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

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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)

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.

[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

Mauricio R. Bellon

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.

* 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.

Location and Importance of the Constraints

The distribution of the biophysical constraints reviewed above is shown in Table 5, by maize ecology and geographic region. The constraints are ordered within each cell according to importance. For example, for the midaltitude/subtropical zone of East and Southeast Asia, drought is the number one constraint to increasing maize production, banded leaf and sheath blight is second, corn borers are third, and so forth. The overall constraint rankings and those within the cells are based on the expert judgment of CIMMYT maize scientists.

As Table 5 clearly indicates, some constraints transcend geographic and ecological boundaries, for example, drought and low soil fertility. Alternatively, other biophysical stresses warrant notice only in particular regions, e.g., high temperature stress generally affects only maize grown in South Asia and West Asia/North Africa (WANA); soil acidity is a predominant constraint only in the lowland tropics of Latin America and Southeast Asia, and so forth. Insect and disease problems also tend to be specific to particular ecologies and geographic regions.

Given the many constraints identified in Table 5, it becomes obvious that they cannot all be adequately addressed within the budgetary and human resource limitations faced by national agricultural research systems (NARSs) and the international agricultural research centers (IARCs). It is therefore necessary to prioritize the constraints, with an eye toward the feasibility of technological solutions, and identify those upon which national and international public research sectors should concentrate. The identification of priority areas for public sector involvement implies divestment from areas in which the private sector has increased its activity or in which, looking to the future, it will have a compelling comparative advantage. The process we used for priority setting and the outcome of the exercise are presented in the following section.

Prioritized Constraints and Technology Solutions

Methodology

Identifying priority constraints that can be alleviated through public sector research and technology development is a daunting task, requiring consideration and weighting of numerous diverse criteria. For example, one can assign priorities purely on efficiency grounds, in other words, based on the criterion of maximizing returns to research investments. But an equally valid efficiency-related criterion would be alternative sources of research and technology supply. For instance, if the private sector is active and successful in a geographic region and/or in a particular field of research, then it may make sense for the public sector to withdraw its investments and efforts from those areas. In other cases, public sector research investments may be justified solely on the basis of their benefit to poor rural communities, i.e., enhanced food supplies and/or food security, regardless of efficiency criteria. In fact, priority ranking based on poverty criteria has emerged as an important counterpoint to efficiency ranking. Strong cases can also be made for other priority ranking criteria, including the importance of certain regions (such as sub-Saharan Africa), the strength and capacity of individual NARS, and so forth. For a comprehensive review of cutting-edge priority setting methods, see Alston et al. (1997).

In this report, three criteria are used for prioritizing the list of constraints: efficiency, the extent of poverty, and the extent of subsistence farming. Details of how each of the indices was created and the weights used for deriving a composite index that includes all three criteria may be found in Table 6.

The efficiency index prioritizes constraints in terms of getting the biggest "bang for the (research) buck." Constraints are quantified in terms of the expected production gain associated with alleviating the constraint. The inherent risk associated with research investments is quantified in terms of the probability of success in finding a technological solution to alleviating the constraint. Probabilities of research success are based on CIMMYT maize scientists' knowledge of technologies specific to a given region or environment. These technologies are either currently available to farmers, available in other ecologies or regions from which they can be imported and adapted to the target location, or they are in the development pipeline.

Even where appropriate technologies are available, their adoption by farmers is by no means guaranteed. To quantify the probability that farmers in a particular location will adopt a technology, we drew on the farmer history of technology adoption and patterns of adoption for that ecology or region. This information was readily available for most tropical maize growing regions through CIMMYT's extensive collection of adoption and impact studies (for the most recent global assessment of improved maize germplasm adoption and impact, see Morris 2001).

The poverty index used in this report redirects the focus of the efficiency criteria by targeting investments to areas where rural poverty is the highest. The most commonly accepted measure of absolute poverty is that individuals in a given population are living on less than US$ 1 a day, in absolute or proportionate terms. The poverty measure used in this paper is the share of global population living under a dollar a day in a particular ecology and geographic region. Table 7 shows the number of absolute poor by maize ecology and geographic region; the global share of poverty for the regions are included in parenthesis.

The subsistence farming index modifies the efficiency index by targeting investments toward agricultural areas that are more subsistence oriented, with the presumption that more commercially oriented areas are being, or will be, served by the private sector. The percentage of farmers in a particular ecology or geographic region that produce maize primarily for subsistence food needs was used to quantify subsistence status. The area grown to unimproved (traditional) maize cultivars was used as the best available indicator of subsistence status.

The constraints presented in Table 5 were ranked across all ecologies and geographic regions using the three indices described above: efficiency, poverty, and subsistence orientation. A composite index and ranking were then generated by aggregating the three criteria using a set of arbitrary weights: 50% for efficiency, 30% for poverty, and 20% for subsistence orientation (Table 6). One can reasonably dispute this weighting, but developing an objective process for determining the relative importance of the three indices proved elusive. It is apparent that the weighting can shift depending on the mission and perspective of the user, e.g., if one represents a community development agency, poverty might be more heavily weighted, while someone representing a NARS might give efficiency more weight. We decided that efficiency should still be the primary determining factor in resource allocation with important consideration given to the extent of poverty within a particular cell. Given CIMMYT's focus on public sector research priorities, the rankings are weighted to favor areas that are not adequately served by the private sector—the subsistence production zones.

Research priorities highly depend on the criteria that are used. For example, the constraint ranking based on efficiency is quite different from that based on poverty. Table 8 shows the top ten constraints (associated by region) based on the indices for efficiency and for poverty. Simply assessing priorities based on efficiency would indicate that managing the problem of soil acidity in the tropical lowlands of Latin America would provide the highest returns on the research dollar. This is not surprising given the large area of tropical lowlands in Latin America that suffer from soil acidity problems and the potential production impact from alleviating this particular constraint. On the other hand, based on the poverty index, the lack of early maturing germplasm (that complements intensive production systems) in the tropical lowlands of South Asia is the top constraint. This result, again, is not surprising given that the majority of the world's poor (those living on under US$ 1 a day) live in South Asia, with the largest share of that population living in the lowland tropics.

Based on the poverty index ranking, the needs of the South Asian lowland tropics predominate among the top priority constraints. In addition to early maturing germplasm, downy mildew, drought, and

Table 6. Prioritizing constraints across maize ecologies and geographic regions

Efficiency Index	Poverty Index	Subsistence farming index	Combined index
Is a product of: • Importance of constraint • Yield gain associated with constraint alleviation • Total production by maize ecology and region • Probability of success in finding solution • Adoption history (% farmers that have adopted new technologies in the past)	Is a product of the efficiency index and share of the global population living under US$ 1/day in the particular ecology and geographic region	Is a product of the efficiency index and percentage of farmers in the particular ecology and geographic region that produce food primarily for meeting subsistence needs	Is a sum of: .5* Efficiency index + .3* Poverty index + .2* Subsistence farming index

Table 7. Population living under US$ 1 per day ('000)

	Highland	Midaltitude/ Subtropical	Tropical lowlands	Regional total
E, SE Asia	8,618 (1%)	8,618 (1%)	68,943 (8.4%)	86,179 (10.4%)
South Asia	25,738 (3%)	128,692 (15.6%)	360,338 (43.7%)	514,769 (62.4%)
WANA	-	5,211 (0.6%)	-	5,211 (0.6%)
SSA	8,456 (1%)	67,649 (8.2%)	93,018 (11.3%)	169,123 (20.5%)
LAC	12,266 (1.5%)	7,360 (0.9%)	29,438 (3.6%)	49,064 (5.95%)

Note: WANA = West Asia/North Africa; SSA = sub-Saharan Africa; LAC = Latin America and the Caribbean.

Table 8. Top ten priority constraints to maize productivity based on efficiency vs. poverty rankings

Efficiency ranking			Poverty ranking		
Region	Ecology	Constraint	Region	Ecology	Constraint
1. LAC	T. lowlands	Soil acidity	1. S. Asia	T. lowlands	Early germplasm
2. E, SE Asia	T. lowlands	D. mildew	2. S. Asia	T. lowlands	D. mildew
3. E, SE Asia	T. lowlands	Early germplasm	3. E, SE Asia	T. lowlands	D. mildew
4. SSA	Midaltitude	Soil infertility	4. E, SE Asia	T. lowlands	Early germplasm
5. LAC	T. lowlands	Drought	5. S. Asia	T. lowlands	Drought
6. SSA	Midaltitude	Gray leaf spot	6. SSA	Midaltitude	Soil infertility
7. LAC	T. lowlands	Stunt	7. S. Asia	T. lowlands	High temperatures
8. LAC	T. lowlands	F. armyworm	8. SSA	Midaltitude	Gray leaf spot
9. SSA	Midaltitude	Streak virus	9. SSA	Midaltitude	Streak virus
10. E, SE Asia	Midaltitude	Drought	10. LAC	T. lowlands	Soil acidity

note: WANA = West Asia/North Africa; SSA = sub-Saharan Africa; LAC = Latin America and the Caribbean.

susceptibility to high temperatures also appear among the top ten constraints. The needs of sub-Saharan Africa are also well represented under both indices, as low soil fertility, gray leaf spot, and maize streak virus, all found in the midaltitude maize growing areas of the region, appear in the top ten constraints. The largest divergence between the two indices emerges from the Latin America analysis. On efficiency grounds, four of the five constraints to productivity growth in the tropical lowlands of Latin America appear in the top ten constraints overall, while on poverty grounds, only soil acidity remains, ranked tenth. By explicitly incorporating poverty levels into our priority setting, we consciously engaged in trading off higher economic efficiency for increased food supply and food security for the poor (both rural subsistence farm families and poor urban consumers).

Global and Regional Priorities

The top 20 priority constraints that according to our combined index should be addressed through public sector research are presented in Table 9. The combined ranking provides a balance between efficiency and poverty considerations. Nine of the top ten constraints in the efficiency index (Table 8) appear in the top ten constraints of the combined rankings. Drought during the flowering stage for the midaltitude environments of East and Southeast Asia fell from the top ten. This may be because the active private sector involvement in this mega-environment of Asia makes it a low priority for public sector investment. All of the top ten constraints in the poverty index also appear in the combined ranking.

Table 9. Top 20 priority constraints to maize productivity based on combined ranking

1. E, SE Asia	T. lowlands	D. mildew
2. E, SE Asia	T. lowlands	Early germplasm
3. LAC	T. lowlands	Soil acidity
4. SSA	Midaltitude	Soil infertlity
5. S Asia	T. lowlands	Early germplasm
6. LAC	T. lowlands	Drought
7. SSA	Midaltitude	Streak virus
8. SSA	T. lowlands	F. armyworm
9. LAC	T. lowlands	Stunt
10. LAC	T. lowlands	F. armyworm
11. S Asia	T. lowlands	D. mildew
12. E, SE Asia	T. lowlands	Drought
13. S Asia	T. lowlands	Drought
14. AE, SE Asia	T. lowlands	Borers
15. S Asia	T. lowlands	High temp
16. SSA	T. lowlands	Soil infertlity
17. SSA	Midaltitude	Drought
18. SSA	Midaltitude	Weevils
19. SSA	T. lowlands	Drought
20. S Asia	Midaltitude	Turc. blight
21. SSA	T. lowlands	*Striga*

Note: WANA = West Asia/North Africa; SSA = sub-Saharan Africa; LAC = Latin America and the Caribbean.

Of the 20 prioritized constraints, seven are specific to sub-Saharan Africa, five to South Asia, and four each to Latin America, East Asia, and Southeast Asia. Although the priorities are well balanced regionally, they are skewed in terms of mega-environments: 14 are specific to the tropical lowlands and six to the midaltitude/subtropical environments. In the latter case, five of the six are constraints specific to sub-Saharan Africa, while one is specific to South Asia. This reinforces the presumption that the subtropical and midaltitude maize growing environments are, in general, served by the private sector. The area under subsistence farming is relatively low in the subtropical/midaltitude areas in all regions except sub-Saharan Africa, thus, this ecology drops out of the priority listing for the other regions.

None of the constraints from the tropical highlands appear in the top 20 constraints. Why? Only a very small amount of total tropical maize production is grown in the tropical highlands. However, the tropical highlands are important on a regional basis, particularly in Latin America, East Africa, and the hills of Nepal. Moreover, the concentration of poor, subsistence households is the greatest in the highlands relative to other maize growing ecologies. It is therefore important to continue investing (relatively modestly) in highland maize improvement research, with an emphasis on Latin America. Within such efforts, mechanisms should be established to promote spillovers from the research to other highland environments, such as the mid- and upper hills of Nepal and the highlands of East Africa.

To derive regional priority constraints, we took the top 20 global priority constraints and augmented them with others from our total ranking of 49 constraints, ultimately obtaining the most important constraints by region. Regional rankings are shown in Table 10; constraints/regions not found among the top 20 global constraints are italicized, with the global ranking indicated in parenthesis. With two significant exceptions, all of the specific constraints may be found on the global priority constraints list, but associated with different regions or environments. For instance, drought was added for the midaltitude and subtropical environments of Asia, but it was already listed in the top global priorities for the lowland tropics of Asia. A similar case is found with borers and streak virus (added for the midaltitude regions of sub-Saharan Africa) and turcicum leaf blight (added for the midaltitude regions of Latin America).

The two additions to regional priorities that are not reflected in the top 20 global priorities are *Striga* in the tropical lowlands of sub-Saharan Africa (priority 21) and soil erosion in the midaltitude and highland areas of Latin and Central America.

Priority Technology Interventions

The prioritization exercise identified constraints that should be addressed by the public research system (international/national). To effectively set priorities for public sector maize research on a global and/or a regional basis, we need (1) to identify the most effective means for mitigating the constraints we have cited and (2) to identify a supplier with a comparative advantage in delivering the particular research product. This section looks specifically at viable technological options for overcoming these constraints. The question of who might best provide those research products is explored in the next section of the report.

Technology Interventions for Abiotic Constraints

Drought

Technologies to reduce the effects of drought involve development of cultivars that either escape or tolerate the stress, or better crop and water management strategies. Through conventional breeding, CIMMYT scientists have made significant progress in developing drought tolerant cultivars, especially for drought that occurs at the critical flowering stage. Biotechnology, specifically molecular genetics, holds great promise for accelerating progress. Molecular markers have been identified for traits associated with drought resistance, and their value is currently being assessed in developing tolerant cultivars. Structural and functional genomics offer additional possibilities and efforts are underway to examine their potential.

Early maturing germplasm for drought avoidance. The use of cultivars that mature early can be an effective strategy for drought avoidance where the rainy season is reliable but short. Early maturity allows the crop to escape terminal drought; it may also avoid coincidence between flowering and a midseason dry spell, which often affects maize production in the tropics. The period from sowing to flowering or physiological maturity is a highly heritable trait, and therefore selecting for earliness is a very viable approach (Bänzinger et. al. 2000). Indeed, evolutionary pressures and farmer selection have produced "local" early maturing maize cultivars in dry tropical areas of Indonesia, Kenya, Mexico, and Colombia. These cultivars escape drought but are relatively low yielding when rainfall is not limited. Over the last two decades, breeding programs have substantially improved yields of early maturing maize varieties under low rainfall conditions, but earliness continues to carry a yield "penalty" when rainfall levels are above average (Bänzinger et al 2000).

Cultivars with drought tolerance. For drought tolerance, matching crop development to rainfall pattern is the single most important breeding goal for the rainfed environments (Edmeades et al 1997c). Maize breeding at CIMMYT and elsewhere has concentrated on developing later maturing cultivars that stabilize yield by reducing the effect of drought on grain number and size. For

Table 10. Regional priority constraints limiting tropical and subtropical maize productivity

	E, SE, and Asia	Sub-Saharan Africa	Latin America
Tropical lowlands	Early germplasm Drought Downy mildew High temperatures (S.Asia) Borers	Drought Soil infertility *Striga (21)*	Soil acidity Drought Fall armyworm Stunt *Borers (24)*
Midaltitudes	Turcicum blight *Drought (22,23)* High temperatures (31) *Borers (32, 33)*	Drought Soil infertility Weevils Gray leaf spot Streak virus *Borers (28)*	*Soil erosion (36)* *Turcicum blight (37)*

Note: Figures in parenthesis are ranking of constraints beyond the top 20.

selection, conventional breeding has depended on plant performance criteria such as yield or secondary traits highly associated with yield under drought (e.g., anthesis-silking interval [ASI[4]]). A long ASI is generally equated with drought susceptibility—low harvest index, slow ear growth, and barrenness under drought. A short ASI is associated with fewer but larger florets that grow more rapidly at anthesis and which are therefore more tolerant of reductions in photosynthesis caused by drought and other stresses. In this vein, much effort has been devoted to sharply reducing the ASI, and yield gains associated with success in this area have been of the order of 100 kg/ha/yr (5% per annum) in tropical lowland germplasm (Edmeades et al. 1997b). Although the breeding strategy based on reducing ASI can claim some success, progress has been slow on genotype x environment (G x E) interactions because of annual variations in the timing and intensity of drought stress in field breeding nurseries. This has limited development of drought tolerant germplasm that is locally adapted to the tropical growing environments.

Advanced science and drought tolerance. New molecular tools are now available that can be integrated with conventional breeding and physiology to increase our understanding of drought tolerance and accelerate the development of tolerant cultivars. Using genomics techniques, genes and quantitative trait loci (QTL) that are related to improved stress tolerance can be identified. A key application of this knowledge is the work underway at CIMMYT to validate and optimize marker-assisted selection (MAS) approaches for drought tolerance improvement (Ribaut et al. 1999). The time and expense associated with conventional breeding efforts could be substantially reduced through the use of MAS, and we foresee it playing a major role in tandem with conventional breeding methods over the next 5–10 years. Beyond the five-year time horizon, we anticipate a quantum leap in the development of drought tolerance through the application of functional genomics.

The ultimate goal of functional genomics is to identify and determine the role and environmental reactions of every gene of interest. Comparative genomics goes even further and seeks to identify and find the role of every gene across species, to determine exactly which genes and interactions result in differences among species, and as important, to determine where synteny exists. One projected use of this knowledge is to identify and utilize the best drought tolerance alleles in nature, regardless of source, for crop improvement. For instance, it is likely that maize and sorghum share the same basic drought tolerance pathways, but that sorghum has acquired superior allelic versions of the genes because it evolved in drought prone environments. If the sorghum genes that are responsible for superior drought tolerance are identified, it is possible that these genes could be "activated" in maize to provide superior drought tolerance. Clearly, using information (and eventually genes) from diverse species will provide a synergistic route for the improvement of any and all individual crops. The technology and biological materials needed to accomplish this ambitious task now exist. The appropriate team and requisite resources are all that is needed to undertake this important work (Bennetzen 2000).

Farm-level drought management strategies. A sustainable strategy for mitigating farm-level yield losses to drought must be based on the use of tolerant cultivars and appropriate management options. Integrated drought management includes escape measures, which may incorporate crops other than maize, and crop and water management strategies to reduce water stress. The latter include options such as planting on the optimum date to align critical stages of plant development with rainfall; tillage to promote greater rooting depth, better entry and storage of water in the soil, and reduced competition from weeds; prevention of run-off and better direction of available water to the crop; and mulching to reduce water loss. Crop and water management strategies are environment and location specific and consequently costly to develop and disseminate to farmers.

One issue that often arises regarding the appropriate germplasm to promote for drought tolerance at the farm level is whether to concentrate exclusively on OPVs. There is a general misconception that hybrids perform poorly in stress environments, despite good evidence suggesting that hybrids maintain their yield advantage over OPVs in both favorable and stressed environments. Some developing countries, including China, Thailand, and Vietnam, are already switching to two-parent hybrids for such environments. The choice between OPVs and hybrids depends more on economics than on agronomic conditions. In environments that are well

[4] A characteristic of maize under drought stress is an increase in the ASI—the time between the beginning of pollen shed and the appearance of silks on the ear. When late emerging silks on drought stressed plants are pollinated, fertilization can be shown to occur, but grain development is arrested shortly afterwards, giving rise to patchy grain formation, bare ear tips, or complete barrenness (Edmeades et al. 1995).

integrated into the market and where maize production is profitable, hybrids may well be the preferred choice.

Low Soil Fertility

Adoption of N-use efficient maize implies an important yield benefit at modest additional recurrent costs to the farmer, making it relatively easy for resource poor farmers to adopt (Waddington and Heisey 1997). Sustainable soil fertility management in the tropics requires an integrated approach that consists of the efficient use of purchased chemical and organic inputs, crop rotations, and nutrient efficient cultivars.

Progress has been made in developing maize cultivars that efficiently utilize available soil nutrients, especially nitrogen, and convert it to grain. And fortuitously, many cultivars selected for drought tolerance also yield higher under low-N conditions, thereby allowing spillover benefits to low N environments (Edmeades et al. 1997c). At CIMMYT-Mexico, three cycles of full sib recurrent selection for grain yield under low soil N (zero N added), while maintaining grain yield under high soil N (200 kg N/ha applied per cycle), were conducted in tropical lowland populations (Lafitte and Edmeades 1994a, b). A modest gain in yield potential was recorded under low N conditions. Further work on breeding for N-use efficient germplasm is ongoing in southern and eastern Africa.

Although important, N-use efficient maize will likely provide only part of the hefty productivity gains needed in many parts of the developing world. Waddington and Heisey (1997) estimate that N-use efficient cultivars could increase maize yield gains in southern Africa, over a ten-year period (1996-2006), by 25%, an average yield increase from 1.2 t/ha in 1996 to 1.5 t/ha. Further increases in average farm yields must come from enhanced and more efficient use of chemical fertilizers and organic manures, and the adoption of crop management practices that increase fertilizer responsiveness, such as early planting, weeding, and appropriate land management practices.

Kumwenda et al. (1996) suggest a three-pronged strategy for enhancing fertilizer-use efficiency in smallholder maize production systems:

- the type of inorganic fertilizer and its use are carefully tailored to the conditions faced by smallholders;
- the proportion of locally produced organic materials is increased, which reduces the cash cost of fertilizer while increasing the efficiency of inorganic fertilizer use; and
- agronomic and economic factors must receive greater consideration in breeding priorities for maize and legumes, so that future improved materials fit smallholders' circumstances.

Substantial research has been conducted on techniques for increasing the efficiency of chemical fertilizer use, addressing issues such as the types and amounts of fertilizer to apply, timing of fertilizer applications, and the placement of fertilizer. Little progress has been made, however, in tailoring the research to the agro-ecologies and farming systems of most smallholders. Biophysical and socioeconomic factors also must be considered in the development of the field recommendations if the practices are to be adopted on a sustainable basis. For instance, labor-intensive hand placement methods are not likely to be adopted in areas where the opportunity cost of labor is high. Similarly, recommendations that require fertilizer timing decisions based on monitoring crop nutrient status, a highly knowledge intensive process, will work only when farmers have adequate levels of education or training (Pingali et al. 1998).

A central aspect of sustaining soil fertility on smallholder farms in the tropics is the maintenance and management of soil organic matter (SOM). In tropical low input agricultural systems, SOM helps retain mineral nutrients in the soil and makes them available to plants in small amounts over many years (Woomer et al. 1994). Current SOM inputs are insufficient to maintain organic matter levels in tropical agricultural soils (Kumwenda et al. 1996). Supplies of traditional sources of organic matter, such as farmyard manure and crop residues, are rapidly declining because of escalating labor costs associated with their collection, transportation, and incorporation.

Crop rotations, intercropping, and in some instances improved fallows with legume green manure crops have been promoted as a means of replenishing SOM. Under favorable conditions, green manure crops can generate large amounts of organic matter (up to 200 kg N/ha in 100–150 days), of which 30–40 kg are available to the plants (Kumwenda et al. 1996). Annual grain legumes offer a good compromise for meeting both the food security and soil fertility needs of farm households. Grain legumes can provide seed and sometimes leaves for home consumption while adding organic matter and nitrogen to the soil. The most promising species combine some grain with high root and shoot biomass; these include self-nodulating promiscuous types of soybeans, pigeonpea, groundnut, dolichos bean, and cowpea.

It must be emphasized that without a substantial increase in adaptive research targeted to specific maize production zones, and widespread dissemination of research recommendations, farm-level adoption of efficient fertilizer use practices, and attendant increases in yield, will remain limited.

Soil Acidity in Latin American Tropical Lowlands

As noted, in countries such as Brazil and the United States, liming has been the most widely used method to counter the negative effects of high soil acidity. Lime applications, however, must be repeated every few years and are too expensive for resource poor farmers. Moreover, liming subsoils deeper than 30 cm is difficult and also incompatible with the current trend towards conservation tillage on sloping lands in the developing world (Pandey et al. 1994).

The development of acid tolerant cultivars will provide a less expensive, permanent solution. Acid tolerant cultivars have been developed that do reasonably well at higher levels of aluminum toxicity, thereby reducing the need for liming. Molecular markers have been identified for aluminum and phosphorus tolerance, but because they address only individual stresses, they have not led to commercially successful cultivars. A gene associated with aluminum tolerance has been identified in another plant species and transferred to maize, but again, it has not led to a commercially successful cultivar. Nevertheless, we believe additional work with molecular markers and genomics will promote the development of more acid tolerant maize cultivars.

Soil Erosion

The threat posed by soil erosion to tropical maize production systems can be substantially reduced by the adoption of conservation or zero tillage systems. Conservation tillage may be defined as "any tillage or planting system that leaves 30% or more of the soil surface covered with residues at planting time" (CTIC 1994). Zero tillage may be defined as the planting of crops in previously unprepared soil by opening a narrow slit, trench, or band of sufficient width and depth for proper seed coverage (Derpsch 1999). In both cases it is understood that the soils remain covered by residues from previous crops (including green manure cover crops) and that most of the crop residues remain undisturbed at the soil surface after seeding. A primary advantage of both approaches is that no additional land conservation investments, such as terraces, contour bunds, or soil conservation barriers are required, thereby making this technology equally accessible to small- and large-scale farmers. In addition, conservation and zero tillage offer (1) substantial cost savings from reduced power needs, (2) sizeable decreases in capital requirements (as less machinery and less powerful tractors are needed), and (3) significant reductions in labor requirements.

It is estimated that 45 million hectares of agricultural land in 1998/99, grown to wheat, maize, and soybeans, was under zero tillage worldwide. The United States (19.3 million ha), Brazil (11.2 million ha), Argentina (7.3 million ha), Canada (4.1 million ha), and Australia (7.3 million ha) lead the world in area under zero tillage (Derpsch 1999). Another 1.6 million hectares of zero tillage is found elsewhere in South America and Mexico. Area under conservation/zero tillage is quite small in Asia and Africa. With the worldwide fall in cereal crop prices, the increasingly widespread availability of safe and inexpensive herbicides, and the rising costs of labor and fuel, we anticipate further expansion of these tillage technologies in other parts of the developing world.

However, we must recognize that conservation/zero tillage techniques are not equally applicable everywhere. From an agroclimatic perspective, reduced tillage systems are least applicable in the arid fringe environments and on soils with poor drainage. In the arid fringe environments, the availability of adequate quantities of crop residues for incorporation into the soil is a major limiting factor. Moreover, these soils tend to compact easily and therefore need significant amendments before they are suitable for conservation/zero tillage. Heavy vertisol soils in valley bottoms and river basins, as seen in the Asian rice lands, tend to require high levels of tillage, particularly for wet season rice cultivation.

From a socioeconomic viewpoint, two factors can limit the adoption of conservation/zero tillage systems: competition for crop residues and the availability of inputs. Where crop residues are important for livestock feed, it is difficult for farmers to divert some of that residue for incorporation into the soil. Herbicides and machinery are crucial inputs for conservation tillage, and in remote, subsistence production systems, access to these inputs can often be a constraint to adoption.

Conservation/zero tillage is also knowledge intensive—it is highly location specific and where not adopted appropriately, it can create a set of negative unintended effects. Research is urgently needed on the long-term impacts of these tillage techniques on ecosystems, particularly changes in weed and pest populations. The off-site effects of increased herbicide use on human health and the environment also must be closely monitored and evaluated, particularly during the early years of adoption.

Early Maturing Germplasm for Asian Lowlands

Despite the significant advantages offered by early maturing maize varieties, formidable challenges remain to their development and use. The most noteworthy of these for breeders is their susceptibility to biotic stresses that makes it more difficult to extract useful inbred lines. Nevertheless, several approaches are being tried to breed high-yielding early maturing cultivars. Selection for higher yield in low yielding and early maturity populations has generally been ineffective. However, breeders have developed some superior early maturing cultivars by crossing early maturing (low yielding) and late maturing (high yielding) maize varieties. Another approach has been to cross late-maturing tropical maize with temperate maize. This scheme has produced some encouraging results in subtropical and midaltitude tropical environments, but it has been less useful in lowland tropical environments because of the temperate germplasm's high susceptibility to tropical diseases and insects. Still, even in the lowlands, limited success has been achieved by incorporating only small fractions of temperate germplasm into the adapted tropical maize.

High-Temperature Tolerant Germplasm

Much of breeding for tolerance to higher temperatures in maize is routinely carried out in nurseries planted in tropical and subtropical environments where selection is practiced for higher yield, better plant development, and lesser tassel blast. Tolerance to drought, which has been receiving considerable attention in recent years, also provides partial benefits under high temperature conditions. However, better targeted and more focused research on tolerance to higher temperatures, using traditional as well molecular approaches, will surely result in the development of superior and more tolerant cultivars.

Improved Germplasm for the Tropical Highlands

As noted earlier, multiple constraints act to reduce yields in the tropical highlands. For technology interventions that bear on these problems, see the subsections on drought, low soil fertility, and soil erosion in this section, and turcicum leaf blight under "Disease Resistance" in the following section.

Technology Interventions for Biotic Constraints

Disease Resistance

Downy mildew. Most of the commercial cultivars sold by private sector in mildew prone areas are now treated with a systemic fungicide, Ridomil, and the private sector is only now beginning to develop resistant cultivars. Seed treated with Ridomil is expensive and generally beyond the financial reach of the resource-poor farmers. The public sector has focused its attention on developing resistant cultivars through traditional breeding and has been relatively successful (de Leon and Lothrop 1994). Unfortunately, many resistant cultivars are not reaching farmers for lack of seed production and distribution. Genetic studies indicate that only a few genes control resistance to this disease and field screening is relatively inexpensive, reliable, and efficient. Efforts are now underway to identify molecular markers associated with downy mildew resistance and this may further enhance the speed with which resistant cultivars are developed.

Turcicum leaf blight. The only known economical solution to the problem is resistant cultivars. Fortunately, it is easy to breed for resistance to this disease, and many cultivars developed by public and private institutions have reasonably good levels of resistance. Some genes for resistance have been cloned and tagged. This technology has helped the private sector quickly introduce resistance into susceptible but high yielding genotypes. The challenge is to continue transferring genes for resistance to turcicum leaf blight into newer high-yielding cultivars as they become available.

Maize streak virus. Conventional breeding for MSV resistance has been notably successful. CIMMYT and the International Institute for Tropical Agriculture (IITA) have worked jointly since 1980 on MSV resistance and have generated a sizable collection of improved streak-resistant germplasm for the tropical lowlands (Diallo and Dosso 1994). Molecular markers associated with MSV resistance have been identified and are accelerating the development of resistant cultivars. Further breeding effort is needed, however, to introduce MSV resistance into tropical germplasm that is tolerant to a range of abiotic stresses such as drought and low N, and important biotic stresses found in particular environmental niches. Substantial efforts are also needed to find effective mechanisms, including seed production and distribution, for disseminating the MSV resistant germplasm to the farm populations most in need.

Gray leaf spot. Fortunately, breeding for resistance to GLS is not complicated and many resistant improved cultivars are already available. Molecular markers associated with GLS resistance have been reported in recent years, but it is not clear if they have been successfully used in the development of resistant cultivars. Traditional genetic and RFLP analyses have shown that additive gene effects generally contribute the most to resistance. Unfortunately, most maize grown in sub-Saharan Africa is unimproved and susceptible to the disease. Introduction of resistance in traditional/local cultivars as well increased efforts to produce and distribute seed of improved cultivars would help combat the disease more effectively.

Corn stunt. A crop-free period and the use of resistant genotypes are the most effective measures for controlling corn stunt. Resistant inbreds, hybrids, and OPVs have been developed both under artificial inoculation with mixed infections and under natural infection in Central and South America. Yield potential of the stunt resistant germplasm is equal to or better than the best germplasm available in those regions. Molecular markers for resistance, when identified, will further enhance efforts to develop effective cultivars. Again, seed production and distribution of resistant cultivars must be improved to maximize the benefits of resistant cultivars for resource poor farmers.

Insect Resistance

Appropriate insecticide use will continue to play an important role in insect control, but nonchemical alternatives remain a safer and more environmentally beneficial approach for tropical farmers. Some nonchemical control measures that have been used on a limited basis include the application of sand and ash in the whorls, oil applications to silk to control earworms, and the use of plant products with repelling capabilities, such as neem (*Azadirachta indica*). The latter approach has been incorporated into a habitat management strategy called the "push and pull method." Under active development in Kenya, this approach involves planting insect-attracting plants (napier grass) on field borders and insect-repelling plants (*Desmodium* spp.) intercropped with maize to deter pests from laying their eggs on the crop (Khan et al. 2000). Reports indicate that "push and pull" also improves the performance of biological control agents that attack stem borers (Khan et al. 1997). Another nonchemical approach under investigation is based on using the volatiles produced by certain varieties of maize (released when pests incur damage) to attract biological controls (Turlings et al. 1995). Traits related to volatiles can be improved through conventional breeding and may enhance the effectiveness of this innovative tactic.

Cultivars possessing genetic resistance offer the most effective and acceptable technology for resource poor farmers. Fortunately, genetic variation for most of the important insects exists within maize. Unfortunately, efforts to develop and deliver resistant cultivars to farmers have only been moderately successful. This shortcoming can be attributed to (1) the prevalence of large numbers of different types of insects in the developing countries, (2) variations in their feeding habits and aggressiveness, (3) lack of efficient insect-rearing technologies and facilities, (4) lack of trained scientists, and (5) an overall shortage of resources for research. Development of insect resistant cultivars is certainly within our grasp given adequate resources and the concerted efforts of research centers such as CIMMYT.

Armyworm. Armyworm resistance has been developed through conventional breeding and genetic engineering. Armyworm resistant populations have been developed based on a polygenic mechanism that produces a thicker epidermal cell wall to restrict larval establishment in the whorl of the maize plant. Efforts are now underway to move these sources of resistance into elite tropical germplasm. Genetic engineering has been used to incorporate genes derived from *Bacillus thuringiensis* (Bt) into maize; proteins expressed by these genes bind to the armyworm's gut and pierce it, leading to its death. A major concern about this technology is the development of Bt resistant insects. Effective insect resistance management (IRM) strategies must be established to counter this natural adaptation. "Refugia" are needed to maintain populations of susceptible insects to mate with resistant insects to delay the development of Bt resistance. Stacking or pyramiding Bt genes, to ensure that multiple toxins are expressed in the plant, will also prolong resistance, which may be further enhanced through the incorporation of conventional resistance.

Earworm. Earworm resistance has been developed in temperate germplasm based on elevated levels of maysin, a compound found in the silk tissue that stunts the growth of larvae. In tropical maize growing areas, high levels of maysin combined with tight husk cover may provide effective control of larvae. Additional resistance measures, however, may be needed, including accelerated rates of kernel hardening. In the future, transgenic maize that expresses Bt toxins in the silk and/or kernel may be an effective means of delivering earworm resistance, especially for the floury endosperm germplasm found in the Andean regions of South America.

Stem Borer. Stem borer resistance has been developed and involves the same mechanisms already outlined for armyworms. One area warranting further research is the development of germplasm that resists "second-generation" attack, larvae attacking maize during flowering. Selection for resistance at this stage of maize development has been slow because the borers feed on diverse plant tissues at this time. Historically, selection focused on increasing stalk strength to withstand tunneling, thereby facilitating mechanical harvesting. To reduce second generation damage, researchers are now screening plants for reduced feeding damage in the tissues first fed upon by larvae, specifically, the sheath, husk, and ear. The use of Bt maize in developing countries could also provide effective control of stem borers if management strategies to delay the development of resistance are in place.

Postharvest insect pests. Proper grain conditioning and storage can control postharvest losses in maize in temperate and tropical environments. The challenge for developing countries is to deliver appropriate on-farm storage technologies to their small-scale farmers. To this end, husk cover of improved varieties plays an important role in reducing the population of primary pests, such as weevils, brought in from the field. A second line of defense is found in the kernel itself, which can be selected for elevated levels of resistance. One component of this resistance is increased kernel hardness that reduces kernel colonization rates by some insects. Using genetic engineering, scientists have inserted a gene into maize that could potentially control postharvest pests, the avidin gene. A protein expressed by the gene binds free biotin, a common vitamin essential for insect growth and development, so the insect stops developing and dies. Studies on food safety and the efficacy of this technology are now being conducted by the private sector.

Striga Resistance/Tolerance

In the short term, the most promising approach to suppressing or delaying *Striga* parasitism is the application of minuscule rates of herbicide to the seed of herbicide resistant maize varieties. CIMMYT agronomists have shown that seed dressing these varieties with the herbicides imazapyr and pyrithiobac at the time of planting gives season-long *Striga* control and dramatically increases yields (Kanampiu et al., forthcoming). In addition, this technology allows maize to exude germination stimulants into the rhizosphere, which induce germination of *Striga* seeds, thereby depleting the *Striga* seed banks. This treatment costs less than US$ 5/ha and more than doubles yields in infested areas. Farmers realized returns of up to 20 times the cost of the herbicide. Seed dressing with imazapyr and pyrithiobac, coupled with pulling rare *Striga* escapes, may provide a stopgap measure until more long-lasting genetic resistance becomes available. Adaptive research is needed to integrate the various components of this approach for major farming systems.

In the medium term, *Striga* control may be achieved through the development of tolerant germplasm. The consensus is that resistance does not exist within commonly used African germplasm, i.e., all induce *Striga* germination and attachment. However, variability does exist for tolerance; while some germplasm is extremely susceptible to *Striga* phytotoxins, other lines can sustain high levels of attachment and growth with only limited effects on yield. Resistance has been detected among wild relatives of maize (teosinte and *Tripsacum*) and within a population of transposon-induced mutations. Taking this approach a step further would entail characterizing those alleles and introducing them into adapted germplasm.

Because of *Striga's* reproductive prolificacy—with a single plant producing a large number of progenies and soils serving as reservoirs for millions of dormant seeds—it is likely that any given resistance will break down relatively quickly. Maintaining resistance will require utilizing a set of unrelated resistance mechanisms (e.g., combining herbicide-based control with genetic resistance) and/or implementing strict resistance management practices.

Among the agronomic practices that could help control *Striga*, particular attention should go to trap crops (cowpea, sorghum, etc.) that lower *Striga* seed germination and weed count in the field. These cropping practices, however, have not been widely accepted because of the investment of labor and time they require.

In the longer term, a deeper knowledge of the physiological, biochemical, and molecular basis of the host-pathogen interaction will be the best insurance policy against *Striga*.

Sources of Research and Technology Supply

Having explored the technological options available for alleviating our priority constraints, we will now spell out how the public sector should position itself relative to the private sector to develop these technologies. A general framework is laid out for discussing the roles and responsibilities of the public and private sectors, followed by an examination of the priority areas identified in this report. The research and technology suppliers that we consider are the IARCs, such as CIMMYT, the NARSs, and the national and multinational private sectors. Each of these players has unique capabilities, resources, and comparative advantages that can be brought to bear on alleviating production constraints.

Public and Private Sectors: Delineation of Research Responsibilities

When prioritizing future public sector maize research, it is important to accurately anticipate prospective private sector activity in order to minimize duplication of effort and to identify potential areas of collaboration. The private sector has been active in maize research, development, and dissemination since the 1930s and 1940s. In the case of tropical maize systems, the private sector has been active in geographic areas that support commercial maize production, developing and selling hybrids adapted to particular geographic and ecological regions. The role of the private sector in seed production and dissemination in developing countries is discussed at length in Part 2 of this report and in Morris (1998). At this point, we simply wish to acknowledge and endorse the view that the private sector is far more effective than the public sector in providing seed to farmers in most developing countries.

During the past five years, private sector research investment in tropical maize has increased substantially. This growth can be attributed to four factors:

1) rapid growth in feed maize demand and the consequent commercialization of maize production systems have provided an impetus for private sector investment;

2) global amalgamation of agribusiness has brought significant resources to bear on the problems of tropical maize systems;

3) emergence of biotechnology as a strategic force in the development of agricultural technology and enormous investments by the private sector in its exploitation; and

4) increased use of intellectual property rights (IPR), which allows developers of a technology to appropriate the profits it generates.

The question then arises: In which areas should the public and private sectors work independently, and in which areas should they work together?

The Public Sector Role

A key role of national and international public sectors has been training and human resource development, which has encouraged private firms to become involved in agricultural research and development (R&D) by lowering costs of learning and capacity building. The public sector will continue to enjoy a strong comparative advantage in this area for the foreseeable future, especially in the developing world.

The national and international public sectors have also been the sole source of genetic resource conservation and management, a service that is expected to continue over the long term. Public sector efforts in collection, characterization, and preservation of genetic resources have resulted in significant social and private sector benefits. Social benefits are gained in terms of conserving the rich genetic heritage of landraces and wild relatives of maize (and other crops) that are in danger of disappearing from developing country farming systems. Private sector benefits accrue in terms of free access to genetic resource collections that private companies can use to enhance their crop breeding activities.

Prebreeding research, to produce elite breeding materials that can be used as the basis for developing locally adapted varieties, will remain an important public sector activity. Although there is a counterview that prebreeding research will become obsolete with anticipated advances in genomics, we believe it will remain an important component of maize research in developing countries for the next 5–20 years.

Within the realm of genomics and biotechnology, national advanced research institutes (ARIs) and multinational companies will probably maintain their dominance in basic and applied research. Nevertheless, the international public sector could act as a conduit that provides access to these technologies by developing countries and trains scientists in their use.

CIMMYT Technology Improves Nutritional Quality of Maize

Janet Lauderdale

CIMMYT is dedicated to helping feed the world's poor—not only through increasing the supply of maize and wheat, but also by raising the nutritional quality of these grains. Malnutrition stems from many sources, and though considerable progress has been made in ameliorating some of its causes, it is still prevalent in many parts of the world. From 1990 to 1998, about 30% of the world's children under five years of age were moderately or severely underweight. The percentage rises to 40% overall for the least developed countries (UNICEF 2000).

In general, CIMMYT's strategy in the fight against malnutrition has been based on increasing production of maize and wheat to increase total energy supply to the world's ever-growing population. As understanding of nutritional requirements has increased, however, CIMMYT has placed greater emphasis on raising the nutritional quality of maize and wheat. CIMMYT projects now in the pipeline aim at increasing important vitamin and mineral levels. Although the payoffs for these micronutrient projects reside in the future, work on increasing protein levels in maize is bearing fruit today. Quality protein maize (QPM) has been or will soon be introduced into more than a dozen developing countries all over the world through the efforts of CIMMYT, national programs, and Sasakawa-Global 2000.

The earliest version of QPM was a maize mutation discovered in the 1960s called opaque-2. It displayed greatly elevated levels of the amino acids lysine and tryptophan, which are required for the production of complete proteins. Opaque-2 has almost twice the overall available protein of its conventional counterparts. Early attempts to introduce opaque-2 to resource poor farmers, however, were unsuccessful, mainly because of its low yield, high susceptibility to pests, and high rates of storage loss. The pest and storage problems resulted largely from opaque-2's very soft kernel. Scientists at CIMMYT and elsewhere eventually overcame these shortcomings by producing opaque-2 varieties with greatly increased yield potential and much harder kernels. In addition, the new varieties are virtually indistinguishable from conventional improved varieties without special testing. With these advances came a new name—quality protein maize.

Quality protein maize can increase protein availability in regions where maize consumption is high and better sources of protein are unobtainable. Often, as populations grow and more land is dedicated to cash or cereal crops, alternative sources of protein become scarce or inaccessible. Traditional diets that once satisfied basic nutritional needs are lost. Furthermore, reports indicate that consumption of fruits and vegetables has dropped among many populations. Lower protein consumption has also been observed in parts of the world where pulse consumption has decreased without being replaced by another protein source. Women and children are usually hit the hardest because they make up the vast majority of people living in poverty. In addition, women have an increased need for protein during pregnancy and lactation, while small children have difficulty meeting their protein requirements during periods of weaning and recovery from illnesses. Although QPM cannot fulfill all their nutritional needs, it can fill the gap when protein needs are especially high and are not being met with available diets. Essentially, QPM can serve as a fortification program within their normal nutritional regime.

Quality protein maize can also play an important role in providing inexpensive, improved animal feed. Unlike multiple ruminant animals (i.e., cattle, sheep, and goats), monogastric animals such as pigs and poultry require more complete protein than cereals like conventional maize can provide on their own. In response to the dearth of lysine and tryptophan in maize, livestock feeds are usually supplemented with soybeans, pulses, or commercially produced synthetic amino acids. Quality protein maize presents another option. It has been successfully introduced into Brazil and China for use as livestock feed, with 200,000 hectares now being grown in the latter principally for this purpose.

Estimated area ('000 ha) planted with QPM hybrids and varieties, 2000-2003

Country	2000	2003
Mexico	160	2,500
El Salvador	5	120
Guatemala	3	100
Nicaragua	Release	25
Columbia	Release	50
Venezuela	Release	100
Peru	Release	50
Brazil	50	50
Ghana	100	100
Ethiopia	Release	
China	200	400
India	Release	
Vietnam	Release	
Total	518	3,495

Source: CIMMYT Maize Program, July, 2000 (H. Cordova).

Perhaps most important to some of the world's poorest farmers and communities, the public sector will continue to be the sole source of research and technology supply for geographic areas that the private sector considers unprofitable. These include areas that are predominantly subsistence oriented, that have low market potential, or are marginal in terms of crop productivity, e.g., the drought prone environments. Globally, one may expect private sector involvement to be relatively low in sub-Saharan Africa and parts of South Asia and Central America.

The Private Sector Role

Private sector investments aimed at developing maize hybrids (and varieties in some instances) for developing countries will increase, particularly in areas where secure profits can be anticipated. A greater research emphasis on tropical maize production systems is also envisioned. Private sector activity in Latin America and Southeast Asia surely serves as an early indicator of this trend (see Part 2 for a detailed assessment of the maize private sector in developing countries).

The private sector will continue to be the predominant player in genomics and biotechnology—both in terms of investment and as a source of technology and bioinformation. Through consortiums and alliances, these resources will be made available to national and multinational companies in the developing world.

Following on the heels of transgenic maize, the private sector promises to provide maize cultivars that tolerate or resist a wide range of stresses and that offer improved nutritional quality. This could broaden the range of environmental conditions under which maize can be grown and increase its productivity and stability. However, maize farmers and consumers in the developing world have yet to reap the full benefits of these technologies (e.g., Bt maize), as the private sector has moved cautiously and slowly in extending these technologies to the developing world. There are several reasons for this, including inadequate IPR protection, the inability of farmers to afford the product, and biosafety concerns.

The fast growing fields of genomics and proteomics are also dominated by the private sector. These research areas will allow scientists to identify and study a multitude of individual genes, how they interact, and their expression under diverse environmental conditions. In addition, the discovery of syntenies among species promises to revolutionize plant breeding by allowing scientists to capitalize on the basic similarity across all cereal genomes to quickly apply advances in one species to all of the others. Coupled with the ability to transfer genes of interest through genetic engineering, advances in these fields will undoubtedly change the pace and scope of agricultural research and development.

The Public and Private Sector Working Together

Mutual Advantages

There are mutual advantages in the public and private sectors working together to maximize benefits to society. Public/private sector alliances would help narrow the science and technology gap between the rich and poor nations and also help deliver new technologies to farmers' fields. There is a clear advantage for the private sector to participate in such ventures: successful endeavors would accelerate the progress of subsistence societies along the path of commercialization, thereby increasing their client base. The public sector would benefit through easier access to technologies available through the private sector and also access to the private sector's more sophisticated networks and techniques for technology dissemination.

At the research level, the relative strengths of the private sector in biotechnology and genomics, and the public sector in germplasm (especially information and expertise related to desirable traits and germplasm improvement for developing countries) provide a strong basis and considerable impetus for the creation of alliances.

In subsistence maize production areas (particularly the tropical lowlands in sub-Saharan Africa, South Asia, and Central America, and the tropical highlands), the public sector will continue to be the leading source of technology supply, although the need for private sector support will increasingly emerge. Private and public sector alliances could promote spillover of research results from high potential to low potential environments and from economically advanced to economically deprived areas. Private sector innovations from more favored areas could be shared with (or licensed to) the public sector for use in less favored areas. Such arrangements could provide an opportunity for the private sector to contribute to the social good and also promote the long-term commercialization of the less-favored subsistence environments.

In the high-potential commercial maize producing areas, the public sector can actively complement the activities of the private sector. Prebreeding research and the provision of source germplasm would reduce the cost of private sector development of hybrids suited to particular ecological and geographic niches. Public sector research aimed at developing maize with improved tolerances and resistances to abiotic and biotic stresses for low-potential agro-ecological zones could also provide considerable benefits for the high-potential environments. Similarly, the public sector could play a crucial complementary role to the private sector in developing appropriate crop and resource management technologies for the high-potential environments. Indeed, it would be mutually beneficial for the private sector to fund such efforts.

Genetic Improvement

Several areas of genetic improvement, of interest to both the public and private sectors, do not require the proprietary protection associated with genetic engineering. Strategic alliances in these areas would be enormously beneficial to both parties. A case in point is the development of early maturing maize varieties and hybrids that accommodate the intensive cropping systems of the Asian lowland tropics. The private sector is particularly keen to develop hybrids for the lowlands of Southeast Asia for the feed market, while the public sector is interested in OPVs with similar characteristics that could be used in South Asia to enhance food supplies and food security. The public and private sectors could also play mutually supportive roles in the development of maize that is resistant to diseases and pests such as downy mildew (Asia) and corn stunt and fall armyworm (Latin America).

Crop/Resource Management

Public/private sector alliances are also possible in the realm of crop and resource management technologies. Very successful partnerships have been documented between the two sectors in the development and promotion of zero tillage systems in Argentina and Brazil (Ekboir 2000a; Ekboir and Parellada 2000). Public sector interest in promoting sustainable land use, together with private sector interest in promoting RoundUp™, an effective and inexpensive herbicide (also relatively benign in terms of human health), gave rise to a partnership that by 1999 resulted in the adoption of zero tillage on seven million hectares of land in Argentina and 20 million hectares in Brazil. Clearly, it would be constructive to explore similar win-win alliances in other ecologies and geographic areas.

Priorities for Public Research and Technology Development

Based on the preceding discussions about the current and future roles of the public and the private sector, and on technology priorities, the following priorities were derived for public sector maize research. Although the focus is on the international public sector (primarily the IARCs), some of these priorities may also apply to national public sectors (e.g., NARSs).

Priorities by Region and Maize Ecology

- Sub-Saharan Africa and South Asia should garner more research emphasis and investments than the other maize growing regions. In these two regions we find the highest concentrations of poor facing critical food security problems, while at the same time, alternative sources of technology supply are very limited.
- Lowland tropical maize growing environments should receive the highest priority and highest share of public maize research resources. Emphasis should be given to lowland areas that are poorly served by the private sector: sub-Saharan Africa, South Asia, and Central America. Research to enhance maize productivity in the midaltitude and subtropical environments should concentrate on sub-Saharan Africa.
- A modest effort should be directed to highland maize research targeted to the highlands of Mexico and other Latin American countries. Spillovers from this research would benefit similar agro-ecologies, particularly in the Himalayan region.

Technological Priorities

- From a global perspective, the highest priority for public sector maize improvement research should be the identification and development of technologies that help alleviate the constraints of water stress (drought) and low soil fertility. To achieve maximum impact, a holistic approach should be employed that incorporates genetic as well as crop and resource management approaches.
- High levels of public sector investments are needed (over the 5–10 year planning horizon) for crop improvement through conventional breeding methods coupled with marker-assisted selection (MAS). Significant advances in tolerance/resistance to biotic and abiotic stresses can be anticipated beyond this time period through the exploitation of genomics.
- The development of N-use efficient maize should be an important priority for the public sector within the context of an integrated management approach. Proper management should include the efficient use of chemical and organic fertilizers, crop rotations, and agronomic practices

that enhance fertilizer responsiveness (e.g., timely fertilizer applications, weeding, and appropriate land management practices).

- Arresting soil erosion should be the top resource management priority for the public sector, with a particular emphasis on the development and deployment of conservation or zero tillage technologies.
- The public sector should develop methods and systems that control maize insects and diseases in an integrated and sustainable approach that combines germplasm improvement with modifications in farmers' knowledge, attitudes, and pest control practices.
- For the lowland tropics of Asia, priority should be given to the development of early maturing maize that conforms to the requirements of intensive multicrop systems.
- Development of acid tolerant maize cultivars should be given a high priority for the lowlands of Latin America.
- Managing *Striga* infestations in African maize production systems, in a cost-effective and environmentally benign manner, should be among the top priorities for pest management research and technology development for tropical Africa.
- Finally, research on identifying the socioeconomic and institutional factors that limit technology adoption is absolutely crucial for enhancing farm household food security and increasing national maize supplies in developing countries.

Maize Research and Development of Partnerships at CIMMYT

When looking ahead and planning future technology development activities, those in the public sector, specifically IARCs such as CIMMYT, must consider our role relative to other players in the field and seek mutually beneficial partnerships with them. Because the task at hand is enormous, effective technology development requires partnerships with the custodians of advanced scientific techniques and technologies; these include scientific laboratories of the developed world, the multinational private sector, practitioners of adaptive research, NARSs, and the NGO community. We picture the international public sector, through centers such as CIMMYT, fulfilling its mission by engaging in a range of activities and partnerships during the next decade:

- IARCs, specifically CIMMYT, will continue to play a global leadership role and act as a central supplier in the areas of maize germplasm conservation and characterization, prebreeding, and trait development, particularly for developing countries.
- International research on maize should be organized around regional hubs. Research would be conducted on particular constraints and the results disseminated to other regions. For example, drought tolerant germplasm developed at CIMMYT-Zimbabwe could be transferred to other regions facing similar types of water stress.
- Collaboration with the NARSs should be strengthened to foster the development of improved maize germplasm (both OPVs and hybrids) targeted toward the less advantaged environments and societies.
- The development of hybrids for the commercial maize-producing environments can be relinquished to the private sector, but the public sector, specifically the international public sector, will continue to develop inbred lines that can be used by the private sector—particularly small national private sectors.
- Those involved with public sector maize research should actively pursue collaborative arrangements with the multinational private sector and advanced laboratories in developed countries in order to gain timely access to advances in genomics and genetic engineering.
- The international public sector should act as a conduit for the transfer of biotechnology tools and technologies from the advanced country laboratories and the multinational private sector to the NARSs, especially for countries with low biotechnology research capacity.
- The IARCs could help developing country maize programs in contractual arrangements needed for accessing patented technologies and information to help meet the needs of poor subsistence farming households.
- While the development of site-specific crop and resource management technologies is largely a responsibility of the NARSs, IARCs could participate in the process by facilitating the transfer of knowledge and methods.
- The transfer of improved seed and other technologies to the subsistence maize-production sector continues to be a challenge that calls for enhanced partnerships between IARCs, NARSs, NGOs, and local (small) private sectors.
- The IARCs in association with the NGO community should foster farmer involvement in technology design, development, and dissemination, particularly in subsistence maize-production systems.