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.