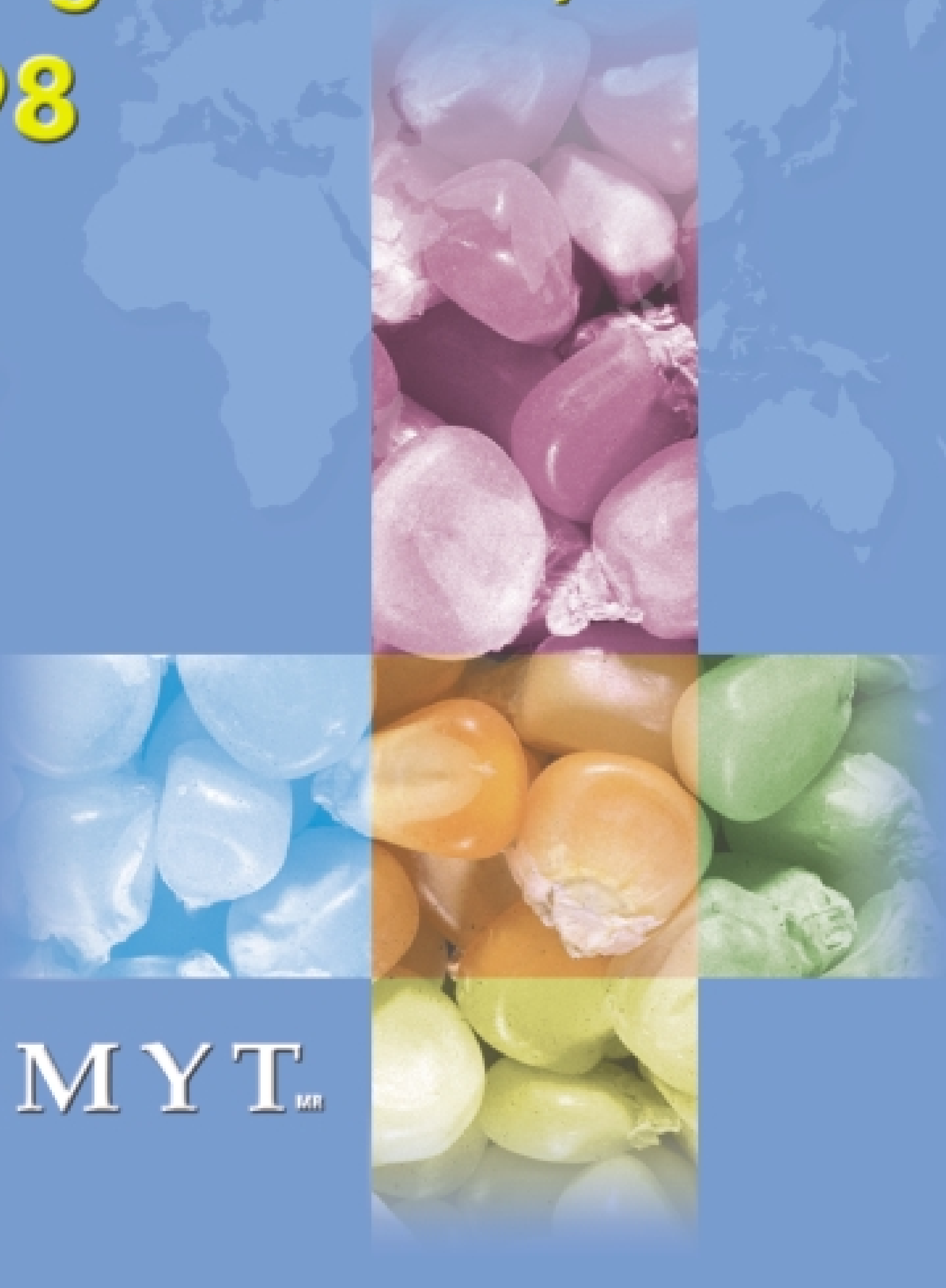
Impacts of International Maize Breeding Research in Developing Countries, 1966-98



Michael L. Morris

CIMMYT

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ECONOMICS PROGRAM

INTERNATIONAL MAIZE AND WHEAT IMPROVEMENT CENTER (CIMMYT)

CIMMYT[MR]

CIMMYT® (www.cimmyt.org) is an internationally funded, nonprofit, scientific research and training organization. Headquartered in Mexico, CIMMYT works with agricultural research institutions worldwide to improve the productivity, profitability, and sustainability of maize and wheat systems for poor farmers in developing countries. It is one of 16 food and environmental organizations known as the Future Harvest Centers. Located around the world, the Future Harvest Centers conduct research in partnership with farmers, scientists, and policymakers to help alleviate poverty and increase food security while protecting natural resources. The centers are supported by the Consultative Group on International Agricultural Research (CGIAR) (www.cgiar.org), whose members includes nearly 60 countries, private foundations, and regional and international organizations. Financial support for CIMMYT's research agenda also comes from many other sources, including foundations, development banks, and public and private agencies.

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Abstract: This report, which updates and extends the findings of an earlier CIMMYT study published in 1994, documents the impacts of international maize breeding research in the developing world. Covering the period 1966-98, the report reviews public and private investment in maize breeding research, describes the products of public and private maize breeding programs, estimates farm level adoption of modern varieties (MVs), and estimates the gross value of additional grain production attributable to international breeding efforts. Although private companies have greatly increased their investment in maize breeding research in recent years, public maize breeding programs still play an important role, especially in breeding for subsistence-oriented farmers. Seed sales data show that the maize seed industry in many developing countries has effectively been privatized and that hybrid seed sales now dominate sales of all other seed types. The area planted to MVs continues to expand at an impressive rate. Maize MVs are currently grown on at least 58.8 million ha in developing countries, including at least 21.2 million ha planted to MVs that contain CIMMYT germplasm. The gross value of additional grain production attributable to the adoption of maize MVs in developing countries is estimated to range from US$ 3.7 million to US$ 11.1 billion per year. Analysis of varietal pedigrees shows that breeders in both the public and private sectors have made extensive use of CIMMYT germplasm. Over 54% of publicly bred MVs released in the developing world since 1966 have contained CIMMYT germplasm. The pedigrees of many privately bred cultivars are confidential, but CIMMYT germplasm was present in 58% of MVs developed by private breeding programs being sold in the late 1990s for which pedigree information is available. The gross benefits attributable to CIMMYT's maize breeding program are estimated to range from US$ 167 million to US$ 1.5 billion per year.

AGROVOC descriptors: Maize; Plant breeding; Breeding methods; Germplasm; Research; Public sector; Private sector; Agricultural development; Innovation adoption; Economic analysis; Research institutions; Developing countries

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Several people who made exceptional contributions warrant special mention, however. I owe a particular debt to the authors of the three regional impacts studies that preceded this global synthesis study: Miguel López-Pereira (Latin America); Rashid Hassan, Mulugetta Mekuria, and Wilfred Mwangi (Eastern and Southern Africa); and Roberta Gerpacio (Asia). Without their efforts, much of the information reported in this document would not have been available.

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Executive Summary

This report presents summary findings of a major CIMMYT-led study undertaken to document the impacts of international maize breeding research in developing countries. Designed to update CIMMYT's original global maize impacts study published in 1994, the study had multiple objectives: to estimate public and private investment in maize breeding research, to identify the products of public and private maize breeding programs, to document the use of germplasm that has been improved by CIMMYT breeders, to estimate farm-level adoption of scientifically-bred modern varieties (MVs), and to estimate the gross value of additional grain production attributable to international maize breeding research.

Data for the study were collected during the late 1990s through a survey of 371 public and private maize breeding organizations and seed companies in 37 developing countries. With the use of secondary data, the coverage for selected analyses was extended to 51 countries that together represented over 97% of the developing world's maize area.

Maize differs from most other crops in a number of respects that affect not only the way breeding efforts are organized and carried out, but also the process by which MVs are adopted by farmers and diffused across the countryside. Because of the distinctive characteristics of maize (especially the tendency for the genetic composition of successive generations of plants to change as a result of cross pollination), maize farmers who wish to maintain the genetic purity of their crops are dependent on external sources of fresh seed in a way that farmers of self-pollinating and vegetatively propagated crops are not. The need for frequent seed replacement in maize has created a large market for commercial seed and provided strong incentives for the private sector to invest in maize breeding research. Public breeding programs that work on maize thus face stiffer competition than public breeding programs that work on other crops. At the same time, because the high price of commercial maize seed places it beyond the reach of many poor farmers, public breeding programs also face a more difficult challenge in ensuring that their germplasm products reach those who need them most.

Although most maize breeding research now takes place in the private sector, the public sector remains an important player, especially in developing countries. Public maize breeding programs continue to be very productive, developing and releasing a steady stream of MVs. On aggregate, the rate at which publicly bred maize MVs are being released has increased through time and shows no sign of slowing, suggesting that public breeding programs have not suffered any decline in productivity.

Use of CIMMYT germplasm by public breeding programs has been extensive. Of the publicly bred maize MVs released in developing countries from 1966-98 and for which information is available, over one-half (54%) contained CIMMYT germplasm. Excluding MVs adapted for temperate environments (which are not directly targeted by CIMMYT maize breeders), the proportion containing CIMMYT germplasm was even higher (59%). Belying predictions that CIMMYT's role would decline as national breeding programs grow stronger, use of CIMMYT germplasm by public breeding programs has increased.

While the extensive use of CIMMYT germplasm by public breeding programs has long been known, an unexpected finding of the study is the degree to which private breeding programs also use CIMMYT germplasm. Aggregating across all developing regions, 58% of the MVs developed by private breeding programs that were sold during the late 1990s and for which information is available contained CIMMYT germplasm. The use of CIMMYT germplasm by private breeding programs varied by region, however, being high in Latin America and more modest in other regions.

Maize seed sales data collected as part of this study make clear why the private sector invests so heavily in maize breeding research. In 1996/97, maize seed sales by companies that participated in the CIMMYT survey exceeded half a million tons. This number would have been significantly higher if seed sales data had been included for companies that did not participate in the survey, especially companies operating in northern China. The seed sales data show also that the maize seed industry has effectively been privatized in most developing countries. Excluding China, where control of the maize seed industry remains in the hands of provincial and municipal governments, private seed companies outsold public seed agencies by more than ten to one. Finally, the seed sales data indicate that as in industrialized countries, in developing countries the market for commercial maize seed is dominated by hybrids. In 1996/97, seed of open-pollinated varieties (OPVs) accounted for only 6% of all seed sold by companies that participated in the CIMMYT survey.

Scientifically-bred maize MVs have diffused widely throughout the developing world. By the late 1990s, of the 94.2 million ha planted to maize in the 51 countries covered by the study, at least 58.8 million ha (62.4%) were planted to MVs, including at least 21.2 million ha (22.5%) planted to MVs that had been developed using germplasm obtained from CIMMYT.

What influences the adoption and diffusion of maize MVs? Because farmers' technology choices are determined by a large number of factors, many of which are location specific, it is difficult to analyze varietal adoption and diffusion processes at the global level. Recent empirical work clearly shows, however, that the spread of hybrid maize is influenced not only by demand side factors that affect the profitability of the technology at the farm level, but also by supply side factors that shape incentives for firms to invest in crop improvement research, seed production, and seed distribution.

What have been the economic benefits generated by international maize breeding research? Estimating the returns to agricultural research and development (R&D) presents many practical and theoretical problems. Quantifying and valuing all the direct and indirect benefits generated by international maize breeding research would be a major task far beyond the scope of this report, so we estimate only the gross value of additional maize production attributable to the adoption of maize MVs. Based on a range of plausible assumptions about the yield gains that result from MV adoption, the gross value of additional grain production attributable to the adoption of maize MVs in developing countries is estimated to range from US$ 3.7 billion to US$ 11.1 billion per year. Approximately one-half of these gross benefits can be attributed to changes in germplasm use and approximately one-half to changes in crop management practices.

CIMMYT's maize breeding program, although modest by international standards, has achieved enormous payoffs. Depending on how credit is assigned among the various organizations that contribute to international maize breeding efforts, the gross benefits attributable to CIMMYT's maize breeding program are estimated to range from US$ 167 million to US$ 1.5 billion per year. This does not include the value of non-yield benefits, such as improved grain quality, improved fodder quality, and shorter growth cycles.

International maize breeding research clearly has been successful in the past. Will it continue to be as successful in the future? Looking ahead, there is little doubt that public breeding programs will be called upon to help bring about the substantial productivity gains that will be needed if maize production is to keep pace with projected strong growth in demand. This will mean continuing to take advantage of tried-and-true conventional breeding methods, as well as exploiting new possibilities offered by emerging biotechnology-based crop improvement techniques. Changes in the economic and institutional environments in which plant breeding research is carried out will require changes in operating procedures, however. In coming years, public breeding organizations will face a number of unprecedented challenges, including how to maintain access to genetic resources, how to maintain access to cutting edge technologies, how to maintain access to genomic databases and other sources of information needed for biotechnology-assisted crop improvement research, and how to ensure adequate levels of funding. These challenges will have to be overcome if CIMMYT and its partners are to reach the millions of small-scale, subsistence-oriented farmers who still do not enjoy full access to the fruits of the international breeding system.

Introduction

Objectives of Study

During the early 1990s, researchers at the International Maize and Wheat Improvement Center (CIMMYT) carried out a major study to document the global impacts of international maize breeding research. The results, published in 1994 in a CIMMYT monograph entitled *Impacts of International Maize Breeding Research in the Developing World, 1966-1990*, provided a wealth of information about germplasm products of maize breeding programs in developing countries and sketched out a compelling picture of the widespread dissemination of improved maize varieties and hybrids (López-Pereira and Morris 1994). In subsequent years, the data generated by CIMMYT's global maize impacts study came to be recognized as definitive and were widely used for a broad range of research investment and research management activities.

Following the completion of the initial study, CIMMYT made a commitment to update and extend its global maize impacts database and to publish summary reports approximately every five years. Regular updating of the database was considered important given the rapid rate of technological change that characterizes the global maize economy. Extending the database was considered necessary given the lack of success achieved during the initial study to collect detailed and comprehensive information from the private sector. Publishing summary reports was considered essential for making the latest information available to a wide range of research managers, policy analysts, and government decision-makers.

Efforts to update and extend CIMMYT's global maize impacts database were initiated in 1997. Given the enormity of the data collection task, the global impacts study was divided into three regional impacts studies—one each for Latin America, Eastern and Southern Africa, and Asia (see Morris and López-Pereira 1999; Hassan, Mekuria, and Mwangi 2001; Gerpacio 2001). This report summarizes and extends the results of the three regional studies and discusses the implications for future maize breeding research.

Many objectives of the current study resemble those set out in the original global maize impacts study:

- estimate the level of public- and private-sector investment in maize breeding research in developing countries,
- document germplasm outputs of public and private maize breeding programs in developing countries,
- document the use of CIMMYT materials by public and private maize breeding programs in developing countries,
- estimate the rate of farm-level adoption of improved maize germplasm in developing countries, and
- estimate the use of modern maize varieties developed using CIMMYT germplasm.

Two additional objectives of the current study are to estimate the value of additional grain production attributable to (1) international maize breeding research in general, and (2) CIMMYT's maize breeding program in particular.

Sources of Information

In addition to drawing on the original impacts data collected in 1992, this report presents new data collected during 1997, 1998, and 1999 through an extensive survey of public and private maize breeding organizations and seed companies located in 37 developing countries in Latin America; Eastern and Southern Africa; and East, South, and Southeast Asia (see Table 1 for list of countries).

Table 1. Coverage of CIMMYT global maize impacts study.

Latin America	Africa	Asia
Caribbean	*Eastern Africa*	*East Asia*
Cuba[a]	Ethiopia[a]	Southern China[a]
Dominican Republic[a]	Kenya[a]	Northern China[d]
Haiti[a]	Tanzania[a]	
	Uganda[a]	*South Asia*
Mexico and Central America		India[a]
		Nepal[a]
Costa Rica[a]	*Southern Africa*	Pakistan[d]
El Salvador[a]	Angola[a]	
Guatemala[a]	Lesotho[a]	*Southeast Asia*
Honduras[a]	Malawi[a]	Indonesia[a]
Mexico[a]	Mozambique[a]	Philippines[a]
Nicaragua[a]	South Africa[a]	Thailand[a]
Panama[a]	Swaziland[a]	Vietnam[a]
	Zambia[a]	
Andean Zone	Zimbabwe[a]	
Bolivia[a]		
Columbia[a]	*West and Central Africa*	
Ecuador[a]	Benin[b]	
Peru[a]	Burkina Faso[b]	
Venezuela[a]	Cameroon[b]	
	Chad[b]	
Southern Cone	Congo, D.R.[b]	
Argentina[a]	Côte d'Ivoire[c]	
Brazil[a]	Ghana[b]	
Paraguay[a]	Guinea[b]	
	Mali[b]	
	Nigeria[b]	
	Senegal[b]	
	Togo[b]	
	North Africa	
	Egypt[c]	

[a] CIMMYT survey [b] IITA survey
[c] Subjectively estimated [d] National maize program
Source: CIMMYT maize research impacts survey.

Compared to the first survey conducted in 1992, the follow-up survey went to greater lengths to collect data from the private sector. Detailed questionnaires were completed by the directors of 104 public maize breeding institutes and seed production agencies, as well as by representatives of 267 private seed companies. Virtually all of these respondents were personally interviewed; only in rare cases was information collected by mail, through a telephone interview, or from secondary sources.

Many survey respondents—not only from the private sector but also from the public sector—indicated that some of the information solicited for this study is considered sensitive due to its potential value to competitors (for example, pedigrees of commercial hybrids, research investment data, cultivar-specific seed sales data). For this reason, CIMMYT pledged to treat as confidential all primary data.

To extend the coverage of the study, secondary data were obtained for a number of additional countries and regions that were not directly surveyed:

- ***West and Central Africa:*** Among the international agricultural research centers supported by the Consultative Group for International Agricultural Research (CGIAR), the mandate for maize improvement in West and Central Africa is held by the International Institute for Tropical Agriculture (IITA). IITA recently conducted an impacts study within its mandate area (Manyong et al. 2000). To provide a more complete global picture of MV adoption and impacts, selected findings of the IITA impacts study relating to West and Central Africa were included in the present analysis. Since Côte d'Ivoire was not included in the IITA survey, MV adoption data for Côte d'Ivoire were subjectively estimated by adjusting the results of the 1992 CIMMYT survey to account for recent developments in the national maize sector.
- ***Northern China:*** For logistical reasons, northern China was not included in the CIMMYT survey. Shortly before this publication went to press, sources in China's national maize breeding program reported that approximately 10% of the

area planted to maize in northern China (roughly 2 million ha) is planted to cultivars with some degree of CIMMYT parentage (S. Zhang, personal communication). Because northern China was not included in the CIMMYT survey, this estimate could not be supported by seed sales data or variety-specific adoption data. Nonetheless, the area was included in the varietal adoption estimates and economic benefits calculations.

- ***West Asia and North Africa (WANA region):*** For logistical reasons, countries in the WANA region were not included in the survey. The WANA region includes five countries in which 100,000 ha or more are planted to maize: Afghanistan, Egypt, Iran, Iraq, Morocco, and Turkey. For Egypt, the area planted to maize MVs was subjectively estimated by adjusting the results of the 1992 CIMMYT survey to account for recent developments in the national maize seed sector. The other five countries account for less than 3% of the developing world's maize area, so their omission is not likely to have a significant influence on global summary statistics.
- ***Pakistan:*** Mainly for logistical reasons, Pakistan was not included in the survey. The area planted to maize MVs in Pakistan was subjectively estimated by adjusting the results of the 1992 CIMMYT survey to account for recent developments in the national maize sector, taking into consideration information provided by sources in Pakistan's national maize research program (M. Aslam, personal communication).

Geographical Coverage

The geographical coverage of the analysis presented in this report varies depending on whether it is based on the primary survey data alone or on the primary survey data plus the secondary data. The descriptions of research investment trends (Section 3) and cultivar release patterns (Section 4) are based on primary survey data and therefore relate to 37 countries representing 75% of the developing world's maize area. The analysis of varietal adoption patterns (Section 5) and the economic benefits calculations (Section 6) are based on primary survey data plus secondary data and therefore relate to 51 countries representing over 97% of the developing world's maize area.

WHY MAIZE IS DIFFERENT FROM OTHER CROPS

Distinctive Characteristics of Maize

Maize differs from other crops in a number of respects that affect not only the way international breeding efforts are organized and carried out, but also the process by which improved varieties[1] are taken up by farmers and diffused across the countryside. Before attempting to interpret the impacts data presented later in this report, it is important to understand these distinctive characteristics that make maize different.

OPEN POLLINATION

Maize (*Zea mays L.*) is a monoecious species, with a male flower (tassel) located at the top of the stem and female flowers (ears) located about mid-way down on the same plant. This spatial arrangement of the flowers facilitates both selfing (pollination of the female flower with pollen from the same plant) and crossing (pollination of the female flower with pollen from a different plant). Reproduction in maize is initiated when pollen shed from a tassel fertilizes ovules located in the ear. Each tassel on a mature maize plant can produce up to 10 million male gametes (pollen grains). These pollen grains are enclosed in anthers, which open a few days before the silks (stigmas) emerge on the ears. Within minutes of

[1] Throughout this report, the term *varieties* is used in a generic sense to refer to both open-pollinating varieties as well as hybrids. The term *OPVs* more specifically refers to open-pollinated varieties that have been improved by a formal breeding program.

landing on a silk, a pollen grain germinates, sending a pollen tube down along the stigma to the ovary, where fertilization is completed within 24 hours. A single ear can produce up to 1,000 female gametes (ovules), with each gamete eventually producing a viable seed. Although a maize plant may be shedding pollen when its silks emerge, normally more than 97% of the seeds produced by any given plant result from pollination with pollen from other plants (Aldrich, Scott, and Leng 1975).

The ability to open-pollinate distinguishes maize from other leading cereals such as wheat and rice, which are self-pollinating. When self-pollinating crops reproduce, the pollen used to fertilize a given ovary almost always comes from the same plant, with the result that each generation of plants retains the essential genetic and physiological identity of the preceding generation. By contrast, when maize reproduces, genetic material is exchanged between neighboring plants, with the result that unless pollination is carefully controlled, all of the maize plants in a given field will tend to differ from the preceding generation and from each other.

Importance of inbreeding/heterosis

Because it is a cross-pollinating crop, when maize reproduces, much depends on whether the pollen grain used to fertilize a given kernel comes from the same plant or from a different plant. Unlike self-pollinating crops such as rice and wheat, when maize plants self-fertilize, the resulting progeny are often characterized by undesirable traits, such as reduced plant size and low yields. But when maize plants cross-fertilize, some of the resulting progeny demonstrate desirable traits, such as increased plant size and high yields. Commonly referred to as "hybrid vigor," this phenomenon is attributable to the complementary action of favorable genes and is frequently exploited by plant breeders in their efforts to develop commercial varieties.

Multiple end uses

No other cereal can be used in as many ways as maize. Virtually every part of the maize plant has economic value. The grain can be consumed as human food, fermented to produce a wide range of foods and beverages, fed to livestock, and used as an industrial input in the production of starch, oil, sugar, protein, cellulose, and ethyl alcohol. The leaves, stalks, and tassels can be fed to livestock, either green (in the form of fodder or silage) or dried (in the form of stover). Even the roots can be used for mulching, incorporated into the soil to improve the physical structure, or dried and burned as fuel.

In view of the multiple end uses, it is not surprising that the maize varieties being grown today include literally thousands of distinct cultivars with different combinations of consumption traits (ear size and shape; grain size, shape, color, texture, smell, and taste; grain processing, storage, and cooking quality; endosperm oil or starch content; husk quality). Although maize is not the only crop to feature a lot of genetic diversity, what distinguishes maize from most other crops is the extent to which genetic diversity is actively managed at the household level. In most developing countries where maize is an important crop, it is not uncommon to find the same household growing three, four, and sometimes even more distinct maize varieties, each carefully selected to satisfy a specific food, feed, or industrial use.

Location-specificity of germplasm

Maize is the world's most widely grown cereal, reflecting its ability to adapt to a wide range of production environments. Maize is cultivated at latitudes ranging from the equator to approximately 50° North and South, at altitudes ranging from sea level to over 3,000 meters elevation, under temperatures ranging from extremely cool to very hot, under moisture regimes ranging from extremely wet to semi-arid, on terrain ranging from completely flat to precipitously steep, and in many different types of soil.

No universally recognized system exists for classifying maize production environments. The closest thing to a global classification system was developed by CIMMYT, which recognizes four major production environments, known as *mega-environments*: lowland tropical, subtropical and mid-altitude transition, tropical highland, and temperate. These four mega-environments, which are defined mainly in terms of climatic criteria (for example, mean temperature during the maize growing season, elevation above sea level, day length), theoretically are characterized by their relative within-class uniformity. Since the growth habits of maize plants are influenced by complex interactions among many different climatic factors, however, it is not always clear exactly where one mega-environment ends and the next begins.

There is a fundamental dichotomy between where maize grows in industrialized as compared to developing countries. Over 90% of the maize produced in industrialized countries is grown in temperate environments, but only about 20% of the maize produced in developing countries is grown in temperate environments, mainly in Argentina, northern China, and South Africa. Of the maize produced in non-temperate environments in developing countries, about 53% is grown in lowland tropical environments, 37% in subtropical and mid-altitude transition environments, and 10% in tropical highland environments.

Implications for Breeding Research

The distinctive characteristics of maize have at least three important implications for crop improvement efforts.

Farmer breeding

Because maize is an open-pollinating crop, new genetic combinations are continuously being formed in farmers' fields through natural outcrossing. In many parts of the world, farmers understand that the genetic composition of their varieties changes with every cropping cycle, and when the time comes to select seed for replanting in the following season, they are careful to choose materials that exhibit desirable traits. Some farmers take this process a step further and deliberately generate new genetic combinations by planting seed of different varieties within the same plot or in adjacent plots to encourage cross-pollination. Alternatively, through a process known as *rustification* or *creolization*, farmers may acquire seed of improved varieties, and by applying selection pressure alter their characteristics to better meet local production and/or consumption requirements. Although maize is not the only crop subjected to farm-level selection pressure, few other species can be manipulated as rapidly as maize.

Emphasis on hybrids

The distinctive biological characteristics of maize have not only encouraged farm-level breeding activity, but they have also had an important influence on institutional breeding efforts. Because the physical separation of the male and female flowers in maize makes controlled cross-pollination relatively easy, and because the twin phenomena of inbreeding and heterosis are so pronounced in maize, formal maize improvement programs have tended to concentrate on development of hybrids. The focus on hybrids as a way of achieving genetic gains makes sense from a scientific point of view, but it also makes sense from an economic point of view. Most formal maize breeding work has been carried out by profit-oriented private companies, for whom hybrids are a much more attractive business proposition than OPVs.

Location specificity of improved germplasm

The fact that most maize in industrialized countries is grown in temperate environments and that most maize in developing countries is grown in non-temperate environments has important implications for the flow of improved technology. Maize germplasm that performs well in temperate regions generally cannot be introduced into non-temperate regions without undergoing extensive local adaptation. Most of the improved varieties grown in the United States, Western Europe, and northern China therefore are of little direct use in developing countries. This means that with maize, unlike with most other major food crops, it is very difficult to transfer the fruits of the strong breeding programs of the North to the generally much weaker breeding programs of the South.

Implications for Germplasm Diffusion

The distinctive characteristics of maize not only influence breeding efforts, but they also have two important implications for the dissemination of improved germplasm.

Critical importance of seed

The dissemination of improved maize germplasm is critically dependent on the timely availability and affordability of high-quality seed. Because the genetic composition of maize plants grown from farm-saved seed tends to change considerably from generation to generation, if farmers want to be certain of maintaining a high level of genetic purity in their crops, they must purchase fresh seed for each cropping cycle.

Maize differs in this respect from self-pollinating crops such as rice and wheat, in which each generation of plants retains the essential genetic and physiological identity of the preceding generation. This means that farmers can set aside a portion of their harvest for use as seed in future cropping seasons, as long as they are careful to avoid mixing seed of different varieties. Furthermore, if they choose they can easily distribute seed to other farmers. This is precisely what happened during the green revolutions in rice and wheat: after relatively small quantities of seed were released by public breeding programs, rice and wheat MVs quickly spread though farmer-to-farmer seed exchanges, with relatively little involvement on the part of any sort of formal seed industry. Improved varieties of vegetatively propagated crops such as potato, sweet potato, cassava, plantain, and banana also can spread without the assistance of a formal seed industry, since farmers can replant materials harvested from their own fields.

Need for an effective seed industry

Since genetically pure maize seed is costly and technically difficult to produce, the fact that fresh seed must be acquired for each cropping cycle means that improved maize varieties and hybrids can disseminate only with the support of a viable seed industry. On the face of it, this would not seem to present a problem. The global maize seed industry is enormous, and the leading seed companies invest enormous sums in crop improvement research, seed production, and seed distribution activities. As will be shown below, however, the focus of most seed companies does not extend to all farmers in all regions, and in many parts of the world, particularly in developing countries, the seed industry is conspicuous by its absence. Most farmers in these areas that have been neglected by the seed industry simply do not have reliable access to sufficient quantities of high-quality seed, and as a result few grow improved varieties.

Reaching the Subsistence Farmer: A Unique Challenge

Because maize has so many distinctive characteristics that affect the way in which improved germplasm is developed and disseminated to farmers, public breeding programs that work on maize face a much more difficult task than public breeding programs that work on other crops. The challenge faced by public maize breeding programs is unique in a number of respects:

- ***Stiff competition from the private sector:*** Private-sector investment in maize breeding research far exceeds public-sector investment in breeding research for any other food crop. Public maize breeding programs thus face extremely stiff competition in the form of a flourishing global maize seed industry made up of large, well-funded, multinational corporations, all of which invest enormous sums in crop improvement research. In this respect, maize differs from rice, wheat, barley, millet, and most other food crops, which have attracted little interest from the private sector.
- ***Limited scope for capturing research spillins:*** Public maize breeding programs could potentially benefit from the extensive private-sector investment in breeding research if they could take advantage of improved materials developed by the private sector. Unfortunately, the possibility of capturing "spillin" benefits is precluded by the location specificity of maize germplasm. Virtually all of the germplasm being worked on by leading private seed companies is temperate germplasm destined for the commercial production zones of North America, Western Europe, northern China, Argentina, and South Africa; this germplasm is generally of limited use in the non-temperate production zones targeted by many public breeding programs.
- C***onsiderable achievements of farmer-breeders:*** Since maize was domesticated 5,000-10,000 years ago, farmers have developed an enormous number of varieties that not only meet specialized consumption preferences but also show excellent adaptation to local growing conditions. Although farmers impose selection pressure in all crops, in the case of maize the open-pollinating characteristic has allowed progress to be achieved unusually fast. Modern maize breeding programs thus face a particularly difficult challenge in attempting to compete with landraces and farmer-bred varieties.
- ***Diversity of farmers' varietal preferences:*** Because maize has multiple end uses, maize breeders face the additional challenge of having to develop many different types of varieties to meet farmers' varietal preferences. The problem is particularly daunting for breeders who are trying to develop varieties for subsistence farmers, who typically grow several varieties with completely different characteristics. In a world of finite research resources, the greater the number of varieties being developed, the less resources that can be devoted to each cultivar, and the less progress that is likely to be achieved.
- ***High cost of hybrid seed:*** The high cost of producing hybrid seed poses a final challenge to public-sector maize breeding programs, because even when it is possible to develop hybrids that significantly outperform farmers' current varieties, often it is not possible to produce improved seed at a price that subsistence farmers will be willing and able to pay. In most developing countries, the private seed industry is now targeting commercial farmers who regularly purchase improved seed, meaning that public breeding programs for all intents and purposes are left serving those farmers who are unable to afford improved seed.

Investment in Maize Breeding Research

International maize breeding efforts are carried out on a global stage populated by many different actors. No effort will be made here to enumerate all of these actors and to describe their activities in detail. Such an exercise would in any case be pointless; the global maize breeding industry is evolving very rapidly, and the actors and their roles change practically on a daily basis. The more modest objectives of this section therefore are to provide a brief overview of international maize breeding efforts, to introduce the major institutional players, and to summarize their germplasm improvement activities.

International Agricultural Research Centers (IARCs)

Maize improvement work is carried out at two of the 16 international agricultural research centers (IARCs) that are members of the CGIAR. CIMMYT, headquartered in Mexico, holds a global mandate for maize improvement. IITA, headquartered in Nigeria, holds a regional mandate for maize improvement and targets mainly humid tropical zones of West and Central Africa. This report focuses mainly on the impacts of the CIMMYT maize breeding program, which is by far the larger of the two. Information about the impacts of the IITA maize breeding program can be found in Manyong et al. (2000).

The organization of maize breeding activities at CIMMYT is consistent with the Center's mandate to provide support to local breeding programs in developing countries. The objective of the CIMMYT maize breeding program is not to produce finished varieties that can be delivered directly to farmers. Rather, the CIMMYT maize breeding program seeks to develop intermediate products for use by local breeding programs, i.e., improved germplasm showing high yield potential, good agronomic characteristics, resistance to important biotic and abiotic stresses, and/or enhanced nutritional quality. CIMMYT scientists accomplish this goal by collecting, evaluating, and preserving a wide range of maize germplasm; by improving materials in their own breeding plots; and by managing an international testing network through which sets of experimental materials (known as "nurseries") are distributed to key sites around the world for evaluation by local collaborators. In return for growing the nurseries under specified levels of management and recording key performance data, the collaborators are free to request additional seed of promising materials for use in their own breeding programs. The CIMMYT-managed international testing networks thus provide national breeding programs with ready access to germplasm and information that they would not be able to generate on their own.

The germplasm improvement strategy pursued by the CIMMYT Maize Program has evolved over the years in response to changes in the environment in which CIMMYT operates. During the first several decades of CIMMYT's existence, at a time when maize breeders in most industrialized countries were concentrating almost exclusively on hybrid development, CIMMYT maize breeders continued to work mainly with open-pollinating materials. The emphasis on OPVs was justified by four beliefs prevailing at the time:

(1) hybrid technology could not succeed without the support of a sophisticated seed industry, which was still lacking in most developing countries;

(2) hybrid technology was inappropriate for small-scale farmers, who could not afford to purchase new seed annually;

(3) OPV seed could be produced with simple technology, and once distributed, would travel from farmer to farmer; and

(4) improved breeding methods for population improvement offered the opportunity for OPVs to match hybrids in terms of yield potential, and, in any event, population improvement would improve the genetic base from which hybrids could later be developed.

Over time, these beliefs began to be challenged by events in farmers' fields. In many developing countries, despite large-scale efforts to promote OPVs, adoption was less extensive than expected, and even where OPVs were initially adopted, few farmers replaced seed on a regular basis. In the absence of a private seed industry, OPV seed production was left to inefficient parastatal seed companies or assigned to development projects lacking in technical expertise, long term sustainability, or both. As a result, OPV seed supply and quality were often inadequate.

As efforts to promote the use of OPVs foundered, interest in hybrids gradually increased. Despite the widely held belief that hybrid technology was not suitable for small-scale subsistence-oriented farmers, evidence was emerging to show that hybrids could be adopted successfully by smallholders. In El Salvador, Kenya, Venezuela, Zambia, and Zimbabwe, adoption of hybrids by smallholders resulted from "spillover" out of the commercial farming sector. In all of these cases, hybrids were initially targeted at large-scale commercial growers, but when the superior performance of commercial hybrids generated demand for these materials among small-scale producers, seed companies recognized a potential new market and adjusted their marketing strategies accordingly. The diffusion of hybrids by smallholders gained additional momentum following the privatization of many national seed industries, since private seed companies concentrated almost exclusively on hybrids for commercial reasons.

The shift in interest to hybrids, which also coincided with the rise of the private seed industry, led eventually to a change in the breeding strategy of the CIMMYT Maize Program (CIMMYT 1998). While the traditional population improvement work was maintained, beginning in the late 1980s, an inbreeding program was established with the goal of generating inbred lines for use in hybrid crossing programs. The inbreeding program gathered strength throughout the 1990s and currently accounts for about half of CIMMYT's total maize breeding effort.

In terms of of researchers, the IARCs are minor actors in the global maize breeding industry. The CIMMYT Maize Program currently includes about 35 scientist FTEs (full-time equivalents), of which approximately 30 are engaged in breeding or breeding support (including genetic resources conservation and management). The IITA Crop Improvement and Plant Health Management Divisions currently include about 12 maize scientist FTEs, of which approximately 8 are engaged in breeding or breeding support. Numbering less than 50 scientist FTEs between them, the CIMMYT and IITA maize breeding programs thus are considerably smaller than many national maize breeding programs.

How has CIMMYT's investment in maize genetic improvement evolved through time? The question is not as straightforward as it seems, because CIMMYT's investment in maize genetic improvement can be defined broadly or narrowly. Given that CIMMYT is first and foremost a plant breeding institute, it could be argued that CIMMYT's entire budget is ultimately dedicated to the improvement of its two mandate crops. Yet certain activities carried out by CIMMYT staff have little direct connection to plant breeding (for example, farming systems research, natural resource management research, certain types of social science research, networking and training activities), so it could also be argued that something less than the Center's entire budget is spent on crop improvement research.

Figure 1 shows the evolution of CIMMYT's expenditures on maize improvement research under two sets of assumptions. In Scenario 1, it is assumed that CIMMYT's entire budget is dedicated to crop improvement research and that the budget can be allocated between maize and wheat

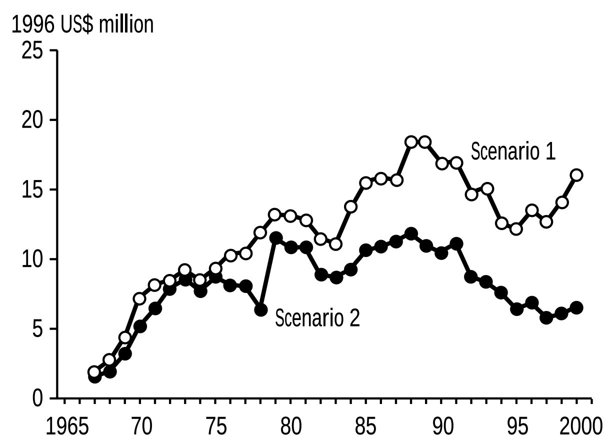

Figure 1. CIMMYT maize research expenditures, 1967-99.
Source: CIMMYT Audited Financial Statements, Annual Reports.

programs in proportion to the relative sizes of the budgets. In Scenario 2, it is assumed that the proportion of CIMMYT's entire budget that can be allocated to maize improvement research is proportional to the number of senior Maize Program staff among all senior staff (not only Maize and Wheat Program staff, but also staff of other research programs and support units). The assumptions underlying Scenario 1 are very generous, while those underlying Scenario 2 are very conservative, so the amount spent by CIMMYT on maize breeding research probably lies somewhere in between these two extremes. All expenditures have been adjusted for inflation by converting to 1996 US dollars (1996 was selected as the base year to facilitate comparison with other research investment data presented later in this report).

Under Scenario 1, CIMMYT's real investment in maize genetic improvement rose steadily throughout the 1960s, 1970s, and 1980s, peaking in 1989 at just over US $21 million per year. Thereafter, investment declined, falling to just under US $14 million per year during the mid 1990s before beginning to rise again at the end of the decade. Under Scenario 2, CIMMYT's real investment in maize genetic improvement rose throughout the 1960s and 1970s, peaked in 1978 at about US $13 million per year, remained more or less constant until the early 1990s, and subsequently declined. The marked difference between the two scenarios results from the fact that Scenario 2 figures were calculated based on staff numbers. In recent years, numbers of Maize Program staff have declined as a proportion of total staff with the diversification of CIMMYT's research portfolio and associated growth in the number of non-crop program staff.

Based on these data, it can be concluded that CIMMYT currently invests between US $8 and US $18 million per year on maize genetic improvement. In interpreting these figures, it should be noted that a portion of CIMMYT's budget (estimated at 8-15%) consists of flow-through funds that go directly to national program partners, so the amount spent by CIMMYT on its own research is actually somewhat lower.

Public National Breeding Programs

Traditionally, the principal clients of the CIMMYT Maize Program have been public maize breeding programs in developing countries. These public breeding programs vary in size, organization, and focus. Generally speaking, the level of sophistication varies as a function of the economic and political importance of maize. In countries in which maize is a relatively minor crop, the expected returns to investment in maize research are low, so national maize programs tend to be quite small. In these countries, the national breeding program often concentrates on importing materials developed elsewhere and screening them to identify those that are well adapted to local conditions. In countries in which maize is of intermediate importance, the expected returns to investment in maize research are greater, and therefore a more substantial investment in maize research is justified. In these countries, the national breeding program may take on additional functions, such as crossing inbred lines and testing the resulting hybrids. In countries in which maize is a major crop, the potential returns to investment in maize research are large, and often it will be economically efficient to establish a full-fledged national breeding program that engages in the full range of germplasm improvement activities, including germplasm conservation, population improvement and pre-breeding, inbred line development, test-crossing, and cultivar evaluation.

The level of public investment in maize research in developing countries is difficult to estimate with precision. Commodity-specific research investment data are rarely available, and when they are available, usually do not provide a full accounting of all expenses (e.g., capital investment, administrative overheads). In addition, national accounts frequently do not include funds obtained from external sources, particularly development assistance grants from foreign donors, which can be significant.

Where financial data are unavailable, a less complete but more easily quantified measure of research investment is the number of people working in research. Table 2 presents data on numbers of scientists working on maize improvement research in public institutes in developing countries. (A scientist working on maize improvement research was defined as someone who engages in breeding or directly supports germplasm improvement work.) During the late 1990s, the public sector was still a major player in the international maize breeding industry, supporting nearly 1,000 scientists. These scientists were quite evenly distributed across all developing regions, with the exception of China, which supported a disproportionately large share.[2] The organization of public breeding programs varied considerably, however. Public breeding activities in Latin America and Asia were generally more decentralized, with larger numbers of relatively small breeding programs, whereas in Eastern and Southern Africa they were generally more centralized, with fewer numbers of larger breeding programs.

The data in Table 2 also reveal some interesting patterns in the intensity of public investment in maize research. Controlling for the size of the maize sector, the number of publicly supported maize scientists was much higher in Asia than other regions, presumably reflecting the relatively low cost of human capital in Asia. Interestingly, both of the research intensity indicators shown in Table 2 (scientists/million ha planted to maize, scientists/million tons of maize production) have decreased since the first CIMMYT global impacts survey was conducted, indicating that public investment in maize breeding (measured in terms of numbers of scientists) declined during the 1990s.

Table 2. Public-sector maize research investment indicators, developing countries, late 1990s.

	Number of countries surveyed	Public maize breeding programs	Maize scientists (FTEs)	Maize scientists per program	Maize scientists per million ha maize area	Maize scientists per million t maize production
Latin America	**18**	**49**	**290**	**5.9**	**10.2**	**4.2**
Brazil		*7*	*55*	*7.9*	*4.1*	*1.7*
Mexico		*13*	*131*	*10.0*	*16.8*	*7.4*
Eastern and Southern Africa	**12**	**4**	**109**	**27.3**	**7.6**	**4.1**
East, South, and Southeast Asia	**7**	**116**	**505**	**4.4**	**26.3**	**11.0**
China (southern)		*65*	*270*	*4.2*	*65.6*	*17.5*
India		*27*	*56*	*2.1*	*9.1*	*5.7*
All regions	**37**	**169**	**904**	**5.3**	**14.6**	**6.4**

FTEs = Full-time equivalents
Source: CIMMYT maize research impacts survey.

[2] Since the China data in Table 2 refer only to the five southern provinces of China in which maize is grown mainly in non-temperate production zones, they do not include an additional 1,500 Chinese breeders working in central and northern China. When these additional breeders are included, two out of every three maize breeders in the developing world are Chinese!

Table 3 presents estimates of the average annual support cost (salary and benefits) of four categories of research personnel: senior scientists, junior scientists, research technicians, and field laborers. The estimates do not include operating budgets and capital investment costs, so they significantly understate total investment costs. Even so, they provide valuable insights into the size and distribution of public investment in maize breeding research during the late 1990s. Personnel support costs varied considerably between regions, being highest in Latin America and lowest in Asia. (Average research investment costs for Asia are greatly influenced by the large national maize breeding programs of China and India, countries in which salaries and benefits paid to public-sector employees are very low by international standards.)

Private Seed Companies

Maize breeding programs are also found in the private sector. This has not always been the case, at least not in the developing world. Until quite recently, policy makers in many developing countries believed that research on maize and other staple food crops was too important to be entrusted to the private sector, and private companies were legally prohibited from engaging in maize breeding research. Over time, as the performance of many government seed organizations deteriorated, opposition to private-sector participation in the seed industry gradually subsided. Beginning in the 1970s in Latin America, in the 1980s in Asia, and in the 1990s in Africa, reforms were enacted in many countries that broke up longstanding government seed monopolies and paved the way for increased private-sector participation in plant breeding research and commercial seed production.

The privatization of national maize seed industries played out differently in different countries, depending on the nature and sequencing of reforms, on the structure of the pre-existing seed industry, and on the prevailing business climate into which reforms were introduced. In many countries in which maize is economically or politically important, reforms to the maize seed industry were initially designed to favor domestic companies; restrictions were often maintained on foreign investment in the maize seed industry, ostensibly to protect national food security. Effectively sheltered from foreign competition, newly-formed domestic seed companies moved quickly to establish a presence in what initially were still largely uncontested markets. The number of seed companies that sprang up varied from country to country. In countries where the small-scale business sector was already well established, seed industry liberalization often resulted in the emergence of large numbers of small private seed companies that thanks to their low capital investment requirements, operational flexibility, and intimate knowledge of local markets were able

Table 3. Direct support costs of public-sector maize research personnel, developing countries, late 1990s.

	Senior researchers		Junior researchers		Technicians		Casual laborers		Total direct personnel costs (US $)
	Number	Cost (US $)	Number	Cost (US $)	Number	Cost (US $)	Number	Cost (US $)	
Latin America	126	39,000	164	18,000	207	10,000	312	4,000	11,079,000
Eastern and Southern Africa	83	15,000	53	8,000	165	7,000	1,045	3,000	5,878,000
East, South, and Southeast Asia	182	6,000	295	3,000	294	4,000	435	3,000	4,307,000
All regions	391	18,000	512	8,000	666	6,000	1,792	3,000	21,263,000

Source: CIMMYT maize research impacts survey.

to compete effectively with the large, inflexible, and sluggish government seed monopolies on which farmers previously depended. In countries where the small-scale business sector was less well developed, seed industry liberalization often resulted in the privatization of well-established government seed agencies, resulting in national seed industries that were populated by relatively small numbers of large players.

Lacking established breeding programs of their own, virtually all of the newly formed private companies started out producing and selling seed of varieties that had been developed by public breeding programs. A high proportion of the first-generation private seed companies in fact were founded by public-sector breeders who quit their posts in the national breeding program to form seed companies. Since all of the companies offered basically the same varieties, competition was not based on germplasm per se, but rather on seed quality, price, and availability. In many countries, private start-ups quickly wrested a significant portion of the market away from government seed agencies, which continued to be plagued by problems of poor seed quality, inadequate supplies, and late delivery.

When fears that privatization of national seed industries would bring disastrous results proved unfounded, the initial cautious policy reforms were followed by more substantial reforms that among other things opened the door to increased foreign investment. Beginning in the late 1980s, most of the leading multinational seed companies began to take advantage of the lowering of investment barriers by expanding into developing country markets from their bases in Europe and North America. Initially, these expansionary efforts targeted mainly big countries with important commercial maize sectors, such as Argentina, Brazil, and Mexico in Latin America; Kenya, Nigeria, and South Africa in Africa; and India, Indonesia, the Philippines, and Thailand in Asia. Market penetration strategies varied. Some companies chose a more conservative course and at first set up only seed production facilities, intending to produce commercial seed using imported parental lines that had been developed elsewhere. Other companies opted for a more aggressive strategy by investing immediately in local research facilities, realizing from the outset that most of the commercial hybrids being sold in North America and Europe were unlikely to perform well in tropical and non-tropical production environments.

With the rapid proliferation of national seed companies and the appearance of more multinationals, competition began to heat up. In many countries, it soon became clear that the industry had over-expanded; excess production capacity began to manifest itself at the end of every planting season in the form of increasing numbers of companies left with unsold stocks of seed. Seed companies soon realized that the only way to survive in saturated markets was by offering distinctive products, i.e., unique varieties that could be differentiated in the marketplace from those of competing companies. Since the obvious way to acquire unique varieties was by establishing an in-house breeding program, companies with access to sufficient capital began to invest in research, with the goal of developing their own proprietary hybrids. Companies that were not able to establish breeding capacity had little choice but to continue multiplying and selling seed of public varieties; unable to survive on the low margins that characterized this intensely competitive sector, many of these companies eventually folded.

Meanwhile, many multinational companies were also running into problems. Many discovered that their hybrids were not suitable for developing countries; either the germplasm was poorly adapted to local production conditions, or the grain quality was unacceptable. Even when their hybrids were suitable, often the multinationals found that it was difficult to produce and distribute seed in countries where prevailing business practices were unfamiliar. Faced with these unexpected problems, the multinationals had two basic options: withdraw from the market altogether, or adopt an alternative strategy. In some instances, they chose to withdraw, if not from all developing countries, then at least from some. Many leading multinationals have closed down operations in some developing countries, and most multinationals continue to avoid entire regions of the developing world (for example, West Africa).

More commonly, however, the multinationals adopted an alternative strategy. Usually this involved joining forces with an established local partner, whether through a joint-operating agreement, a partnership, or an outright acquisition. Typically the multinational brought to the partnership a strong breeding program, a steady supply of improved germplasm products, and investment capital, while the local partner (more often than not a seed company) brought an established distribution network, knowledge of local markets, and the ability to operate effectively in the prevailing business climate.

These twin pressures—the pressure on national seed companies to come up with improved germplasm products that can be differentiated in the market from those of competitors, and the pressure on multinationals to gain access to effective distribution networks for their proprietary hybrids—have led to a structural transformation of most national seed industries. During the past decade, many small national seed companies have been swallowed by larger competitors, which themselves have formed alliances with multinational partners who can provide improved germplasm and capital.

One result of this structural transformation, which is still very much underway, has been a blurring of the distinction between "domestic seed companies" and "multinationals." Although at the extremes it is often possible to differentiate between the two categories, in between the small family-owned local seed companies that populate one end of the spectrum and the large multinationals that populate the other are a large number of medium-sized companies that may be registered as domestic corporations and operate within the boundaries of a single country but that share financial assets, germplasm, and/or business services with an overseas partner.

Table 4 presents data on private-sector maize research investment indicators for developing countries during the late 1990s. Subject to the caveat described above, the data are disaggregated into two categories, national companies and multinationals. By the late 1990s, the private sector

Table 4. Private-sector maize research investment indicators, developing countries, late 1990s.

	Number of countries surveyed	Private seed companies with breeding programs		Private-sector maize researchers		Maize scientists per million ha maize area	Maize scientists per million t maize production
		National	Multinational	National	Multinational		
Latin America	**18**	**65**	**27**	**101**	**109**	**7.4**	**3.1**
Brazil		*14*	*5*	*24*	*42*	*4.9*	*2.1*
Mexico		*20*	*4*	*23*	*20*	*5.5*	*2.4*
Eastern and Southern Africa	**12**	**10**	**2**	**10**	**35**	**3.1**	**1.7**
East, South, and Southeast Asia	**7**	**24**	**22**	**64**	**96**	**8.3**	**3.5**
China (southern)		*1*	*1*	*n.a.*	*n.a.*	*n.a*	*n.a*
India		*18*	*10*	35	40	*12.2*	*7.7*
All regions	**37**	**99**	**51**	**174**	**240**	**6.7**	**3.0**

Source: CIMMYT maize research impacts survey.

had become a major player in the maize breeding industries of most developing countries, employing over 400 senior breeders. Nearly 60% of these were employed by multinational companies, a marked increase from earlier years, when most maize breeding work was still being carried out in national companies. In contrast with the public sector, however, breeding capacity in the private sector was not distributed evenly throughout the developing world. Latin America and Asia (with the exception of China) supported a large number of private seed companies, reflecting not only the presence in those regions of important commercial maize sectors, but also a friendlier business climate. Private seed companies were much less common in Eastern and Southern Africa, reflecting the relative scarcity in this region of commercial maize sectors, as well as generally more challenging business environments.

Regional differences in numbers of private seed companies and numbers of private-sector maize breeders were reflected in similar differences in the intensity of private-sector investment in maize research. Controlling for the size of the maize sector, the number of private maize breeders was more than twice as high in Latin America and Asia than in Eastern and Southern Africa. Both research intensity indicators (scientists/million ha planted to maize, scientists/million tons of maize production) have risen significantly since the first CIMMYT survey was conducted, indicating that private investment in maize breeding (measured in terms of numbers of scientists) increased during the 1990s.

Table 5 presents estimates of the direct costs reported by private seed companies of supporting four categories of maize researchers: senior scientists, junior scientists, research technicians, and field laborers. Direct personnel support costs varied between regions. As in the public sector, personnel support costs in the private sector were highest in Latin America, but for private companies the cost of supporting research personnel was also relatively high in Asia. In all three developing regions, researchers employed by multinationals cost approximately twice as much to support as researchers employed by national companies, a difference attributable partly to differences in salaries and partly to differences in benefits (for example, international relocation costs).

Table 5. Direct support costs of private-sector maize research personnel, developing countries, late 1990s.

	Senior researchers		Junior researchers		Technicians		Casual laborers		Total direct personnel costs (US $)
	Number	Cost (US $)	Number	Cost (US $)	Number	Cost (US $)	Number	Cost (US $)	
Latin America									
National companies	47	71,000	54	29,000	84	14,000	238	4,000	7,095,000
Multinationals	52	137,000	57	60,000	241	29,000	318	6,000	19,531,000
Eastern and Southern Africa									
National companies	28	19,000	5	8,000	21	3,000	172	1,000	814,000
Multinationals	19	46,000	16	16,000	41	5,000	150	2,000	1,562,000
East, South, and Southeast Asia									
National companies	35	20,000	35	11,000	45	6,000	158	3,000	1,858,000
Multinationals	51	75,000	37	45,000	105	15,000	153	5,000	7,830,000
All regions									
National companies	109	42,000	93	21,000	150	10,000	568	3,000	9,767,000
Multinationals	123	97,000	110	49,000	386	23,000	621	5,000	28,923,000

Source: CIMMYT maize research impacts survey.

Importance of the Public and Private Sectors

Even though they represent an incomplete measure, these data on direct personnel support costs still provide a basis for comparing the relative size of public and private investment in maize breeding research. Summarizing across all three developing regions, during the late 1990s public expenditure on maize research personnel totaled approximately US $ 21.3 million per year. Over half of this amount was spent in Latin America (US $ 11.1 million), while the rest was spent in Africa (US $ 5.9 million) and Asia (US $ 4.3 million).

During the same period, private-sector expenditures on maize breeding research were considerably higher. Summarizing across all three developing regions, private-sector expenditures on direct personnel support costs totaled about US $ 38.7 million per year, of which about US $ 25.6 million was spent in Latin America, US $9.7 million in Asia, and US $ 2.4 million in Africa. Multinational seed companies outspent national seed companies by nearly 3:1, confirming the increasingly dominant role of multinationals in the developing world's maize seed industry. The investment advantage enjoyed by multinationals was even larger than these figures suggest, because no attempt has been made to factor in the cost of research carried out in industrialized countries. In breeding hybrids destined for developing-country markets, all multinationals draw heavily on technology and improved germplasm produced in their advanced laboratories and breeding stations located in North America and Europe.

Case study evidence from several countries suggests that direct personnel support costs make up 40-50% of total operating costs of a typical maize breeding program, so these figures can be doubled to arrive at a rough approximation of total investment in maize breeding research.

Products of Maize Breeding Research

The principal product of any maize breeding program is improved germplasm, so an important first step in assessing the impacts of international maize breeding research in developing countries is to compile a complete inventory of germplasm products.

Information about maize varieties developed by public breeding programs was collected in 1992 during the original CIMMYT global impacts survey. The public-sector varietal releases database was updated and expanded during the more recent survey. The database currently contains descriptive information about approximately 1,350 varieties and hybrids released since the mid-1950s by public breeding programs in 37 developing countries.[3] Collectively, these countries account for more than 75% of the area planted to maize in Latin America, Eastern and Southern Africa, and Asia and for more than 95% of the area planted to maize in non-temperate environments.

Information about maize varieties developed by private seed companies was collected through direct interviews carried out over a three-year period (1997-99). The CIMMYT maize impacts database currently contains information about nearly 1,900 varieties sold by private seed companies during the late 1990s in the 37 developing countries that participated in the CIMMYT survey. Approximately 1,100 of these were proprietary varieties that had been developed by private breeding programs.[4] Unlike the public sector, it was not possible to compile a complete list of all varieties developed by the private sector since 1966, the year in which CIMMYT was established.

[3] Since a major objective of this study is to assess CIMMYT's contribution to international maize breeding efforts, the following discussion relates only to the approximately 1,200 varieties released since 1966, the year in which CIMMYT was officially established.

Many seed companies that were in business during the 1960s, 1970s, and 1980s no longer exist, and it is simply not possible to obtain information about varieties developed many years ago by companies that are now defunct. Furthermore, few of the currently active companies that date back to those earlier years are able to provide detailed information about varieties that have long since been dropped from their product lines. For these reasons, private seed companies were asked to provide information only about varieties they were selling at the time of the survey. In most instances, these consisted of relatively recent hybrids developed during the 1990s.

The temporal coverage for public- and private-sector varietal releases thus is very different (see Figures 2 and 3). The public-sector varietal releases database includes information about all public varieties released from 1966 through 1998. Since the data form a complete time series, they provide insights into changes through time in the numbers and types of varieties developed by public breeding programs. In contrast, the more limited private-sector varietal releases database includes information only about private-sector varieties that were being sold during the late 1990s; it does not include information about private-sector varieties that were sold in earlier years and have now been discontinued. The private-sector varietal releases database provides a detailed snapshot of the materials found in the market during the late 1990s, but it does not provide a complete picture of changes that have occurred through time in the numbers and types of varieties developed by private seed companies.

Public Varietal Releases

Summary information about the maize varieties released by public breeding programs in developing countries between 1966 and 1999 appears in Table 6.[5] The data have been broken down into five-year periods to make it easier to

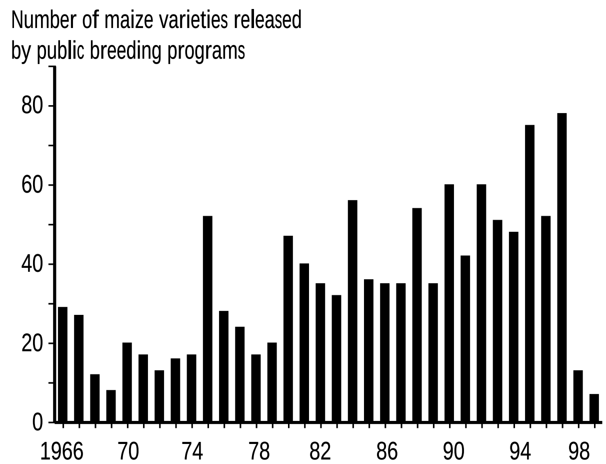

Figure 2. Coverage of CIMMYT's public-sector varieties database.
Source: CIMMYT public-sector varieties database.

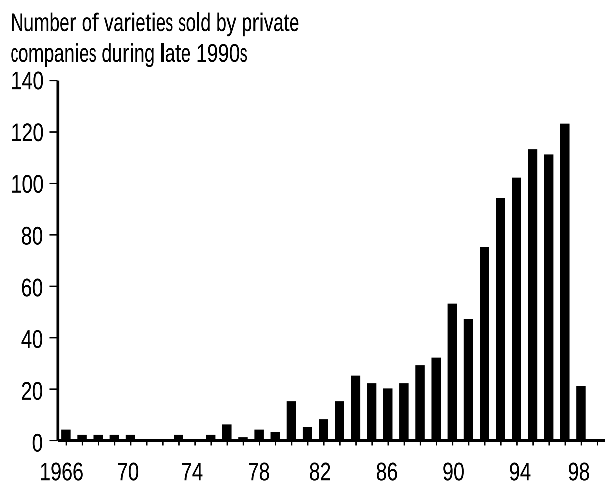

Figure 3. Coverage of CIMMYT's private-sector varieties database.
Source: CIMMYT private-sector varieties database.

4 This number includes multiple counts of varieties that were being sold by more than one seed company, in more than one country, and/or under more than one name. Adjusting for multiple counting, the CIMMYT database contains information about approximately 850 *different* private-sector varieties.

5 As noted earlier, the CIMMYT varietal releases database contains information about nearly 1,400 varieties released by public breeding programs. For most of these varieties, a complete set of descriptors is available, but in a few cases one or more descriptors is missing. The statistics presented in Tables 6-9 refer to percentages of valid responses, which varied slightly from one descriptor to the next.

discern trends in the pattern of varietal releases through time. To enable regional comparisons, results are also reported separately for Latin America (Table 7); Eastern and Southern Africa (Table 8); and South, East, and Southeast Asia (Table 9).

NUMBER OF RELEASES

Public maize breeding programs have been very productive, developing and releasing a steady stream of improved varieties. On aggregate, the rate at which varieties are released has grown steadily through time and shows no sign of slowing. Assuming that varietal testing and release procedures have not changed, this suggests that public maize breeding programs have not suffered any significant decline in productivity.

Over 60% of all public-sector releases came from Latin America, reflecting not only the large area planted to maize in that region but also the large number of public breeding programs. About 8% of all public-sector varietal releases came from Eastern and Southern Africa, reflecting the relatively modest area planted to maize in that region as well as the small number of public breeding programs. Approximately 32% of all public-sector varietal releases came from Asia, many of them from the powerful national breeding programs of China and India.

In interpreting these data, it is important to keep in mind that the number of varietal releases in and of itself is an imperfect measure of research productivity. To begin with, unless some sort of adjustment is made to control for differences in the area planted to maize, regional differences in

Table 6. Public-sector maize varietal releases, developing countries, 1966-98.

	1966 to 1970	1971 to 1975	1976 to 1980	1981 to 1985	1986 to 1990	1991 to 1995	1996 to 1999	1966 to 1998
Total varietal releases (number)	97	114	137	205	216	266	137	1,172
Type of material								
OPVs (%)	0.69	0.57	0.69	0.65	0.69	0.50	0.48	0.61
Hybrids (%)	0.31	0.43	0.30	0.35	0.32	0.50	0.52	0.39
Ecological adaptation								
Lowland tropical (%)	0.50	0.58	0.70	0.61	0.64	0.60	0.55	0.60
Subtropical/Mid-altitude (%)	0.32	0.37	0.18	0.30	0.30	0.23	0.28	0.28
Highland (%)	0.07	0.04	0.11	0.07	0.06	0.05	0.06	0.06
Temperate (%)	0.12	0.02	0.02	0.02	0.00	0.12	0.12	0.06
Maturity range								
Extra early/Early (%)	0.15	0.21	0.19	0.16	0.30	0.27	0.30	0.23
Intermediate (%)	0.34	0.29	0.34	0.32	0.31	0.28	0.28	0.30
Late/Extra late (%)	0.52	0.50	0.47	0.52	0.39	0.45	0.42	0.46
Grain color								
White grain (%)	0.45	0.61	0.50	0.51	0.43	0.50	0.47	0.49
Yellow/Other color grain (%)	0.55	0.39	0.50	0.49	0.57	0.50	0.53	0.51
Grain texture								
Flint/Semi-flint (%)	0.60	0.49	0.50	0.44	0.51	0.59	0.49	0.52
Dent/Semi-dent (%)	0.11	0.30	0.20	0.22	0.26	0.19	0.20	0.21
Other (%)	0.28	0.21	0.31	0.34	0.24	0.22	0.31	0.27
Containing CIMMYT germplasm								
All materials (%)	0.41	0.28	0.50	0.58	0.65	0.56	0.64	0.54
Non-temperate materials (%)	0.45	0.29	0.50	0.60	0.67	0.68	0.73	0.59

Source: CIMMYT maize impacts database.

numbers of varietal releases to some extent simply reflect regional differences in the area planted to maize. In addition, previous analysis has shown that for a number of reasons having to do with the non-divisibility of crop improvement research, small countries have a tendency to overinvest in maize breeding, and the rate of varietal releases in these countries is therefore often disproportionately high (see López-Pereira and Morris 1994). Thus it is perhaps not surprising that the number of varietal releases has been high in Latin America, a region that includes many very small countries.

Rate of releases

In addition to showing regional differences in numbers of varieties released by public breeding programs, the data also reveal differences in the historical rate of varietal releases. In Latin America, the rate of varietal releases grew during the late 1960s and 1970s, peaked in the early 1980s, and subsequently leveled off (Table 7). In Eastern and Southern Africa, the rate of varietal releases declined from a low base during the 1960s and 1970s, increased substantially during the 1980s and early 1990s, and appears to have dropped sharply in recent years (Table 8). In Asia, the rate of varietal releases has increased steadily since the 1960s, with every five-year period registering an increase over the previous period (Table 9).

In the absence of comparable data on historical trends in maize varieties released by private companies, it is difficult to establish with certainty whether these trends reflect a "crowding out" effect attributable to the emergence of the private seed industry. Superficially at least, the timing of the observed changes in the rate of public-sector

Table 7. Public-sector maize varietal releases, Latin America, 1966-98.

	1966 to 1970	1971 to 1975	1976 to 1980	1981 to 1985	1986 to 1990	1991 to 1995	1996 to 1998	1966 to 1998
Total varietal releases (number)	65	78	98	140	111	126	90	708
Type of material								
OPVs (%)	0.60	0.55	0.67	0.71	0.69	0.63	0.51	0.63
Hybrids (%)	0.40	0.45	0.33	0.29	0.32	0.37	0.49	0.37
Ecological adaptation								
Lowland tropical (%)	0.58	0.63	0.71	0.66	0.69	0.51	0.43	0.61
Subtropical / Mid-altitude (%)	0.17	0.31	0.13	0.23	0.22	0.21	0.32	0.23
Highland (%)	0.08	0.05	0.13	0.08	0.09	0.07	0.08	0.08
Temperate (%)	0.17	0.01	0.02	0.03	0.00	0.21	0.17	0.08
Maturity range								
Extra early / Early (%)	0.07	0.13	0.09	0.09	0.14	0.15	0.11	0.11
Intermediate (%)	0.42	0.26	0.37	0.39	0.42	0.27	0.33	0.35
Late / Extra late (%)	0.52	0.61	0.54	0.53	0.44	0.58	0.56	0.54
Grain color								
White grain (%)	0.40	0.68	0.53	0.57	0.53	0.52	0.59	0.55
Yellow / Other color grain (%)	0.60	0.32	0.47	0.43	0.47	0.48	0.41	0.45
Grain texture								
Flint / Semi-flint (%)	0.57	0.41	0.41	0.40	0.39	0.54	0.37	0.44
Dent / Semi-dent (%)	0.09	0.35	0.22	0.19	0.34	0.18	0.23	0.23
Other (%)	0.35	0.24	0.37	0.41	0.27	0.28	0.40	0.33
Containing CIMMYT germplasm								
All materials (%)	0.37	0.24	0.44	0.61	0.67	0.56	0.66	0.53
Non-temperate materials (%)	0.40	0.25	0.45	0.62	0.67	0.67	0.75	0.56

Source: CIMMYT maize impacts database.

varietal releases seems closely linked to the introduction within each region of seed industry reforms. Seed industry liberalization measures were implemented in many Latin American countries beginning in the mid-1980s and in many countries in Eastern and Southern Africa in the early 1990s; in both regions, the appearance of private seed companies appears to have been immediately followed by a slowdown in the rate of public-sector varietal releases. In Asia, the record has been mixed; while seed industry reforms have been embraced in some countries, private-sector investment in maize breeding research continues to be proscribed in others, including China and Vietnam. A large number of public breeding programs in Asia thus continue to enjoy a relatively sheltered position, so it is not surprising that the rate at which they develop and release new varieties has not slowed.

Types of materials

Since 1966, public maize breeding programs in developing countries have developed and released significantly greater numbers of OPVs than hybrids, reflecting the traditional emphasis in the public sector on breeding open-pollinating materials (Table 6). However, the ratio of OPVs to hybrids has changed noticeably through time in response to changes in the prevailing philosophy about the suitability of hybrid technologies for small-scale farmers. The proportion of hybrids among public-sector varietal releases rose steadily during the 1990s, and during the most recent period for which data are available (1996-98), hybrids outnumbered OPVs by a slight margin.

Interestingly, the shift to hybrid breeding occurred earlier in Eastern and Southern Africa than in the other two regions. By the late 1970s,

Table 8. Public-sector maize varietal releases, Eastern and Southern Africa, 1966-98.

	1966 to 1970	1971 to 1975	1976 to 1980	1981 to 1985	1986 to 1990	1991 to 1995	1996 to 1998	1966 to 1998
Total varietal releases (number)	12	9	6	18	15	36	2	98
Type of material								
OPVs (%)	0.83	0.56	0.33	0.33	0.47	0.44	0.50	0.48
Hybrids (%)	0.17	0.44	0.67	0.67	0.53	0.56	0.50	0.52
Ecological adaptation								
Lowland tropical (%)	0.08	0.11	0.00	0.17	0.20	0.31	0.00	0.20
Subtropical/Mid-altitude (%)	0.75	0.78	0.75	0.72	0.67	0.61	1.00	0.69
Highland (%)	0.08	0.00	0.25	0.11	0.13	0.06	0.00	0.08
Temperate (%)	0.08	0.11	0.00	0.00	0.00	0.03	0.00	0.03
Maturity range								
Extra early/Early (%)	0.17	0.00	0.00	0.06	0.13	0.08	0.50	0.09
Intermediate (%)	0.17	0.44	0.25	0.06	0.13	0.42	0.00	0.26
Late/Extra late (%)	0.67	0.56	0.75	0.89	0.73	0.50	0.50	0.65
Grain color								
White grain (%)	1.00	1.00	1.00	0.89	1.00	0.94	1.00	0.96
Yellow/Other color grain (%)	0.00	0.00	0.00	0.11	0.00	0.06	0.00	0.04
Grain texture								
Flint/Semi-flint (%)	0.25	0.67	0.50	0.22	0.33	0.67	0.00	0.46
Dent/Semi-dent (%)	0.42	0.22	0.50	0.61	0.33	0.31	1.00	0.40
Other (%)	0.33	0.11	0.00	0.17	0.33	0.03	0.00	0.15
Containing CIMMYT germplasm								
All materials (%)	0.00	0.00	0.25	0.28	0.29	0.50	1.00	0.31
Non-temperate materials (%)	0.00	0.00	0.25	0.28	0.29	0.51	1.00	0.32

Source: CIMMYT maize impacts database.

when most public breeding programs in Latin America (Table 7) and Asia (Table 8) were still emphasizing OPVs, programs in Eastern and Southern Africa were already releasing more hybrids than OPVs (Table 9). Quite possibly this was due to the early hybrid "success stories" of Kenya and Zimbabwe, where smallholders demonstrated the ability to grow hybrids that had been developed originally for the commercial farming sector. Convinced relatively early that hybrid technology could be adapted to the needs of small-scale farmers, public maize breeders in Eastern and Southern Africa were the first to complement their traditional work on open-pollinating materials with inbred line development activities.

Ecological adaptation

At the risk of oversimplifying, maize growing ecologies can be grouped into four main mega-environments: (1) lowland tropics, (2) subtropical and midaltitude transition zones, (3) tropical highlands, and (4) temperate zones. Table 10 shows the current distribution of the area planted to maize within each of these four mega-environments.

The ecological adaptation of maize varieties released by public breeding programs has been highly congruent with the relative importance of the four main mega-environments, both at the overall global level as well as regionally. Varieties adapted to lowland tropical production environments have accounted for 60% of all releases. Varieties adapted to subtropical and mid-altitude production conditions have accounted for

Table 9. Public-sector maize varietal releases, South, East, and Southeast Asia, 1966-98.

	1966 to 1970	1971 to 1975	1976 to 1980	1981 to 1985	1986 to 1990	1991 to 1995	1996 to 1999	1966 to 1999
Total varietal releases (number)	20	27	33	47	90	104	45	366
Type of material								
OPVs (%)	0.90	0.63	0.82	0.62	0.72	0.39	0.42	0.59
Hybrids (%)	0.11	0.37	0.18	0.38	0.28	0.62	0.58	0.41
Ecological adaptation								
Lowland tropical (%)	0.50	0.59	0.74	0.63	0.64	0.91	0.86	0.74
Subtropical/Mid-altitude (%)	0.50	0.41	0.26	0.37	0.36	0.07	0.14	0.26
Highland (%)	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Temperate (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maturity range								
Extra early/Early (%)	0.55	0.63	0.52	0.55	0.70	0.49	0.71	0.58
Intermediate (%)	0.09	0.32	0.28	0.16	0.11	0.26	0.17	0.21
Late/Extra late (%)	0.36	0.05	0.21	0.29	0.19	0.26	0.12	0.21
Grain color								
White grain (%)	0.26	0.24	0.30	0.20	0.21	0.30	0.20	0.24
Yellow/Other color grain (%)	0.74	0.76	0.70	0.80	0.79	0.70	0.80	0.76
Grain texture								
Flint/Semi-flint (%)	0.94	0.67	0.75	0.68	0.71	0.64	0.82	0.72
Dent/Semi-dent (%)	0.00	0.17	0.09	0.13	0.13	0.14	0.08	0.12
Other (%)	0.06	0.17	0.16	0.18	0.16	0.22	0.11	0.17
Containing CIMMYT germplasm								
All materials (%)	0.93	0.52	0.75	0.59	0.68	0.58	0.60	0.64
Non-temperate materials (%)	0.93	0.82	0.79	0.73	0.76	0.79	0.67	0.77

Source: CIMMYT maize impacts database.

Table 10. Distribution of maize area in developing countries, by mega-environment, late 1990s.

	Lowland tropical (%)	Subtropical and mid-altitude (%)	Highland (%)	Temperate (%)	All (%)	Maize area, late 1990s (million ha)
Latin America	65	12	12	11	100	26.1
Sub-Saharan Africa	50	33	7	10	100	21.4
West Asia and North Africa	0	39	0	61	100	3.6
South, East, and Southeast Asia	34	13	2	51	100	42.9
All developing countries	47	18	6	29	100	94.0

Source: CIMMYT maize mega-environments database, FAO AGROSTAT website.

an additional 28% of all releases. Varieties adapted to tropical highland production conditions have been much less important, accounting for approximately 6% of the total number of releases. These numbers suggest that research resources in public maize breeding programs have been allocated appropriately, in the sense that no single mega-environment has been over- or under-emphasized. Temperate production environments have been relatively reglected by public breeding programs, which makes sense considering the large investment made by private seed companies in breeding for these environments.

Maturity classes

Since the time needed for a maize crop to achieve physiological maturity depends on numerous environmental factors (e.g., temperature, altitude, rainfall, day length), the length of the maize growing season varies by location. Maize breeders frequently distinguish at least three maturity classes, defined relative to whatever constitutes the normal growing season for a given location. Early-maturing varieties usually require less than 110 days to reach full physiological maturity, intermediate-maturing varieties from 110-120 days, and late-maturing varieties more than 120 days. Generally speaking, late-maturing varieties tend to be grown in favorable production environments characterized by relatively low levels of climatic variability and assured water supplies. Early-maturing varieties tend to be grown in marginal production environments subject to high levels of climatic variability, including frequent water stress (drought or waterlogging). Farmers in marginal environments choose to grow early-maturing varieties precisely because these varieties' reduced growth cycle minimizes their exposure to stresses. Early-maturing varieties tend to be popular also in highly intensified cropping systems, since the earlier the maize crop can be harvested, the sooner the field can be prepared for the following crop.

Nearly one-half of all varieties released by public breeding programs since 1966 have been late-maturing varieties. About 30% of all public-sector releases have been intermediate-maturity varieties, and about 24% have been early-maturing varieties. Interestingly, late-maturing varieties have dominated in Latin America and Africa, while early-maturing varieties have dominated in Asia. This suggests that Asian breeders have placed a lot of emphasis on developing short-duration materials that can be accommodated into the region's highly intensified cropping systems.

Grain color and texture

The predominant grain color of publicly bred maize varieties has differed by region, indicating that breeders have made a deliberate effort to respond to local consumer preferences. Latin American releases have been fairly evenly divided between white-colored varieties (used mainly for food) and yellow-colored varieties (used mainly for feed), reflecting the dual-purpose nature of maize in that region. Releases in Eastern and Southern Africa have nearly all been white-colored, which is not surprising considering that most maize in Africa is consumed as food, and consumers strongly prefer white-colored varieties. Yellow-colored varieties have predominated in Asia, where maize is used mainly as animal feed, and where color preferences for food maize are in any case less pronounced.

Regional differences have also been evident in the grain texture of publicly bred maize varieties. Hard-grained varieties (flints, semi-flints) have predominated in all three regions, reflecting their better storability, particularly in humid tropical and subtropical environments. Soft-grained varieties (dents, semi-dent, floury types) have been relatively more common in Latin America and Africa, where a greater proportion of maize is consumed as human food and consumers generally prefer soft-grained materials

CIMMYT GERMPLASM CONTENT

To what extent have public maize breeding programs in developing countries made use of CIMMYT germplasm?

Unfortunately it is not easy to document the use of CIMMYT germplasm by public breeding programs. At least three factors complicate the task:

1. CIMMYT maize breeders routinely work with a wide range of source materials obtained from all over the world. After undergoing improvement at one or more CIMMYT breeding stations, the most promising of these materials are distributed to collaborators in national programs for testing and evaluation. In this context, it is not always clear how credit should be attributed among the various breeding programs, so the definition of "CIMMYT germplasm" becomes somewhat arbitrary. Much of the germplasm distributed by the CIMMYT Maize Program can be considered a joint product of CIMMYT and national breeding programs.
2. Maize breeders working in national programs who use source materials obtained from CIMMYT themselves may not know exactly how much of the CIMMYT source materials are present in finished varieties that are eventually released to farmers. Modern maize breeding involves repeated cycles of selfing, crossing, and backcrossing. Selection strategies vary widely and change often. Because of the complex and frequently ad hoc nature of the breeding process, the precise genetic composition of finished varieties cannot be known with certainty.
3. Even when maize breeders working in national programs know how much CIMMYT germplasm is present in a finished variety, they may not be willing to reveal this information. Most commercial maize varieties now have closed pedigrees, meaning that information about their genetic background is not publicly available.[6]

Despite these complicating factors, a rigorous effort was made to document the use of CIMMYT germplasm by public breeding programs. Survey respondents were asked whether each variety (OPV or hybrid) had been developed using CIMMYT germplasm, defined as materials that had been improved by the CIMMYT Maize Program. Materials that may have been obtained from CIMMYT's gene bank but that had not been improved by CIMMYT breeders were expressly excluded.

[6] Breeding programs, especially commercial programs that respond to economic incentives, have an interest in keeping pedigrees closed, because once the genetic background of a variety becomes public knowledge, other breeders will be able to copy the variety. In the past, public breeding programs were rarely concerned with earning profits from sales of their germplasm products, so they were usually willing to provide pedigree information. More recently, the situation has changed. With the strengthening of intellectual property rights on genetic resources, many public breeding programs have adopted closed-pedigree policies. In some cases, they have done this because they hope eventually to generate income from the sale of their germplasm products. In other cases, adopting a closed-pedigree policy is seen as more of a defensive measure designed to prevent losses of intellectual property to unscrupulous competitors. In yet other cases, the motivation may be the reluctance to acknowledge use of proprietary germplasm owned by others, since this might expose them to claims for compensation.

By any standard, use of CIMMYT germplasm by public breeding programs has been extensive. Of all the publicly bred maize varieties released from 1966-99, over one-half (54%) contained CIMMYT germplasm (Table 6). Excluding varieties adapted for temperate environments (which are not targeted by CIMMYT maize breeders), the proportion containing CIMMYT germplasm was even higher (59%).

The use of CIMMYT germplasm by public breeding programs has increased through time. During the most recent period, 64% of all public-sector varietal releases contained CIMMYT germplasm (73% of all non-temperate materials). Belying predictions that CIMMYT's role would decline as national programs gained in strength, the CIMMYT Maize Program continues to represent an important source of breeding materials for public breeding programs in developing countries.

Use of CIMMYT germplasm by public maize breeding programs has varied by region. Public breeding programs in Asia and Latin America have used CIMMYT germplasm most extensively; 64% of the public varieties released in Asia and 53% of the public varieties released in Latin America contained CIMMYT germplasm. Public breeding programs in Eastern and Southern Africa have used CIMMYT source materials somewhat less extensively; only 31% of the public varieties released in Eastern and Southern Africa contained CIMMYT germplasm. These regional differences in the use of CIMMYT germplasm can be explained partly in terms of environmental factors. Since its inception, the CIMMYT Maize Program has invested more resources in breeding for lowland tropical environments than other environments. Most of the maize grown in Asia and Latin America is grown in lowland tropical environments, so public breeding programs in these regions have been able to take advantage of some of CIMMYT's best materials. By contrast, much of the maize area in Eastern and Southern Africa is located in subtropical and mid-altitude environments, which until the mid 1980s received less emphasis from CIMMYT breeders. Public breeding programs in Africa until recently thus had a more limited range of CIMMYT materials on which to draw.

Within each region, use of CIMMYT germplasm by public breeding programs has varied through time. In Latin America and Asia, use of CIMMYT germplasm did not change much during the 1990s, but in Eastern and Southern Africa it increased appreciably. The increased use of CIMMYT source materials in Eastern and Southern Africa during the 1990s reflects the strengthening of CIMMYT's breeding station in Harare, Zimbabwe.

Private Varietal Releases

Summary information about maize varieties developed by private seed companies and sold in developing countries during the late 1990s appears in Table 11. Unlike varieties developed by public breeding programs, which are released initially in a single country, varieties developed by private seed companies ("proprietary varieties") often are released simultaneously in several countries. In order to avoid double-counting, the database used to calculate the statistics presented in Table 11 contains no duplication (i.e., varieties that may have been released in more than one country were counted only once).[7]

Number of varieties and rate of releases

Since the private-sector varietal releases database contains only information about varieties sold during the late 1990s, it cannot be used to draw

[7] As in the case of public varieties, a complete set of descriptors is not available for all private-sector varieties, so the statistics presented in Table 11 were calculated based on valid responses only.

conclusions about the past productivity of private breeding programs. But even if the historical coverage is incomplete (and recognizing that the CIMMYT survey undoubtedly missed some varieties), the regional variability in the data is striking. During the late 1990s, nearly 500 different proprietary varieties were sold in Latin America, and well over 300 different proprietary varieties were sold in Asia. In comparison, only about 25 different prorietary varieties were sold in Eastern and Southern Africa. This pattern is consistent with the research investment estimates reported earlier and confirms that Eastern and Southern Africa has attracted much less attention from the private sector than the two other regions.

Types of materials

As expected, private breeding programs have focused almost exclusively on developing hybrids. Fully 98% of all proprietary varieties sold during the late 1990s were hybrids.

Ecological adaptation

Most proprietary varieties sold in developing countries during the late 1990s were adapted to lowland tropical production environments (59%). Varieties adapted to subtropical and mid-altitude conditions accounted for an additional 21%. Compared to public breeding programs, private companies have evidently made very little effort to target tropical highland environments; only 1% of all proprietary varieties were adapted to these environments. On the other hand, private companies have placed much more emphasis on temperate environments; 19% of all proprietary varieties sold during the late 1990s were adapted to temperate environments. The high proportion of temperate varieties among private-sector releases reflects the efforts of private companies to exploit spillover benefits from breeding research done for industrialized countries.

Maturity classes

Although the varieties developed by private breeding programs are distributed across all maturity classes, on the whole breeders in the private sector have placed greater emphasis on short duration materials than have breeders in the public sector. Fully 42% of all proprietary varieties sold during the late 1990s were classified as early or extra-early.

Grain color and texture

In terms of grain color and grain texture, proprietary varieties again reflect the efforts of private sector breeders to take advantage of germplasm originally developed for commercial markets in industrialized countries. Compared to varieties developed by public breeding programs, a much higher proportion of proprietary varieties are yellow-colored (71%) and hard-textured (63%). None of the varieties developed by private seed companies exhibited non-traditional grain texture (starchy or waxy types).

CIMMYT germplasm content

To what extent have private seed companies made use of CIMMYT germplasm?

Some of the difficulties inherent in tracking the use of CIMMYT germplasm were described earlier with reference to public breeding programs (see Section 4.1.7). In the case of private breeding programs, these difficulties are compounded by differences in breeders' perceptions. In order to understand this, it is useful to review a bit of history. Forty years ago, when most private maize seed companies were located in the United States and Western Europe, private-sector breeding programs were oriented almost exclusively toward developing hybrids adapted to the temperate production conditions of the North American and Western European corn belts.

Private-sector interest in breeding for tropical and subtropical environments picked up only during the 1970s and 1980s, when markets for commercial maize seed began to emerge in several large developing countries (e.g., Brazil, China, India, Indonesia, Mexico, the Philippines, Thailand). At that time, many leading seed companies launched maize breeding programs targeted at non-temperate environments. Most stocked their breeding plots with materials obtained from CIMMYT, whose breeding program was one of the few programs with experience working with non-temperate germplasm. Several sets of breeding materials available from CIMMYT were used by almost all private seed companies that had intentions of expanding into non-temperate environments, especially materials derived from the Tuxpeño germplasm complex (used extensively as a source of lines for Latin American hybrids) and materials derived from the composite variety Suwan-1 (used extensively as a source of lines for Asian hybrids).

Since most of the private seed companies that today breed for developing countries started out using Tuxpeño and Suwan materials, it is probably not too much of an exaggeration to say that most of the hybrids grown in non-temperate environments trace their parentage back in one way or another to Tuxpeño or Suwan sources. For this reason, many CIMMYT breeders feel that most of the area currently planted to private-sector hybrids can be considered planted to CIMMYT-derived germplasm. Breeders working in the private sector tend to see things a bit differently, however. Because private-sector breeders constantly make selections within their breeding populations, many of the Tuxpeño and Suwan populations today being maintained by private seed companies have changed significantly from the time they were originally acquired from CIMMYT. For this reason, even if one or more of the parental lines used to produce a hybrid was developed from Tuxpeño or Suwan sources, breeders in the private sector may not consider the hybrid to be "CIMMYT-derived."

How to overcome this difference in breeders' perceptions? If the complete breeding history of a variety is known, credit can be assigned among the different breeding programs that participated in its development with the use of a formal attribution rule. With the so-called geometric rule, for example, credit is assigned to past breeding operations in geometrically declining fashion. Thus the most recent breeding operation receives a large weight, the previous operation receives a smaller weight, the operation before that an even smaller weight, and so on back. In the earliest generation considered, the weight is doubled to make all weights sum to 1 (Heisey, Lantican, and Dubin, 2002). The advantage of the geometric rule is that it acknowledges the contribution made by all breeding programs, but at the same time it explicitly recognizes that selections performed during the later stages of the breeding process merit more credit than selections performed during earlier stages.

Unfortunately for this study, use of formal attribution rules is usually not possible with maize, since the pedigrees of most commercial maize hybrids are closed. Despite the difficulty of obtaining detailed pedigree information, however, it is clear that use of CIMMYT germplasm by private breeding programs has been substantial. Aggregating across the three developing regions, 58% of all maize varieties developed since 1966 by private seed companies and sold during the late 1990s contained CIMMYT germplasm (Table 11). The proportion varied greatly by region, however. In Latin America, nearly three-quarters (73%) of all private-sector varieties contained CIMMYT germplasm. In other regions, use of CIMMYT germplasm by private companies was more modest. In Eastern and Southern Africa, 21% of the varieties developed by private breeding programs contained CIMMYT germplasm, and in Asia, 19% of the varieties developed by private breeding programs contained CIMMYT germplasm.

The extensive use of CIMMYT germplasm by private breeding programs in Latin America can be attributed to three main factors. First, because the majority of CIMMYT maize breeders are stationed in Latin America (either at headquarters in Mexico or in one of several outreach offices), contacts between private-sector breeders and CIMMYT breeders have been more frequent than in other regions. Second, seed companies in Latin America have been well placed to take advantage of CIMMYT's excellent lowland tropical materials, most of which have been developed in Mexico and Central America from local landraces that themselves benefited from thousands of years of selection pressure at the hands of farmers. Third, many countries in Latin America have private seed industries that feature large numbers of small seed companies; many of these companies lack strong breeding programs of their own and thus have had to rely heavily on CIMMYT as a source of materials.

The same three factors—opportunities for collaboration, suitability of germplasm, and seed industry structure—also explain the more modest use of CIMMYT germplasm by private breeding programs in other regions, although the relative importance of each factor tends to vary. In Eastern and Southern Africa, the key factors have been the structure of local seed industries and the suitability of CIMMYT's germplasm. Most private seed companies in Eastern and Southern Africa are extremely large and consequently have correspondingly large (and generally very

Table 11. Characteristics of maize varieties developed by private seed companies.[a, b]

	Latin America	Eastern and Southern Africa	South, East, and Southeast Asia	All regions
Total varieties (number)	498	25	330	853
Type of material				
OPVs (%)	0.03	0.08	0.00	0.02
Hybrids (%)	0.97	0.92	1.00	0.98
Ecological adaptation				
Lowland tropical (%)	0.47	0.04	0.91	0.59
Subtropical / Mid-altitude (%)	0.25	0.78	0.07	0.21
Highland (%)	0.01	0.13	0.00	0.01
Temperate (%)	0.27	0.04	0.02	0.19
Maturity range				
Extra early / Early (%)	0.19	0.17	0.79	0.42
Intermediate (%)	0.36	0.30	0.15	0.28
Late / Extra late (%)	0.46	0.52	0.06	0.31
Grain color				
White grain (%)	0.38	0.88	0.10	0.29
Yellow / Other color grain (%)	0.62	0.12	0.90	0.71
Grain texture				
Flint / Semi-flint (%)	0.59	0.21	0.74	0.63
Dent / Semi-dent (%)	0.41	0.79	0.26	0.37
Other (%)	0.00	0.00	0.00	0.00
Containing CIMMYT germplasm				
All materials (%)	0.73	0.21	0.19	0.58
Non-temperate materials (%)	0.89	0.15	0.18	0.70

[a] Includes all proprietary varieties being sold during the late 1990s
[b] Varieties sold in more than one country counted only once each (no duplicates)
Source: CIMMYT maize impacts database.

competent) in-house breeding programs. Perfectly capable of developing their own germplasm sources, these companies have usually not had to rely on CIMMYT for breeding materials. Perhaps more importantly, the germplasm available from CIMMYT has not always been well suited for African production environments. Most of the maize produced in Eastern and Southern Africa is grown in subtropical and mid-altitude transition zones, which for many years received relatively little attention from the CIMMYT Maize Program. When it became apparent that germplasm developed in Mexico could not be introduced successfully into Africa without undergoing additional adaptation breeding, CIMMYT established a major breeding station near Harare, Zimbabwe. Fifteen years later, this investment is paying off. The Harare program has released a number of high-yielding, drought-tolerant inbred lines showing excellent levels of resistance to major diseases and pests. These lines are being used by private seed companies and are starting to show up in commercial releases. Seed industry contacts say that many experimental hybrids currently in the pipeline were developed using CIMMYT source materials, suggesting that use of CIMMYT lines is increasing.

In Asia, the relatively modest use of CIMMYT germplasm by private breeding programs can be explained mainly in terms of institutional constraints. Forced to cover a vast area with limited human and financial resources, the CIMMYT Maize Program for a long time was not able to interact as closely with the private sector in Asia as it was in other regions. The situation has improved in recent years following concerted efforts to strengthen links with private companies, and private-sector breeders now actively participate with public-sector scientists in CIMMYT-sponsored collaborative networks.

Adoption of Modern Varieties (MVs)

Information presented in the preceding sections of this report about improved varieties developed by public and private maize breeding programs in developing countries attests to the productivity of these programs and makes clear that breeders in both sectors have made extensive use of germplasm obtained from CIMMYT. What the data about varietal releases do not tell us, however, is the extent to which farmers have made use of these varieties. This section of the report presents information about the adoption of maize MVs in developing countries.

Before we turn to the evidence on adoption, a caveat is necessary. Estimating the area planted to improved germplasm is complicated by at least three factors. First, the physical environments and cropping systems in which maize is grown are extremely diverse, so the uptake of MVs often varies considerably even within the same country. Second, in many developing countries maize is grown by subsistence-oriented farmers who do not regularly purchase commercial seed; since these farmers often plant farm-saved seed, it can be extremely difficult to identify improved germplasm in the field, because the genetic makeup of successive crops can quickly change in the presence of seed recycling (for a review of evidence, see Morris, Risopoulos, and Beck 1999). Third, most commercial maize seed is now produced in the private sector; since many private companies consider seed sales information to be confidential, it is often difficult to get seed sales data for use in gauging varietal adoption trends.

Because of the difficulties inherent in estimating the adoption of improved germplasm, we present two types of data relating to the uptake and use of improved OPVs and hybrids. First we present data about commercial seed sales. Although seed sales data do not always provide a reliable indicator of the area planted to improved cultivars, they provide important insights about the strength of the demand for improved varieties.[8] After reviewing the evidence on commercial seed sales, we turn to direct estimates of the area planted to improved OPVs and hybrids.

Sales of Commercial Maize Seed

Table 12 shows sales of commercial maize seed for 1996/97 reported by the public seed agencies and private companies that participated in the CIMMYT survey. Since the survey targeted mainly larger companies with breeding programs, the figures reported in Table 12 do not include sales by many small local seed companies. Actual seed sales therefore were higher, with the margin of error varying by region. In Latin America, the survey coverage was quite extensive, so the figures reported in Table 12 are believed to be accurate to within 10%. In Asia, where it was not possible to achieve the same degree of coverage in the survey, the figures reported in Table 12 could under-report actual seed sales by as much as 20%. In Eastern and Southern Africa, where small local seed companies are relatively uncommon, the figures reported in Table 12 are probably accurate to within 15%.

The seed sales data presented in Table 12 are noteworthy in three respects. First, maize seed is big business in the developing world. In 1996/97, maize seed sales by companies that participated in the CIMMYT survey exceeded half a million tons. This number would increase significantly with the addition of seed sales by companies that did not participate in the CIMMYT survey, especially companies operating in northern China. Second, outside China, the global maize seed industry has effectively been privatized. Excluding China, where control of the maize seed industry remains in the hands of provincial and municipal governments, private seed companies outsell public seed agencies by more than ten to one. Third, the global market for maize seed is dominated by hybrids. Sales of OPV seed account for only 6% of the total market, a number that would decrease even further if seed sales in northern China were included.

Table 12. Commercial maize seed sales, by type of seed and seed organization, 1996/97 (tons).

	Public sector			Private sector			Total		
	OPVs	Hybrids	Total	OPVs	Hybrids	Total	OPVs	Hybrids	Total
Latin America	4,700	4,500	9,200	14,400	280,700	295,100	19,100	285,200	304,300
Eastern and Southern Africa[a]	5,600	14,100	19,700	4,100	67,700	71,800	9,700	81,800	91,500
East, South, and Southeast Asia[b]	1,700	94,400	96,100	3,200	67,800	71,000	4,900	162,200	167,100
All regions	12,000	113,000	125,000	21,700	416,200	437,900	33,700	529,200	562,900

[a] Estimated for some countries.
[b] Southern China only.
Source: CIMMYT maize impacts survey.

[8] Commercial seed sales data can be combined with information about average planting rates to derive estimates of the area potentially planted to modern varieties, but the results must be interpreted with caution. For a number of reasons, the procedure may generate misleading results. For example, use of commercial seed sales data will produce an underestimate of the area potentially planted to modern varieties when use of farm-saved seed is extensive. Alternatively, use of commercial seed sales data will produce an overestimate of the area potentially planted to modern varieties if a portion of the commercial seed that is reported as sold never gets planted, or if large areas must be replanted to overcome the effects of low germination, poor stand establishment, early season crop failure, etc.

Additional descriptive statistics relating to maize seed sold in 1996/97 are presented in Table 13a (global summary) and Tables 13b-d (regional sub-totals).[9]

In terms of ecological adaptation, maturity range, grain color, and grain texture, seed sales data offer few surprises. Regional differences in characteristics of maize seed sold in 1996/97 are consistent with regional differences in production environments, cropping systems, and consumption requirements, indicating that seed producers are adept at identifying local germplasm needs and tailoring seed supply to meet those needs.

More interesting are the insights provided by the seed sales data into the relative popularity of public and private varieties. Of all maize seed sold in 1996/97, one-quarter (25%) was seed of varieties developed and released by public breeding programs, and three-quarters (75%) was seed of varieties developed and released by private breeding programs. Publicly-bred varieties were

Table 13a. Characteristics of commercial maize seed sold by public and private seed companies, developing countries, late 1990s.

	Seed sold by:			
	Public agencies	Private companies		All organizations
		Domestic	MNCs	
Estimated total seed sales (t)	127,000	129,000[b]	301,700[b]	557,700
Origin of variety				
Public sector (%)	0.89	0.27	0.01	0.25
Private sector (%)	0.11	0.73	0.99	0.75
Type of material				
OPVs (%)	0.17	0.14	0.00	0.07
Hybrids (%)	0.83	0.86	1.00	0.93
Ecological adaptation				
Lowland tropical (%)	0.22	0.66	0.63	0.55
Subtropical / Mid-altitude (%)	0.26	0.15	0.11	0.15
Highland (%)	0.06	0.00	0.00	0.02
Temperate (%)	0.45	0.19	0.25	0.28
Maturity range				
Extra early / Early (%)	0.25	0.30	0.23	0.25
Intermediate (%)	0.35	0.32	0.31	0.32
Late / Extra late (%)	0.40	0.39	0.47	0.44
Grain color				
White grain (%)	0.34	0.19	0.15	0.20
Yellow / Other color grain (%)	0.66	0.81	0.85	0.80
Grain texture				
Flint / Semi-flint (%)	0.33	0.47	0.60	0.51
Dent / Semi-dent (%)	0.67	0.53	0.41	0.49
Other (%)	0.00	0.00	0.00	0.00
Containing CIMMYT germplasm				
All materials (%)	0.19	0.61	0.70	0.58
Non-temperate materials (%)	0.36	0.81	0.83	0.75

a Percentages refer to commercial seed for which information is available.
b Sales by domestic companies estimated to comprise 30% of total private sector seed sales.
Source: CIMMYT maize impacts database.

9 As with the statistics reported earlier for varietal releases, the statistics relating to commercial seed were calculated based on commercial seed for which descriptive information was available. Assuming that seed for which information was not available was similar to seed for which information was available, the statistics reported in Tables 13a-d are representative of all commercial maize seed sold in 1996/97.

very popular in Eastern and Southern Africa (accounting for 75% of all seed sales within the region), whereas privately-bred varieties were highly favored in Latin America (accounting for 89% of all seed sales within the region). Use of public- and private-sector varieties was more evenly balanced in Asia, although variability within the region was great; most of the seed sold in China (also parts of India) was seed of public varieties, while most of the seed sold in other countries was seed of private varieties.

Last but not least, the seed sales data presented in Tables 13a-d provide additional evidence that germplasm obtained from CIMMYT is being used extensively. Of all commercial maize seed sold during 1996/97 in the survey countries and for which variety-specific information is available, 58% was seed of varieties that had been developed using germplasm obtained from CIMMYT.[10] Focusing more directly on environments targeted by CIMMYT maize breeders, of all commercial maize seed sold during 1996/97 in countries with predominantly non-temperate production

Table 13b. Characteristics of commercial maize seed sold by public and private seed companies in 1996/97, Latin America.[a]

	Seed sold by:			
	Public	Private companies		All
	agencies	Domestic	MNCs	organizations
Estimated total seed sales (t)	9,200	82,600[b]	212,400[b]	304,200
Origin of variety				
Public sector (%)	1.00	0.34	0.00	0.11
Private sector (%)	0.00	0.66	1.00	0.89
Type of material				
OPVs (%)	0.47	0.18	0.00	0.06
Hybrids (%)	0.53	0.83	1.00	0.94
Ecological adaptation				
Lowland tropical (%)	0.74	0.66	0.60	0.62
Subtropical / Mid-altitude (%)	0.23	0.14	0.10	0.11
Highland (%)	0.03	0.00	0.00	0.00
Temperate (%)	0.00	0.20	0.31	0.27
Maturity range				
Extra early / Early (%)	0.06	0.15	0.14	0.14
Intermediate (%)	0.50	0.38	0.32	0.34
Late / Extra late (%)	0.44	0.48	0.54	0.52
Grain color				
White grain (%)	0.60	0.23	0.13	0.17
Yellow / Other color grain (%)	0.40	0.77	0.87	0.83
Grain texture				
Flint / Semi-flint (%)	0.46	0.50	0.58	0.56
Dent / Semi-dent (%)	0.52	0.50	0.42	0.44
Other (%)	0.02	0.00	0.00	0.00
Containing CIMMYT germplasm				
All materials (%)	0.57	0.66	0.80	0.76
Non-temperate materials (%)	0.57	0.82	0.99	0.93

[a] Percentages refer to commercial seed for which information is available.
[b] Sales by domestic companies estimated to comprise 28% of total private sector seed sales.
Source: CIMMYT maize impacts database.

[10] Figures referring to the CIMMYT germplasm content of commercial seed sold in 1996/97 must be interpreted with caution, because data were not available for several important maize-producing countries in which CIMMYT germplasm has not been used extensively. Including seed sales data from these countries would reduce the proportion of all commercial seed classified as "CIMMYT-derived."

environments and for which variety-specific information is available, 75% was seed of varieties developed using CIMMYT germplasm.

Use of CIMMYT-derived varieties varied widely by region, however. In Latin America, 76% of all commercial maize seed sold in 1996/97 was seed of varieties developed using CIMMYT germplasm (93% of all seed sold in non-temperate regions). By contrast, in Eastern and Southern Africa, only 13% of all commercial maize seed sold in 1996/97 was seed of varieties developed using CIMMYT germplasm (14% of all seed sold in non-temperate regions). In East, South, and Southeast Asia, 21% of all commercial maize seed sold in 1996/97 was seed of varieties developed using CIMMYT germplasm (36% of all seed sold in non-temperate regions).

The seed sales data presented in Tables 12 and 13 are revealing, but because they relate to a single year, the picture they provide is static. In order to get a better sense of how the maize seed industry has changed through time, it is useful to examine longer term trends in seed sales data. Figure 4 shows the evolution of total commercial maize seed sales from 1990-97. Summing across all three developing regions, the data show a slight upward trend. The aggregate global data mask significant differences at the regional level, however. In Latin America and Asia, total commercial seed sales increased steadily throughout the 1990s, while in Africa they decreased (Figures 5a-c).

Table 13c. Characteristics of commercial maize seed sold by public and private seed companies in 1996/97, Eastern and Southern Africa.[a]

	Seed sold by:			
	Public	Private companies		All
	agencies	Domestic	MNCs	organizations
Estimated total seed sales (t)	21,700	21,500[b]	43,100[b]	86,300
Origin of variety				
Public sector (%)	0.98	0.00	0.22	0.75
Private sector (%)	0.03	1.00	0.78	0.25
Type of material				
OPVs (%)	0.21	0.00	0.00	0.15
Hybrids (%)	0.79	1.00	1.00	0.85
Ecological adaptation				
Lowland tropical (%)	0.00	0.00	0.22	0.07
Subtropical / Mid-altitude (%)	0.72	1.00	0.69	0.71
Highland (%)	0.22	0.00	0.09	0.18
Temperate (%)	0.06	0.00	0.00	0.04
Maturity range				
Extra early / Early (%)	0.09	0.33	0.12	0.10
Intermediate (%)	0.08	0.33	0.28	0.14
Late / Extra late (%)	0.83	0.33	0.60	0.76
Grain color				
White grain (%)	0.96	1.00	0.97	0.96
Yellow / Other color grain (%)	0.04	0.00	0.04	0.04
Grain texture				
Flint / Semi-flint (%)	0.26	0.00	0.25	0.26
Dent / Semi-dent (%)	0.74	1.00	0.75	0.74
Other (%)	0.00	0.00	0.00	0.00
Containing CIMMYT germplasm				
All materials (%)	0.07	n.a.	0.31	0.13
Non-temperate materials (%)	0.07	n.a.	0.31	0.14

[a] Percentages refer to commercial seed for which information is available.
[b] Sales by domestic companies estimated to comprise 33% of total private sector seed sales.
Source: CIMMYT maize impacts database.

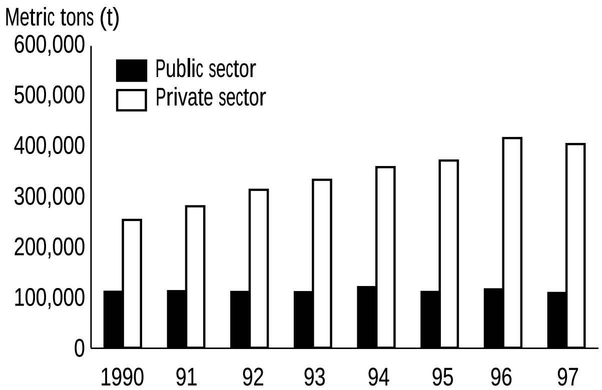

Figure 4. Total maize seed sales, all developing countries, 1990-97.
Source: CIMMYT survey.

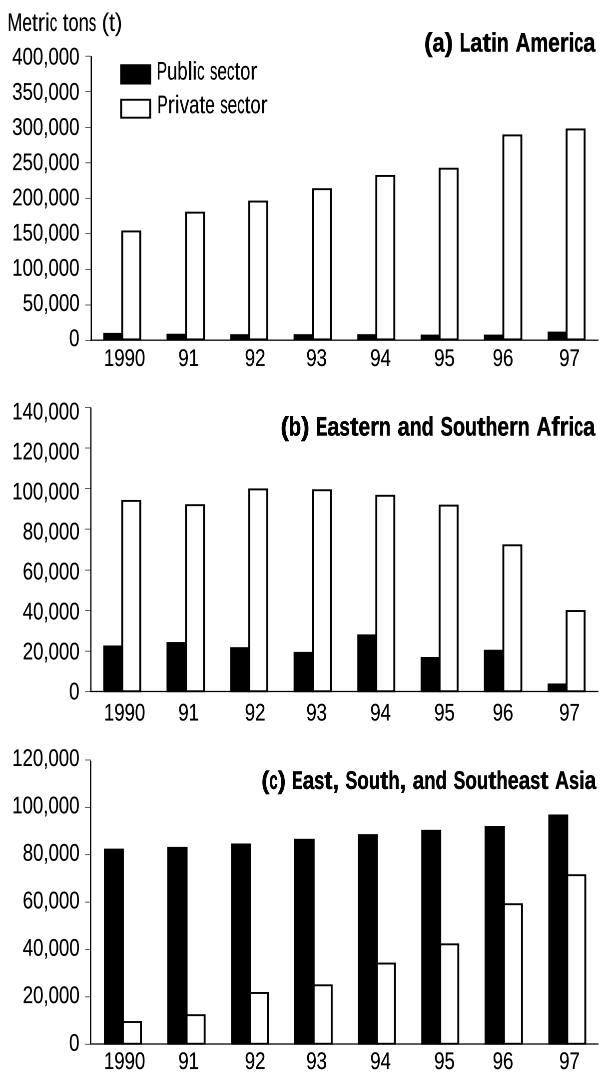

Figure 5. Total maize seed sales, by region, 1990-97.
Source: CIMMYT survey.

To what degree have public seed agencies contributed to these trends? Figure 6 shows the evolution of seed sales by public seed agencies from 1990-97. Summing across all three developing regions, public-sector seed sales remained relatively unchanged during this period. Overall, growth in public-sector seed sales was driven by developments in Asia, particularly in China, where demand for improved seed strengthened as farmers expanded plantings to meet the exploding demand for animal feed (Figure 7c). Public-sector seed sales were more erratic in Latin America and Eastern and Southern Africa (Figures 7a, 7b), partly as the result of highly variable weather that affected both regions.

Meanwhile, what was happening in the private sector? Figure 8 shows the evolution of seed sales by private seed companies from 1990-97. Since private-sector seed sales dominate total seed sales, it is not surprising that trends in private-sector seed sales closely resemble trends in total seed sales. Summing across all three developing regions, the data show a slight upward trend. Again, there was considerable variability between regions; in Latin America and Asia, private-sector seed sales increased steadily throughout the 1990s, while in Eastern and Southern Africa they decreased (Figures 9a-c).

Adoption of MVs

How extensive is the area planted in the developing world to improved maize cultivars? Survey respondents were asked to estimate the percentage of total national maize area under each of three categories of materials: (1) cultivars grown from farm-saved seed (including landraces, farmers' traditional varieties, and older OPVs and hybrids grown from advanced-generation recycled seed); (2) newer OPVs grown from commercial seed or from recycled seed emanating from recently-purchased commercial seed; and

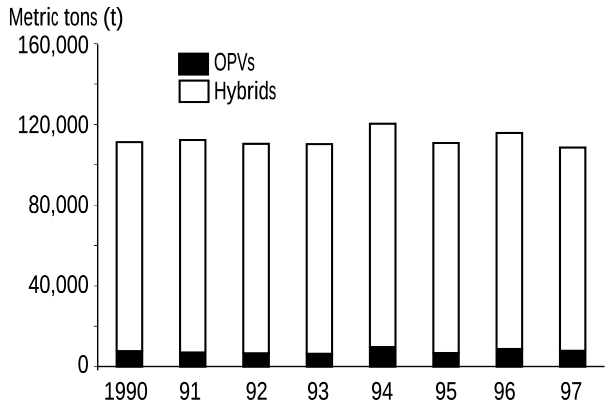

Figure 6. Public-sector maize seed sales, all developing countries, 1990-97.
Source: CIMMYT survey.

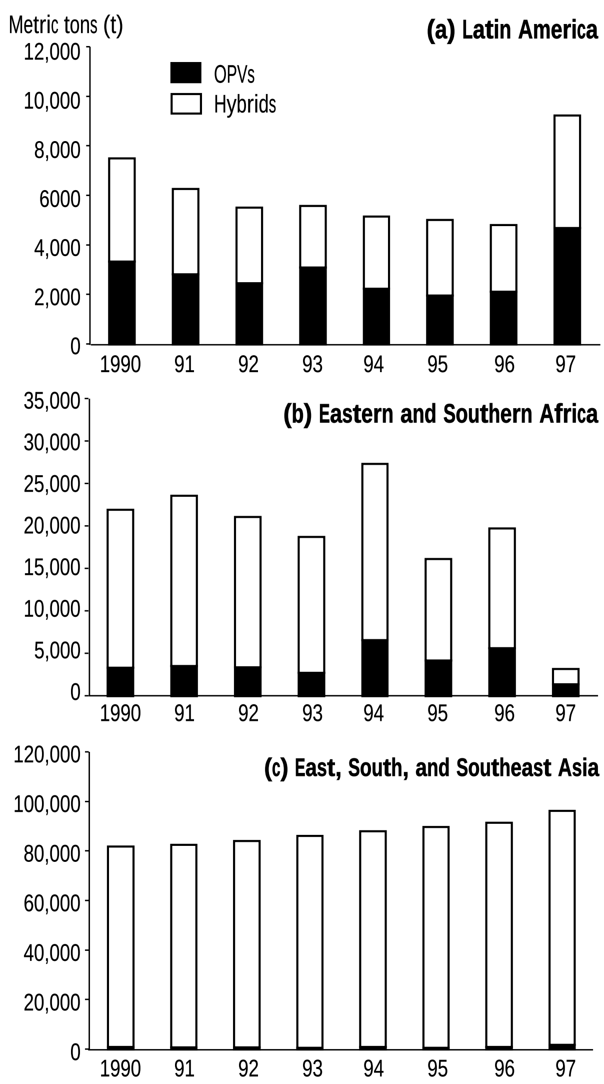

Figure 7. Public-sector maize seed sales, by region, 1990-97.
Source: CIMMYT survey.

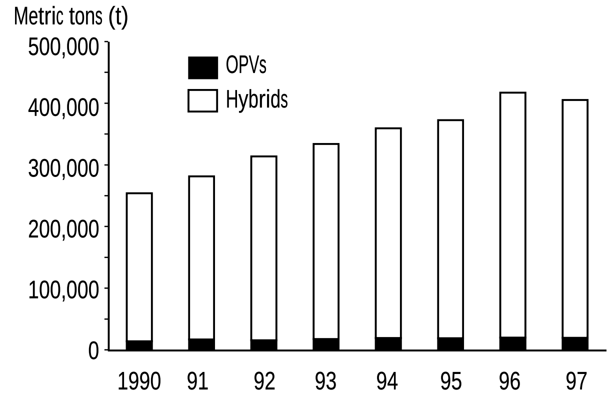

Figure 8. Private-sector maize seed sales, all developing countries, 1990-97.
Source: CIMMYT survey.

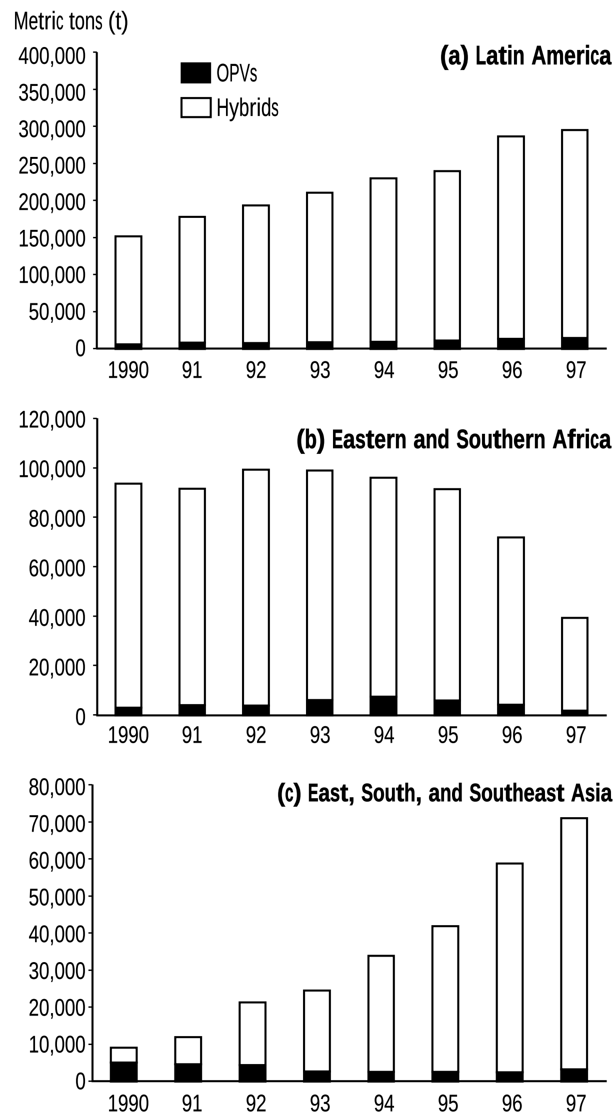

Figure 9. Private-sector maize seed sales, by region, 1990-97.
Source: CIMMYT survey.

(3) hybrids grown from newly-purchased commercial seed. Ideally these estimates would have been based on farm-level data, but varietal adoption surveys are rarely carried out at the national level because of their high cost. Therefore in most cases the respondents had to make subjective estimates based on whatever adoption data were available. These subjective estimates were later double-checked against commercial seed sales data for consistency.

Tables 14a-d present estimates of the area planted to each of the three germplasm categories during the late 1990s.[11] To provide a more complete picture of global adoption patterns, the tables reflect not only MV adoption data collected through the CIMMYT survey, but also MV adoption rates reported by IITA for 11 countries in West and Central Africa. In addition, adoption data were subjectively estimated for four non-surveyed countries: Côte d'Ivoire, northern China, Egypt, and Pakistan.

Table 13d. Characteristics of commercial maize seed sold by public and private seed companies in 1996/97, East, South, and Southeast Asia.[a]

	Seed sold by:			
	Public agencies	Private companies		All organizations
		Domestic	MNCs	
Estimated total seed sales (t)	96,200	24,900[b]	46,200[b]	167,200
Origin of variety				
Public sector (%)	0.86	0.00	0.00	0.44
Private sector (%)	0.14	1.00	1.00	0.56
Type of material				
OPVs (%)	0.12	0.00	0.02	0.07
Hybrids (%)	0.88	1.00	0.98	0.93
Ecological adaptation				
Lowland tropical (%)	0.23	0.83	0.93	0.50
Subtropical / Mid-altitude (%)	0.13	0.17	0.07	0.11
Highland (%)	0.02	0.00	0.00	0.01
Temperate (%)	0.62	0.00	0.00	0.39
Maturity range				
Extra early / Early (%)	0.31	0.89	0.70	0.53
Intermediate (%)	0.41	0.10	0.23	0.30
Late / Extra late (%)	0.28	0.02	0.07	0.17
Grain color				
White grain (%)	0.12	0.01	0.11	0.10
Yellow / Other color grain (%)	0.88	0.99	0.89	0.90
Grain texture				
Flint / Semi-flint (%)	0.33	0.37	0.74	0.48
Dent / Semi-dent (%)	0.67	0.63	0.26	0.52
Other (%)	0.00	0.00	0.00	0.00
Containing CIMMYT germplasm				
All materials (%)	0.19	0.27	0.23	0.21
Non-temperate materials (%)	0.52	0.30	0.26	0.36

[a] Percentages refer to commercial seed for which information is available.
[b] Sales by domestic companies estimated to comprise 35% of total private sector seed sales.
Source: CIMMYT maize impacts database.

[11] The country-level maize area planted data reported here were downloaded on 03/31/01 from the FAOSTAT Agricultural Production online database. The FAOSTAT database is periodically updated, so the maize area planted data reported here may differ slightly from those that were reported in the three regional maize impacts studies published previously. For this reason, estimates of the area planted to MVs reported here also may differ slightly from those reported in the regional impacts studies.

Overall, of the 94.2 million ha planted to maize in 51 developing countries, approximately 62.4% (representing about 58.8 million ha) were planted to improved cultivars. Excluding Argentina, northern China, and South Africa, where maize is grown mainly in temperate environments, of the 65.7 million ha planted to maize in non-temperate environments, approximately 47.2 % (representing 31 million ha) were planted to improved cultivars.

How do these findings compare to those of the CIMMYT global impacts study carried out in 1992? Since the geographical coverage of the earlier study was different, care should be taken in comparing the two sets of results. The 1992 survey covered mainly non-temperate countries; Argentina, northern China, and South Africa were not included. On the other hand, the earlier survey included a number of countries in WANA that were not included in the more recent survey, but these countries account for a small proportion of global maize production and have relatively little influence on regional and global totals. The estimated current MV adoption level in the non-temperate countries of 47.2% is significantly higher than the MV adoption level estimated during the earlier CIMMYT impacts study, which found that in 1990 approximately 42.6% of the developing world's maize area was planted to improved cultivars (López-Pereira and Morris 1994).

Several conclusions can be drawn from the adoption data summarized in Tables 14a-d.

- Maize MVs have spread widely throughout the developing world.

Table 14a. Maize area planted to traditional and modern varieties, Latin America, 1996.

	1996 maize area planted (000 ha)	Planted to farm-saved seed[a] (%)	Planted to modern varieties:		
			OPVs[b] (%)	Hybrids (%)	Total (%)
Caribbean	**379**	**66.2**	**20.0**	**13.8**	**33.8**
Cuba	89	5.5	36.0	58.5	94.5
Dominican Republic	33	24.0	76.0	0.0	76.0
Haiti	257	92.8	7.3	0.0	7.3
Mexico and Central America	**9,676**	**79.5**	**1.5**	**19.0**	**20.5**
Costa Rica	16	58.0	1.1	40.9	42.0
El Salvador	278	51.9	0.5	47.6	48.2
Guatemala	575	82.8	1.7	15.5	17.2
Honduras	407	84.3	7.2	8.6	15.7
Mexico	8,051	79.7	1.1	19.2	20.3
Nicaragua	278	93.1	5.6	1.3	6.9
Panama	72	57.1	0.6	42.3	42.9
Andean Zone	**2,203**	**58.4**	**8.7**	**32.9**	**41.6**
Bolivia	287	47.9	27.1	25.1	52.1
Colombia	593	73.7	6.6	19.8	26.3
Ecuador	556	73.2	5.0	21.8	26.8
Peru	401	75.3	11.7	13.0	24.7
Venezuela	366	1.0	0.0	99.0	99.0
Southern Cone	**14,862**	**38.5**	**6.3**	**55.2**	**61.5**
Argentina	2,604	12.7	2.4	84.9	87.3
Brazil	11,934	43.4	7.3	49.3	56.6
Paraguay	325	64.5	1.7	33.9	35.5
Latin America	**27,121**	**55.1**	**5.0**	**39.9**	**44.9**
w/o Argentina	**24,517**	**59.6**	**5.3**	**35.1**	**40.4**

[a] Includes landraces and very old OPVs and hybrids grown from advanced-generation recycled seed.
[b] Includes area planted to recycled OPV seed.
Source: CIMMYT global maize impacts survey.

- The area planted to maize MVs continues to expand.
- Maize MVs have been adopted less extensively in non-temperate areas than in temperate areas.
- The area planted to hybrids is much larger than the area planted to OPVs.
- A significant proportion of the developing world's maize area continues to be planted to farm-saved seed.
- Expressed as a percentage of the total area planted to maize, the area under MVs has increased markedly during the past decade.

Adoption of MVS Developed Using CIMMYT Germplasm

The MV adoption estimates presented in Tables 14a-d were combined with information about varietal releases and/or commercial seed sales data to derive estimates of the area planted to cultivars developed using CIMMYT germplasm. Depending on the availability of data, two different estimation methods were used.

Table 14b. Maize area planted to traditional and modern varieties, sub-Saharan Africa, 1997.

	1997 maize area planted (000 ha)	Planted to farm-saved seed[a] (%)	Planted to modern varieties:		
			OPVs[b] (%)	Hybrids (%)	Total (%)
Western and Central Africa[c]	**9,067**	**64.0**	**32.3**	**3.7**	**36.0**
Benin	577	74.7			25.3
Burkina Faso	241	54.5			45.5
Cameroon	375	72.0			28.0
Chad	104	30.0			70.0
Congo, D.R.	1,427	68.7			31.3
Côte d'Ivoire[d]	700	68.0			32.0
Ghana	652	47.0			53.0
Guinea	84	77.4			22.6
Mali	202	77.1			22.9
Nigeria	4,200	60.0			40.0
Senegal	62	10.8			89.2
Togo	423	98.7			1.3
Eastern Africa	**3,821**	**60.3**	**11.6**	**28.1**	**39.7**
Ethiopia	1,718	94.2	1.9	3.9	5.8
Kenya	1,505	27.6	7.5	65.0	72.5
Uganda	598	45.3	50.0	4.7	54.7
Southern Africa	**11,088**	**43.0**	**5.2**	**51.7**	**57.0**
Angola	620	74.5	25.0	0.5	25.5
Lesotho	144	25.2	10.9	63.9	74.8
Malawi	1,234	88.6	4.4	7.0	11.4
Mozambique	1,154	92.0	8.0	0.1	8.0
South Africa	4,023	2.4	3.1	94.5	97.6
Swaziland	61	24.6	2.2	73.2	75.5
Tanzania	1,564	90.0	4.0	6.0	10.0
Zambia	649	80.8	0.6	18.6	19.3
Zimbabwe	1,640	4.5	4.5	91.0	95.5
Eastern and Southern Africa	**14,910**	**47.5**	**6.9**	**45.7**	**52.6**
w/o South Africa	**10,886**	**64.1**	**8.3**	**27.6**	**35.9**
Sub-Saharan Africa	**23,957**	**53.7**	**16.5**	**29.8**	**46.3**
w/o South Africa	**19,934**	**64.1**	**19.2**	**16.8**	**36.0**

[a] Includes landraces and very old OPVs and hybrids grown from advanced-generation recycled seed.
[b] Includes area planted to recycled OPV seed.
[c] MV adoption data for Western and Central Africa provided by IITA.
[d] Not included in IITA survey; data estimated indirectly.
Source: CIMMYT global maize impacts survey.

Table 14c. Maize area planted to traditional and modern varieties, East, South, and Southeast Asia, 1999.

	1999 maize area planted (000 ha)	Planted to farm-saved seed[a] (%)	Planted to modern varieties:		
			OPVs[b] (%)	Hybrids (%)	Total (%)
East Asia	**25,939**	**1.0**	**5.2**	**93.8**	**99.0**
Southern China	4,114	1.0	11.8	87.2	99.0
Northern China[c]	21,825	1.0	4.0	95.0	99.0
South Asia	**8,207**	**50.0**	**24.6**	**25.4**	**50.0**
India	6,511	49.0	22.0	29.0	51.0
Nepal	802	36.0	45.4	18.6	64.0
Pakistan[d]	894	70.0	25.0	5.0	30.0
Southeast Asia	**8,144**	**37.8**	**24.8**	**37.4**	**62.2**
Indonesia	3,456	30.0	41.0	29.0	70.0
Philippines	2,701	64.0	12.0	24.0	36.0
Thailand	1,300	0.3	13.9	85.8	99.7
Vietnam	687	44.5	14.7	40.8	55.5
East, South, and Southeast Asia	**42,290**	**17.6**	**12.3**	**69.6**	**82.4**
w/o northern China	**20,465**	**35.3**	**22.1**	**42.6**	**64.7**

[a] Includes landraces and very old OPVs and hybrids grown from advanced-generation recycled seed.
[b] Includes area planted to recycled OPV seed.
[c] Not included in CIMMYT survey. MV adoption estimated based on information provided by sources in the Chinese national maize breeding program (Zhang, personal communication).
[d] Not included in CIMMYT survey. MV adoption estimated based on information provided by sources in the Pakistan national maize breeding program (Aslam, personal communication).
Source: CIMMYT global maize impacts survey.

Table 14d. Maize area planted to traditional and modern varieties, developing countries, late 1990s.[a]

	1990s maize area planted[b] (000 ha)	Planted to farm-saved seed[c] (%)	Planted to modern varieties:		
			OPVs[d] (%)	Hybrids (%)	Total (%)
Latin America	27,121	55.1	5.0	39.9	44.9
w/o Argentina	24,517	59.6	5.3	35.1	40.4
Western and Central Africa[e]	9,047	64.0	32.3	3.7	36.0
Eastern and Southern Africa	14,910	47.5	6.9	45.7	52.6
w/o South Africa	10,886	64.1	8.3	27.6	35.9
Sub-Saharan Africa	23,957	53.7	16.5	29.8	46.3
w/o South Africa	19,934	64.1	19.2	16.8	36.0
East, South, and Southeast Asia	42,290	17.8	12.8	69.6	82.4
w/o northern China	20,465	35.3	22.1	42.6	64.7
All regions	94,182	37.6	11.5	51.0	62.4
All non-temperate regions[f]	65,731	52.8	14.8	32.4	47.2

[a] Includes data for 48 countries covered by the CIMMYT and IITA surveys, plus northern China, Côte d'Ivoire, Pakistan, and Egypt. Countries with 100,000 ha or more planted to maize that were not included: Turkey (545,000 ha), Korea DPR (496,000 ha), Morocco (341,000 ha), Myanmar (203,000 ha), Afghanistan (200,000), Somalia (200,000 ha), Madagascar (190,000 ha), Iran (133,000 ha), Burundi (115,000).
[b] Years: Latin America = 1996; Eastern and Southern Africa = 1997; Western and Central Africa = 1998; East, South, and Southeast Asia = 1999.
[c] Includes landraces and very old OPVs and hybrids grown from advanced-generation recycled seed.
[d] Includes area planted to recycled OPV seed.
[e] Estimated based on results of IITA impacts study, 1992 CIMMYT impacts study.
[f] Excluding Argentina, South Africa, and northern China.
Source: CIMMYT global maize impacts survey.

Seed-based method

For many countries, the survey of seed organizations generated data on a significant proportion of all commercial maize seed sold during the reference year (1996 for Latin America, 1997 for Africa and Asia). Most of the seed sales data were cultivar-specific, and since the CIMMYT germplasm content of most cultivars was known, it was often possible to calculate the proportion of commercial seed sold in each country that was seed of CIMMYT-derived cultivars. This proportion was then applied to the area planted to MVs to derive an estimate of the area planted to CIMMYT-derived MVs. In other words, if 40% of the commercial maize seed sold during the reference year was known to be seed of CIMMYT-derived cultivars, it was assumed that 40% of the area planted to MVs during the reference year was planted to CIMMYT-derived cultivars. This method is based on the assumption (reasonable when data are available about a significant proportion of total seed sales) that the seed for which no information is available is similar in its CIMMYT germplasm content to the seed for which information is available.

Varietal releases-based method

One disadvantage of the seed-based method is that it requires detailed knowledge of the germplasm content of a significant proportion of all seed planted by farmers. The method therefore can give misleading results if data on commercial seed sales are incomplete. This was a concern for the present study, because in some countries the survey generated limited information about commercial seed sales, at least for certain types of cultivars. In five African countries (Angola, Lesotho, South Africa, Swaziland, Tanzania), relatively little information was generated about sales of OPV or hybrid seed. In six Asian countries (India, Indonesia, Nepal, the Philippines, Thailand, Vietnam), relatively little information was generated about sales of OPV seed.[12]

The seed-based method has a second potential drawback. Even when detailed information is available about the germplasm content of commercial seed, the method can give misleading results if a significant proportion of the area planted to maize MVs is planted to farm-saved seed. Farm-saved seed often includes advanced-generation seed of older varieties, especially OPVs, so estimating the area planted to CIMMYT-derived cultivars on the basis of commercial seed is risky, because the CIMMYT germplasm content of varieties currently being sold may differ from that of varieties sold in earlier years.

In countries where commercial seed sales data were deemed incomplete, therefore, the area planted to CIMMYT-derived cultivars was estimated based on the CIMMYT content of varietal releases. This was done by calculating the proportion of all cultivars released between 1966 and 1999 that had been developed using CIMMYT germplasm; this proportion was then applied to the area planted to MVs during the reference year to derive an estimate of the area planted to CIMMYT-derived MVs. In other words, in countries where limited information was available about the germplasm content of commercial seed, if 70% of the MVs released between 1966 and 1997 had been developed using CIMMYT germplasm, then it was assumed that 70% of the area planted to MVs during the reference year was planted to CIMMYT-derived MVs. In African countries, where variety-specific seed sales data were sometimes unavailable for OPVs and hybrids, this method was applied to the entire area planted to

[12] The fact that the survey generated relatively little information about sales of OPV seed is not surprising, because relatively little OPV seed was sold by the organizations that participated in the survey. OPV seed is produced mainly by small local seed companies, community-based seed organizations, and NGOs, which were underrepresented in the survey.

MVs. In Asian countries, where variety-specific seed sales data were available only for hybrids, the varietal releases-based method was applied only to the area planted to improved OPVs.

Estimates of the area planted to CIMMYT-derived cultivars appear in Tables 15a-d. Overall, of the 94.2 million ha planted to maize in 51 developing countries, approximately 58.8 million ha were planted to MVs, of which 21.2 million ha were planted to CIMMYT-derived MVs. Excluding Argentina, northern China, and South Africa, of the 65.7 million ha planted to maize, approximately 31 million ha were planted to MVs, of which 18.2 million ha were planted to CIMMYT-derived MVs. In other words, over one-third (36.1%) of the total area planted to modern maize varieties in the developing world and over one-half (58.7%) of the non-temperate area planted to modern maize varieties in the developing world was planted to varieties developed using germplasm obtained from CIMMYT.

The area planted to CIMMYT-derived MVs varied by region. In Latin America, 9.8 million ha were planted to CIMMYT-derived MVs (Table 15a). In Africa, 3.8 million ha were planted to CIMMYT-derived MVs (Table 15b). In East, South, and Southeast Asia, 7.2 million ha were planted to CIMMYT-derived MVs (Table 15c).

Table 15a. Maize area planted to CIMMYT-derived modern varieties, Latin America, 1996.[a]

	1996 maize area planted (000 ha)	Proportion of maize area under MVs (%)	1996 maize area under MVs (000 ha)	Proportion of MVs with CIMMYT germplasm (%)[b]	Maize area under CIMMYT-derived MVs (000 ha)
Caribbean	**379**	**33.8**	**128**	**36.9**	**47**
Cuba	89	94.5	84	50.0	42
Dominican Republic	33	76.0	25	7.9	2
Haiti	257	7.3	19	16.9	3
Mexico and Central America	**9,676**	**20.5**	**1,988**	**90.4**	**1,796**
Costa Rica	16	42.0	7	100.0	7
El Salvador	278	48.2	134	93.4	125
Guatemala	575	17.2	99	98.5	97
Honduras	407	15.7	64	99.9	64
Mexico	8,051	20.3	1,634	88.9	1,453
Nicaragua	278	6.9	19	100.0	19
Panama	72	42.9	31	100.0	31
Andean Zone	**2,203**	**41.6**	**916**	**97.2**	**891**
Bolivia	287	52.1	149	96.9	145
Columbia	593	26.3	156	100.0	156
Ecuador	556	26.8	149	99.4	148
Peru	401	24.7	99	88.3	87
Venezuela	366	99.0	362	97.7	354
Southern Cone	**14,862**	**61.5**	**9,140**	**77.8**	**7,109**
Argentina	2,604	87.3	2,272	29.0	659
Brazil	11,934	56.6	6,752	93.9	6,340
Paraguay	325	35.5	115	94.9	109
Latin America	**27,121**	**44.9**	**12,171**	**80.9**	**9,842**
w/o Argentina	**24,517**	**40.4**	**9,899**	**92.8**	**9,183**

[a] Data presented for 18 countries covered by the CIMMYT survey.
[b] Based on proportion commercial seed sold in 1996 that contained CIMMYT germplasm.
Source: CIMMYT global maize impacts survey.

Factors Affecting MV Adoption

Why does the use of maize MVs differ between countries? What explains the fact that MV adoption rates are high in some countries and low in others? Can the factors associated with differences in MV adoption rates be identified?

Evidence at the farm level

Technology adoption decisions in developing countries have been extensively analyzed. (For surveys of the adoption literature, see Feder, Just, and Zilberman, 1985; Rauniyar and Goode 1992.) Complementing the large amount of theoretical work that focuses on technology adoption in

Table 15b. Maize area planted to CIMMYT-derived modern varieties, sub-Saharan Africa, 1997.[a]

	1997 maize area planted (000 ha)	Proportion of maize area under MVs (%)	1997 maize area under MVs (000 ha)	Proportion of MVs with CIMMYT germplasm (%)[b]	Maize area under CIMMYT-derived MVs (000 ha)
Western and Central Africa	**9,047**	**36.0**	**3,256**	**66.7**	**2,170**
Benin	577	25.3	146	66.7	97
Burkina Faso	241	45.5	110	66.7	73
Cameroon	375	28.0	105	66.7	70
Chad	104	70.0	73	66.7	48
Congo, D.R.	1,427	31.3	447	66.7	298
Côte d'Ivoire[c]	700	32.0	224	66.7	149
Ghana	652	53.0	345	66.7	230
Guinea	84	22.6	19	66.7	13
Mali	202	22.9	46	66.7	31
Nigeria	4,200	40.0	1,680	66.7	1,120
Senegal	62	89.2	56	66.7	37
Togo	423	1.3	6	66.7	4
Eastern Africa	**3,821**	**39.71**	**1,517**	**21.2**	**321**
Ethiopia	1,718	5.8	100	36.4	36
Kenya	1,505	72.5	1,090	11.1	121
Uganda	598	54.7	327	50.0	164
Southern Africa	**11,088**	**57.0**	**6,317**	**20.7**	**1,308**
Angola	620	25.5	158	33.3	53
Lesotho	144	74.8	108	5.0	5
Malawi	1,234	11.4	140	55.6	78
Mozambique	1,154	8.0	92	75.0	69
South Africa	4,023	97.6	3,925	5.0	196
Swaziland	61	75.5	46	5.0	2
Tanzania	1,564	10.0	156	33.3	52
Zambia	649	19.3	125	13.6	17
Zimbabwe	1,640	95.5	1,566	53.3	835
Eastern and Southern Africa	**12,168**	**52.6**	**7,834**	**20.8**	**1,629**
w/o South Africa	**10,886**	**35.9**	**3,910**	**36.7**	**1,433**
Sub-Saharan Africa	**23,957**	**46.3**	**11,090**	**34.3**	**3,800**
w/o South Africa	**19,934**	**36.0**	**7,165**	**50.3**	**3,603**

[a] Data presented for 23 countries covered by the CIMMYT and IITA surveys, plus Côte d'Ivoire.
[b] Based on proportion of commercial seed sold in 1997 that contained CIMMYT germplasm. For Angola, Lesotho, Mozambique, South Africa, and Swaziland based on proportion of varietal releases from 1966-98 that contained CIMMYT germplasm.
[c] Not included in IITA survey; data estimated indirectly.
Source: CIMMYT global maize impacts survey.

Table 15c. Maize area planted to CIMMYT-derived modern varieties, East, South, and Southeast Asia, 1999.[a]

	1999 maize area planted (000 ha)	Proportion of maize area under MVs (%)	1999 maize area under MVs (000 ha)	Proportion of MVs with CIMMYT germplasm (%)[b]	Maize area under CIMMYT-derived MVs (000 ha)
East Asia	**42,290**	**99.0**	**25,670**	**10.9**	**2,786**
Southern China	4,114	99.0	4,073	15.4	625
Northern China[c]	20,465	99.0	21,607	10.0	2,161
South Asia	**7,313**	**50.0**	**4,102**	**40.5**	**1,662**
India	6,511	51.0	3,321	36.7	1,218
Nepal	802	64.0	514	60.3	310
Pakistan[d]	894	30.0	268	50.0	134
Southeast Asia	**8,144**	**62.2**	**5,069**	**54.7**	**2,775**
Indonesia	3,456	70.0	2,420	63.5	1,536
Philippines	2,701	36.0	972	40.0	389
Thailand	1,300	99.7	1,296	53.0	687
Vietnam	687	55.5	381	42.5	162
East, South, and					
Southeast Asia	**42,290**	**82.4**	**34,851**	**20.7**	**7,222**
w/o northern China	**20,465**	**64.7**	**13,244**	**38.2**	**5,062**

a Data presented for seven countries covered by the CIMMYT survey, plus northern China and Pakistan.
b For improved OPVs, based on proportion of varietal releases from 1966-98 that contained CIMMYT germplasm. For hybrids, based on proportion of commercial seed sold in 1998 that contained CIMMYT germplasm.
c Not included in the CIMMYT survey; data estimated indirectly.
d Not included in the CIMMYT survey; data estimated indirectly.
Source: CIMMYT global maize impacts survey.

Table 15d. Maize area planted to CIMMYT-derived modern varieties, developing countries, late 1990s.[a]

	1990s maize area planted (000 ha)[b]	Proportion of maize area under MVs (%)	1999 maize area under MVs (000 ha)	Proportion of MVs with CIMMYT germplasm (%)[c]	Maize area under CIMMYT-derived MVs (000 ha)
Latin America	27,121	44.9	12,171	80.9	9,842
Sub-Saharan Africa	23,957	46.3	11,090	34.3	3,800
East, South,					
Southeast Asia	42,290	82.4	34,851	20.7	7,222
West Asia, North Africa[d]	814	85.0	692	50.0	346
All environments[e]	94,182	62.4	58,805	36.1	21,210
Non-temperate					
environments[f]	65,731	47.2	31,001	58.7	18,195

a Data presented for 51 countries representing 97% of total area planted to maize in developing countries.
b Reference year varies by region. Latin America = 1996; Eastern and Southern Africa = 1997; Western and Central Africa = 1998; East, South, and Southeast Asia = 1999.
c For details about estimation methods, see notes to Tables 15a, 15b, and 15c.
d Includes Egypt.
e Includes data for the 48 countries covered by the CIMMYT and IITA surveys, plus Côte d'Ivoire, northern China, Egypt, and Pakistan.
f Excluding Argentina, South Africa, and northern China.
Source: CIMMYT global maize impacts survey.

general, numerous empirical case studies provide a wealth of information about the factors affecting farm-level decision to adopt hybrid maize (for example, see Gerhart 1975; Walker 1981; CIMMYT 1992; Byerlee, Morris, and López-Pereira 1993; Smale et al. 1991, 1995; Kumar 1994; Heisey et al., 1998). The common theme emerging from this literature is that farm-level decision to adopt hybrid maize is influenced by a complex and highly variable set of factors. Depending on the context, these can include demographic characteristics of the household (for example, size, age and gender composition, wealth, education level of the household head), the expected profitability and/or perceived risk of the technology, farmers' consumption preferences, and the availability and cost of inputs, especially seed.

Evidence at the industry level

While the farm-level decision to adopt hybrid maize has been the focus of considerable research, much less work has been done at the aggregate industry level to identify factors that influence the diffusion of hybrid technology. In his pioneering study of the spread of hybrid maize in the US, Griliches (1957) hypothesized that the uneven rate of diffusion could be linked to both demand and supply factors. Griliches determined that variability in the demand for hybrid maize is related to the additional profits that farmers expect to gain by switching from open-pollinating varieties to hybrids. He also found that variability in the supply of hybrid seed is related to the revenue that seed suppliers expect to earn by entering the market, which depends on factors such as the size of the market, marketing costs, product innovation costs, and expected rate of acceptance.

More recently, Heisey et al. (1998) used cross-sectional data to investigate how demand and supply factors influence the spread of hybrid maize in 32 developing countries. Heisey et al. concluded that at the aggregate (country) level, diffusion of hybrid maize depends partly on the expected profitability of the technology, which is driven by germplasm performance and seed price. As well, they determined that the diffusion of hybrid maize is strongly influenced by industry-level profitability, which depends on characteristics of the seed market, the organization of the local seed industry, and the cost of research innovation, among other factors.

Using a similar approach, Kosarek, Garcia, and Morris (2001) examined the diffusion of hybrid maize in 23 developing countries in Latin America and the Caribbean region. Like the earlier authors, Kosarek et al. found that diffusion of hybrid maize is influenced not only by demand side factors that affect the profitability of the technology at the farm level (including the level of government policy support provided to maize producers), but also by supply side factors that shape the incentives for firms to invest in seed research and development, seed production, and seed distribution (including the prevailing level of intellectual property protection).

The empirical studies by Griliches, Heisey et al., and Kosarek et al. highlight an important but frequently overlooked point: even when farmers have become convinced that they can benefit from adopting hybrids, successful adoption cannot occur without adequate supplies of hybrid seed. In attempting to explain the diffusion of hybrid technology, therefore, it is important not only to analyze farmers' varietal adoption decisions, but also to examine the factors that shape incentives for firms to produce and sell improved seed. The question of supply-side incentives is especially relevant in developing countries, where private companies have often been reluctant to enter into the production and marketing of hybrid maize seed.

The presence or absence of incentives to produce and sell hybrid seed may be related to the stage of development of the local seed industry. Several authors have advanced life cycle theories of seed industry development in which national seed industries are described as evolving in a path-dependent manner through successive growth stages (Douglas 1980, Pray and Ramaswami 1991; Rusike 1995; Dowswell, Paliwal, and Cantrell 1996; Morris and Smale 1997; Morris, Smale, and Rusike 1998). According to the various life cycle theories, the characteristics associated with the initial stages of seed industry development mitigate against the diffusion of hybrid maize, because incentives to produce and sell hybrid maize are not yet present. In the early stages of seed industry development, maize producers consist mainly of small-scale, subsistence oriented farmers who use mostly farm-saved seed retained from their own harvest or obtained from neighbors. Under these circumstances, there is no adequate market capable of sustaining firms looking to generate profits through the production and sale of commercial seed. Not until the seed industry reaches more advanced stages of development, when farmers understand the benefits of improved germplasm and are willing to purchase seed on a regular basis, does the effective demand for hybrid seed become strong enough to support a commercial seed industry—thereby paving the way for widespread diffusion of hybrids. In short, the production and delivery of hybrid maize seed go hand-in-hand with the existence of well-developed commercial seed industries.

Economic Benefits Associated with MV Adoption

As more and more demands are placed on the limited pool of funds available for agricultural research, research organizations face increasing pressure to show that resources are being used efficiently. In today's highly competitive funding environment, scientists must not only demonstrate that their work is having an impact, but frequently they are also required to quantify the economic benefits that have been generated.

What have been the economic benefits generated by international maize breeding research? More specifically, what have been the economic benefits generated by CIMMYT's maize breeding program? For reasons that are discussed extensively in the investment literature, estimating economic benefits generated by agricultural research organizations is often difficult (for a comprehensive summary, see Alston, Norton, and Pardey 1995). In the case of plant breeding programs, economic benefits include not only benefits received by farmers in the form of increased production, but also benefits received by consumers (who pay lower prices for grain and fodder), by food and feed processors (who experience increased demand for their services), by agricultural laborers (who derive increased employment opportunities), and by other groups that benefit via price- or income-transmitted multiplier effects. Quantification and valuation of these indirect benefits is a major undertaking requiring multi-market or general-equilibrium modeling and large amounts of data (for an example involving the economic benefits generated by wheat breeding research, see Renkow 1993).

The economic benefits estimates presented below were not generated using a formal modeling approach. Instead, they were derived through "back-of-the-envelope" calculations involving a number of simplifying assumptions. Furthermore, they refer only to the benefits received by developing-country maize farmers in the form of increased grain production; no attempt was made to account for indirect benefits received by consumers, food and feed processors, agricultural laborers, and other groups. Despite these limitations, however, the estimates provide useful information about the value of additional production attributable to international maize breeding efforts in general and to CIMMYT's maize breeding program in particular.

Economic Benefits Not Reflected in Yield Gains

The following discussion regarding the economic benefits generated by international maize breeding research focuses on the value of additional grain production associated with adoption of MVs. Mainly because of data limitations, benefits from plant breeding research that are not reflected in the form of yield gains are ignored. Examples of traits that confer non-yield benefits include:

- ***improved grain quality*** (benefits: easier processing, better storability, improved nutritional status of humans and livestock)
- ***improved fodder quality*** (benefits: easier processing, better storability, faster growth, and improved nutritional status of livestock) and
- ***shorter growth cycle*** (benefit: additional crops can be accommodated in multi-crop rotations without compromising maize yields).

While non-yield benefits associated with MV adoption can be extremely important, quantifying and valuing them tends to be difficult. In contrast, yield gains associated with MV adoption are more easily measured, and since the price of maize grain is usually available, the economic value of the additional production can be readily estimated.

Parameters Needed to Calculate Value of Additional Production

In order to calculate the value of the additional maize grain production attributable to international maize breeding efforts, three key parameters must be estimated: (1) the area planted to maize MVs, (2) the productivity gains attributable to adoption of maize MVs, and (3) the price of maize grain. Using a simple economic surplus model, these three parameters can be combined to calculate the value of additional production in a given period (t):

$$B_t = A_t \quad y_t \quad P_t$$

where:

B = value of additional production attributable to maize breeding research,
A = area planted to maize MVs,
y = yield gain attributable to maize breeding research,[13] and
P = price of maize grain.

Area planted to MVs

Estimates of the area planted to maize MVs (A) have been presented earlier in this report (see Sections 5.2 and 5.3).

Yield gain attributable to maize breeding research

At the farm level, the yield gain attributable to maize breeding research (y) is the difference between the yield obtained with a farmer's current variety (which depending on the circumstances may be a landrace or an older MV) and the yield obtained with a newly adopted MV, holding

[13] The productivity gains associated with MV adoption are conventionally measured in terms of the yield increase per unit land area achieved when input costs are held constant. An alternative approach is to measure cost savings at a given yield level.

constant inputs and management. In practice, this difference is difficult to estimate for at least two reasons:

1. ***Genotype by environment (GxE) interactions*:** The genetic potential of any cultivar interacts with environmental factors, so the yield difference between the same variety will tend to vary across locations and between cropping seasons because of agro-climatic effects. Case study evidence suggests that yield gains associated with adoption of the same MV can vary widely (Morris, Risopoulos, and Beck 1999). To further complicate matters, where farmers are recycling seed, the genetic composition of their cultivars may change from generation to generation due to GxE interactions, which further affects the yield difference.
2. ***Germplasm vs. crop management effects:*** Yield gains achieved in farmers' fields come not only from adoption of MVs; yield gains come also from adoption of improved crop management practices, which frequently interact with MVs. In estimating the economic benefits attributable to plant breeding research, it is therefore necessary to distinguish between the germplasm effect on yields and the crop management effect (Figure 10). Relatively little empirical research has been done on this topic, but it is reasonable to assume that improved germplasm and improved management practices each have contributed about 50% to observed yield gains in cereal crops (Bell et al. 1995, Thirtle 1995, Fuglie et al. 1996).

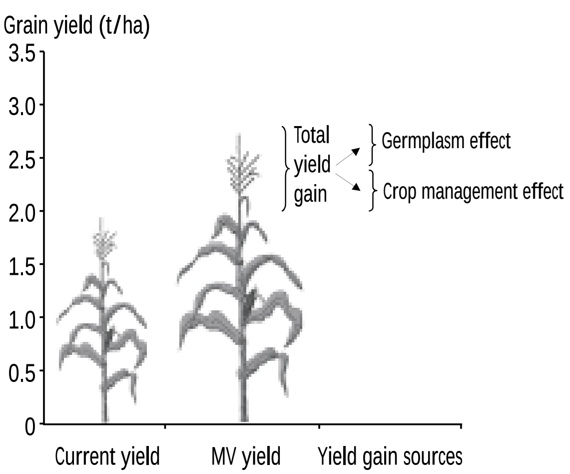

Figure 10. Yield gain components: Germplasm vs. crop management effect.
Source: Author.

The practical difficulties inherent in measuring the yield gains attributable to MV adoption are compounded by a conceptual problem. Many plant breeding impacts studies implicitly assume that in the absence of the breeding program being evaluated, farmers' yields would have remained unchanged. This assumption is often unrealistic, as usually there are alternative sources of improved technologies. Thus the relevant comparison is not between current yields and yields being achieved at the time the breeding program was established, but rather between current yields and yields that farmers would currently be achieving had the breeding program being evaluated not been established.[14]

Figure 11 illustrates this problem. The horizontal dashed line represents the average yield achieved by farmers prior to the establishment of the breeding program being evaluated. The upper solid line represents average yields achieved by farmers as the result of growing a total of seven MVs produced by the breeding program; since MV replacement occurs at irregular intervals, the line is stepped. A common mistake in many impacts studies is to assume that the yield gain attributable to the breeding program is the difference between the farmers' original yield and their current yield, represented by the vertical distance (a + b). A more realistic estimate would take into account the fact that yield gains would likely have been realized even in the absence of the breeding program being evaluated, because farmers would have grown MVs obtained from other sources. This so-called counterfactual scenario is represented in Figure 11 by the lower solid line; the yield gains that would have been achieved under the counterfactual scenario are represented by the vertical distance (b). The yield gain attributable to the breeding program being evaluated thus should be estimated as something less than the difference between farmers' original

[14] This concept is well-known in the literature on benefit:cost analysis, in which it is referred to as the "with and without project" comparison (see Gittinger 1982: 47-50).

yields and their current yields; a more realistic estimate might be the yield gain represented by the vertical distance (a). Although it is impossible to know what would have happened to farmers' yields had the breeding program being evaluated not existed, some sort of subjective judgment is needed to account for the yield gains that would have been achieved under the counterfactual scenario.

One final point must be made concerning yield gain estimates. Many published impacts studies have used annual yield gain parameters that when considered in a temporal dimension imply yield growth far exceeding actual historical yield growth. According to FAO data, maize yields in developing countries grew at an average annual rate of 2.5% from 1966-98, the period covered by this study (FAOSTAT online database). This growth rate, which reflects both the germplasm effect and the crop management effect, is consistent with yield data suggesting that long-term growth in genetic potential has averaged 1-2% per year in maize (Duvick 1992; Troyer 1996, 1999). Yield gains attributed to MV adoption that implicitly would have led to aggregate yield growth in excess of actual observed growth rates are clearly unrealistic.

In view of these practical and conceptual difficulties, estimating a single average global annual yield gain parameter (y) is problematic. Calculation of such a parameter would require time-series data on MV adoption, disaggregated by environment, by level of management, and by type of adoption behavior (initial adoption of an MV to replace a landrace, replacement of an older MV by a newer MV). In the absence of such data, the approach used here is to estimate economic benefits generated under a range of plausible yield gain estimates (15%, 25%, 35%, 45%).[15] Estimates on this order of magnitude imply that since CIMMYT was founded in 1966, international maize breeding efforts have boosted average maize yields gains realized in developing countries by 0.25 – 1% per year.

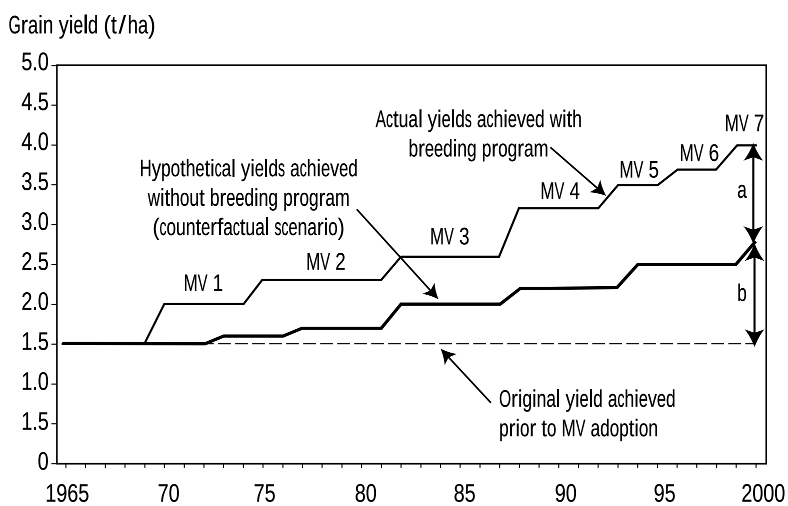

Figure 11. Estimating MV yield gains: Accommodating the counterfactual scenario.
Source: Author.

Price of maize grain

The price of maize grain (p) is conservatively valued at US$ 120/ton. During the late 1990s, the main international reference price of maize (#2 Yellow, FOB US Gulf ports) varied between US$ 60/ton and US$ 105/ton. Since most developing countries are net importers of maize, the appropriate price to use in valuing incremental production is the

[16] In order to calculate the additional amount of grain produced as a result of MV adoption, the percentage yield gain (y) must be multiplied by the average MV yield (Y). Farm survey data suggest that maize MV yields in developing countries range from 2.5 t/ha to more than 10 t/ha. For purposes of this study, the average maize MV yield is assumed to be 3.5 t/ha.

import parity price. The figure of US$ 120/ton was derived by adding representative international transport and handling costs to the reference price.

If there were any evidence that the additional production attributable to adoption of maize MVs in developing countries influences international maize prices (for example, by shifting out the global supply curve and depressing world markets), then some sort of adjustment to the international reference price would be needed. Such an adjustment is unnecessary in the present context, however, because international maize prices are determined mainly by supply and demand conditions in industrialized countries. With very few exceptions (for example, unusually severe global weather disruptions), changes in the quantity of maize produced in developing countries are unlikely to have a significant effect on international reference prices. Also, to the extent that changes in production in developing countries do affect international prices, these changes would normally occur in large countries such as Argentina, China, and South Africa, which grow mainly temperate varieties produced by breeding programs that are not being considered in this study.

Gross Benefits Associated with MV Adoption

The value of additional maize grain production attributable to the adoption of MVs in developing countries is shown in Table 16. Depending on the average yield gain associated with MV adoption (Columns 1 and 2), gross benefits are estimated to range between US$ 3.7 billion and US$ 11.1 billion per year (Column 3). Assuming that 50% of the yield gain is attributable to the germplasm effect and 50% is attributable to the crop management effect, gross benefits attributable to the germplasm effect alone are estimated to range between US$ 1.9 billion and US$ 5.6 billion per year (Column 4).

Benefits Attributable to CIMMYT's Breeding Program

What portion of the estimated gross benefits shown in Table 16 can be attributed to CIMMYT's maize breeding program? Estimated gross benefits attributable to the adoption of CIMMYT-derived maize MVs are shown in Table 17. Depending on the average yield gain associated with MV adoption (Columns 1 and 2), gross benefits realized on the area planted to CIMMYT-derived MVs (germplasm effect plus crop management

Table 16. Value of additional production attributable to international maize breeding efforts, developing countries.

Yield gain attributable to adoption of maize MVs (germplasm effect plus crop management effect)		Gross economic benefits from MV adoption	Net economic benefits from germplasm effect
(%)	(t/ha)	(US$ million/year)	(US$ million/year)
15 %	0.53	3,705	1,852
25 %	0.88	6,175	3,087
35 %	1.23	8,644	4,322
45 %	1.58	11,114	5,557

Assumptions:
Area planted to maize MVs in developing countries: 58.8 million ha
Average yield of MVs: 3.5 t/ha (implies average yield of non-MVs: 1.2 t/ha)
Proportion of yield gain attributable to germplasm effect: 50%
Average price of maize grain: 120 US$/t
Source: Calculated by author.

effect) range between US$ 1.3 billion and US$ 4.0 billion per year (Column 3). Assuming that 50% of the yield gain associated with MV adoption is attributable to the germplasm effect and 50% to the crop management effect, then gross benefits attributable to the germplasm effect alone range between US$ 668 million and US$ 2 billion per year (Column 4).

Although they have been adjusted to account for the crop management effect, the gross benefits estimates shown in Table 17, Column 4, still overstate the impacts of CIMMYT's maize breeding program because they include the contribution made by other research organizations. To isolate the benefits generated by CIMMYT's breeding program, it is necessary to estimate the proportion of germplasm effect associated with adoption of CIMMYT-derived MVs that can be credited directly to their CIMMYT germplasm content. This turns out to be difficult, since CIMMYT serves as the hub of a global breeding network consisting of CIMMYT's own breeding program, public-sector breeding programs, private sector breeding programs, and advanced research institutes. These organizations collaborate to various degrees and frequently share breeding materials, making it difficult to attribute credit among them.

To further complicate matters, maize breeding presents unusual attribution problems that are not found in other major cereals. As mentioned earlier, attribution of credit for maize breeding is made difficult by two factors. First, the pedigrees of most commercial maize hybrids are confidential, so it is not possible to assign breeding credit by examining selection histories to determine the role played by different organizations in the varietal development process. Second, breeding strategies for maize (especially hybrid maize) tend to be more variable than breeding strategies for self-pollinating cereals such as rice and wheat. Hybrid maize development schemes often involve a lengthy process of population improvement, extraction of inbred lines, improved and/or recycling of inbred lines, introgression of desirable alleles, repeated backcrossing with a recurrent parent, and finally test crossing with other inbred lines. The non-standardized and ad hoc breeding strategies followed by maize breeders defy easy description, and at the end of the day it is often very difficult to trace the germplasm contained in a finished hybrid back to a particular source. This means that with maize, even when pedigree information is available, application of formal attribution rules may still be very complicated.

Table 17. Value of additional production attributable to CIMMYT's maize breeding program, developing countries.

Yield gain attributable to adoption of CIMMYT-derived maize MVs (germplasm + crop management effects)		Gross benefits from adoption of CIMMYT-derived maize MVs US$ million/year)	Net benefits attributable to germplasm effect of MV adoption (US$ million/year)	Contribution of CIMMYT germplasm		
				25%	50%	75%
(%)	(t/ha)			Net benefits generated by CIMMYT maize breeding program:		
15 %	0.53	1,336	668	167	334	501
25 %	0.88	2,227	1,114	278	557	835
35 %	1.23	3,118	1,559	390	770	1,169
45 %	1.58	4,009	2,004	501	1,002	1,503

Assumptions:
Area planted to maize CIMMYT-derived MVs in developing countries: 21.2 million ha
Average yield of MVs: 3.5 t/ha (implies average yield of non-MVs: 1.2 t/ha)
Proportion of yield gain attributable to "germplasm effect": 50%
Average price of maize grain: 120 US$/t
Source: Calculated by author.

In the absence of detailed information about the breeding history of maize MVs, it is not possible to formulate pedigree-based rules for assigning credit among different research organizations. Therefore, gross benefits are calculated using a range of plausible values for the parameter that denotes the contribution of CIMMYT materials (these values are shown at the top of Table 17, Columns 5 to 7). Under the most conservative value (25% of the germplasm effect attributable to CIMMYT), and depending on the average yield gain associated with MV adoption, CIMMYT's maize breeding program generates from US$ 167 million to US$ 501 million per year in gross benefits. Under the most generous assumptions (75% of the germplasm effect attributable to CIMMYT), and once again depending on the average yield gain associated with MV adoption, CIMMYT's maize breeding program generates from US$ 501 million to US$ 1.5 billion per year in gross benefits.

In a recent review of the literature on returns to agricultural R&D, Alston et al. (2000) point out that a common error made by research evaluators is mis-measurement of research costs and benefits. Here, every effort has been made to avoid inflating the benefits attributed to CIMMYT's maize breeding efforts by failing to account for other sources of maize productivity gains, including breeding research done by NARSs and private companies, as well as changes in farmers' management practices.

The gross benefits reported in Table 17 are somewhat speculative, but they point toward an important conclusion: Even under conservative assumptions, the CIMMYT maize breeding program pays for itself many times over. One factor contributing to this result is simply the global importance of maize. Considering the extensive area that is planted to maize, CIMMYT-derived varieties do not have to achieve complete dominance in order to generate attractive returns to the CIMMYT breeding effort; current adoption rates already translate into enormous benefits.

Summary and Conclusions

Past Impacts of International Maize Breeding Research

The first global impacts study for maize carried out by CIMMYT nearly 10 years ago concluded that international maize breeding research has been extremely successful. The information presented in this report confirms the central finding of the earlier study and shows that international maize breeding efforts continue to have enormous impacts. Maize MVs currently are grown on 58.8 million ha in developing countries, representing about 62.4% of the area planted to maize in these countries. The widespread diffusion of maize MVs is particularly impressive given the distinctive characteristics of maize compared to other leading cereals. Because maize is an open-pollinated crop, farm-saved seed quickly loses its genetic purity, so farmers who wish to grow maize MVs must replace their seed regularly. For this reason, maize MVs can disseminate only with the help of an effective national seed industry—something that is still lacking in many developing countries.

International maize breeding research has brought increased incomes to millions of maize-producing households that have adopted MVs. In developing countries, the additional grain production resulting from the use of maize MVs is worth from US$ 3.7 to US$ 11.1 billion per year (germplasm effect plus crop management effect). Production increases resulting from the use of maize MVs have also benefited consumers, food and feed processors, agricultural laborers, and many other groups via price- and income-transmitted multiplier effects, although these benefits are difficult to quantify and value.

Against a backdrop of declining public support for agricultural research, CIMMYT continues to play a vital facilitating role in support of international maize breeding efforts. As the hub of a global network dedicated to maize germplasm improvement and exchange, CIMMYT has been active in producing improved materials and promoting their dissemination. The effectiveness of CIMMYT's maize breeding program is evident from the extensive use of CIMMYT source materials by public and private breeding programs. Currently, CIMMYT-derived MVs are grown on at least 21.2 million ha in developing countries, including 18.2 million ha located in non-temperate regions. This represents nearly one-half (36.1%) of the area planted to maize MVs in the developing world and over one-half (58.7%) of the area planted to maize MVs in non-temperate regions of the developing world.

CIMMYT's maize breeding program, although modest in size by international standards, has achieved enormous payoffs. The value of additional grain production attributable to CIMMYT's maize breeding activities is estimated to range between US$ 167 million and US$ 1.5 billion per year, not including non-yield benefits associated with adoption of CIMMYT-derived MVs (for example, improved grain and fodder quality, shorter growth cycles).

Impressive though they may be, the economic benefits attributable to CIMMYT-derived MVs show only part of the CIMMYT impacts story. In addition to developing large amounts of improved germplasm, CIMMYT's maize breeding program generates benefits in other ways that are very difficult to quantify and value. What is the value of the international germplasm exchange network managed by CIMMYT, which serves as a major source of information and breeding materials for hundreds of public and private breeding programs? And what is the value of the training services that CIMMYT has provided to thousands of crop improvement researchers throughout the developing world?

The success of the CIMMYT maize breeding program is particularly impressive considering the intensely competitive nature of the global maize seed industry. Unlike most other food crops grown in developing countries, maize attracts a lot of interest from commercial breeding programs in industrialized countries. Because the global market for hybrid maize seed is so large, private firms invest more resources in maize breeding—by far—than they invest in breeding for any other crop. True, private-sector maize breeding efforts are focused primarily on commercial producers in industrialized countries, but seed companies are quick to take advantage of market opportunities in developing countries. Public maize breeding programs, including CIMMYT's, consequently face much stiffer competition than do public breeding programs that work on other crops.

Future Prospects for International Maize Breeding Research

International maize breeding research clearly has been successful in the past. Will it continue to be as successful in the future? Looking ahead, there is little doubt that maize breeding programs, public as well as private, will be called upon to help bring about the substantial productivity gains that will be needed if maize production is to keep pace with projected strong growth in demand. Maize breeders will be expected to push forward the yield frontier by developing varieties with more efficient metabolisms, enhanced resistance to biotic and abiotic stresses (especially drought), and shorter growth cycles. In addition, they will face increased demand for non-yield benefits, such as enhanced nutritional content and improved industrial quality.

Will the international maize breeding system be able to meet these expectations? Future progress in maize improvement research will come in part from continued use of tried-and-true conventional breeding methods, which thus far show few signs of reaching the stage of diminishing returns. Traditional selection strategies continue to produce steady genetic gains, and those gains continue to be disseminated widely through global testing and evaluation networks.

While traditional methods will no doubt remain popular, emerging technologies meanwhile will provide new opportunities for making plant breeding cheaper and faster. Biotechnology, after a longer-than-expected gestation period, is beginning to pay real dividends. Recent advances in functional genomics and proteomics have greatly improved scientists' understanding of the molecular basis for many plant metabolic processes, opening the door to rapid progress in overcoming challenges that thus far have defied solution. Molecular marker-assisted selection methods are introducing greater precision into breeding and could significantly accelerate rates of progress. Genetic engineering, despite lingering questions surrounding its safety and appropriateness, holds great promise as a way of producing novel cultivars with economically valuable traits.

These technological advances are taking place against a backdrop of institutional changes that have significant implications for the way plant breeding research is organized and carried out. In an effort to reduce fiscal deficits, governments in many countries have implemented policy reforms designed to scale back the role of public breeding programs and to stimulate increased investment by private firms in crop improvement research. Typically these reforms have included significant strengthening of intellectual property rights (IPR) laws relating to ownership of plant genetic resources, research technology, and scientific information.

Recent growth in the numbers of maize breeders working in the private sector suggest that these reforms have succeeded in paving the way for greater participation by the private sector in the maize seed industries of many developing countries. Increased privatization has brought generally positive results, but at the same time there are grounds for concern. The accelerating cost of crop improvement research, coupled with the growing importance of IPRs, is rapidly changing the rules of the plant breeding game (Falcon 2000). Fearful of conceding advantages to potential competitors, many of the large multinational corporations that currently dominate the global seed industry are becoming less enthusiastic about sharing germplasm, technology, and information. As a result, maize breeding is rapidly being transformed from a collaborative activity undertaken for the common good into a competitive activity undertaken for shareholder profit.

Since most public breeding organizations (including CIMMYT) depend heavily on the free exchange of germplasm, technology, and information, these developments raise troubling questions about the future role of the international breeding system. In coming years, public breeding organizations will face a number of challenges, including:

- how to maintain access to genetic resources,
- how to maintain access to cutting edge technologies,
- how to maintain access to genomic databases and other sources of information needed for biotechnology-assisted crop improvement research, and
- how to maintain and stabilize funding.

The privatization of national seed industries also raises questions about the distributional impacts of technical change. The MV adoption data presented in this report show that it is simply wrong to argue—as many policymakers and development agency officials continue to do—that the best way to get improved germplasm to farmers is by relying on the magic of the market. Market liberalization measures have indeed opened the door to greater participation in national maize seed industries, but despite the proliferation of private companies, during the past 10 years the area planted to maize MVs in developing countries has increased very slowly in percentage terms. The sad reality is that significant numbers of small-scale, subsistence-oriented farmers have been ignored because they do not represent attractive customers for profit-oriented firms. Market-based solutions clearly do not work for these farmers who lack the resources needed to pay for improved seed and the information needed to manage it properly.

Despite the encouraging progress that has been achieved, considerable challenges remain to be overcome if the products of the international maize breeding system are to reach the poorest of the poor. Over one-third of the developing world's maize area (nearly one-half of the maize area in non-temperate environments) is still planted to farm-saved seed of uncertain genetic background and variable quality. In many instances, farmers continue to use farm-saved seed not because MVs are unavailable; rather, the problem is that small-scale, subsistence-oriented farmers located in isolated rural areas are not well integrated into the market economy. As CIMMYT and its partners look to the future, they will be challenged to come up with creative approaches to reaching the millions of non-commercial farmers who still do not enjoy full access to the fruits of the international breeding system.

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