Part 1

Meeting World Maize Needs: Technological Opportunities and Priorities for the Public Sector

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Introduction

A major shift in global cereal demand is underway: by 2020, demand for maize in developing countries will surpass the demand for both wheat and rice. This shift will be reflected in a 50% increase in global maize demand from its 1995 level of 558 million tons to 837 million tons by 2020. Maize requirements in the developing world alone will increase from 282 million tons in 1995 to 504 million tons in 2020 (IFPRI 2000). The challenge of meeting this unprecedented demand for maize is daunting, especially for the developing world and its poor and subsistence farmers.

Why the Shift to Maize?

Rising incomes in much of the developing world and the consequent growth in meat and poultry consumption have resulted in a rapid increase in the demand for maize as livestock feed (especially for poultry and pigs). This trend is particularly evident in East and Southeast Asia, where maize requirements are projected to rise from 150 million tons in 1995 to 280 million tons in 2020 (IFPRI 2000) (Table 1). Meanwhile, in the least developed parts of the world, unabated population growth and the persistence of poverty have maintained upward pressure on the demand for food maize; this is the case in sub-Saharan Africa, Central America, and parts of South Asia. Relative to its 1995 level, annual maize demand in sub-Saharan Africa is expected to double to 52 million tons by 2020. In many maize-consuming countries of Latin America, where the culture and diet have been bound to maize for centuries, food maize demand has remained high even as incomes have risen.

Meeting the Challenge of Future Maize Demand

The exploding demand for maize presents an urgent challenge for most developing countries. Although increased maize imports are anticipated, especially in the higher income developing countries, it should be remembered that international trade traditionally has supplied less than 10% of the developing world's maize requirements. At the global level, the proportion of maize demand met through imports is not expected to change, even as the absolute quantity of maize traded is projected to grow to 90 million tons in 2020, a 67% increase relative to the 1995 level (IFPRI 2000). For most developing countries, particularly those with large populations, the accelerating demand for maize must be met through dramatic increases in domestic supply. Given the limited opportunities for augmenting maize area in most countries, future output growth must come from intensifying production on current maize land.

Table 1. Maize demand projections, 1995–2020

Region	1995 demand	2020 demand	% change
Global	558	837	50
Developing world	282	504	79
E and SE Asia	150	280	46
S Asia	12	23	92
Sub-Saharan Africa	27	52	93
Latin America	76	123	62
WANA	16	26	63

Source: IFPRI (2000).
* WANA = West Asia/North Africa

Generally speaking, the commercial-maize production sector in the developing world is targeted toward feed maize. We anticipate that this sector will respond rapidly to the increased demand through the adoption of productivity-enhancing technologies such as hybrid seed. Demand could be met even more rapidly by providing the private seed industry more liberal access to the commercial feed-maize sector.

The prospects for increasing maize productivity growth for the food-maize sector are far less certain—especially for the subsistence farming systems of the tropics. The private sector has generally found investments in tropical food-maize production to be unprofitable, a state of affairs that is unlikely to change soon. Where technological change has occurred in the tropical food-maize systems, it has generally resulted from public sector research investment or through farmer experimentation and innovation. The latter has been observed particularly in areas that are too remote (or "unimportant") even for public sector involvement. Although the public sector will probably continue to be the primary source of technology supply for subsistence food-maize systems, funding uncertainties and mounting restrictions to accessing technologies, i.e., intellectual property rights (IPR), may adversely affect its performance.

To better understand how research and new technologies can help developing countries, particularly those in the tropics, meet their maize requirements, this report reviews and explores the following points:

- Where is maize grown in the developing world, by agro-ecological zones and geographical regions?
- What environmental or biophysical constraints limit maize production in those zones and regions?
- How do we rank the constraints in each zone and region, given a research focus on production problems that affect the poorest of the poor, and taking into consideration the ease or difficulty of readily resolving a particular problem?
- Is the public or private sector, or both, best suited or most likely to develop solutions?
- Finally, what are the implications for organizations such as CIMMYT that work toward reducing hunger and poverty through maize research?

Maize Production in the Developing World

Where is Maize Grown in the World?

Of the 140 million hectares of maize grown globally, approximately 96 million hectares are in the developing world. Four countries account for more than half (53.6%) of the developing world's maize area: China, 26 million hectares; Brazil, 12 million hectares; Mexico, 7.5 million hectares; and India, 6 million hectares. Although 68% of global maize area is in the developing world, only 46% of the world's maize production of 600 million tons (1999) is grown there. Low average yields in the developing world are responsible for the wide gap between the global share of area and share of production. The average maize yield in the industrialized countries is more than 8 t/ha, while in the developing world it is slightly less than 3 t/ha. Wide disparities in climatic conditions (tropical versus temperate) and in farming technologies account for the 5 t/ha yield differential between the developed and the developing world.

Temperate vs. Tropical Maize Production

More than 90% of the maize produced in industrialized countries is grown in temperate production environments.[1] This stands in sharp contrast to the developing world, where only about 25% (25 million ha) of the maize is grown in temperate environments, most of which are found in China and Argentina. Of the 70 million hectares of maize produced in nontemperate or tropical environments, about 65% is grown in the tropical lowlands, 26% in the subtropics and midaltitude tropical zones, and 9% in the tropical highlands (Table 2).[2] Across the developing world, the dominant maize production ecology is the tropical lowlands; however, the tropical highlands and the tropical midaltitude/subtropical ecologies are important in particular regions. Approximately 60% of the highland maize production systems are located in Latin America, while 45% of the subtropical and midaltitude maize production systems are located in sub-Saharan Africa. Latin America, followed closely by sub-Saharan Africa, produces the most tropical maize; between them, they account for 48 million hectares of tropical maize land.

From a research perspective, it is important to note that maize germplasm that performs well in temperate regions generally cannot be introduced directly into tropical regions without undergoing extensive adaptive breeding. Most of the improved open pollinated varieties

Table 2. Maize area* (million ha) in the developing world

	Highland/Transitional	Midaltitude/Subtropical	Tropical lowland
East and Southeast Asia	0.1	3.5	8.5
South Asia	0.6	2.0	5.5
West Asia/North Africa	-	0.84	-
Sub-Saharan Africa	1.7	8	12.3
Latin American countries	3.5	3.5	19
Total	**5.9**	**17.8**	**45.3**

* Temperate maize area is not included (around 25 million ha, mainly in China, the Southern Cone countries of Latin America, and southern Africa)

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[1] CIMMYT recognizes four major maize production environments, termed *mega-environments*: (1) lowland tropics, (2) subtropics and midaltitude tropical zones, (3) tropical highlands, and (4) temperate zones. These four mega-environments are defined primarily in terms of climatic factors, such as mean temperature during the maize growing season, elevation, and day length.

[2] The terms *tropical maize system* or *tropical maize area,* as used in this report, comprise production systems or areas found in the three major nontemperate maize production environments (tropical lowlands, highlands, subtropical/midaltitude environments)**.**

(OPVs) and hybrids developed for use in the United States, Western Europe, and China are of little direct use to maize farmers in developing countries (Morris 1998). Since the vast majority of the world's poor live in the tropics, and a large proportion of them depend on maize as their primary staple food, the need for research and development programs tailored to their needs has long been recognized by CIMMYT and other international agricultural research centers (IARCs).

The vast majority of tropical maize farmers continue to grow maize to meet their subsistence requirements and have had little need for and/or poor access to improved technologies. Less than 50% of tropical maize area is sown to improved seed (hybrids or OPVs); the rest is sown to low yielding "local" or "traditional" varieties (see Part 2 for details). This is unfortunate because genetic improvements in tropical maize have resulted in significant shifts in the yield frontier, with economically exploitable yield levels of around 5 t/ha for the tropical lowlands and the highlands, and 8–10 t/ha for the subtropical and midaltitude environments (CIMMYT Maize Program, unpublished). The yield gap between the achievable and the observed average farmer yields is very large across all tropical maize growing environments and geographic regions in the developing world (Table 3). Unlike wheat and rice farmers who now face stagnant productivity because their yields are close to the frontier[3] (Pingali et al. 1997; Pingali and Rajaram 1997), for maize farmers the primary source of productivity growth is through reducing the yield gap. Both socioeconomic and biophysical factors lie behind the persistence of the maize yield gap on farmers' fields.

Poor market integration of tropical maize farmers could be the primary socioeconomic explanation for the large yield gap (Table 4). As access to the market improves and farmers become more market-oriented, one usually observes the rapid adoption of productivity-enhancing technologies such as improved seed and fertilizer. Also, when improved roads, transport, and communications reach subsistence communities, private sector suppliers of seed and other inputs become more active in those areas. Reducing the yield gap and thereby boosting tropical maize productivity growth is intrinsically tied to the broader policy challenge of integrating poor, subsistence-oriented rural communities into the market. A related but secondary challenge is identifying effective mechanisms for technology delivery and input supply, both for societies that are integrated into the market and for those in transition to market integration.

Even in tropical farming systems where improved maize seed is used, the gap between achievable and actual yields is quite large because of the various biological (biotic) and environmental/physical (abiotic) stresses faced by farmers in particular ecologies and geographic environments. While significant progress has been made in raising the yield potential of tropical maize, substantial research is needed to adapt the improved genetic materials to particular physical, biological, and ecological conditions. Even the best genetic materials often do not possess the tolerance and resistance needed to overcome the biophysical stresses encountered by maize farmers in a particular ecology and/or geographic

Table 3. Yield potential*relative to current yield (t/ha) in the developing world (figures in parentheses are current yields)

	Highland/Transitional	Midaltitude/Subtropical	Tropical Lowland
East and Southeast Asia	5.0 (3.5)	8.0 (3.0)	5.5 (2.2)
South Asia	5.0 (0.7)	7.0 (2.6)	4.5 (1.4)
WestAsia/North Africa	-	4.5 (3.2)	-
Sub-Saharan Africa	5.0 (0.6)	7.0 (2.5)	4.5 (0.7)
Latin America and Caribbean	6.0 (1.1)	10.0 (4.0)	5.0 (1.5)

* Potential yield refers to the highest yield achievable on farmers' fields – with use of improved seed (high yield, tolerance to disease and pests), appropriate levels of nutrients, water, and weed control.

Table 4. Area (%) under commercial maize production systems* in the developing world

	Highland/Transitional	Midaltitude/Subtropical	Tropical Lowland
East and Southeast Asia	60	80	30
South Asia	1	60	15
WestAsia/North Africa	-	80	-
Sub-Saharan Africa	5	50	10
Latin America and Caribbean	6	90	50

* Nontemperate maize production systems.

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[3] The yield frontier is the maximum achievable yield given no physical, biological, or economic constraints. The exploitable yield frontier is the maximum yield that can be *profitably* obtained. The yield gap is the difference between the yields that can be profitably achieved and those that are actually realized in farmers' fields. The existence and size of the gap is particularly unfortunate, because genetic improvements in tropical maize have resulted in significant shifts in the yield frontier, as noted above.

Participatory Methods in the Development and Dissemination of New Maize Technologies

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The use of participatory methodologies in plant breeding and natural resource management has increased significantly as scientists and policymakers recognize that the "clients" of these technologies have much to contribute to their development and dissemination. Farmer participation is viewed as an effective instrument for boosting the impact of agricultural research because technologies are developed that respond closely to farmers' concerns and conditions, and consequently, are more widely adopted.

Participatory methods recognize the value of farmers' local knowledge, their interests and ability to experiment and innovate, and their active exchange of information and technologies. They also recognize that farmers are not a homogeneous group—they have different preferences and priorities.

Local knowledge. Farmers possess considerable knowledge about their crops, their farming environment, and their socioeconomic conditions. Farmers use this knowledge as a key reference point when making decisions and communicating among themselves. It follows that scientists should also understand the farmers' reference point if they wish to improve farmer welfare through the effective communication of new information or the joint development of appropriate technologies.

Farmer experimentation. It is well documented that small-scale farmers in the developing world conduct experiments on their own. Such experimentation is important because it promotes knowledge and evaluation of new and unproven technologies without jeopardizing farmers' livelihoods or scarce resources. By joining forces with farmers on their terms, scientists can evaluate and modify new technologies in ways that ensure their relevance to farmers' actual needs and concerns.

Information and technology exchange. Farmers are constantly sharing information about topics they consider important. Indeed, the diffusion of many innovations has occurred on a farmer-to-farmer basis, without the intervention of formal agricultural extension services. Farmer-to-farmer diffusion of information and technology usually occurs within a social network (a group of people that share certain bonds, most often stemming from family or traditional social obligations). This social network may play a fundamental role in the adoption of new technologies, particularly if they require collective action. Tapping into the farmers' networks and mechanisms for information exchange and collective action should facilitate the diffusion and adoption of new technologies.

Heterogeneity. Small-scale farmers in the developing world are not homogenous; their needs, priorities, and preferences are diverse. Failure to consider these differences in the past has often led to the downfall of otherwise promising agricultural projects. For example, if some farmers in a region raise cattle and others do not, a maize variety that produces significant fodder may be highly desirable to the former group, but not the latter. Similar differences could arise between farmers who sell part of their maize crop and those who use it entirely for their own needs. Storage characteristics may be less important for those selling their crop than for those using it solely for consumption. It is critically important, therefore, that a range of farmers be involved in the selection and testing process, and that researchers pay careful attention to their views on what constitutes an appropriate and attractive maize variety.

While a strong case can be made for the efficacy of participatory methods, they do have their limitations. They may entail high transaction costs (e.g., time and effort) for farmers and scientists, which may discourage the participation of poorer farmers. Care must also be taken in interpreting results because participating farmers may be a biased sample of the general farming population, and therefore they may not reflect the views or interests of the overall group that scientists or policymakers want to reach. Participatory methodologies have been shown to work well at the household and community levels, but there are still questions about how to scale them up.

CIMMYT has incorporated participatory methodologies into much of its work.* Currently, at least 14 projects include participatory methodologies; of those, six relate specifically to maize (in the areas of plant breeding, natural resource management, and conservation of genetic resources). Examples include the Southern Africa Drought and Low Soil Fertility Project (SADLF), the Soil Fertility Network for Maize-Based Cropping Systems in Malawi and Zimbabwe (SoilFertNet), and CG Maize Diversity Conservation: A Farmer-Scientist Collaborative Approach (Oaxaca Project).

The SADLF Project seeks to develop maize cultivars that produce more grain under severe drought and low soil fertility—two of the most common challenges facing subsistence agriculture in Southern Africa. Experimental cultivars that yield 25–50% more under drought stress than popular local cultivars have already been developed. Now researchers must verify the cultivars' performance and acceptance under resource poor farmers' conditions. To accomplish this, the project uses an experimental participatory methodology that integrates the knowledge and interests of scientists and farmers: "mother/baby" trials. The "mother" trial, designed by researchers, evaluates a set of promising maize cultivars under optimal and farmer-representative management conditions. The "baby" trials contain a subset of the cultivars from the mother trial and are planted and managed exclusively by the farmers that host them. A strength of this approach is that the local partner provides established links to the community and intrinsic knowledge of the problems faced by local farmers.

SoilFertNet focuses on helping smallholder farmers in Malawi and Zimbabwe produce higher, more sustainable, and profitable yields from maize-based cropping systems through improved soil fertility technology and better management of scarce organic and inorganic fertilizer inputs. As part of the project, a pilot study in a region of Zimbabwe is actively using participatory methodologies for a joint assessment of soil fertility improvement technologies by farmers, researchers, and extension officers. An additional objective is to foster adoption of effective technologies by promoting farmer experimentation with them. Currently, the project is examining ways to scale up this type of participatory effort.

The goal of the Oaxaca Project is to assess whether farmer welfare can be increased through participatory maize breeding while maintaining or enhancing the genetic diversity found in a set of communities in the state of Oaxaca, Mexico. To investigate this, the project compares different types of participatory interventions involving small-scale farmers, including (1) giving farmers access to seed of diverse sets of improved and unimproved landraces, as well as information on their performance; (2) providing farmers with training in seed selection, management techniques, and in principles to assist them in maintaining the characteristics of the landraces they value; and (3) conducting joint experiments to test the performance of the selected landraces in a systematic manner.

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* See Bellon (2001) for a description of participatory research methods used by CIMMYT.

region. Furthermore, even where the cultivars have been adapted to specific stresses, crop management practices are usually poor. Innovations in soil fertility management, sustainable land management, and improved water management techniques are urgently needed to increase and sustain productivity growth across all tropical maize environments.

Constraints to Productivity Growth in Tropical Maize Systems

This section provides a detailed review of the biotic and abiotic factors that constrain tropical maize production. Abiotic factors discussed here are climatic conditions, such as temperature, rainfall regimes, and season length, and soil-related factors such as fertility, acidity, and susceptibility to erosion. Biotic factors covered here are primarily related to tropical insects, diseases, and weeds. CIMMYT maize researchers throughout the world identified the most important abiotic and biotic constraints for each of the maize production ecologies and geographic regions (see Table 5). The constraints are prioritized by their global and regional importance at the end of this section. A discussion of potential technological solutions to these constraints is provided in the next section of this report.

Abiotic Constraints

Drought

Most tropical maize is produced under rainfed conditions, in areas where drought is widely considered to be the most important abiotic constraint to production (CIMMYT 1999). Drought stress is evenly distributed across the

Table 5. Dominant constraints to bridging the yield gap between potential and actual yields

	Highland / Transitional	Midaltitude / Subtropical	Tropical Lowland
East and Southeast Asia	1. Limited technological options 2. Banded leaf and sheath blight 3. Borers (*Chilo* spp.)	1. Drought/moisture stress 2. Soil acidity 3. Downy mildew 4. Borers (*Chilo*, *Sesamia* spp.) 5. Drought/moisture stress	1. Limited superior early germplasm
South Asia	1. Low and declining soil fertility 2. Limited technology options 3. Turcicum blight	1. High temperature 2. Drought/moisture stress 3. Turcicum Blight 4. Borers (*Chilo*, *Sesamia* spp.)	1. Limited superior early germplasm 2. High temperature 3. Drought/moisture stress 4. Downy mildew 5. Borers (*Chilo*, *Sesamia* spp.)
West Asia/ North Africa		1. High temperature 2. Drought/moisture stress	
Sub-Saharan Africa	1. Low and declining soil fertility 2. Limited technology options 3. Turcicum blight 4. Rust	1. Low and declining soil fertility 2. Gray leaf spot 3. Streak virus 4. Weevils 5. Borers (*Chilo*, *Sesamia* spp.) 6. Drought	1. Low and declining soil fertility 2. Drought/moisture stress 3. *Striga* 4. Streak virus 5. Borers
Latin America	1. Limited technology options 2. Drought/moisture stress 3. Ear rot 4. Rust	1. Soil erosion 2. Drought/moisture stress 4. Turcicum blight 5. Borers (S.W. corn borer)	1. Low soil fertility 2. Soil acidity 3. Drought/moisture stress 4. Fall armyworm 5. Stunt

world's major regions and is a particularly severe problem for slightly more than one-fifth of the tropical and subtropical maize planted in developing countries (Heisey and Edmeades 1999). Drought at any stage of crop development affects production, but maximum damage is inflicted when it occurs around flowering. Farmers may respond to drought at the seedling stage by replanting their crop, and at later stages some yield may yet be salvaged, but drought at flowering can be mitigated only by irrigation.

Most global estimates of losses from drought are based on expert opinion and must be regarded with caution (Heisey and Edmeades 1999). Nonetheless, Edmeades et al. (1992) estimated that annual drought losses in the early 1990s across tropical maize growing environments totaled about 19 million tons, representing a 15% loss in production. Individual episodes of losses, however, can be far more extreme: a devastating drought in southern Africa in 1991–92 reduced maize production by about 60% (Rosen and Scott 1992, as reported in Heisey and Edmeades 1999).

Low Soil Fertility

Tropical soils are renowned for their low soil fertility, particularly low nitrogen, and consequently this ranks as the second most important abiotic constraint to maize production in tropical ecologies. Intensified land use and the rapid decline in fallow periods, coupled with the extension of agriculture into marginal lands, have contributed to a rapid decline in soil fertility, particularly in sub-Saharan Africa. Nitrogen (N) and phosphorus (P) deficits are a severe and widespread biophysical constraint to smallholder maize productivity, and in turn to the long-term food security of the resource poor in southern and eastern Africa (Sanchez et al. 1997). For these farmers, drought and low soil fertility are intertwined, because the risk of crop failure due to drought influences their decision on whether to apply fertilizer.

Even when fertilizers are applied, the quantities are often so low that they contribute little to long-term fertility management. It has been estimated that the average fertilizer application in sub-Saharan Africa is a mere 7 kg/ha. Similarly, calculations for 1993 by Heisey and Mwangi (1996) give an average of 10 kg/ha of fertilizer nutrients. Relatively high grain to nutrient price ratios and high levels of production risk are two of the underlying factors for the low use of fertilizer in Africa (Heisey and Mwangi 1996). The same factors could apply to sub-optimal rates of fertilizer applications in marginal, subsistence farming systems in other parts of the developing world. Even when fertilizer is applied on farmers' fields, it is often used inefficiently (measured by the grain yield response to the addition of chemical N and P fertilizers), which reduces its overall profitability (Kumwenda et al. 1996).

High Soil Acidity

Acidic soils cover approximately 43% of the world's tropical land area. About 64% of tropical South America, 38% of Asia, and 27% of tropical Africa have acidic soils. Some have suggested that more land with acidic soils must be brought under cultivation to meet the growing demand for food, especially in developing countries. Some of these soils, particularly the ultisols and oxisols, offer reasonable prospects for boosting production. Approximately 300 million hectares of acidic savannas in Latin

America and Asia may be readily cultivated at an environmental cost much lower than that of clearing tropical rain forests.

Acidic soils are characterized by low pH; deficiencies of phosphorus, calcium, and magnesium, and toxic levels of aluminum. Lime application is the most widely used remedy for high soil acidity in countries such as Brazil and the United States, but it is financially prohibitive for resource poor farmers and cannot be considered a viable solution to the problem.

Soil Erosion

Inappropriate intensification of maize production systems, particularly in the hillsides of the tropical lowlands and the midaltitude environments, has resulted in high rates of soil erosion in many areas. Lack of investment in erosion control and the widespread use of mechanized tillage systems (including tillage with animal draft power) are the primary causes of erosion across the tropics. Soil erosion and degradation are most often observed in areas where population growth is rapid, rights to land ownership and use are ill defined, and farmers face an inappropriate policy environment (Pingali 2001). Where short- and long-term incentives for protecting the land resource base are not established, one generally finds high levels of degradation; where such incentives are in place, intensive and sustainable agricultural systems have been observed, though this is not universal. Even with appropriate incentives in place, severe soil erosion has been observed in areas where the physical conditions are such that the returns to investments in such measures are low. Arid fringe areas, upper hillsides in the semiarid and the humid zones, and areas with shallow sandy soils exhibit the highest levels of erosion, other things being equal.

Lack of Early Maturing Germplasm (Seasonality)

Though only a biophysical constraint in the broadest sense, lack of early maturing germplasm poses a constraint to maize production, especially in intensive cropping systems in the tropical lowlands. For example, early maturing varieties allow Asian farmers to get a maize crop in addition to two crops of rice in irrigated paddy lands or a second crop of maize in rainfed environments. Unfortunately, early maturing maize germplasm is often lower yielding and susceptible to many diseases. Moreover, there is often a strong positive correlation between high yields and a longer growing cycle, hence early materials tend to have lower yield potential (Beck et al. 1990). Largely as a result of these difficulties, elite early maturing germplasm is relatively scarce worldwide. Although a few early hybrids are now available, especially in Asia, the majority of the subsistence farmers cannot afford the seed.

High Temperatures

Maize grows best at temperatures ranging from 24 to 30ºC. Temperatures higher than this interfere with the plant's physiological processes, resulting in lower yield. At temperatures above 38ºC, the plant is unable to maintain adequate moisture in its system; evaporation from the soil and transpiration from plant surfaces also increase, further compounding the drought effect. In many tropical lowland areas, temperatures can reach 45ºC, at which point pollen desiccation and silk death can occur. The alternatives to farmers are few. In some areas, farmers now grow maize during their "winter" season, when temperatures are lower. Increased water supply during periods of high temperature also helps, but this option is generally not available to resource poor farmers. Conscientious selection for tolerance to high temperatures in tropical maize is now receiving greater attention among the research community.

Lack of Improved Germplasm for the Tropical Highlands

Highland maize is grown on approximately 6.3 million hectares in the developing world (nearly half of it in Mexico), at altitudes ranging from 1,500 to 3,600 masl. Cultivated by some of the poorest farmers in the nontemperate developing world, highland maize is grown at lower temperatures than maize in other tropical zones and is often subject to drought, low soil fertility, frost, and hail. Principal biotic constraints are *Puccinia sorghi* rust, *Exserohilum turcicum* leaf blight, and *Fusarium* ear and stalk rots. Insects usually are not a problem, although corn earworm can cause significant damage, particularly in soft endosperm materials. The myriad of highland environments and the resulting germplasm x environment (G x E) interactions, coupled with strong farmer preferences related to consumption characteristics (grain texture, size, and color) present significant breeding challenges.

Biotic Constraints

Diseases

Downy mildew. Maize downy mildew, mainly caused by *Peronosclerospora sorghi*, is a major disease in the tropics, especially in Asia. Depending on infection levels, farmers can lose more than 80% of their crop to this disease. Most commercial cultivars sold by the private sector in mildew prone areas are treated with the systemic fungicide, Ridomil™, and only recently has the private sector begun to develop resistant cultivars. Seed treated with Ridomil, however, is generally too expensive for resource poor farmers, thus precluding its widespread use.

Turcicum blight. This disease, caused by *Exserohilum turcicum*, is most serious in relatively cool and humid regions, specifically in the tropical midaltitude areas where maize is grown as a winter crop. It causes large lesions on the leaves that affect photosynthesis and therefore yields. Yield losses up to 70% have been recorded, but normally yield losses are around 15-20%. The only known economical solution to the problem has been resistant cultivars.

Maize streak virus. Maize streak virus (MSV) is a major disease of maize in Africa and is most prevalent in tropical lowlands and parts of tropical midaltitude maize growing areas. The pathogen is transmitted by leafhoppers and causes serious yield losses, but its occurrence is sporadic. A severe outbreak in Kenya in 1988, for example, destroyed more than half the crop over large areas. Practices such as timely planting and treatment of seed with systemic insecticides can help control yield losses, but a more effective and practical solution for subsistence farmers is high yielding maize that carries genetic resistance to the disease.

Gray leaf spot. Gray leaf spot (GLS), caused by the fungus *Cercospora zeae-maydis*, has become a serious leaf blight pathogen in temperate, subtropical, and midaltitude maize growing areas worldwide during the past 30 years. Because of its serious effects on maize yields and its rapid spread, GLS has quickly caught the attention of scientists and policymakers. In the 1970s and 1980s, GLS epidemics occurred in the United States. Researchers determined that the epidemics were related to minimum tillage practices and cultivation of susceptible hybrids. During the 1990s, GLS was reported in many countries in southern and eastern Africa. When infection is present when the maize crop flowers, losses of 30% or more can occur, attributable to both loss of leaf area and subsequent stalk lodging.

Banded leaf and sheath blight. An emerging disease problem in Asia, banded leaf and sheath blight (BLSB) is most prevalent in hot and humid conditions and often in association with paddy rice cultivation. The disease makes its appearance at the preflowering stage (plants 45–50 days old). Leaves and sheaths in such plants appear blighted with prominent banding (Sharma et al. 1993). The importance of BLSB as a constraint to maize production could grow as the use of maize rises in rice cropping systems.

Corn stunt. This endemic disease affects maize production in Latin America, from Mexico to Argentina. Significant economic losses from the disease have been reported in Central America, the Caribbean, and Brazil. A complex of pathogens, including the corn stunt *Spiroplasma kunkelii*, the maize bushy stunt phytoplasma, and the maize fine stripe (rayado fino) virus, are involved in the disease complex; all are transmitted by species of the *Dalbulus* leafhoppers, with *D. maidis* being the most noteworthy. Severe epidemics are associated most frequently with the continuous planting of susceptible cultivars, thereby allowing the buildup of the transmitting vector. Yield losses of 50% have been documented in plantings severely infected with corn stunt.

Insects

Insects in the developing world cut annual maize production by attacking roots (rootworms, wireworms, white grubs, and seed-corn maggots), leaves (aphids, armyworm, stem borers, thrips, spider mites, and grasshoppers), stalks (stem borers, termites), ears and tassels (stem borers, earworms, adult rootworms, and armyworm), and grain during storage (grain weevils, grain borers, Indian meal moth, and the Angoumois grain moth). Insect damage can occur at any stage of maize production and storage. Its severity depends on germplasm used, cultivation practices, levels of pest infestation, control strategies used, and climate. Some of the most important insect pests are described here.

Armyworm. *Spodoptera* spp. is a voracious leaf feeder that inflicts dramatic damage early in the crop cycle. The fall armyworm, *S. frugiperd*a, is found throughout the Americas and can cause severe yield losses by reducing stand density. Leaf damage can result in yield reductions of 10%. Currently, control is usually achieved by seed treatments of systemic insecticides or application of granular insecticides into the whorl of maize. Other important *Spodoptera* that attack maize include *S. exempta* (African armyworm) and *S. exigua* (beet armyworm).

Earworm. The corn earworm (*Helicoverpa zea*) is found throughout the Americas, from Canada to Argentina, and causes damage by feeding on the silk and grain during the early stages of grain fill. Grain loss comes from the physical injury caused by the insect feeding and ear rots that subsequently enter the damaged ear. Control strategies include the use of vegetable oil applied to the silks during flowering. Although resistance to insecticides has been a problem, especially in cotton, the following classes of pesticides have been used: sulprofos, profenofos, methomyl, thiodicarb, chlorpyrifos, acephate, amitraz, and pyrethroids. Sprays of *Bacillus thuringiensis* are also used to control larval feeding. Spray applications are used primarily for sweet corn. In developing countries, oil is the preferred method of control.

Cutworms. Within this group, the black cutworm (*Agrotis ipsilon*) is the most serious in maize and is generally considered to be worldwide in distribution. As its common name implies, these worms cut young seedlings, often resulting in their death. Given the insect's wasteful feeding habits, several plants may be cut by a single larva. Damage can be minimized by not planting maize in areas under pasture and by monitoring fields for timely application of insecticides.

Stem borers. Throughout the world, stem borers have been the most damaging group of insect pests in maize cultivation. The most important species in the Americas include the European corn borer (*Ostrinia nubilalis*), the southwestern corn borer (*Diatreaea grandiosella*), the sugarcane borer (*D. saccharalis*), and the neotropical corn borer (*D. lineolata*). For Asia the most important species are the Asian corn borer *(O. furnacalis*) and the spotted stem borer (*Chilo partellus*). For Africa, the most prominent stem borer species include the spotted stem borer (*C. partellus*), the African stem borer (*Sesamia calamistis*), the African maize stalk borer (*Busseola fusca*), the pink stem borer (*S. cretica*), and the sugarcane borer (*Eldana saccharina*).

Stem borers first establish on leaf tissue, but in later stages of development, they bore into vascular structures of the plant (midribs, stalk, pedicle), which reduces the ability of the plant to move assimilates into the grain. Moreover, this damage also provides a portal for fungal infection leading to stalk and ear rots. Control of these pests through insecticide sprays is difficult given their cryptic nature.

Postharvest pests. These pests are particularly damaging in the humid storage conditions often found in developing countries. For maize, the most important insects associated with storage include the grain weevils (*Sitophilus zeamais, S. oryzae, S. granarius*), the larger grain borer (*Prostephanus truncatus*), the Indian meal moth (*Plodia interpunctella*), and the Angoumois meal moth (*Sitotroga cerealella*). For some species, such as the grain weevils, the infestation starts in the field and is brought into the store. Grain is usually most susceptible to damage when it is stored under high grain-moisture content. Losses during storage vary considerably from undetectable levels in commercial silos to 80% in tropical on-farm stores in many developing countries.

Current control strategies include the proper conditioning of grain by sun drying or forced air dryers, and storage in sealed containers to deplete oxygen levels to arrest insect development and to permit fumigation treatments. Insecticides can also be applied to husks, ears, and grain to reduce insect damage, one of the more popular of the insecticides being pirimiphos-methyl (Actellic). Plant breeding to reduce storage losses in the tropics has largely focused on improving husk cover, which serves as an important first line of defense against insect invasion.

Striga

Striga hermonthica and *S. asiatica* are parasitic weeds that negatively affect the livelihood of more than 100 million Africans and inflict crop damage totaling approximately US$ 7 billion annually to the African economy (Berner et al. 1995). *Striga* attaches to growing maize roots beneath the ground and siphons off nutrients that would normally feed the plant. *Striga* also exerts a potent phytotoxic effect on its host that results in severe stunting and a characteristic "bewitched" and chlorotic whorl (Ransom et al. 1995). Hand pulling the weed reduces reinfestation but is deemed uneconomical because most of the damage is inflicted on the crop before the *Striga* emerges (Parker and Riches 1993). Several pre- and post-emergence herbicides are available for *Striga* control, but they are often too expensive or inaccessible to resource poor farmers. Due to years of neglect, *Striga* infested areas have extremely high levels of long-lived *Striga* seeds in the soil, with only some of the seed breaking dormancy each season when stimulated by crop exudates. Cost-effective technologies are urgently needed to control *Striga* early in its development before crop yields are affected and to deplete the *Striga* seed bank to control further yield losses.