-rainfall (ME2 and ME11) (Table 4.2). In contrast, durum wheat varietal releases have been targeted for a mixture of favorable and unfavorable environments, both irrigated (ME1) and dry rainfed (ME4 and ME9).

At the regional level, varietal release patterns are generally congruent with wheat production patterns. In East and South Asia, where wheat production is largely irrigated, most bread wheat varietal releases have been targeted for irrigated environments (ME1 and ME7). In WANA, where irrigated and rainfed wheat production are both significant, about 33% of spring

bread wheat releases were targeted for irrigated environments (ME1), while 15% were targeted for dry rainfed environments (ME4). In Latin America, where a significant amount of wheat is produced in areas characterized by acid soils, about 28% of all spring bread wheat releases were targeted for environments with acid soils (ME3), which is more than double the proportion recorded during the 1997 study. In Eastern Europe and the former Soviet Union, where winter wheat dominates, 77% of winter bread wheat varietal releases were targeted for irrigated and well-watered rainfed environments (ME11).

Generally speaking, the varietal release data suggest that wheat breeders in developing countries have directed their efforts in

a way that is compatible with wheat production patterns. The proportion of wheat varietal releases targeted for a particular environment has been roughly congruent with the area planted to wheat in that environment. As a result, international wheat breeding efforts have concentrated mainly on a set of target environments that includes both favorable (ME1, ME2, ME7, ME8, ME10) and unfavorable (ME4, ME9, ME12) environments.

Varietal Releases by Semidwarf Character

Figure 4.3¹⁰ shows the proportion of spring bread wheat varieties, spring durum wheat varieties, and winter bread wheat varieties that were semidwarfs and released between 1988 and 2002. The data have been

Table 4.2 Wheat varietal distribution (%) by production mega-environments, region, and wheat type, 1998-2002.

Wheat type	Mega-environment												Total
	ME1	ME2	ME3	ME4	ME5	ME6	ME7	ME8	ME9	ME10	ME11	ME12	
South and East Africa	35	41	6	18	0	0	0	0	0	0	0	0	100
West Asia and North Africa	33	2	0	15	0	0	5	9	6	12	2	17	100
South And East Asia	28	5	0	16	2	5	37	2	2	1	0	3	100
Latin America	7	33	28	17	6	0	0	3	6	0	0	0	100
Eastern Europe and the former Soviet Union	1	6	0	3	0	3	5	0	0	3	77	3	100
All bread wheat	16.5	12.4	5.6	11.8	1.7	2.3	12.6	2.3	2.5	2.7	25.4	3.9	100
All durum wheat	42.9	8.6	0.0	22.9	0.0	2.9	5.7	0.0	17.1	0.0	0.0	0.0	100
All wheat	18.2	12.2	5.3	12.5	1.6	2.4	12.2	2.2	3.5	2.5	23.8	3.6	100

¹⁰ The 1990 and 1997 global wheat impact studies published by CIMMYT both reported the percentage of wheat varietal releases that were semidwarfs. However, these earlier studies did not include information for Eastern Europe and the former Soviet Union, so the information presented in Figure 4.3 differs slightly from information contained in the earlier reports.

disaggregated into three five-year periods to highlight differences through time in the importance of semidwarfs.

In the case of spring bread wheat, the proportion of semidwarfs has remained fairly constant, rising from 88% in 1988-92 to 91% in 1993-97 before falling to 86% in 1998-2002. In the case of spring durum wheats, the pattern was similar, although the changes were more pronounced: the proportion of semidwarfs rose from 87% in 1988-92 to 92% in 1993-97 before falling rather sharply to 79% in 1998-2002. For both types of spring wheat, the decline in semidwarfs resulted from the increasing number of tall-statured varieties released in some countries and targeted for stressed environments.

In the case of winter bread wheat, the story has been different. The proportion of winter bread wheat varietal

releases that were semidwarfs fell from 77% in 1988-92 to 68% in 1993-97 before increasing slightly to 72% in 1998-2002. The latter increase reflects the large number of semidwarf winter bread wheat varieties released in China in recent years.

Origin of Released Wheat Varieties

All wheat varieties

Earlier studies have shown that CIMMYT-related germplasm has made an important contribution to international wheat breeding efforts (Byerlee and Moya 1993; Heisey, Lantican, and Dubin 2002; Evenson and Gollin 2003). Varietal pedigree data collected during this global survey (1988-2002) were examined to determine the extent to which public wheat breeding programs in developing countries continue to make use of CIMMYT-related germplasm.

CIMMYT's contribution to international wheat breeding efforts was estimated by classifying all wheat varieties released in developing countries between 1988 and 2002 into five categories.

Category 1: CIMMYT-crossed variety

Category 1 varieties are releases of CIMMYT-crossed materials (segregating lines or advanced lines).¹¹

Category 2: NARS/CIMMYT-bred variety

Category 2 varieties are derived from a cross made by a national research program. The cross was made in the country in which the variety was released or in another country, and involved one or more immediate CIMMYT parents.

Category 3: NARS-bred variety with CIMMYT ancestry

Category 3 varieties are derived from a cross made by a national research program. The cross was made in the country in which the variety was released or in another country, and did not involve an immediate CIMMYT parent. Category 3 varieties contain CIMMYT-related germplasm, but the CIMMYT-related germplasm was used two or more generations back in the breeding process (grandparent stage or earlier).

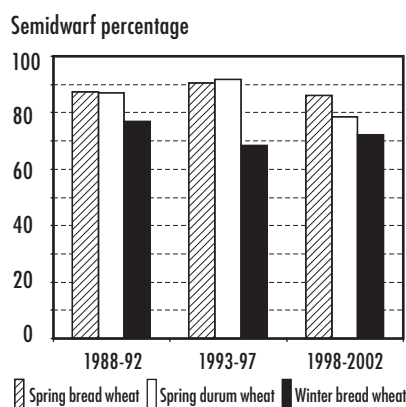


Figure 4.3. Percentage of wheat releases that were semidwarfs, by wheat type, 1988-2002.

¹¹ This category includes direct use of a CIMMYT advanced line with no further selection (37% of all Category 1 varieties); use of a CIMMYT advanced line or segregating line with further selection in the country of release or in another country (63% of all Category 1 releases).

Category 4: Other semidwarf variety

Category 4 varieties are semidwarf genotypes (i.e., modern, scientifically-bred varieties) that are not known to contain any CIMMYT germplasm.

Category 5: Tall variety

Category 5 varieties are tall and bred scientifically, but they are not known to contain any CIMMYT germplasm.

The analysis did not include varieties with unknown or unavailable pedigrees.

Considering all wheat types in all regions throughout the entire period for which data are available (1988-2002), about 75% of all wheat varieties with known pedigrees released in developing countries contained CIMMYT-related germplasm (Category 1, 2, or 3).

To bring out changes in the use of CIMMYT germplasm through time, two periods were considered: 1988-1995 and 1996-2002. During 1988-95, CIMMYT-bred varieties (Category 1) accounted for 30% of all wheat varieties released in the developing world (Figure 4.4). During the same period, NARS/CIMMYT-bred varieties (Category 2) accounted for an additional 21% of all wheat varieties released. During the period 1996-2002, the proportion

of CIMMYT-bred varieties (Category 1) decreased by one-fifth, to 24%. However, the proportion of NARS/CIMMYT-bred varieties (Category 2) rose to 23%.

These results confirm the findings of earlier studies that CIMMYT-related germplasm continues to be used extensively by public wheat breeding programs throughout the developing world. They also show the way that CIMMYT-related germplasm is changing over time as national wheat breeding programs evolve and mature. Although direct use of CIMMYT germplasm has decreased (as indicated by a decline in the proportion of Category 1 varieties), indirect use of CIMMYT germplasm has increased (as indicated by increases in the proportion of Category 2 and 3 varieties).

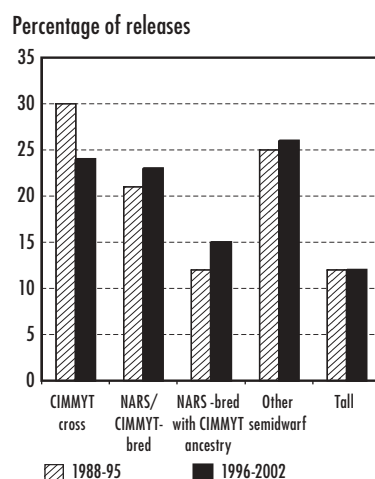


Figure 4.4. Wheat varietal releases in the developing world, 1988-95 and 1996-2002.

Since the use of CIMMYT-related germplasm may have differed between types of wheat and by region, a similar analysis was performed using disaggregated data.

Spring bread wheat

As discussed previously, the bulk of CIMMYT's wheat breeding effort is directed toward spring bread wheat, the single most important type of wheat grown in the developing world. CIMMYT's spring bread wheat breeding program continues to have an enormous impact. During the period 1988-2002, 86% of all spring bread wheat releases in the developing world (excluding Eastern Europe and the former Soviet Union) had some form of CIMMYT ancestry. This proportion was similar to that reported in Heisey, Lantican, and Dubin (2002), confirming the continued widespread use of CIMMYT spring bread wheat germplasm. When Eastern Europe and the former Soviet Union are included, the proportion drops to 82% (Figure 4.5).

The extent and use of CIMMYT-related germplasm in spring bread wheat releases varied among regions. Breeding programs in WANA, Eastern and Southern Africa, and Asian countries other than China and India made considerable use of CIMMYT-bred (Category 1) and NARS/CIMMYT-bred (Category 2)

varieties. These two categories accounted for over 90% of all spring bread wheat releases in these three regions. Breeding programs in Latin America also made extensive use of CIMMYT-related germplasm, with Category 1 and Category 2 varieties making up 80% of all releases. In breeding programs in Eastern Europe and the former Soviet Union, where CIMMYT does not have a long history of collaboration, the use of CIMMYT-related germplasm has been less extensive: only about 30% of spring bread wheat releases had CIMMYT ancestry.

The way in which CIMMYT-related germplasm is used has changed over time in a number of countries and regions. In India, the proportion of spring

bread wheat releases with CIMMYT ancestry increased slightly during 1998-2002 compared with earlier periods. In China, the proportion of NARS/CIMMYT-bred (Category 2) spring bread wheat varieties decreased during the most recent period, but the proportion of NARS-bred varieties with CIMMYT ancestry (Category 3) increased. This supports earlier findings that China uses CIMMYT-related germplasm mostly during the early stages of breeding (see Heisey, Lantican, and Dubin 2002). In Latin America, a decline in the proportion of CIMMYT-bred varieties (Category 1) was offset by an increase in the proportion of NARS/CIMMYT-bred varieties (Category 2).

Spring durum wheat

As is the case of spring bread wheat, CIMMYT's spring durum wheat breeding program continues to have an enormous impact. During the period 1988-2002, 88% of the spring durum wheat varieties released in the developing world had some degree of CIMMYT ancestry (Figure 4.6). When Eastern Europe and the former Soviet Union are excluded, this increases to 94%.

Direct use of CIMMYT-bred germplasm has been extensive. Over 60% of all spring durum wheat varieties released were CIMMYT-crossed materials (Category 1), which made up more than one-third of all releases in all regions except Eastern Europe and the former Soviet Union. The proportion of CIMMYT-bred spring durum wheat varieties was highest in Latin America (83%) and the WANA region (77%), followed by Asian countries other than India (66%), and Eastern and Southern Africa (60%). Very little spring durum wheat is grown in China, so China does not have a spring durum wheat breeding program and does not release these varieties (Figure 4.6).

Percentage of releases

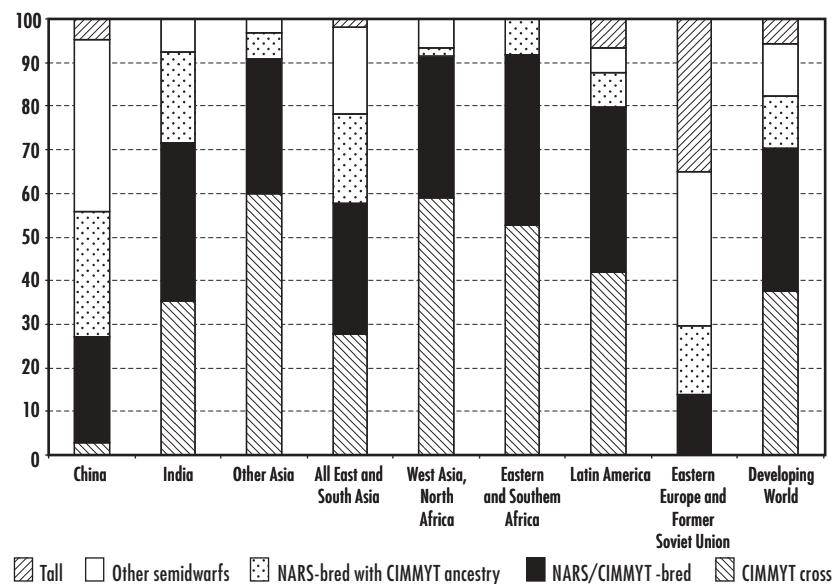


Figure 4.5. Spring bread wheat releases in the developing world, by region, 1988-2002.

With both spring durum and bread wheats, the use of CIMMYT-related germplasm has changed over time in some countries and regions. When the pattern of releases in the most

recent period is compared to the pattern in earlier periods, the proportion of NARS/CIMMYT-bred varieties (Category 2) increased in Eastern and Southern Africa, as well as in

India. In the case of India, the proportion of NARS-bred varieties with CIMMYT germplasm (Category 3) also increased.

In Eastern Europe and the former Soviet Union, most released spring durum wheat varieties were semidwarfs that did not contain CIMMYT-derived germplasm (Category 4). Nonetheless, 22% of the spring durum wheats released in those regions were NARS/CIMMYT-bred varieties that contained at least one CIMMYT parent (Category 2).

Percentage of releases

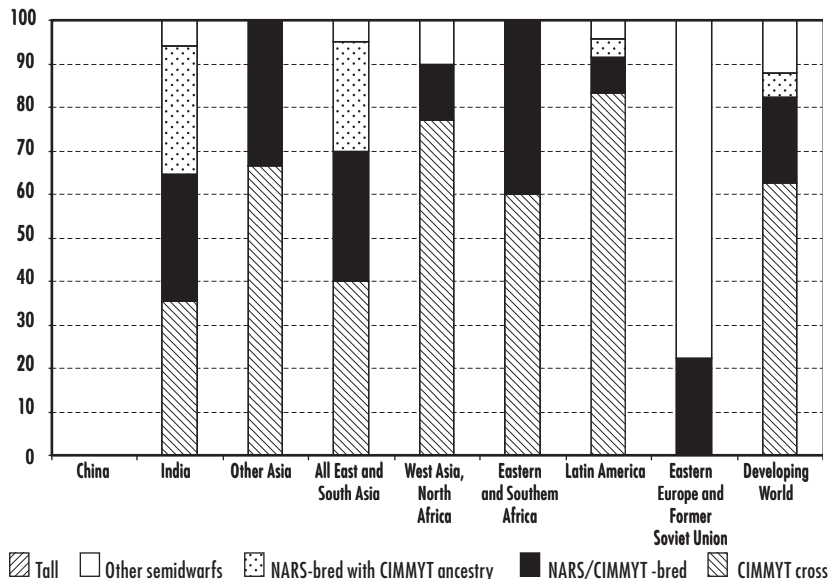


Figure 4.6. Spring durum wheat releases in the developing world, by region, 1988-2002.

Percentage of releases

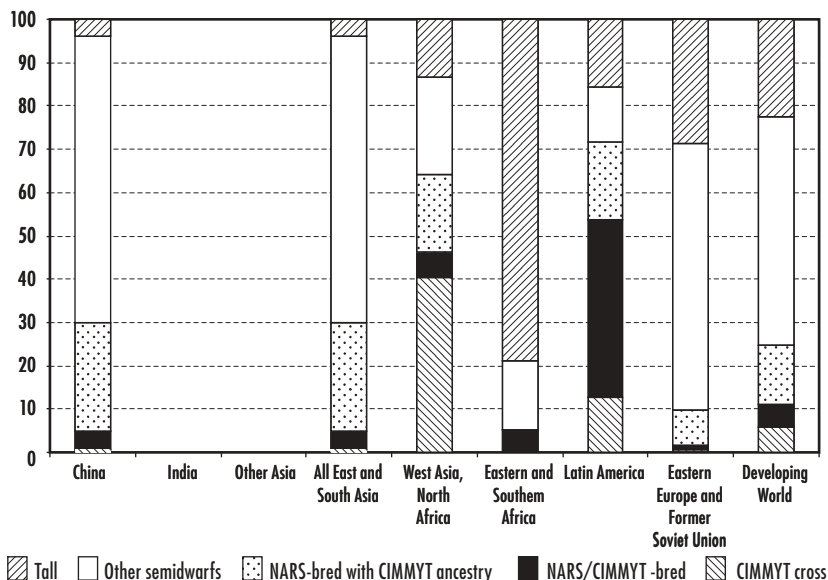


Figure 4.7. Winter/facultative bread wheat releases in the developing world, by region, 1988-2002.

Winter and facultative wheat

During the 1988-2002 period, 24% of all winter and facultative wheat varieties released in the developing world had some form of CIMMYT ancestry (Figure 4.7). When data for Eastern Europe and the former Soviet Union are excluded, the proportion rises to 44%. Considering that the TURKEY/CIMMYT/ICARDA winter wheat breeding program was founded several decades after CIMMYT's spring wheat breeding programs, and that winter wheat breeders in this collaborative program have only recently started targeting environments in Eastern Europe and the former Soviet Union, the widespread use of TURKEY/CIMMYT/ICARDA-related winter wheat germplasm is impressive.

Between 1988 and 2002, use of TURKEY/CIMMYT/ICARDA-related winter wheat germplasm was most extensive in Latin America (72% of all varietal releases classified as Category 1, 2, or 3), followed by the WANA region (64%), China (30%), and Eastern Europe and the former Soviet Union (10%).

The use of TURKEY/CIMMYT/ICARDA-related winter wheat germplasm has increased over time, indicating that the products of this relatively young breeding program have started to emerge from the research pipeline and are finding their way into finished varieties. In Latin America, the WANA region, and China, the proportion of winter wheat varieties that contained TURKEY/CIMMYT/ICARDA-related germplasm increased sharply between the two periods. Only in Eastern and Southern Africa did the proportion of varieties containing TURKEY/CIMMYT/ICARDA-related germplasm decline, probably due to the increasing presence in South Africa of private seed companies, which in recent years have released many varieties that do not contain TURKEY/CIMMYT/ICARDA-related germplasm.

Private-Sector Wheat Varieties

The international wheat breeding system is dominated by public research organizations, but how significant is the impact of private companies that also invest in wheat breeding research? The contribution made by the private sector to international wheat breeding efforts was estimated by classifying all wheat varieties released in developing countries between 1988 and 2002 into two categories: public and private. The analysis excluded varieties of unknown origin.

The private sector's contribution to international wheat breeding efforts has varied not only between countries and regions, but also depending on the type

of wheat. In the case of spring bread wheat, private companies developed 20% of all varieties released in developing countries during the period 1988-2002 (Figure 4.8). Private sector releases were most significant in Eastern Europe and the former Soviet Union (38%), followed by Eastern and Southern Africa (34%), Latin America (34%), and the WANA region (5%). The proportion of spring bread wheat varieties released by private companies in East and South Asia was negligible.

In the case of spring durum wheat, the overall contribution of the private sector has been similar: private companies developed 21% of all spring durum wheat varieties released in developing countries during the period 1988-2002 (Figure 4.9). However, private

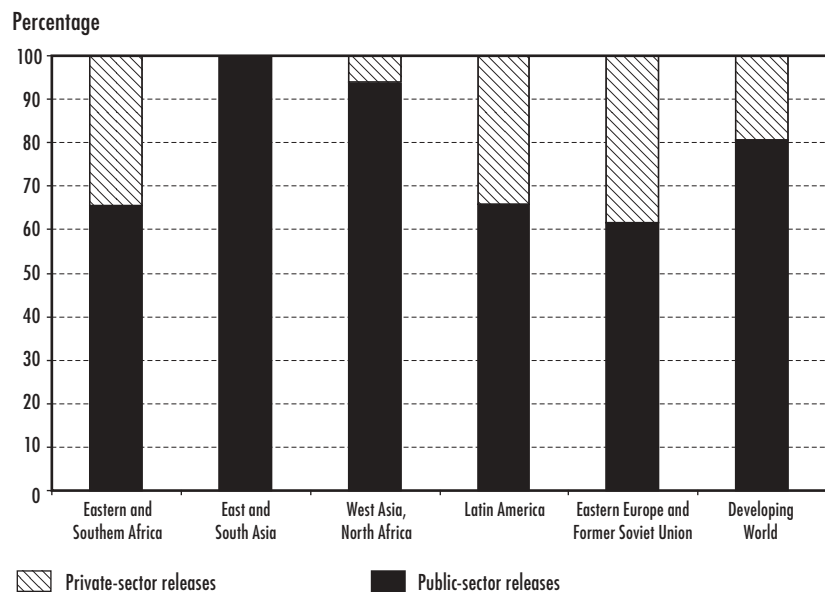


Figure 4.8. Percentage of public- and private-sector spring bread wheat releases, 1988-2002.

sector breeding efforts for spring durum wheat have focused on different areas, which reflect the different spatial distribution of spring durum wheat production relative to spring bread wheat production. Private sector releases for spring durum wheat were concentrated in Eastern and Southern Africa (47%), Latin America (26%), and the WANA region (22%). Elsewhere, the private sector accounted for very few varietal releases.

In the case of winter and facultative wheat, private companies developed 26% of all varieties released in developing countries during 1988-2002 (Figure 4.10). Private sector releases for winter and facultative wheat were concentrated in Eastern and Southern Africa, where private companies developed an impressive 75% of all varieties released. This reflects the presence of a large, flourishing, private wheat industry in South Africa, which along with Zimbabwe, dominates wheat production in the region. (In fact, all of the winter and facultative varieties released in the entire region came from South Africa.) The importance of the private sector in these two countries has also been noted by Heisey and Lantican (1999). Elsewhere, the proportion of private sector releases ranged from relatively high levels of 42% in Latin America and 32% in Eastern Europe and the former Soviet Union to a more modest 9% in East and South Asia, as well as the WANA region.

Intellectual property laws and wheat varietal releases

The modest level of private-sector investment in wheat breeding research is often explained by the alleged difficulty of capturing benefits. Since wheat is a self-pollinating

species whose genetics change little from one generation to the next, farmers have little incentive to purchase commercial seed on a regular basis. Commercial sales of wheat seed are indeed modest in most countries, and most

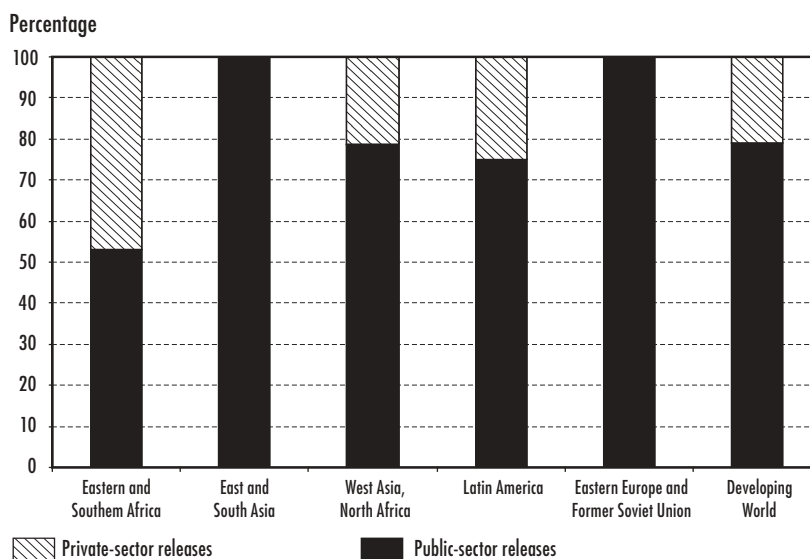


Figure 4.9. Percentage of public- and private-sector spring durum wheat releases, 1988-2002.

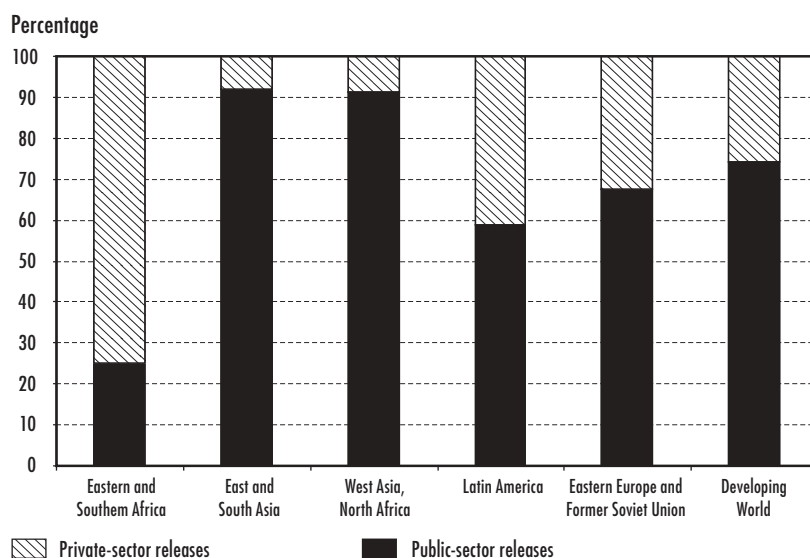


Figure 4.10. Percentage of public- and private-sector winter and facultative bread wheat releases, 1988-2002.

wheat farmers save a portion of their crop for replanting in the following season.

Can observed differences in the contribution made by private breeding programs to international wheat breeding efforts be related in any way to differences in the strength of intellectual property laws relating to plant varieties? The International Union for the Protection of New Varieties of Plants (UPOV) is an international organization that aims to protect new plant varieties with intellectual property rights, including plant breeders' rights (PBRs).¹² Among the countries surveyed for this report, 19 are signatories to the UPOV conventions. Lists of protected wheat varieties were available for five of these countries: Argentina, Brazil, Chile, South Africa, and Uruguay. The origins of wheat varieties released in these five countries were examined in an effort to gain insights as to whether PBRs provide incentives for private companies to increase their investment in wheat breeding research.

Generally speaking, the number of wheat varieties developed by private companies was higher in the five UPOV-member countries

for which data were available than in the non-UPOV countries. However, it is difficult to determine whether there is a causal relationship between UPOV membership and a higher incidence of private-sector releases. Since much of the research that led to the development of wheat varieties included in the CIMMYT dataset was done before UPOV existed, it is difficult to argue that the observed higher incidence of private sector varietal releases in UPOV member countries resulted from UPOV membership. It seems more likely that any causal relationship, if present, would run in the opposite direction: countries in which the private seed industry was already strong were more likely to have become UPOV members.

Another interesting question is whether or not the varieties over which private companies have claimed PBRs contain CIMMYT-related germplasm. Figure 4.11 shows the percentage of protected wheat varieties that are CIMMYT-related in the five UPOV-member countries for which data are available. In the four Latin American countries, the use of CIMMYT germplasm in protected varieties was uniformly high: 83% of protected varieties in Argentina had CIMMYT content, 82% in Uruguay, 80% in Chile, and 76% in Brazil. In South Africa, the fifth country for which data are available, the use of CIMMYT germplasm in protected varieties was lower (45%). Although the sample size is small, these results suggest that private companies have made extensive use of CIMMYT germplasm in developing varieties that are protected by PBRs.

Proportion of all protected wheat varieties (%)

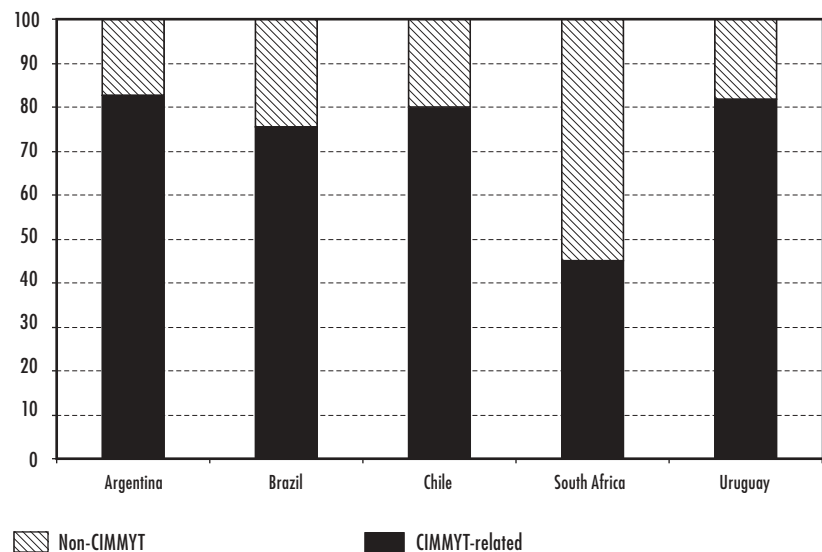


Figure 4.11. Parentage of protected wheat varieties, selected countries, 2002.

¹² For more details, refer to the UPOV website (<http://www.upov.int/eng/protectn/exclusive.html>).

CHAPTER 5. Adoption of Modern Wheat Varieties

Varietal releases may be good indicators of research productivity, but they are not necessarily good indicators of research impact. If wheat breeding research is to deliver tangible benefits, released varieties must be taken up by farmers and planted in their fields. This chapter reviews evidence of the adoption of modern wheat varieties in the developing world. CIMMYT's contribution to the wheat varieties being planted in farmers' fields is assessed using several different attribution methods.

Spread of Modern Wheat Varieties

Table 5.1 and Figure 5.1 show the area planted to modern wheat varieties in developing countries in 2002. Summarizing across all wheat types and all regions, nearly 95% of the developing world's wheat area was planted to modern varieties. Of this, about 70%¹³ was planted to improved semidwarf varieties, and about 18% was planted to improved tall-statured varieties, which have

remained popular in some stress-prone environments, particularly in South America (Brazil), southern Africa (South Africa), and large areas of Turkey and Iran.

Adoption patterns have varied between different types of wheat. Adoption of modern spring bread wheat varieties has been most extensive (modern varieties

Table 5.1. Area (million ha) sown to different wheat types, classified by origin of germplasm, 2002.

Wheat type	CIMMYT cross	NARS cross				Tall	Landraces	All
		CIMMYT parent	CIMMYT ancestor	Other semidwarf				
Spring bread wheat	19.3	22.3	6.5	5.4	4.8	1.7	60.0	
Spring durum wheat	2.3	1.0	0.8	0.2	0.1	0.5	4.8	
Winter/facultative bread wheat	0.7	1.5	7.6	11.2	5.7	2.6	29.3	
Winter/facultative durum wheat		0.1	0.0	0.1	1.7		1.8	
All wheat types	22.3	24.9	14.9	16.9	12.2	4.8	95.9	

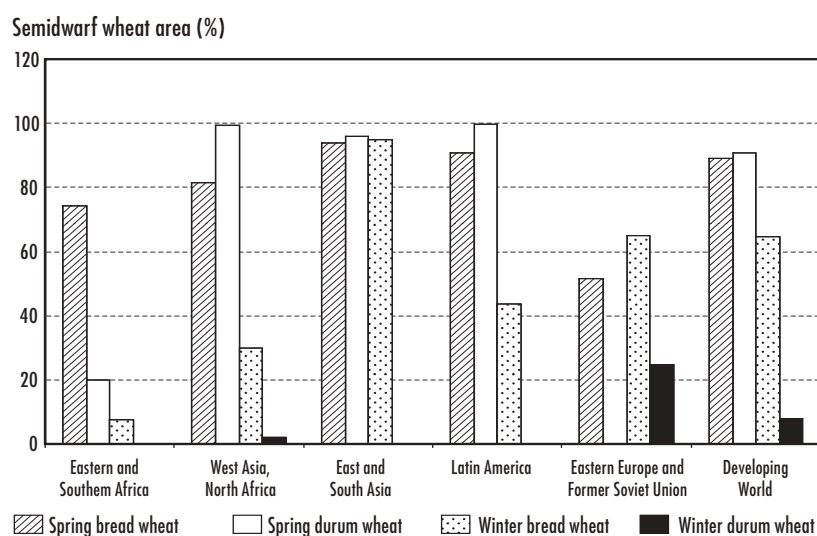


Figure 5.1. Percentage of wheat area planted to semidwarf varieties by wheat type and region, 2002.

¹³ This figure does not include early 1970s semidwarf varieties.

covered 97% of the spring bread wheat area in developing countries), followed by spring durum wheat (modern varieties covered 92% of the spring durum wheat area) and by winter and facultative bread wheat (modern varieties covered 91% of the winter and facultative bread wheat area).

Regional differences in adoption patterns were evident among the three types of wheat.

Adoption of modern spring bread wheat varieties was considerable in all regions of the developing world, ranging from a high of nearly 100% in East and South Asia, Eastern and Southern Africa, and Eastern Europe and the former Soviet Union to a low of 82% in West Asia and North Africa (Figure 5.2).

Adoption of modern varieties of spring durum wheat has been very high in Latin America, West Asia, North Africa, and East and South Asia (Figure 5.3). In East and South Asia (represented mainly by India), the area planted to spring durum wheat increased dramatically between 1997 and 2002, as did the area planted to modern varieties of spring durum. In response to the outbreak of Karnal bunt on bread wheat, many farmers switched to durum wheat, and most of them adopted

semidwarf varieties. Elsewhere, adoption of modern spring durum varieties was less extensive. For example, in Ethiopia, the only country in Sub-Saharan Africa where spring

durum wheat is grown, only 20% of the spring durum wheat area was planted to modern varieties; the remaining 80% was planted to landraces. Only two spring durum wheat varieties, both of

Spring bread wheat area (%)

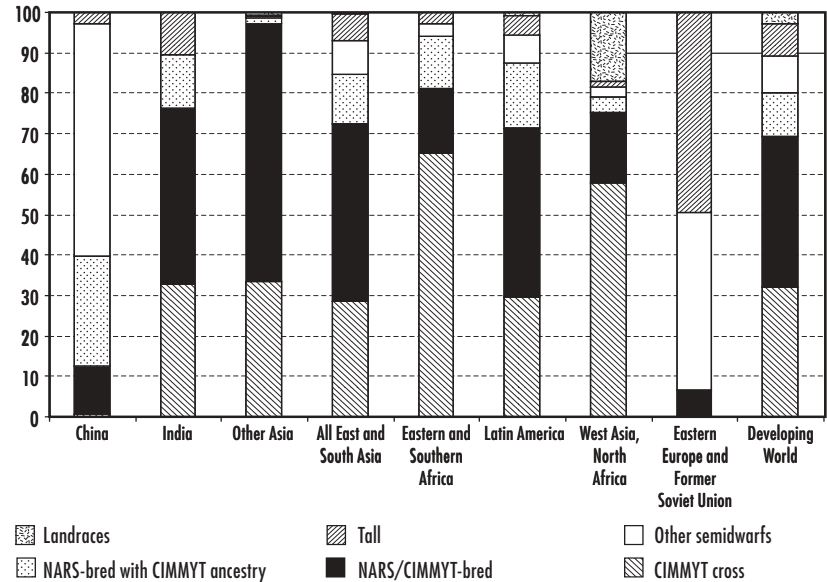


Figure 5.2. Area planted to spring bread wheat in the developing world, 2002.

Spring durum wheat area (%)

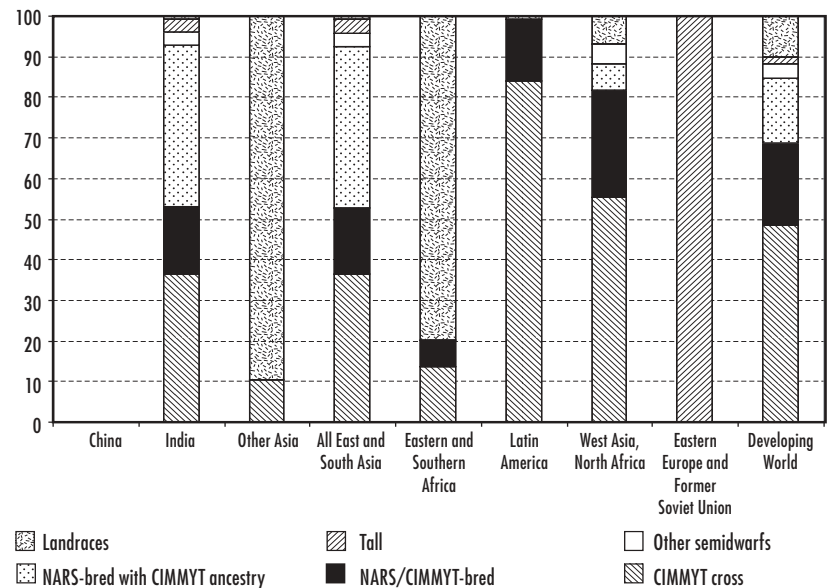


Figure 5.3. Area planted to spring durum wheat in the developing world, 2002.

them improved and tall, were reportedly grown in Eastern Europe and the former Soviet Union in 2002.

Adoption of modern varieties of winter and facultative wheat occurred worldwide, but the types and statures of materials differed among regions. Semidwarf varieties of winter and facultative bread wheat have been adopted in East and South Asia (mostly in China) and in irrigated and higher rainfall areas of Eastern Europe, the former Soviet Union, Iran, Turkey, and the Southern Cone of South America; tall varieties and landraces dominated in other regions. Tall varieties of winter and facultative durum wheat were predominant in West Asia (mainly in Turkey and Iran), North Africa, and Eastern Europe and the former Soviet Union (Figure 5.7).

Area Planted to CIMMYT-Related Germplasm

Adoption of CIMMYT-related germplasm by type of wheat

Table 5.1¹⁴ summarizes the area planted in 2002 to wheat varieties of different origins. As mentioned earlier, across the entire developing world, spring bread

wheat accounts for the highest number of varietal releases and occupies the largest area. In 2002, spring bread wheat was grown on 60 million hectares in the countries covered by our survey. Modern varieties were sown on 97% (58 million hectares) of that land, 91% of which was planted to semidwarfs and 9% to improved tall varieties. CIMMYT-related varieties were planted on 80% (48 million hectares) of the total spring bread wheat area. Category 1 varieties (CIMMYT crosses) or Category 2 varieties (NARS crosses made using at least one CIMMYT parent) covered nearly 70% (42 million hectares), and Category 3 varieties (NARS-bred varieties with some CIMMYT ancestry) covered 11% (6.5 million hectares).

When these results are compared to results of the 1997 CIMMYT study, changes are evident in the use of CIMMYT-related germplasm. The area covered by Category 1 and Category 2 varieties increased, while the area covered by Category 3 varieties decreased. The observed increase in the area planted to Category 1 varieties is somewhat unexpected, because the importance of CIMMYT-bred varieties can be expected to decline over time as NARS wheat breeding programs grow stronger. However, it is

possible that what we are seeing reflects the lengthy lag between the time when varieties are bred and the moment when peak adoption occurs. In other words, the observed increase in the area planted to Category 1 varieties occurred because CIMMYT-bred varieties released in the 1980s and 1990s are continuing to diffuse.

In 2002, nearly five million hectares were planted to spring durum wheat in the countries covered by our survey (Table 5.1). Although this was slightly less than the area planted to the same wheat type in 1997, the difference is likely due to the fact that the 2002 results do not include data from several durum growing countries that did not participate in the CIMMYT survey. Of the area planted to spring durum wheat, 89% (4.3 million hectares) were planted to modern varieties, 95% (4.1 million hectares) of which were planted to varieties containing CIMMYT germplasm. Category 1 or Category 2 varieties covered 3.3 million hectares, or 69% of the total spring durum wheat area. Nearly a million hectares (16%) were sown to improved tall spring durum wheats (those released in the 1990s) with CIMMYT germplasm content.

¹⁴ Data reported in this section on the area planted to CIMMYT-related modern varieties may differ slightly from data reported in the previous section on the area planted to all modern varieties because the area planted to modern varieties whose origin or pedigree was unknown was excluded from this analysis.

In 2002, winter wheat was grown on 31.1 million hectares in the countries covered by our survey, representing nearly one-third of the total wheat area in the surveyed countries. This included 29.3 million hectares planted to winter bread wheat and 1.8 million hectares planted to winter durum wheat (Table 5.1). Modern varieties of winter bread wheat covered 26.7 million hectares. Of this, 9.8 million hectares (37%) were planted to varieties with TURKEY/CIMMYT/ICARDA germplasm content. Improved, tall, winter bread wheat varieties with TURKEY/CIMMYT/ICARDA ancestry covered about 2 million hectares (6%). Winter bread wheat landraces continued to be grown on 2.6 million hectares in 2002 (equivalent to nearly 9% of the total area planted to winter bread wheat).

Summarizing across all wheat types, in 2002 modern varieties were grown on 91.2 million hectares in the countries covered by our survey. Of this, 62.1 million hectares (68%) were planted to varieties containing CIMMYT germplasm. NARS-bred varieties covered nearly 69 million hectares (including nearly 39.8 million hectares planted to NARS-bred varieties with a CIMMYT parent or ancestor). In addition, 16.9 million hectares were planted to NARS-bred semidwarf varieties

with no known CIMMYT ancestry, 12.2 million hectares were planted to NARS-bred tall varieties with no known CIMMYT ancestry, and 4.8 million hectares were planted to landraces (Table 5.1).

The inclusion of Eastern Europe and the former Soviet Union in the 2002 survey markedly increased the area planted to winter wheat compared to the earlier surveys. Taking into account the change in coverage, many of the findings of the 2002 survey are consistent with those of the 1997 survey. Broadly speaking, the results confirm that CIMMYT-related wheat germplasm continues to be used extensively throughout the developing world.

Adoption of CIMMYT-related germplasm by region

The 2002 adoption data were disaggregated by wheat type and by region to determine whether the use of CIMMYT-related germplasm has varied among and within developing countries and regions.

Figure 5.2 shows regional patterns in the area planted to different categories of spring bread wheat. In 2002, 80% of the area planted to spring bread wheat in the developing world was planted to varieties containing CIMMYT-related germplasm (Category 1, 2, or 3).

The proportion of the total spring bread wheat area that was planted to varieties containing CIMMYT-related germplasm totaled 97% in Other Asia, 94% in Eastern and Southern Africa, 85% in East and South Asia, 88% in Latin America, 79% in the WANA region, and 8% in Eastern Europe and the former Soviet Union. Adoption of varieties containing CIMMYT-related germplasm was extensive in India (90%) and significant in China (40%), the two most important wheat-producing countries in the developing world. In all regions except Latin America, the 2002 figures represented increases over the equivalent figures measured in 1997.¹⁵

Regional patterns in the area planted to different categories of spring durum wheat are shown in Figure 5.3. In 2002, 84% of the spring durum wheat area in the developing world was planted to varieties containing CIMMYT-related germplasm (Category 1, 2, or 3). The proportion of the total spring durum wheat area planted to varieties that contain CIMMYT-related germplasm reached 99% in Latin America, 92% in East and South Asia, 88% in the WANA region, 20%

¹⁵ The decline in the percentage area planted to CIMMYT-derived spring bread wheat varieties in Latin America resulted not from an absolute decline in the area planted to CIMMYT-derived varieties, but rather from a sharp increase in the area planted to other varieties that did not contain CIMMYT-related germplasm.

in Eastern and Southern Africa, and 10% in Other Asia. The area planted to varieties containing CIMMYT-related germplasm was negligible in Eastern Europe and the former Soviet Union, where very little spring durum wheat is grown.

Regional patterns in the area planted to different categories of winter bread wheat are shown in Figure 5.4. The adoption of winter bread wheat varieties containing TURKEY/CIMMYT/ICARDA-related germplasm has been less extensive than the adoption of spring bread wheat. The proportion of the total winter bread wheat area planted to varieties that contain TURKEY/CIMMYT/ICARDA-related germplasm was 100% in Other Asia (where very little winter bread wheat is grown), 67% in Latin America, 35% in East and South Asia, 32% in the WANA region, and 8% in Eastern and Southern Africa.

Summarizing across all types of wheat, regional patterns in the area planted to the different categories of wheat are shown in Figure 5.5. Well over one-half (64%) of the area planted to wheat in the surveyed countries was planted to varieties containing CIMMYT-related germplasm (Figure 5.5). The proportion of the total wheat area planted to varieties containing CIMMYT-related germplasm

reached 97% in Other Asia, 83% in Latin America, 74% in East and South Asia (including 90% in India and 37% in China), 63% in

Eastern and Southern Africa, 57% in the WANA region, and 3% in Eastern Europe and the former Soviet Union.

Percentage of winter and facultative wheat area

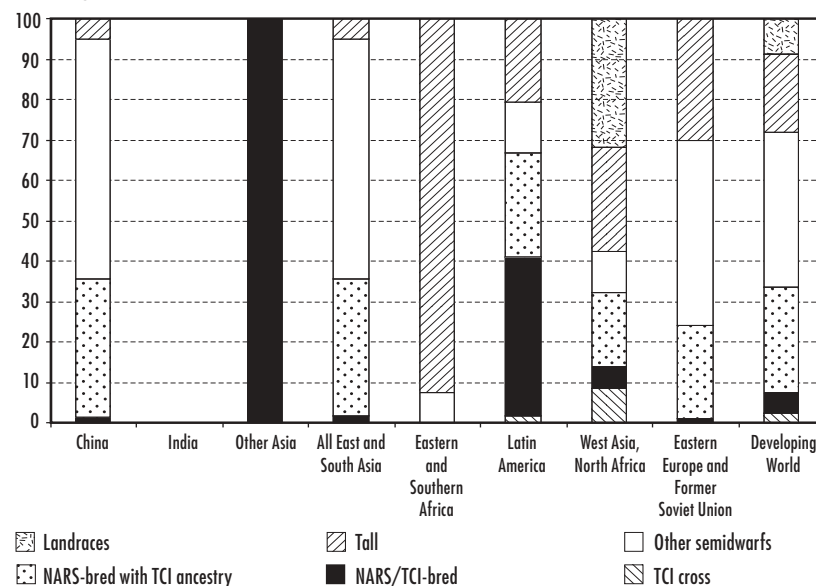


Figure 5.4. Area planted to winter and facultative bread wheat in the developing world, 2002 (TCI = TURKEY/CIMMYT/ICARDA).

Percentage of all wheat area

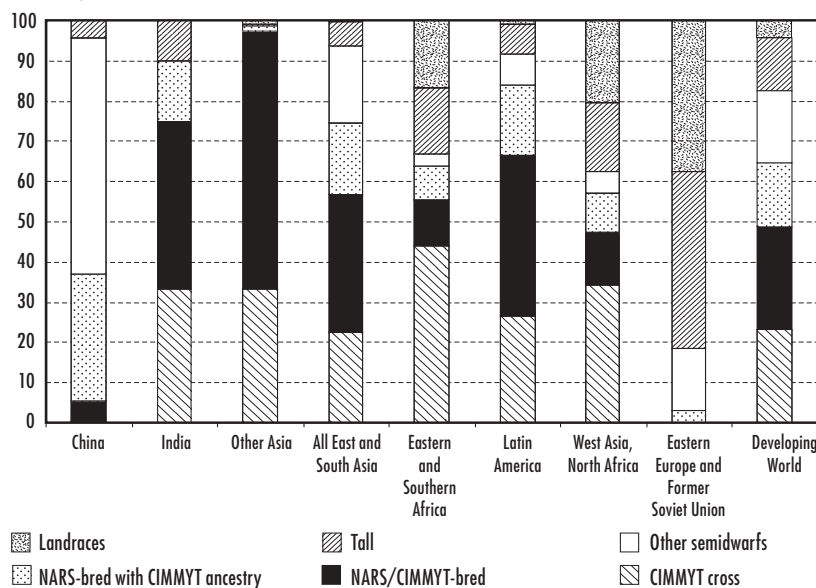


Figure 5.5. Area planted to all wheat in the developing world, 2002.

Implications for genetic diversity

Considering the extensive area planted to wheat varieties that contain CIMMYT-derived germplasm, it is fair to ask whether the success of CIMMYT's wheat breeding program has reduced genetic diversity in farmers' fields. This is of great concern because reduced genetic diversity is associated with an increased risk of widespread crop losses from biotic or abiotic stresses. A breakdown in the resistance of a widely sown variety to current stresses or the emergence of new stresses to which the variety is not resistant could cause such losses.

Figure 5.6 shows the proportion of the national wheat area that was planted in 2002 to CIMMYT-bred (Category 1) varieties in eight leading wheat producing nations: Argentina, Brazil, Mexico, Morocco, Egypt, Iran, India, and Pakistan. The proportion ranged from a low of 16% in Argentina to a high of 92% in Mexico. The experience of these eight countries, which form a representative sample of all developing countries, confirms that CIMMYT crosses account for a large proportion of the total wheat area in the developing world. However, whether or not the use of CIMMYT-bred materials is increasing is difficult to say. Comparing the 2002 results

with the results of earlier surveys, no consistent trend pattern can be observed: in five of the eight countries, the percentage area planted to CIMMYT-bred wheat varieties increased since the last survey in 1997, while in the other three countries the proportion declined (Figure 5.6).

How diverse are the CIMMYT-bred Category 1 materials that farmers grow? The answer to this question depends on two additional questions: (1) How many different CIMMYT-bred varieties are grown? (2) How genetically diverse are CIMMYT-bred varieties?

The results of this survey provide important insights into the first of these two questions. As reported earlier, in 2002 approximately 22.3 million hectares were planted

to Category 1 varieties in the developing world. Of these 22.3 million hectares, approximately one-half are occupied by specific named varieties (Table 5.2). In 2002, nine individual CIMMYT-bred wheat varieties (seven bread wheats and two durums) were each planted on more than 100,000 hectares. Three of these (all bread wheats) were planted on more than 1 million hectares, and of these one (Attila) was planted on 5.7 million hectares, mainly in Chile, Ethiopia, India, Iran, and Pakistan. The other one-half of the area occupied by Category 1 spring bread wheat varieties in the developing world was planted to more than 147 different CIMMYT crosses.

Given that the genetic diversity in farmers' fields has a temporal as well as a spatial dimension, it is of interest to know the rate

Percentage of total wheat area

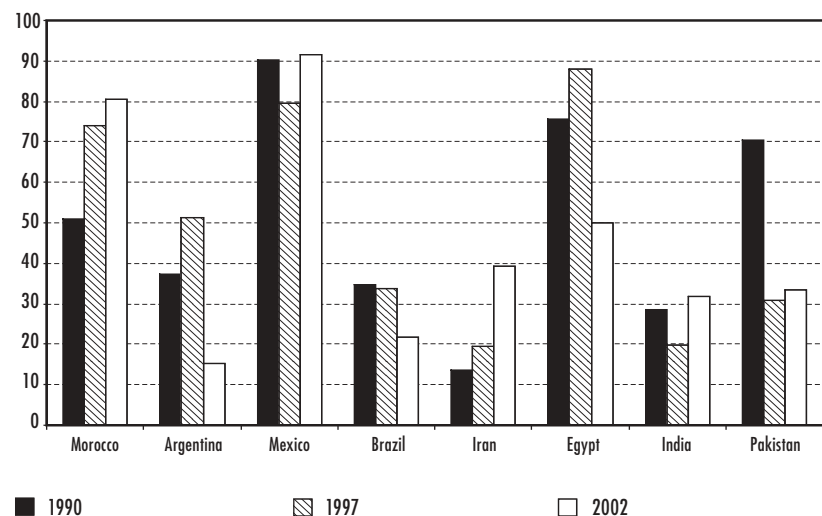


Figure 5.6 Percentage of wheat area sown to CIMMYT crosses in selected developing countries, 1990, 1997, and 2002.

at which older CIMMYT-bred varieties are replaced by newer CIMMYT-bred varieties. In the absence of time series data on the area sown to individual varieties, varietal replacement rates can be inferred by examining the age of varieties that are being grown in a given year (in this case 2002). Worldwide, of the area covered by Category 1 varieties in 2002, the largest proportion was planted to newer varieties released during the 1990s. This

group of varieties includes what is currently the most widely grown variety in the developing world: the bread wheat variety Attila (released in 1996). In 2002 it was grown on 5.7 million hectares, including more than 5 million hectares in India alone. Many CIMMYT-bred varieties released during the 1980s were also widely grown in 2002. The spring bread wheat variety Bobwhite, released in 1988, covered nearly 1 million hectares,

mainly in Argentina and Paraguay. Although many older CIMMYT-bred varieties released during the 1970s had been replaced by 2002, the spring bread wheat Sonalika, released in 1970, was still being grown on more than 1 million hectares in India and Bangladesh.

These data from the 2002 survey show that many newer wheat varieties are taken up quickly, but the rate at which older

Table 5.2. Area sown to popular CIMMYT spring wheat varieties, 2002.

	Area sown in 2002 to varieties developed from CIMMYT crosses (000 ha)	Year of release of varieties developed from CIMMYT crosses	Countries in which varieties developed from CIMMYT crosses were released
Released before 1985			
Sonalika	1,083	1970	Bangladesh , India
Pavon	182	1980	Bolivia, Ethiopia, Pakistan
Gallereta (durum)	217	1984	Mexico
Other (20 crosses)	1,476	1976	Colombia, Nepal, Mexico, Ecuador, Egypt, Ethiopia, India, Pakistan, Morocco, Turkey, South Africa
Subtotal	2,958		
Released 1985-95			
Bittern (durum)	396	1988	Iran, Morocco
Veery	590	1988	China, Iran ,Morocco, Nepal, Pakistan, Uruguay, Zimbabwe
Bobwhite	986	1988	Argentina, Paraguay
PFAU	562	1993	Morocco, Turkey
Kauz	1,726	1994	Chile, India, Morocco, Pakistan, Turkey
Other (70 crosses)	5,109	1991	Bolivia, Brazil, Paraguay, Peru, Turkey, Pakistan, Kenya, Morocco, Mexico, Colombia, Ecuador, Paraguay, Uruguay, Egypt, Nepal, Peru, Turkey, South Africa, Ethiopia, Iran, Zimbabwe
Subtotal	9,369		
Released since 1996			
Attila	5,730	1996	Chile, Ethiopia, India, Iran, Pakistan
Other (57 crosses)	4,259	1998	Bolivia, Brazil, Chile, Colombia, Egypt, Ethiopia, India, Iran, Morocco, Zimbabwe, Mexico, Nepal, Turkey, Korea DPR, Kenya, Pakistan
Subtotal	9,989		
Total	22,316		

wheat varieties are replaced remains slow in some instances. As discussed in Heisey, Lantican, and Dubin (2002) and Byerlee and Moya (1993), wheat varietal replacement rates are influenced by technical, economic, and institutional factors.

Environmental factors also seem to play a role; Lantican, Pingali, and Rajaram (2003) report that, on average, variety turnover in favorable environments occurs three years more quickly than in marginal environments.

The second key question raised earlier relates to the genetic diversity among CIMMYT-bred materials. This question was not examined in detail as part of this study, but it has been addressed elsewhere (for example, see Smale et al. 2001; Dreisigaker et al. 2004; Zhang et al. 2004; Reif et al. 2005). More recently, Warburton et al. (2005) have tested trends in genetic variability in CIMMYT wheat varieties over time. Using molecular markers, they characterized landraces, CIMMYT-bred varieties released during different periods starting with the Green Revolution, and advanced CIMMYT breeding lines that may soon be released. Measured at the molecular level, the amount of diversity present within CIMMYT-bred wheat materials has risen steadily over time, and the newest CIMMYT lines show similar levels of

diversity as landraces (Figure 5.7). The steady increments in diversity reflect the increasing use by CIMMYT wheat breeders of varieties and advanced lines derived from multiple landraces and synthetic wheats.

CIMMYT Contribution to Wheats Grown in Developing Countries

How has CIMMYT contributed to breeding wheat varieties that are being grown in developing countries? Four different attribution rules were used to measure CIMMYT's contributions to international

wheat breeding efforts. Ranked in decreasing order of restrictiveness, these are: (1) the CIMMYT cross rule, (2) the CIMMYT cross or CIMMYT parent rule, (3) the geometric rule, and (4) the any CIMMYT ancestor rule.

The CIMMYT cross rule (Rule 1) is the most restrictive, because it assigns credit to CIMMYT only for varieties that are the direct result of crosses made by CIMMYT breeders (Category 1).

The CIMMYT cross or CIMMYT parent rule (Rule 2) is less restrictive; it assigns credit to CIMMYT for varieties that are

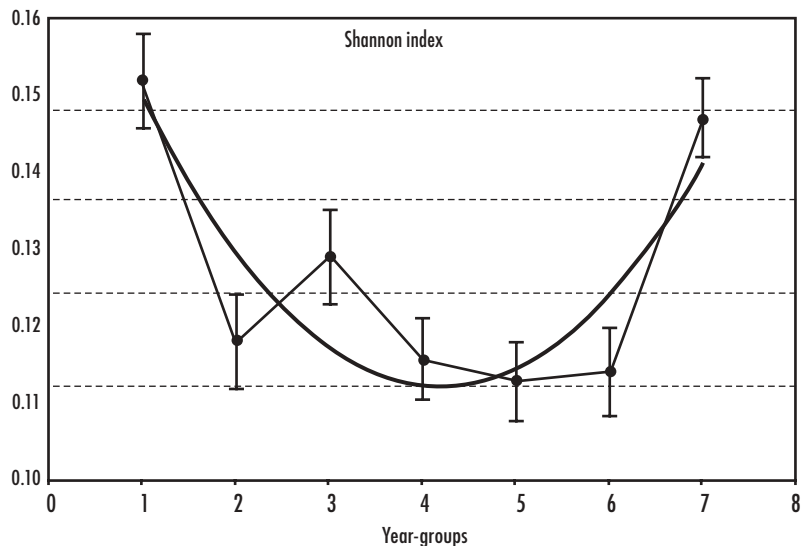


Figure 5.7. Trends in genetic diversity of CIMMYT wheat varieties.

Year-groups (X axis):	4 = 1974 – 1982
1 = Landraces (pre 1950)	5 = 1983 – 1988
2 = 1950 – 1966	6 = 1989 – 1997
3 = 1967 – 1973	7 = 1997 – 2003 (including breeding lines)

Note: Plot of the quadratic response of the Shannon diversity index over time (measured for each year-group). Each observation has \pm standard error.
Source: Warburton et al. (2005).

the result of crosses made by CIMMYT breeders (Category 1) or by NARS breeders using a CIMMYT parent (Category 2). If the variety is the direct result of a CIMMYT cross (Category 1), CIMMYT is assigned 75% of the breeding credit; if the variety has a CIMMYT parent (Category 2), CIMMYT is assigned 50% of the breeding credit. This measure is similar to that used by Byerlee and Moya (1993).

The geometric rule (Rule 3), which was popularized by Pardey et al. (1996), applies geometrically declining weights to each level of crossing, going back as many generations as desired. In other words, a weight of 1/2 is assigned to the final cross that resulted in a variety, a weight of 1/8 is assigned to each of the two crosses that produced the parents, a weight of 1/32 is assigned to each of the four crosses that produced the grandparents, and so on. The weights of the earliest generation are doubled to make all the weights add up to one. This measure assigns more credit to crosses made during the later stages of the breeding process and less credit to crosses made during the earlier stages. For this study's purposes, five generations of crossing were included, similar to the 1997 study.

The any CIMMYT ancestor rule (Rule 4) is the most inclusive, because it gives full credit to CIMMYT for all varieties developed using CIMMYT-related germplasm (Categories 1, 2, and 3), regardless of how far back in the pedigree the CIMMYT-related germplasm may have been used.

The four attribution rules were used to calculate a "CIMMYT germplasm content value" for wheat varieties grown in 2002 in the countries covered by the survey. Landraces were assigned a "CIMMYT germplasm content value" of zero. Aggregate measures of CIMMYT's contribution were then obtained by calculating area-weighted averages at the national, regional, and global levels. Figures 5.8 through 5.11 show the results.

Figure 5.8 shows the CIMMYT germplasm content of spring bread wheat varieties grown in 2002. To facilitate comparisons with the results of the 1997 study, the aggregate global results were calculated with and without data for Eastern Europe and the former Soviet Union. Including (or excluding) Eastern Europe and the former Soviet Union, the proportion of CIMMYT germplasm present in the spring bread wheat varieties grown in the developing world in 2002 was 33% (35%) using the CIMMYT cross rule, 51% (53%) using CIMMYT cross or CIMMYT parent rule, 40% (42%) using the geometric rule, and 80% (84%) using the any CIMMYT ancestor rule.

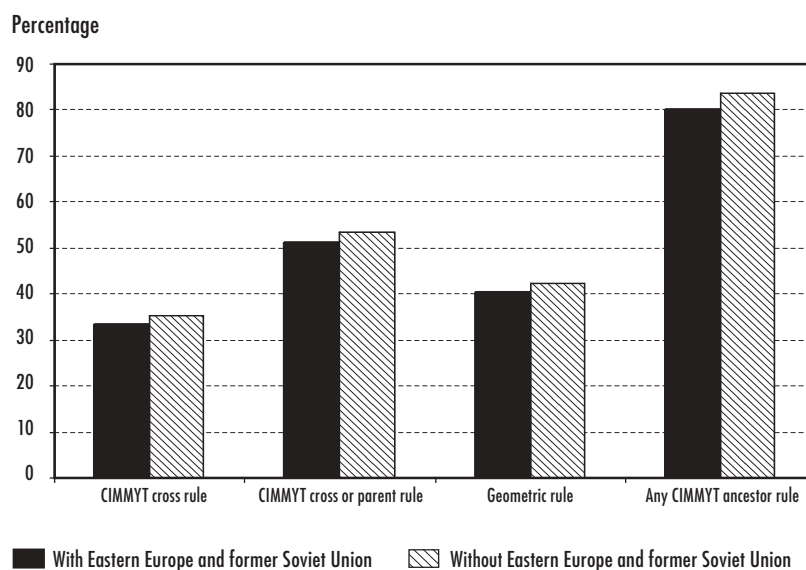


Figure 5.8. Percentage of CIMMYT's contribution to spring bread wheat planted in the developing world, 2002.

Figure 5.9 shows the CIMMYT germplasm content of spring durum wheat varieties grown in 2002. Using all four attribution rules, the values for spring durum wheats were higher than those for spring bread wheats. Only two spring durum wheat varieties were reportedly grown in 2002 in Eastern Europe and the former Soviet Union (both were grown in Russia), so there was little difference between including and excluding the data for that region. The amount of CIMMYT germplasm present in spring durum wheats was 49% using the CIMMYT cross rule, 59% using the CIMMYT cross or parent rule, 48% using the geometric rule, and 85% using the any ancestor rule.

The TURKEY/CIMMYT/ICARDA germplasm content of the winter and facultative bread wheat varieties grown in 2002 is shown in Figure 5.10. Including (or excluding) Eastern Europe and the former Soviet Union, the amount of CIMMYT germplasm present in winter and facultative bread wheats was <1% (1%) using the CIMMYT cross rule, 9% (11%) using the CIMMYT cross or parent rule, 2.8% (3.3%) using the geometric rule, and 32% (34%) using the any ancestor rule. Although estimates of CIMMYT's contributions to winter and facultative wheat planted in the surveyed

countries are not as large as they are in the case of other wheat types, it appears that the TURKEY/CIMMYT/ICARDA program is progressing and making a considerable contribution to this wheat type through collaborative winter wheat breeding.

When the data for all wheat types are combined, the CIMMYT germplasm content measures, which are area-weighted, are similar to those for spring bread wheats, which dominate the total area planted to wheat in the surveyed countries (Figure 5.11).

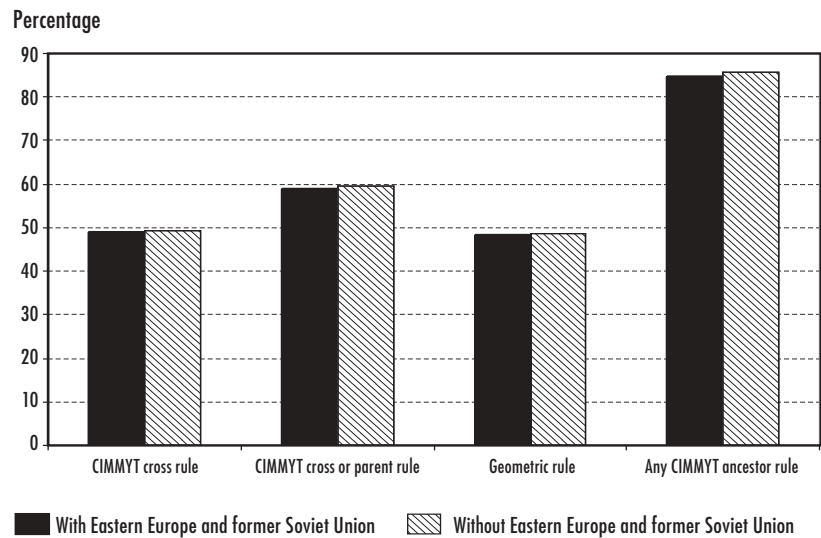


Figure 5.9. Percentage of CIMMYT's contribution to spring durum wheat planted in the developing world, 2002.

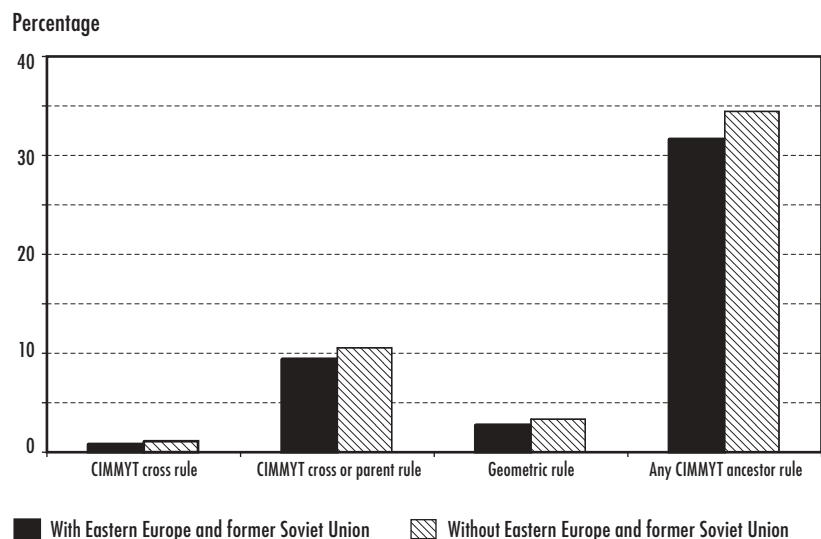


Figure 5.10. Percentage TURKEY/CIMMYT/ICARDA contribution to winter and facultative bread wheat planted in the developing world, 2002.

Regardless of the attribution rule, CIMMYT germplasm content was higher when data for Eastern Europe and the former Soviet Union were excluded.

Including (or excluding) Eastern Europe and the former Soviet Union, the amount of CIMMYT germplasm present in all wheat types was 24% (27%) using the

CIMMYT cross rule, 38% (42%) using the CIMMYT cross or parent rule, 29% (32%) using the geometric rule, and 64% (70%) using the any ancestor rule.

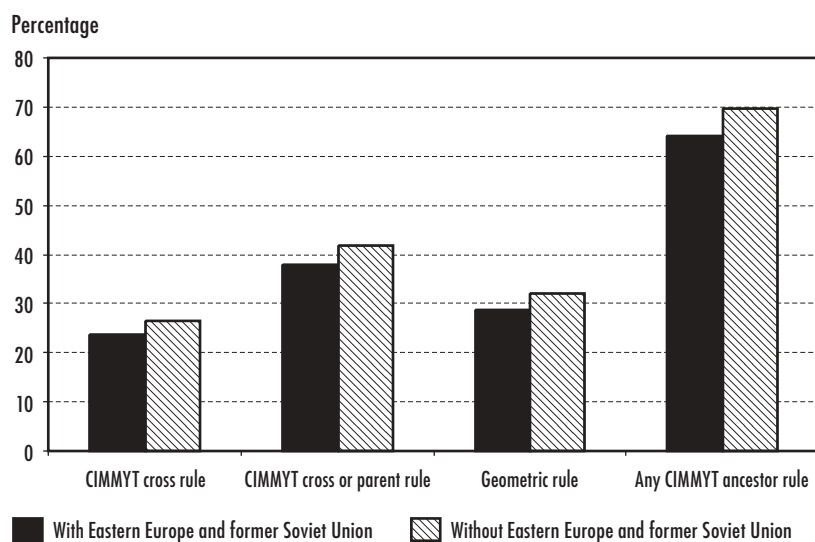


Figure 5.11. Percentage of CIMMYT's contribution to all wheat planted in the developing world, 2002.

CHAPTER 6. Benefits of International Wheat Breeding Research

What have been the economic benefits generated by international wheat breeding research? The question is important, because, as with any investment, the costs of supporting the international wheat breeding system in general and CIMMYT's wheat breeding program in particular (discussed in Chapter 3 of this report) must be assessed against the expected benefits.

Theoretical and Practical Challenges of Estimating Plant Breeding Benefits

Morris and Heisey (2003) recently reviewed the theoretical and practical challenges involved in estimating the benefits of plant breeding programs. They classified into three categories the problems encountered in most empirical studies:

Problems associated with measuring adoption of modern varieties

The first set of problems affecting efforts to estimate the benefits of plant breeding

programs relates to the difficulty of measuring the area planted to modern varieties. This includes difficulties in defining exactly what constitutes a modern variety and in knowing the area planted to modern varieties.

Problems related to evaluating benefits associated with adoption

The second set of problems affecting efforts to estimate the benefits of plant breeding programs relates to the difficulty of evaluating the benefits associated with adoption of modern varieties. They include difficulties in: (a) measuring farm-level yield gains; (b) distinguishing between yield gains attributable to the adoption of modern varieties and those attributable to accompanying changes in crop management practices; (c) accounting for non-yield benefits; (d) distinguishing between increases in yield potential versus maintaining current yields; (e) imagining counterfactual scenarios (i.e., what would have happened in the absence of the evaluated breeding program); (f) modeling aggregate price effects; and (g) accounting for policy distortions.

Appendices 1 and 2 show examples of rates of genetic gain in bread wheat grain yield in developing and developed countries, respectively. Appendix 3 shows time lags associated with wheat breeding.

Problems associated with attributing credit

The third set of problems affecting efforts to estimate the benefits of plant breeding programs relates to the difficulty of attributing credit among the many plant breeding programs that typically contribute to the development of modern varieties. They include: (a) dealing with spillovers between different research programs, and (b) disentangling complementarities between the performance of the research system and that of other supporting institutions and structures—for example, the seed supply system, the extension service, the crop marketing system, transportation and communications infrastructure, and even the school system through which farmers are educated.

Conceptual Framework

The gross annual benefits generated by international wheat breeding research were estimated using a simple economic surplus model:

$$B_t = A_t y_t P_t$$

where:

B = value of additional production attributable to wheat improvement research,

A = area planted to modern wheat varieties,

y = net yield gain attributable to wheat improvement research, and

P = price of wheat grain.

Given that many of the assumptions needed to overcome the problems described by Morris and Heisey (2003) are implicitly embedded in the choice of the economic surplus model and in the parameter values used in estimating the model, it seems useful to briefly discuss each parameter.

Value of additional production attributable to wheat improvement research (B)

The simple economic surplus approach used here focuses on a rather narrow measure of benefits—namely, the value of the additional grain production attributable to wheat improvement research. This measure fails to

capture at least two important additional benefits that may also be attributable to international wheat breeding efforts:

Non-yield benefits. Benefits that do not show up in the form of increased grain yields include improved grain quality, improved fodder and straw quality and quantity, and reduced crop growth cycles. Non-yield benefits can be very important; sometimes they actually exceed the value of yield benefits.

Improved host plant resistance to biotic and abiotic stresses. Modern wheat breeding programs seek to increase yield potential, but they also conduct “maintenance breeding” with the goal of improving host plant resistance to biotic and abiotic stresses, such as diseases, insects, moisture extremes, temperature, and soil conditions. Successful maintenance breeding allows modern varieties to avoid yield losses due to stresses, so the benefits—yield losses foregone—are essentially non-observable.

Area planted to modern wheat varieties (A)

Because wheat is a self-pollinating species, wheat varieties retain their essential genetic identity even when farmers replant farm-saved seed for many generations. This means that it is usually quite easy to determine the identity of wheat varieties being grown in farmers’

fields (the same cannot be said of open-pollinating species such as maize).

The area planted to modern wheat varieties was estimated using data generated by the 2002 survey of national breeding programs.

Net yield gain attributable to wheat improvement research (y)

Undoubtedly the single biggest challenge in estimating the benefits of international wheat breeding research is the determination of a credible estimate of the average annual yield gain attributable to international wheat breeding efforts.

Because of the difficulty of estimating yield gains realized in farmers’ fields, a model was estimated using four different values for the cumulative yield gain attributed to adoption and/or replacement of modern varieties achieved during the period 1988-2002. Under the most conservative scenario, the yield gain was assumed to be 0.15 t/ha. Under the most liberal scenario, the yield gain was assumed to be 0.45 t/ha. Intermediate scenarios were also calculated assuming yield gains of 0.25 t/ha and 0.35 t/ha.

Yield gains of this magnitude have been used in many previous studies that have estimated the benefits from international wheat breeding efforts. Heisey, Lantican, and Dubin (2002) assumed yield

gains ranging from 0.2 to 0.4 t/ha. Evenson (2000) used a figure of about 0.45 t/ha/year in his conservative estimate (intended to show the benefits of CIMMYT's wheat breeding program alone). Maredia and Byerlee (1999) calculated that CIMMYT crosses show an advantage of about 0.25 t/ha over other entries in International Spring Wheat Yield Nursery (ISWYN) trials. Byerlee and Traxler (1995) came up with the figure of about 0.35 t/ha in estimating the yield gains observed in CIMMYT-bred spring bread wheat varieties.

Price of wheat grain (P)

The additional amount of wheat grain attributable to international wheat breeding efforts (calculated as the product of the area planted to modern varieties times the average annual yield gain) must lastly be converted into value terms by multiplying by some price. In reality, the price of wheat varies depending on the location, and significant differences may be observed even within the same country. Since it would be impractical to assign different prices to wheat produced in different locations, we have followed the standard approach used in global impact studies and valued all wheat using a widely used international reference price, in this case the North American export price

(hard red winter wheat, FOB US Gulf ports). During 2002, the year of the survey, this price averaged US\$ 150/ton.

Benefits of International Wheat Breeding Research

Using the adoption data collected during the 2002 survey, as well as the yield gain assumptions described in the previous section, the additional amount of wheat produced in developing countries that is attributable to international wheat breeding research is estimated to range from 13 million tons per year under the most conservative scenario to 41 million tons per year under the most liberal scenario (Table 6.1). Converting these physical quantities into value terms, the total value of additional wheat grain production in developing countries that is attributable to international wheat improvement research ranges from US\$ 2.0 to US\$ 6.1 billion per year (2002 US dollars).

Both measures of impact—the additional quantity of wheat produced, and the monetary value represented by that wheat—increased significantly since the previous CIMMYT study was conducted using 1997 survey data on the area planted to modern varieties. The increases can be attributed to two factors: (1) an expansion in the area planted to modern varieties, and (2) an increase in the international reference price for wheat.

Benefits Attributable to CIMMYT's Wheat Improvement Research

What proportion of the benefits generated by the international wheat breeding system can be attributed to CIMMYT? The same attribution rules used to apportion credit for breeding activities can be used to apportion credit for the benefits generated by those breeding activities. As described earlier, the various attribution rules are

Table 6.1. Global benefits from international wheat breeding research.

Assumed grain yield gain from MVs ^a (t/ha)	Additional annual production (million t)	Value of additional annual production (US\$ billion 2002)
0.15	13.7	2.0
0.25	22.8	3.4
0.35	31.9	4.8
0.45	41.0	6.1

^a MVs= modern varieties.

Note: Area planted to MVs is 91.1 million hectares; the assumed price of wheat is US\$ 150/t (2002 dollars).

based on different assumptions about how credit for breeding should be allocated. The CIMMYT cross rule (Rule 1) assigns the least amount of credit to CIMMYT, the any CIMMYT ancestor rule (Rule 4) assigns the greatest amount, and the CIMMYT cross or parent rule (Rule 2) and the geometric rule (Rule 3) fall in between the two extremes.

Different estimates of the benefits attributable to CIMMYT's wheat breeding activities are shown in Table 6.2. Using the conservative CIMMYT cross rule (Rule 1), the annual benefits range from US\$ 0.5–1.5 billion (2002 dollars). Using the liberal any ancestor rule (Rule 4), the annual benefits range from US\$ 1.3–3.9 billion (2002 dollars). Using the CIMMYT cross or parent rule (Rule 2) or the geometric rule (Rule 3), values fall in between those generated by the other two rules.

Comparison with results of previous studies

How do these findings compare with the results of previous studies? Two basic approaches have been used to assess the benefits of international wheat breeding research: (a) economic surplus approaches, and (b) econometric modeling approaches combined with projection of counterfactual scenarios.

Economic surplus approaches Byerlee and Traxler (1995) evaluated the combined impact of spring bread wheat breeding activities carried out by CIMMYT and NARS. These authors concluded that already by 1990, more than two-thirds of the benefits from spring bread wheat breeding research were being generated in post-Green Revolution areas as farmers replaced older modern varieties with newer modern varieties (Type II adoption); less than one-third of the benefits were

being generated in areas where farmers were adopting modern varieties for the first time (Type I adoption). The economic surplus attributable to international wheat breeding efforts was estimated to total about US\$ 3.2 billion per year (2002 dollars).

Heisey et al. (2001) used an approach similar to the one used in the current study to estimate the impact in developing countries of international wheat breeding research. Using varietal adoption data collected during the 1997 CIMMYT survey, they calculated that the additional wheat production in developing countries directly attributable to international wheat breeding efforts ranged from 17 to 33 million tons per year, worth the equivalent of US\$ 2.0–4.0 billion (values converted to 2002 dollars).

Econometric modeling combined with projection of counterfactual scenarios

Evenson (2000) used an econometric modeling approach to estimate direct and indirect contributions to NARS breeding efforts of crop improvement research done by international agricultural research centers (IARCs). Wheat was one of a number of crops included in the study. IARC germplasm improvement efforts were assumed by Evenson to affect

Table 6.2. Global benefits attributable to CIMMYT wheat breeding research (US\$ billion per year^a).

Assumed yield gain from MVs ^b (t/ha)	CIMMYT contribution			
	0.24	0.29	0.38	0.64
	CIMMYT cross rule	Geometric rule	Cross plus parent rule	Any ancestor rule
0.15	0.5	0.6	0.8	1.3
0.25	0.8	1.0	1.3	2.2
0.35	1.1	1.4	1.8	3.1
0.45	1.5	1.8	2.3	3.9

^a In 2002 dollars.

^b MVs = modern varieties.

Note: Total benefits taken from Table 6.3.

NARSs breeding efforts in two ways: (1) by increasing the number of NARS varietal releases, and (2) by increasing the level of NARS investment in crop genetic improvement. Evenson combined the results of the econometric modeling exercise to project what would have been the number of NARS varietal releases in the absence of the IARC system. These projections were then fed into the IMPACT model at the International Food Policy Research Institute (IFPRI) to estimate the consequences of a lower varietal release rate on key parameters of interest. Evenson concluded that the number of wheat varieties released by NARSs would have been 32–45% lower in the absence of IARC wheat breeding efforts and that wheat imports by developing countries would have been 15–20% higher.

Evenson and Rosegrant (2003) later expanded on this work by using the IMPACT model to assess how prices, production, consumption, and international trade would have differed in the year 2000 under two counterfactual scenarios: (1) the 1965 crop genetic improvement counterfactual (under which investment in international plant breeding is assumed not to have increased from its 1965 level), and (2) the no IARC counterfactual (under which the IARC system is assumed not to have come

into existence, although NARS investment in crop genetic improvement research is assumed to have increased as it actually did). Evenson and Rosegrant used the IMPACT model to simulate these counterfactual scenarios. Under the “1965 crop genetic improvement counterfactual” equilibrium, they estimated that wheat prices in 2000 would have been 29–61% higher than they actually were. Under the “no IARC counterfactual” equilibrium, wheat prices in 2000 would have been 19–22% higher than they actually were. Similarly, they estimated that wheat production in 2000 would have been 9–14% lower under the 1965 crop genetic improvement counterfactual and 5–6% lower under the no IARC counterfactual.

Studies that use econometric modeling approaches combined with projection of counterfactual scenarios do not generate estimates that can be compared directly with the results of economic surplus studies. In both types of study, investment in international wheat breeding research leads to wheat production increases, but in the counterfactual scenarios an additional benefit of productivity gains in wheat is a significant decrease in the price of wheat, which translates into reduced food expenditures and real income gains for wheat consumers.

The two types of studies differ in terms of their conceptual approach, underlying assumptions, and estimation procedures, but generally speaking the findings are consistent. The recurring conclusion—which is consistent with the one reported here—is that the international wheat breeding system generates significant benefits in developing countries, amounting to billions of US dollars per year. As the counterfactual scenarios make clear, if the international wheat breeding system had not come into existence:

- international flows of improved germplasm would have been more limited;
- public investment in wheat breeding research in developing countries would have been significantly lower;
- the productivity of NARS wheat breeding programs would have been significantly lower;
- wheat production in developing countries would today be significantly lower;
- world wheat prices would today be significantly higher in real terms; and
- wheat imports by developing countries would today be significantly higher.

The bottom line is that investment in international wheat research has generated enormous benefits in developing countries, whose annual value far exceeds the investment made each year in wheat breeding research. Significantly, these benefits are broadly distributed across millions of wheat producers and consumers.

CHAPTER 7. Conclusions

The conclusions that emerged from this study were very similar to those of the two earlier global studies, in that: (1) the adoption and diffusion of modern wheat varieties has continued in the post-Green Revolution; (2) improved germplasm developed by CIMMYT's wheat breeding programs continues to be used extensively by breeding programs in developing countries; and (3) public investment in international wheat breeding research has continued to generate high rates of return. In this final section, we briefly summarize the evidence and conclude with some thoughts on the future of the international wheat breeding system.

The adoption and diffusion of modern wheat varieties in developing countries have continued in the last 15 years (1988-2002). Wheat breeding programs continue to be productive. Between 1988 and 2002, public national research organizations and private seed companies in the developing world released nearly 1,700 wheat varieties. Of these, approximately one-third were released after 1997, the year when the last

global survey was conducted by CIMMYT. There does not appear to have been a slowdown in the rate of varietal releases, even though the rates of release have varied between countries and regions. However, there was a notable increase in the proportion of released tall wheat varieties and a corresponding decrease in the release of semidwarf varieties. Most of these improved tall varieties were targeted for stressed environments.

CIMMYT germplasm continues to be used extensively by wheat breeding programs in developing countries. Quantitative estimates of the proportion of CIMMYT germplasm in wheat varieties planted in developing countries have shown that, regardless of the attribution rule used, CIMMYT germplasm content is higher in spring bread wheat, which its breeding efforts have mainly targeted, than in other varieties. Including data from Eastern Europe and the former Soviet Union, the proportion of CIMMYT germplasm content in all wheat types was 24% using the CIMMYT cross rule, 38% using the CIMMYT cross

or parent rule, 29% using the geometric rule, and 64% using the any ancestor rule. Excluding Eastern Europe and the former Soviet Union, the proportion increases to 27% using the CIMMYT cross rule, 42% using the CIMMYT cross or parent rule, 32% using the geometric rule, and 70% using the any ancestor rule.

The international wheat breeding system continues to generate enormous benefits in and for developing countries. The value of these benefits is difficult to assess with precision. Productivity gains associated with modern wheat variety adoption manifest themselves in different ways, not only with increased grain quantity, but also with improved grain and end product quality, lower consumer prices, and reduced environmental degradation. In this study, a simple economic surplus approach was used to estimate the value of the additional grain production attributable to adoption of modern varieties. Using 2002 adoption data, the additional amount of wheat produced in developing countries that is

attributable to international wheat breeding research is estimated to range from 14 million tons per year under the most conservative scenario to 41 million tons per year under the most liberal scenario. Converting these physical quantities into value terms, the total value of additional wheat grain production in developing countries that is attributable to international wheat improvement research ranges from US\$ 2.0 to 6.1 billion per year (2002 dollars). Both the amount and the value of grain have increased significantly since CIMMYT's previous study using 1997 adoption data.

The extensive use of CIMMYT germplasm by public and private breeding programs, and the widespread adoption of CIMMYT-derived varieties generate enormous benefits. Using the most conservative rule to give CIMMYT credit, the annual benefits range from US\$ 0.5 to 1.5 billion (2002 dollars). Using the most liberal rule, the annual benefits range from US\$ 1.3 to 3.9 billion (2002 dollars).

Economic benefits on the order of magnitude reported here suggest that there are attractive returns to investment in international wheat breeding research in general and to CIMMYT's wheat breeding programs in particular. Because the investment cost data collected during the 2002 survey are incomplete, this study did not conduct a rigorous economic analysis to estimate financial rate of return measures. However, clearly the benefits generated each year far exceed wheat breeding research investments. Heisey, Lantican, and Dubin (2002) estimated that the total annual investment in international wheat breeding research ranged from US\$100 to 150 million in 1990. Even if this figure had doubled in real terms in the intervening period (which seems unlikely considering the budgets of most national wheat breeding programs have stagnated), the benefit-to-cost ratio for all investments in international wheat breeding research would range between 16 : 1 and 21 : 1. Data presented earlier in this report suggest that CIMMYT's investment in wheat breeding research currently ranges from US\$ 9 to 11 million (2002 dollars) per year, and that CIMMYT-derived varieties are generating US\$ 0.5–3.9 billion per year, indicating a benefit to cost ratio of between 50 : 1 and 390 : 1.

Although CIMMYT's wheat improvement budget represents a small share of the total investment in international wheat breeding efforts, its influence is significant. By serving as a leader and catalyst in the global wheat improvement system, CIMMYT accounts for a disproportionately large share of the total benefits.

By some measures, resources committed to wheat improvement research at CIMMYT have declined in real terms in recent years. It is not clear how the real decline in wheat breeding support at CIMMYT will affect the international wheat breeding system. The information presented in this report provides compelling evidence that there are strong synergies among CIMMYT and the many collaborating public and private wheat breeding programs. If the investment decline persists, will CIMMYT be able to maintain its pivotal role in the international wheat breeding system? The answer to this question may be clearer when the next global wheat impacts study is undertaken about five years from now.

APPENDIX

Table A.1. Rates of genetic gain in bread wheat grain yield, 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 ^a	1.3	Morris, Dubin, and Pokhrel (1992)
India	1911-54	0.6	Kulshrestha and Jain (1982)
	1967-79	1.2	
India	1989-99	1.9	Nagarajan (2002)
Northwest India	1966-91 ^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	Mashingwani (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	M. Kohli, CIMMYT ^b
	1966-95 ^b	0.9	
		high fertility	
		low fertility	M. Kohli, CIMMYT ^b
Parana, 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	M. Kohli, CIMMYT ^b
		unprotected	
	1971-89 ^a	2.1	
	protected	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	1966-91	0.27	Jain and Byerlee (1999)

(Cont'd next page...)

Table A.1. Rates of genetic (Cont'd...)

Environment/location	Period	Rate of gain (%/yr)	Data source
Acid soils (rainfed)			
Rio Grande do Sul, Brazil	1976-89	3.2	Byerlee and Moya (1993)
Rio Grande do Sul, Brazil	1970-90	3.6	Tomasini (2002)
Parana, Brazil	1969-89	2.2	Byerlee and Moya (1993)
	1970-96 ^a	0.2 (ns)	M. Kohli, CIMMYT ^b
Facultative/Winter Habit Wheat Rainfed			
South Africa	1930-90	1.4	Van Lill and Purchase (1995)

^a Semidwarfs only.

^b Unpublished data.

^c Two-variety comparison only.

Note: This table is an update of Heisey, Lantican, and Dubin (2002), Rejesus, Smale, and Heisey (1999), and Byerlee and Moya (1993).

Table A.2. Rates of genetic gain in bread wheat grain yield, developed 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	Anthony and Brennan (1987)
Western Australia (low rainfall)	1884-1982	0.4	Perry and D'Antuono (1989)
Facultative/Winter Habit 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 (soft/hard)	1934-67	0.4	Feyerherm and Paulsen (1981)
	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. (low fertility)	1908-78	0.5	Austin et al. (1980)
U.K. (high fertility)	1908-78	0.4	Austin et al. (1980)
U.K.	1947-77	1.5	Silvey (1978)
Sweden	1900-76	0.2	Ledent and Stoy (1988)

Note: This table is an update of Heisey, Lantican, and Dubin (2002), Rejesus, Smale, and Heisey (1999), and Byerlee and Moya (1993).

Table A.3. Time lags involved in wheat breeding, selected wheat crosses.^a

Cross	Year cross made	Year of release in Mexico (or first developing country release)	Average year of release by NARS	Area planted, 1990 (million ha)	Area planted, 1997 (million ha)	Area planted, 2002 (million ha)
118156 ^b	1957	1966	1972	1.14	0.29	0.10
Sonalika	1961	1967 ^c	1972	6.29	1.22	1.08
Bluebird ^d	1965	1970	1975	0.94	0.11	--
Veery ^e	1974	1981	1988	3.39	3.35	0.60
Bobwhite	1974	1983 ^f	1988	0.13	1.60	0.98
Kauz	1980	1988	1994	--	1.09	1.73
Attila	1984	1995	1996	--	1.00	5.73

^a Source: Heisey, Lantican and Dubin (2002); CIMMYT Wheat Impacts database.

^b Basis of most important Green Revolution varieties. In the early 1970s, grown on about 13 million hectares, primarily in South Asia (Byerlee and Moya 1993).

^c Not released in Mexico; first released in India.

^d Planted on more than 3 million hectares in the early 1980s.

^e Most popular parent material.

^f First released in Bolivia and Pakistan.

BIBLIOGRAPHY

- Abdalla, O. S., J. Crossa, E. Autrique, and I.H. DeLacy. 1996. Relationships among international testing sites of spring durum wheat. *Crop Sci.* 36(1): 33-40.
- Ali, M., and D. Byerlee. 1991. Economic efficiency of small farmers in a changing world: A survey of recent evidence. *Journal of International Development* 3 (1): 1-27.
- Alston, J.M., and P.G. Pardey. 2001. Attribution and other problems in assessing the returns to agricultural R&D. *Agricultural Economics* 25(2-3): 141-152.
- Amsal, T., G. Getinet, T. Tesfaye, and D.G. Tanner. 1996. Effects of genetic improvement on morpho-physiological characters related to grain yield of bread wheat in Ethiopia. In Woldeyesus Sinebo, Zerihun Tadele, and Nigussie Alemayehu (eds.). *Proceedings of the Annual Conference of the Agronomy and Crop Physiology Society of Ethiopia*. Addis Ababa, Ethiopia: ACPSE.
- Anthony, G., and J.P. Brennan. 1987. *Progress in Yield Potential and Bread-Making Characteristics in Wheat in New South Wales, 1925-26 to 1984-85*. Agricultural Economics Bulletin, Division of Marketing and Economic Services, New South Wales, Australia: Department of Agriculture.
- Austin, R.B., J. Bingham, R.D. Blackwell, L.T. Evans, M.A. Ford, C.L. Morgan, and M. Taylor. 1980. Genetic improvements in winter wheat yields since 1900 and associated physiological changes. *Journal of Agricultural Science, Cambridge* 94: 675-689.
- Bohn, A., and D. Byerlee. 1993. Wheat breeding research in developing countries: Investments and impact. Part 1 of 1992/93 CIMMYT World Wheat Facts and Trends: *The Wheat Breeding Industry in Developing Countries: An Analysis of Investments and Its Impacts*. Singapore: CIMMYT.
- Bohn, A., D. Byerlee, and M.K. Mareida. 1999. Investment in wheat improvement in developing countries. In M.K. Mareida, and D. Byerlee (eds.). *The Global Wheat Improvement System: Prospects for Enhancing Efficiency in the Presence of Spillovers*. CIMMYT Research Report No.5. Mexico, D.F.: CIMMYT.
- Braun, H.-J., W.H. Pfeiffer, and W.G. Pollmer. 1992. Environments for selecting widely adapted spring wheat. *Crop Science* 32: 1420-1427.
- Braun, H.-J., S. Rajaram, and M. van Ginkel. 1996. CIMMYT's approach to breeding for wide adaptation. *Euphytica* 92: 175-183.
- Braun, H.-J., and N.N. Saulescu. 2002. Breeding winter and facultative wheat. In B. Curtis, S. Rajaram, and H. Gómez Macpherson (eds.). *Bread Wheat Improvement and Production*. Plant Production and Protection Series No. 30. Rome: FAO.
- Byerlee, D. 1992. Technical change, productivity, and sustainability in irrigated cropping systems of South Asia: Emerging issues in the post-Green Revolution era. *Journal of International Development* 4(5): 477-496.
- Byerlee, D. 1993. Technical change and returns to wheat breeding research in Pakistan's Punjab in the post-Green Revolution period. *The Pakistan Development Review* 32(1): 69-86.
- Byerlee, D., and P.F. Moya. 1993. *Impacts of International Wheat Breeding Research in the Developing World, 1966-1990*. Mexico, D.F.: CIMMYT.
- Byerlee, D., and G. Traxler. 1995. National and international wheat improvement research in the post green revolution period: Evolution and impacts. *American Journal of Agricultural Economics* 77: 268-278.
- Byerlee, D., and G. Traxler. 2001. The role of technology spillovers and economies of size in the efficient design of agricultural research systems. In J.M. Alston, P.G. Pardey, and M.J. Taylor (eds.). *Agricultural Science Policy: Changing Global Agendas*. Baltimore and London: The Johns Hopkins University Press.
- Chapman, S.C., and H.J. Barreto. 1996. Using simulation models and spatial databases to improve the efficiency of plant breeding programs. In M. Cooper and G.L. Hammer (eds.). *Plant Adaptation and Crop Improvement*. CAB International. Pp. 563-587.

- Chavas, J.P., and T.L. Cox. 1992. A nonparametric analysis of the influence of research on agricultural productivity. *American Journal of Agricultural Economics* 74(3): 583-591.
- Cox, T.S., J.P. Shroyer, B.-H. Liu, R.G. Sears, and T.J. Martin. 1988. Genetic improvement in agronomic traits of hard red winter wheat cultivars from 1919 to 1987. *Crop Science* 28: 756-760.
- Dreisigacker, S., P. Zhang, M.L. Warburton, M. van Ginkel, D. Hoisington, M. Bohn, and A.E. Melchinger. 2004. SSR and pedigree analyses of genetic diversity among CIMMYT wheat lines targeted to different megaenvironments. *Crop Science* 44: 381-388.
- Evenson, R.E. 2000. Crop germplasm improvement: A general perspective. Paper presented at the annual meeting of the American Association for the Advancement of Science. Washington, D.C., 21 February 2000.
- Evenson, R.E., and D. Gollin. 2003. Assessing the impact of the Green Revolution, 1960 to 2000. *Science* 300: 750-762.
- Evenson, R.E., and M. Rosegrant. 2003. The economic consequences of crop genetic improvement programmes. In R.E. Evenson and D. Gollin (eds.). *Crop Variety Improvement and Its Effect on Productivity: The Impact of International Agricultural Research*. Food and Agriculture Organization. Wallingford, U.K.: CABI Publishing.
- Feyerherm, A.M., and G.M. Paulsen. 1981. An analysis of temporal and regional variation in wheat yields. *Agronomy Journal* 73: 863-867.
- Feyerherm, A.M., G.M. Paulsen, and J.L. Sebaugh. 1984. Contribution of genetic improvement to recent wheat yield increases in the USA. *Agronomy Journal* 76: 985-990.
- Fischer, R.A., and P.C. Wall. 1976. Wheat breeding in Mexico and yield increases. *Journal of the Australian Institute of Agricultural Science* 42: 138-148.
- Fox, P.N. 1996. The CIMMYT Wheat Program's international multi-environment trials. In M. Cooper and G.L. Hammer (eds.). *Plant Adaptation and Crop Improvement*. Wallingford, U.K.: CAB International, International Rice Research Institute, and International Center for Research in the Semi-Arid Tropics. Pp. 175-184.
- Heisey, P.W. (ed.). 1990. *Accelerating the Transfer of Wheat Breeding Gains to Farmers: A Study of the Dynamics of Varietal Replacement in Pakistan*. CIMMYT Research Report No.1. Mexico, D.F.: CIMMYT.
- Heisey, P.W., and M.A. Lantican. 1999. International wheat breeding research in Eastern and Southern Africa. In *The Tenth Regional Wheat Workshop for Eastern, Central, and Southern Africa*. Addis Ababa, Ethiopia: CIMMYT.
- Heisey, P.W., M.A. Lantican, and H.J. Dubin. 2002. *Impacts of International Wheat Breeding Research in Developing Countries, 1966-1997*. Mexico, D.F.: CIMMYT.
- Heisey, P.W., C.S. Srinivasan, and C. Thirtle. 2001. *Public Sector Plant Breeding in a Privatizing World*. Agriculture Information Bulletin No. 772. U.S. Department of Agriculture.
- Jain, K.B.L., and D. Byerlee. 1999. Investment efficiency at the national level: Wheat improvement research in India. In M.K. Maredia and D. Byerlee (eds.). *The Global Wheat Improvement System: Prospects for Enhancing Efficiency in the Presence of Spillovers*. CIMMYT Research Report No.5. Mexico, D.F.: CIMMYT.
- Kulshrestha, V.P., and H.K. Jain. 1982. Eighty years of wheat breeding in India: Past selection pressures and future prospects. *Zeitschrift für Pflanzenzüchtung* 89: 19-30.
- Lantican, M.A., P.L. Pingali, and S. Rajaram. 2003. Is research on marginal lands catching up? The case of unfavorable wheat growing environments. *Agricultural Economics* 29: 353-361.
- Ledent, J.F., and V. Stoy. 1988. Yield of winter wheat, a comparison of genotypes from 1910 to 1976. *Cereal Research Communications* 16: 151-156.
- Lopez-Pereira, M.A., and M.L. Morris. 1994. *Impacts of International Maize Breeding Research in the Developing World, 1966-1990*. Mexico, D.F.: CIMMYT.
- Maredia, M.K., and D. Byerlee (eds.). 1999. *The Global Wheat Improvement System: Prospects for Enhancing Efficiency in the Presence of Spillovers*. CIMMYT Research Report No.5. Mexico, D.F.: CIMMYT.
- Marshall, G.R., and J.P. Brennan. 2001. Issues in benefit-cost analysis of agricultural research projects. *The Australian Journal of Agricultural and Resource Economics* 45 (2): 195-213.
- Mashingwani, N.A. 1987. Trends in Production and Consumption of Wheat and the Role of Variety Improvement in Zimbabwe. Department of Research and Specialist Services.
- Matthews, K., S. Chapman, W.H. Pfeiffer, and R.M. Trethowan. 2003. Characterization of CIMMYT's international testing environments. Presentation at a workshop on "Wheat breeding, genetic simulation, and environment characterization," Brisbane, Australia, August 2003.
- Morris, M.L. 2002. *Impacts of International Maize Breeding Research in Developing Countries, 1966-98*. Mexico, D.F.: CIMMYT.
- Morris, M.L., and P.W. Heisey. 2003. Estimating the benefits of plant breeding research: Methodological issues and practical challenges. *Agricultural Economics* 29: 241-252.
- Morris, M.L., H.J. Dubin, and T. Pokhrel. 1992. *Returns to Wheat Research in Nepal*. CIMMYT Economics Working Paper. Mexico, D.F.: CIMMYT.
- Nagarajan, S. 2002. The significance of wheat production for India, in particular under limited moisture conditions. <http://www.biotech.boil.ethz.ch/India/forms/Nagarajan.pdf>
- O'Brien, L. 1982. Victorian wheat yield trends, 1898-1977. *Journal of the Australian Institute of Agricultural Science* 48: 163-68.
- Ortiz-Monasterio, J.I., K. Sayre, S. Rajaram, and M. McMahon. 1990. Genetic progress of CIMMYT germplasm under different levels of nitrogen. *Agronomy Abstracts* 156:60.
- Pardey, P.G., and B. Craig. 1989. Causal relationships between public sector agricultural research expenditures and output. *American Journal of Agricultural Economics* 71 (1): 9-19.
- Perry, M., and M. D'Antuono. 1989. Yield improvement and associated characteristics of some Australian spring wheat cultivars introduced between 1860 and 1982. *Australian Journal of Agricultural Research* 40: 457-472.

- Pingali, P.L., and P.W. Heisey. 2001. Cereal crop productivity in developing countries: Past trends and future prospects. In J.M. Alston, P.G. Pardey, and M.J. Taylor (eds.). *Agricultural Science Policy*. Washington: IFPRI and Johns Hopkins University Press.
- Pingali, P.L., and S. Rajaram. 1999. Global Wheat Research in a Changing World: Options for Sustaining Growth in Wheat Productivity. In P.L. Pingali (ed.). *CIMMYT 1998-99 World Wheat Facts and Trends. Global Wheat Research in a Changing World: Changes and Challenges*. Mexico, D.F.: CIMMYT.
- Rajaram, S., M. van Ginkel, and R.A. Fischer. 1994. CIMMYT's wheat breeding mega-environments (ME). In *Proceedings of the 8th International Wheat Genetic Symposium*. Beijing, China. Pp. 1101-1106.
- Reif, J.C., P. Zhang, S. Dreisigacker, M.L. Warburton, M. van Ginkel, D. Hoisington, M. Bohn, and A.E. Melchinger. 2005. Trends in genetic diversity during the history of wheat domestication and breeding. *Theoretical and Applied Genetics* (in press.)
- Rejesus, R.M., P.W. Heisey, and M. Smale. 1999. *Sources of Productivity Growth in Wheat: A Review of Recent Performance and Medium- to Long-Term Prospects*. CIMMYT Economics Working Paper 99-05. Mexico, D.F.: CIMMYT.
- Sayre, K.D., S. Rajaram, and R.A. Fischer. 1997. Yield potential progress in short bread wheats in northwest Mexico. *Crop Science* 37(1): 36-42.
- Schmidt, J.W. 1984. Genetic contributions to yield gains in wheat. In W.R. Fehr (ed.). *Proceedings of a Symposium on Genetic Contributions to Yield Gains of Five Major Crop Plants*. Sponsored by C-1, Crop Science Society of America, Atlanta, Georgia, 2 December 1981. Madison, Wisconsin (USA): Crop Science Society of America and American Society of Agronomy.
- Siebert, S., and P. Doell. 2001. A Digital Global Map of Irrigated Areas: An Update for Latin America and Europe. Kassel World Water Series 4. <http://www.usf.uni-kassel.de/service/bibliothek/kwvs.4.pdf>.
- Silvey, V. 1978. The contribution of new varieties to increasing cereal (wheat and barley) yields in England and Wales. *Journal of the National Institute of Agricultural Botany* 14(3): 367-384.
- Slafer, G.A., and F.H. Andrade. 1989. Genetic improvement in bread wheat (*Triticum aestivum*) yields in Argentina. *Field Crops Research* 21: 289-296.
- Smale, M., M.P. Reynolds, M.L. Warburton, R. Trethowan, R.P. Singh, I. Ortiz-Monasterio, J. Crossa, M. Khairallah, and M.I. Almanza-Pinzon. 2001. *Dimensions of Diversity in CIMMYT Bread Wheat from 1965 to 2000*. Mexico, D.F.: CIMMYT.
- Tomasini, R.G.A. 2002. *Impact of Mexican Germplasm on Brazilian Wheat Cropping: An Ex-Post Economic Analysis*. CIMMYT Economics Working Paper No. 02-01. Mexico, D.F.: CIMMYT.
- Trethowan, R.M., J. Crossa, M. van Ginkel, and S. Rajaram. 2001. Relationships among bread wheat international yield testing locations in dry areas. *Crop Science* 41(5): 1461-1469.
- Trethowan, R.M., M. van Ginkel, and S. Rajaram. 2002. Progress in breeding for yield and adaptation in global drought affected environments. *Crop Science* 42(5): 1441-1446.
- Trethowan, R.M., M. van Ginkel, K. Ammar, J. Crossa, T.S. Payne, B. Cukadar, S. Rajaram, and E. Hernandez. 2003. Associations among twenty years of bread wheat yield evaluation environments. *Crop Science* 43: 1698-1711.
- van Lill, D., and J.L. Purchase. 1995. Directions in breeding for winter wheat yield and quality in South Africa from 1930 to 1990. *Euphytica* 82: 79-87.
- Waddington, S.R., J.K. Ransom, M. Osmanzai, and D.A. Saunders. 1986. Improvement in the yield potential of bread wheat adapted to Northwest Mexico. *Crop Science* 26: 698-703.
- Warburton, M.L., J. Crossa, J. Franco, M. Kazi, R.M. Trethowan, S. Rajaram, W.H. Pfeiffer, P. Zhang, S. Dreisigacker, and M. van Ginkel. 2005. Bringing wild relatives back into the family: Recovering genetic diversity of CIMMYT improved wheat germplasm. *Crop Science* (in review).
- White, J.W., M. van Ginkel, S. Rajaram, and J.D. Corbett. 2001. A GIS-based approach to revising CIMMYT's wheat mega-environments. *Agronomy Abstracts* 93:1.
- Zhang, P., S. Dreisigacker, A.E. Melchinger, M. van Ginkel, D. Hoisington, and M.L. Warburton. 2004. Quantifying novel sequence variation in synthetic hexaploid wheats and their backcross-derived lines using SSR markers. *Molecular Breeding* (accepted).