

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: <ul style="list-style-type: none"> 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: <ul style="list-style-type: none"> .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 infertility
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 infertility
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 turicum 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 <i>Striga</i> (21)	Soil acidity Drought Fall armyworm Stunt <i>Borers</i> (24)
Midaltitudes	Turicum blight <i>Drought</i> (22,23) High temperatures (31) <i>Borers</i> (32, 33)	Drought Soil infertility Weevils Gray leaf spot Streak virus <i>Borers</i> (28)	<i>Soil erosion</i> (36) <i>Turicum blight</i> (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 [ASI⁴]). 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 pyriithiobac 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 pyriithiobac, 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 synteny 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., NARs).

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.