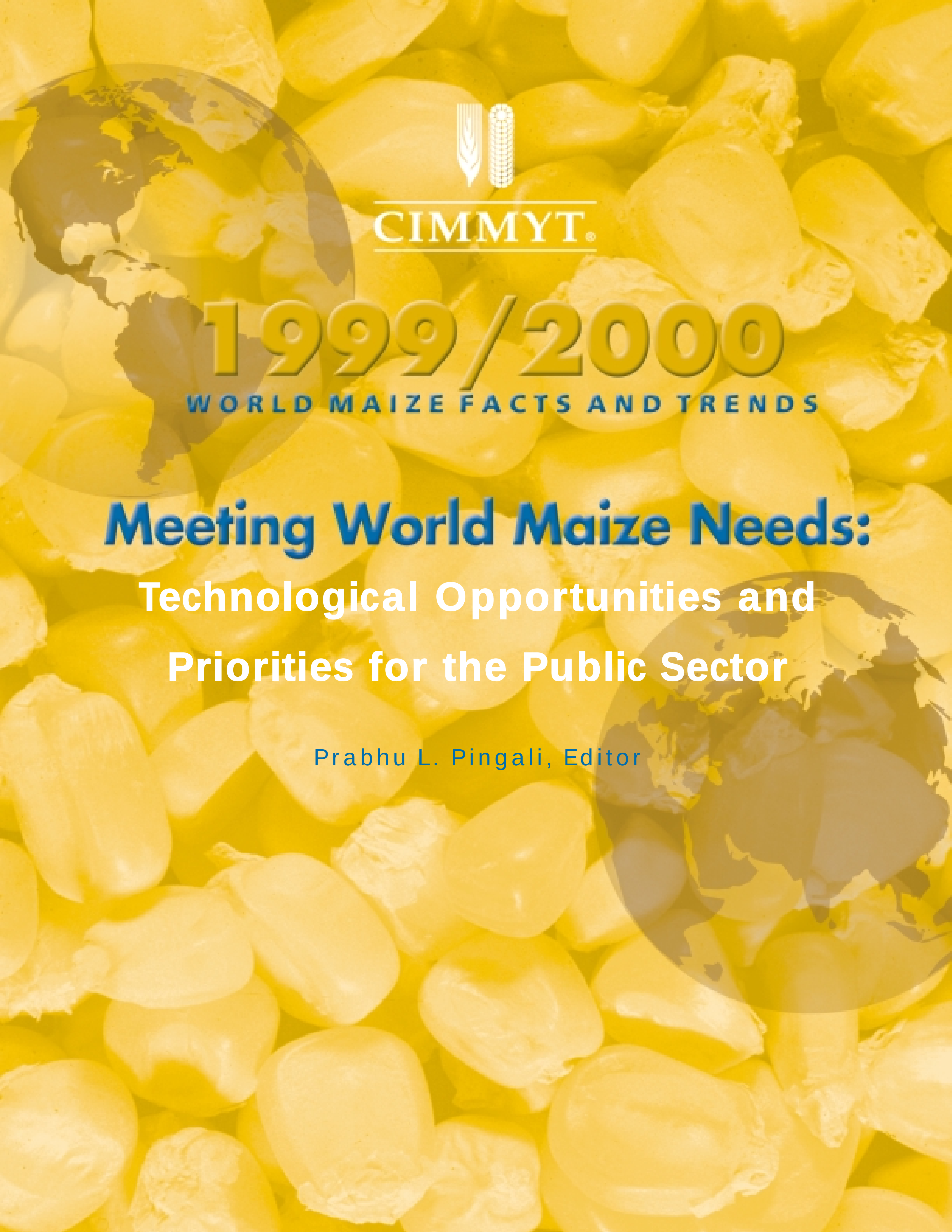

CIMMYT

1999/2000

WORLD MAIZE FACTS AND TRENDS

Meeting World Maize Needs:

Technological Opportunities and Priorities for the Public Sector

Prabhu L. Pingali, Editor

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

Future Harvest® builds awareness and support for food and environmental research for a world with less poverty, a healthier human family, well-nourished children, and a better environment. It supports research, promotes partnerships, and sponsors projects that bring the results of research to rural communities, farmers, and families in Africa, Asia, and Latin America (www.futureharvest.org).

Printed in Mexico.

Correct citation: Pingali, P.L. (ed.). 2001. *CIMMYT 1999–2000 World Maize Facts and Trends. Meeting World Maize Needs: Technological Opportunities and Priorities for the Public Sector.* Mexico, D.F.: CIMMYT

Abstract: This report has four parts. Part 1 focuses on the role international agricultural research institutions should play in meeting the rapid growth in maize demand that is anticipated during the next 20 years. Constraints to maize production in the developing world are prioritized globally and by region, including factors such as levels of poverty and subsistence farming. Technological responses to the constraints are outlined and another prioritization exercise is conducted to determine where and in which technologies public sector research investments would make the most impact. Respective roles of the public and private sectors' maize research efforts are delineated, as are areas for collaboration. Part 2 of the report presents an overview of CIMMYT's Global Maize Impacts Study, wherein the contributions of public and private sector maize breeding are assessed in terms of impact in the developing world. Part 3 discusses future trends in maize production and trade with particular emphasis on the United States, the MERCOSUR countries, and China. Part 4 presents statistics on world maize production and consumption.

ISSN: 0257-8743

AGROVOC descriptors: Zea mays; Maize; Seed production; Plant production; Production economics; Socioeconomic environment; Production policies; Economic development; Production factors; Environmental factors; Technological changes; Innovation adoption; Injurious factors; Drought; Drought resistance; Soil deficiencies; Soil deterioration; Insects; Plant diseases; Biological control; Disease control; Research projects; Research policies; Research support; Resource allocation; Trade policies; Prices; Food production; Food consumption; Statistical data; Less favored areas; Public sector; Developing countries

Additional key words: CIMMYT

AGRIS category codes: E16 Production Economics

E14 Development Economics and Policies

E10 Agricultural Economics and Policies

Dewey decimal classification: 338.14

CIMMYT®

1999-2000
WORLD MAIZE FACTS AND TRENDS

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

P.L. Pingali, Editor

Acknowledgments

This report was a collaborative effort of CIMMYT's Economics and Maize Programs and has benefited greatly from contributors both within and outside of CIMMYT.

For their contributions to the respective parts of this report, I would like to thank David Bergvinson, Miguel López-Pereira, Mulugetta Mekuria, Wilfred Mwangi, Rashid Hassan, and Roberta Gerpacio. Research assistance was provided by Pedro Aquino, Federico Carrión, Ricardo Calvo, and Dagoberto Flores. Clerical and logistical support were provided by Beatriz Rojon and Janin Trinidad.

It would have been impossible to produce this *Facts and Trends* without detailed information about research and production from researchers around the world. I acknowledge the contributions of K. Adhikari, Luis A. Arriola, Dr. Mohammad Aslam, Djafar Baco, Nacib Barboza, J Bolhuis, Samuel R. Cabrera P, Salomé Salinas Carmona, David Moreira Chiong, John Claffey, Jorge A Correa, Antonio J. Cristiani B. Sergio Dávila, Hugo De Groote, Miloje Denic, J. Du Plessis, Hector G. Duque V., M.C. José Luis Gutiérrez Esquivel, George Evgenidis, Carlos René Félix Fregoso, Randolfo A. Funez, Marco A. Neciosup Gallardo, Tendai Gatsi, I. Juan Gear, Cesar Ruiz Gomez, Ramiro Urrea Gómez, Pedro Melvin Torres Granados, Daniel Loor Holguín, Gustavo Villegas Ibañez, Krishibid Jabed Iqbal, Tito Claure Iriarte, J.H. Jager, Guilherme Andrade Junqueira, Denis T. Kyetere, Jorge Millones Liza, Verónica Machado, Eliassaint Magloire, Ricardo Magnavaca, Dr. Tayssir Mansour, José Heberth Arango Marin, Carlos Enrique Méndez, Marcos Mendoza B., Moises Mendoza, Eduardo Mogrovejo J., Mario Motto, Robert Munthalt, Danilo Salamanca Murillo, Victor Noriega Narvarte, Francisco Navarro, Abdellatif Mubarek Nour, Marcio de Camargo Pala, Leonel E. Pinto M., Kamal Poudel, Dr. John L Purchase, Rafael Padilla Ramírez, Jesús Salvador Sotomayor Rivera, Juan Capa Robles, Mario Rodríguez, Abbas Saidi, Juan Fco. Salas G., Artemio M. Salazar, Alejandro Castellanos Sánchez, IGP. Sarasuiha, Cesar Augusto Moyano Sesquen, Dr. Benchaphun Shinawatra-Ekasingh, Guillermo Simone, Dr. N.N. Singh, Otavio Briganti Solferini, Anselmo Pérez Tabares, Clotiste Tesara, Elio B. Rodríguez Tireo, Tran Hong Uy, Mario Abel García Vázquez, René Velásquez, Shihuang Zhang, and Chen Zong-Long.

This report was edited by David Poland and designed by Eliot Sánchez Pineda. Miguel Mellado directed overall production and printing. I am grateful for their assistance.

Contents

Foreword

As we enter the new millennium, the pace and magnitude of change in the world around us continues to rapidly grow. No region of the world, no economic sector, no global problem of note, and—of concern to CIMMYT—no food crop is excluded from the grand transformation taking place before us. Much of what lies on the horizon gives cause for great concern. During this century the earth will be called upon to support billions more people and do it with essentially the same amount of arable land. Crushing poverty, falling largely onto the backs of women and children in the developing nations, remains a persistent, at times intractable problem. And the gap between the *haves* and the *have-nots,* the North and the South, still threatens global stability and calls out to our collective conscience for action.

At the same time, we are witnessing considerable progress on some fronts and the arrival of what were once considered futuristic possibilities. A plateau in population growth is projected, income levels in parts of the developing world, particularly Asia, are up, and the liberalization of markets and economies has brought new energy and initiative to the forces of progress in many corners of the world. For those in the international agricultural research community, the emergence of revolutionary technologies, nearly instantaneous communications, and a new era of partnerships and collaborations have brought fresh vigor as well as challenges to our work.

As seen in this *Facts and Trends*, these global trends also extend to maize demand and production. Ample trials and opportunities are afforded by the currents of change. Making the *right* strategic decisions and putting our effort where it will yield the most headway are key to riding them well. This, in essence, is the focus of Part 1 of this report. Demand for maize in developing countries is projected to surpass both wheat and rice by 2020, meaning that maize supplies for those areas must nearly double. Given the funding and logistical constraints faced by public sector agricultural research organizations, how do we meet this rising demand? Part 1 reviews and prioritizes critical constraints and appropriate technological solutions, while factoring in measures for impact on poverty, on those living in subsistence agricultural areas, and the probability of technology adoption. Following the identification of these areas of need, the authors delineate who might best respond to them—the public sector, private sector, or both working together. In conclusion, Part 1 provides a concise list of priorities for public sector research, and CIMMYT research in particular, by region and maize ecology and by technological options.

Part 2 provides a synopsis of CIMMYT's latest study on the global impacts of international maize breeding research. Data generated by CIMMYT's work on global maize impacts have come to be recognized as definitive and have been widely used to inform research investment and research management decision-making. The study found that use of CIMMYT germplasm by both public and private sector breeding programs has been extensive. Of all publicly bred maize varieties released between 1966 and 1998, 53% contained CIMMYT germplasm. During the most recent period, 65% of all public sector varietal releases contained CIMMYT germplasm (72% when temperate materials are excluded). Use of CIMMYT germplasm by private breeding programs has also been substantial. Of all private sector maize varieties sold during the late 1990s, 58% contained CIMMYT germplasm, though the proportion varied greatly by region.

In Part 3, CIMMYT economists take a look at current and future trends in maize demand, production, and trade, focusing on the major players in this arena: the United States, the South American countries in the MERCOSUR trading alliance, and Asia, with emphasis given to China. The authors examine future trade scenarios and the complex interaction of many factors, including domestic production environments and utilization trends, domestic and international trade policies, exchange rates, commodity prices, population growth, and rates of income growth.

As usual, this edition concludes with a very informative set of regional and national consumption and production statistics, as well as statistics on CIMMYT's tropical and subtropical varieties grown under experimental conditions.

I trust that this latest *Facts and Trends*, like its predecessors, will make a positive contribution to the debate over research strategies and directions and illuminate how, working together with a full range of partners, we can best serve the interests of maize farmers and consumers throughout the developing world.

Timothy Reeves

Timothy Reeves
Director General

Part 1

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

Prabhu L. Pingali and Shivaji Pandey

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.

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.

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 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.

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).

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.

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.

Part 2

Assessing the Benefits of International Maize Breeding Research: An Overview of the Global Maize Impacts Study

Michael L. Morris

Introduction

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

Efforts to update and extend CIMMYT's maize impacts database were initiated in 1997. Given the enormity of the data collection task, the global study was divided into three regional studies—one each for Latin America, eastern and southern Africa, and Asia (see Morris and López-Pereira 1999; Hassan et al. 2001; Gerpacio 2001). The specific objectives of the follow-up study were to

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

Information for the follow-up study was collected through a survey of maize breeding organizations in 37 developing countries (Table 1). Questionnaires were completed by the directors of 104 public breeding institutes and seed production agencies and by representatives of 267 private seed companies. In terms of geographical coverage, the survey concentrated on countries targeted by the CIMMYT Maize Program. All of the important maize-producing regions in the developing world were included, except for West and Central Africa (where the CGIAR mandate for maize genetic improvement is held by CIMMYT's sister institute, IITA), northern China (where farmers grow mainly temperate materials that are not targeted by CIMMYT), and West Asia and North Africa (omitted for logistical reasons). Collectively, the countries included in the survey account for about 95% of the area planted to maize in nontemperate production environments of Latin America, eastern and southern Africa, and Asia.[1]

Table 1. Countries participating in the CIMMYT maize research impacts survey

Latin America	East and Southern Africa	East, South, and Southeast Asia
Caribbean	*East Africa*	*East Asia*
Cuba	Ethiopia	China
Dominican Republic	Kenya	
Haiti	Tanzania	*South Asia*
	Uganda	India
Mexico & Central America	*Southern Africa*	Nepal
Costa Rica	Angola	*Southeast Asia*
El Salvador	Lesotho	Indonesia
Guatemala	Malawi	Philippines
Honduras	Mozambique	Thailand
Mexico	South Africa	Vietnam
Nicaragua	Swaziland	
Panama	Zambia	
	Zimbabwe	
Andean Zone		
Bolivia		
Columbia		
Ecuador		
Peru		
Venezuela		
Southern Cone		
Argentina		
Brazil		
Paraguay		

Source: CIMMYT maize research impacts survey.

---

[1] In China, the survey covered only the five southern provinces in which maize is grown in nontemperate production environments (Guangxi, Guizhou, Hunan, Sichuan, and Yunnan).

Why Maize is Different from Other Crops

Distinctive Characteristics of Maize

Maize differs from other crops in a number of respects that affect the way international breeding efforts are organized and the process by which modern varieties[2] are taken up by farmers and diffused across the countryside. Before assessing the impacts of international breeding efforts, it is important to understand the characteristics of maize that differentiate it from other crops.

Open Pollination

Maize is an open pollinating crop, unlike other leading cereals such as wheat and rice, which are self-pollinating. When self-pollinating crops reproduce, the pollen that fertilizes a given ovary to produce a viable seed almost always comes from a stamen of the same plant. Because the plant fertilizes itself, each generation of plants retains the essential genetic identity of the preceding generation. By contrast, when maize reproduces, genetic material is exchanged between neighboring plants. Consequently, unless pollination is carefully controlled, all of the maize plants in a given field will differ from the preceding generation and from each other.

Importance of Hybrid Vigor

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

Multiple End Uses

No other cereal can be used in as many ways as maize. Virtually every part of the maize plant has economic value, including the grain, the leaves, the stalks, the tassels, and in some cases, even the roots. In view of the multiple end uses, it is not surprising that farmers grow thousands of varieties featuring unique combinations of desirable traits. Although many crops are genetically diverse, maize is notable for the extent to which genetic diversity is actively managed at the household level. In developing countries, it is not uncommon to find the same household growing three, four, or even more distinct maize varieties, each carefully selected to satisfy a specific food, feed, or industrial use.

Variability of Maize Production Environments

Maize is the world's most widely grown cereal. It is cultivated at latitudes ranging from the equator to approximately 50° North and South, at altitudes ranging from sea level to more than 3,000 m elevation. It is grown in extremely cool, moderate, and very hot climates, under moisture regimes ranging from extremely wet to semiarid, on flat terrain as well as precipitously steep hillsides, in many different types of soil, and using a profusion of production technologies.

Implications for Breeding Research

The distinctive characteristics of maize have important implications for crop genetic improvement efforts.

Farmer Breeding

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

Emphasis on Hybrids

The distinctive biological characteristics of maize have not only encouraged farm-level breeding activity, but they have also had an important influence on institutional breeding efforts. Because the physical separation of the male and female flowers in maize makes controlled cross-pollination relatively easy, and because hybrid vigor in maize is so pronounced, formal maize improvement programs have concentrated almost exclusively on development of hybrids. This approach to achieving genetic gains

---

[2] Throughout this report, the term *varieties* is used in a generic sense to refer to both open pollinated varieties of maize as well as hybrids. The term *modern varieties* is used to refer to open pollinated varieties and hybrids that have been improved by a formal breeding program.

makes sense from both a scientific and an economic point of view. Since hybrids are a much more attractive business proposition than open pollinated varieties (OPVs), a great deal of formal maize breeding work has been conducted by profit-oriented companies.

Location Specificity of Improved Germplasm

Most of the maize produced in the industrialized world is grown in temperate environments, while in developing countries, most of the maize is grown in nontemperate environments. This fact has important implications for the flow of improved technology. Maize germplasm that performs well in temperate regions generally cannot be introduced into nontemperate regions without undergoing extensive local adaptation. This means that unlike most other major food crops, modern varieties of maize developed for use in the United States, Western Europe, and northern China offer little direct benefit to developing countries.

Implications for Germplasm Diffusion

The distinctive characteristics of maize heavily influence breeding efforts and also have important implications for the dissemination of improved germplasm.

Critical Importance of Seed

With maize more than with any other crop, the dissemination of improved germplasm is critically dependent on the timely availability and affordability of high quality seed. Because the genetic composition of maize plants grown from farm-saved seed can change considerably from generation to generation, farmers must purchase fresh seed for each cropping cycle if they wish to maintain a high level of genetic purity.

Need for an Effective Seed Industry

Since it is too costly and technically difficult for farmers to produce genetically pure maize seed, the fact that fresh seed must be acquired for each cropping cycle means that modern varieties can disseminate only with the support of a viable seed industry. This can present a bottleneck, particularly in developing countries, because many subsistence-oriented farmers have been neglected by the seed industry, which tends to focus on more lucrative markets. Thus all farmers do not have reliable access to sufficient quantities of high quality seed.

Investment in Maize Breeding Research

International Agricultural Research Centers

Maize genetic improvement is carried out at two of the 16 international agricultural research centers (IARCs) that are members of the Consultative Group for International Agricultural Research. CIMMYT, headquartered in Mexico, holds a global mandate for maize improvement research and targets lowland tropical, subtropical, midaltitude, and tropical highland environments throughout the developing world. Nigeria-based IITA holds a regional mandate for maize improvement research and targets mainly humid tropical zones of western and central Africa.

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

Public National Breeding Programs

Public national breeding programs are major players in the global maize breeding industry, supporting nearly 1,000 senior breeders worldwide (Table 2). These breeders are fairly evenly distributed across all developing regions, with the exception of China, which claims a disproportionately large share.[3] The organization of public breeding programs, however, varies considerably by region. Public breeding activities in Latin America and Asia are generally more decentralized, with larger numbers of relatively small breeding programs, whereas in eastern and southern Africa they are generally more centralized, with fewer but larger breeding programs.

Regional differences also are evident in the intensity of public investment in maize research. Controlling for the size of the maize sector, the number of publicly supported maize breeders is much higher in Asia than in other regions, presumably reflecting the relatively low cost of

---

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

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

	Number of countries surveyed	Public maize breeding programs	Maize scientists (FTEs)	Maize scientists per program	Maize scientists per million ha maize area	Maize scientists per million t maize production
Latin America	18	49	290	5.9	10.2	4.2
Eastern and Southern Africa	12	4	109	27.3	7.6	4.1
East, South, and Southeast Asia[a]	7	116	505	4.4	26.3	11.0
All regions	37	169	904	5.3	14.6	6.4

Source: CIMMY maize research impacts survey.
FTEs = full-time equivalents.
[a] Excludes northern China.

human capital in Asia. Interestingly, both of the research intensity indicators (breeders/million hectares planted to maize, breeders/million tons of maize production) have decreased since the first CIMMYT global impacts study was conducted, indicating that public investment in maize breeding declined during the 1990s.

Private Seed Companies

The private sector has become a major player in the maize breeding industries of most developing countries, employing more than 400 senior breeders worldwide (Table 3). Nearly 60% of them are employed by multinational companies, a marked increase from earlier years when most maize breeding work was still being carried out by national companies. In contrast with the public sector, however, private sector breeding capacity is not distributed evenly throughout the developing world. Latin America and Asia (with the exception of China) support a large number of private seed companies, reflecting the presence in those regions of important commercial maize sectors and also a friendlier business climate. Private seed companies are much less common in eastern and southern Africa, reflecting the relative scarcity in these regions of commercial maize sectors, as well as generally more challenging business environments.

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

Products of Maize Breeding Research

The principal output of maize breeding programs is improved germplasm, so varietal releases represent one obvious productivity measure. CIMMYT maintains two varietal release databases—one for varieties developed by public breeding programs and one for varieties developed by private seed companies. The temporal coverage of these two databases is slightly different. The public sector varietal release database contains information about approximately 1,250 varieties and hybrids released since the mid-1950s by public breeding programs in the 37 developing countries that participated in the CIMMYT survey.[4] The private sector varietal release database contains information about approximately 1,025

---

[4] Here the discussion relates only to varieties released since 1966, the year in which CIMMYT was officially established.

Table 3. Private sector maize research investment indicators, developing countries, late 1990s

	Number of countries surveyed	Private seed companies with breeding programs		Private sector maize researchers		Maize scientists per million ha maize area	Maize scientists per million t maize production
		National	Multinational	National	Multinational		
Latin America	18	65	27	101	109	7.4	3.1
Eastern and Southern Africa	12	10	2	10	35	3.1	1.7
East, South, and Southeast Asia[a]	7	24	22	64	96	8.3	3.5
All regions	37	99	51	174	240	6.7	3.0

Source: CIMMY maize research impacts survey.
[a] Excludes northern China.

varieties that were sold by private seed companies during the late 1990s in the same 37 countries. Unlike the case of the public sector, with the private sector it was not possible to compile a complete list of all varieties developed since 1966, the year CIMMYT was established. Private seed companies therefore were asked to provide information only about varieties they were currently selling. In most instances, these consisted of relatively recent hybrids developed during the 1990s.

Public Sector Releases

Public maize breeding programs have been very productive, developing and releasing a steady stream of modern varieties (Figure 1). On aggregate, the rate at which varieties are released has grown steadily through time and shows no sign of slowing. Assuming that varietal testing and release procedures have not changed, this suggests that public maize breeding programs have not suffered any significant decline in productivity.

Since 1966, public maize breeding programs in developing countries have developed and released nearly twice as many OPVs as hybrids, reflecting the traditional emphasis in the public sector on breeding open pollinated materials. However, the ratio of OPVs to hybrids has changed through time in response to changes in the prevailing philosophy about the suitability of hybrid technologies for small-scale farmers. The proportion of hybrids among public sector releases increased sharply during the 1990s, and during the most recent period (1996–98), hybrids actually outnumbered OPVs by a slight margin.

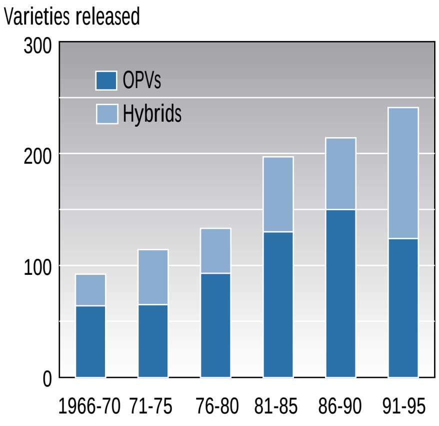

Figure 1. Public sector maize varietal releases, 1966–95.

Source: CIMMYT global maize impacts survey.

To what extent have public maize breeding programs in developing countries made use of CIMMYT germplasm? This question is not easy to answer because it is difficult to track the use of CIMMYT germplasm for at least three reasons:

1) Defining “CIMMYT germplasm” is often problematic. Modern maize breeding is truly international, and today most breeders routinely work with source materials obtained from all over the world. Screening and evaluation require a great deal of teamwork because materials must be evaluated in multiple locations. In this context, it is not always clear how credit for the breeding effort should be attributed, so the definition of “CIMMYT germplasm” becomes very blurry.

2) Breeders who use CIMMYT source materials themselves may not know exactly how much CIMMYT germplasm is actually present in a finished cultivar. Modern maize improvement methods typically involve repeated cycles of selfing, crossing, and backcrossing. Selection strategies vary widely and frequently change. Because of the complex and frequently ad hoc nature of the breeding process, the precise genetic composition of finished varieties cannot be known with certainty. Even if the source materials can be identified, their relative contribution may be unknown.

3) Even when breeders know how much CIMMYT germplasm is present in a finished variety, they may not be willing to reveal this information. Most commercial maize varieties now have closed pedigrees, meaning that information about their genetic background is not publicly available. Breeding programs, especially commercial programs that respond to economic incentives, have an interest in keeping pedigrees closed, because once the genetic background of a variety becomes public knowledge, other breeders will be able to copy the variety. In the past, public breeding programs were rarely concerned with earning profits from sales of their germplasm products, so they were usually willing to provide pedigree information. More recently, the situation has changed. With the strengthening of IPR, many public breeding programs have adopted closed-pedigree policies.

Despite these complicating factors, a robust effort was made to document the use of CIMMYT germplasm. Survey respondents were asked whether the varieties developed by their respective breeding programs had used CIMMYT source materials, defined as materials that had been improved by the CIMMYT Maize Program. Materials that may have been obtained from the CIMMYT gene bank but that had not been selected by CIMMYT breeders were thus excluded.

Use of CIMMYT germplasm by public breeding programs has been extensive (Figure 2). Of all publicly bred maize varieties released from 1966 to 1998, more than one-half (53%) contained CIMMYT germplasm. Excluding varieties adapted for temperate environments (which are not targeted by CIMMYT maize breeders), the proportion containing CIMMYT germplasm was even higher (58%). The use of CIMMYT germplasm by public breeding programs has increased through time. During the most recent period, 65% of all public sector varietal releases contained CIMMYT germplasm (72% when temperate materials are excluded). Belying predictions that CIMMYT's role would decline as national programs gained in strength, the CIMMYT Maize Program continues to represent an important source of breeding materials for public breeding programs.

Private Sector Releases

Since the private sector varietal releases database contains only information about varieties sold during the late 1990s, it cannot be used to draw conclusions about the past productivity of private breeding programs. But while the historical coverage may be incomplete, the regional variability in the data is striking. During the late 1990s, many more proprietary varieties were sold in Latin America and Asia compared to eastern and southern Africa. This suggests that eastern and southern Africa has attracted less attention from the private sector than the two other regions. As expected, private breeding programs have focused almost exclusively on developing hybrids, which accounted for fully 98% of all proprietary materials sold during the late 1990s.

Use of CIMMYT germplasm by private breeding programs has been substantial. Of all private sector maize varieties sold during the late 1990s, 58% contained CIMMYT germplasm. The proportion varied greatly by region, however. In Latin America, nearly three-quarters (73%) of all private sector varieties contained CIMMYT germplasm; excluding varieties adapted for temperate production environments, the proportion containing CIMMYT germplasm was an astonishing 89%. In other regions, use of CIMMYT germplasm by private companies was much more modest. In eastern and southern Africa, 21% of the varieties developed by private breeding programs contained CIMMYT germplasm; in Asia the figure was 19%.

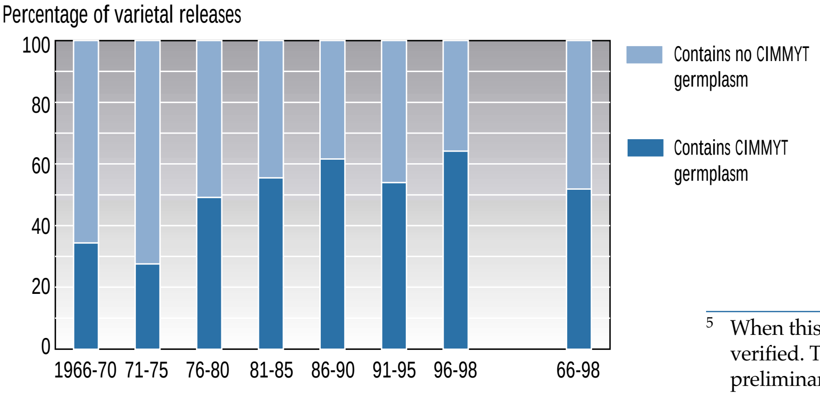

Figure 2. Use of CIMMYT germplasm by public breeding programs.
Source: CIMMYT global maize impacts survey.

Use of Modern Varieties by Farmers

The varietal release data attest to the productivity of maize breeding programs in developing countries and show that breeders, both in the public and private sectors, have made extensive use of CIMMYT germplasm. What the varietal release data do not reveal, however, is the extent to which farmers have taken up modern varieties. For that it is necessary to examine varietal adoption patterns. Because of the difficulties inherent in estimating the adoption of improved germplasm, we present two types of data that relate to the uptake of modern varieties[5]. First, we present information about commercial seed sales. Although seed sales do not provide a direct measure of the area planted to modern varieties, seed sales data nevertheless provide important information about the strength of the demand for modern varieties. Following that we turn to direct estimates of the area planted to improved OPVs and hybrids.

Sales of Commercial Maize Seed

Table 4 shows sales of commercial maize seed for 1996/97 reported by the public seed agencies and private companies that participated in the CIMMYT survey.[6] The seed sales data are noteworthy in four respects:

1) Maize seed is big business in the developing world; sales for the industry as a whole exceeded half a million tons in 1996/97.

---

[5] When this publication went to press, MV adoption data were still being verified. The results presented here should therefore be considered preliminary.

[6] Consistent with the rest of this report, the data for China include only the five southern provinces in which maize is grown in nontemperate production environments.

Table 4. Commercial maize seed sales, by type of seed and seed organization, 1996/97[a]

	Public sector			Private sector			Total		
	OPVs	Hybrids	Total	OPVs	Hybrids	Total	OPVs	Hybrids	Total
Latin America	4,700	4,500	9,200	14,400	280,700	295,100	19,100	285,200	304,300
East and Southern Africa	1,300	1,800	3,200	1,800	37,400	39,200	3,100	39,200	42,300
East, South, and Southeast Asia[b]	1,700	94,000	96,200	3,200	67,800	71,000	4,900	162,300	167,200
All regions	7,700	100,300	108,500	19,300	385,900	405,300	27,100	486,700	513,800

Source: CIMMYT maize impacts survey.

[a] Column totals may not sum exactly due to rounding error.

[b] Excludes northern China.

2) The size of the commercial maize seed industry varies tremendously between regions. Latin America represents by far the largest regional market, followed by East, South, and Southeast Asia, with East and Southern Africa trailing far behind.

3) With the significant exception of China, the maize seed industry has effectively been privatized; at the global level, private seed companies outsell public seed agencies by more than two to one (this ratio increases to nearly ten to one when China is excluded).

4) The market for maize seed is dominated by hybrids; in all three regions, sales of OPV seed account for less than 10% of the total market share.

Of all maize seed sold in 1996/97, one-quarter (25%) was seed of varieties developed and released by public breeding programs, and three-quarters (75%) was seed of varieties developed and released by private breeding programs. Publicly-bred varieties were popular in East and Southern Africa (accounting for 75% of all seed sales within these regions), whereas privately-bred varieties were highly favored in Latin America (accounting for 89% of all seed sales within the region). Use of public and private sector varieties was more evenly balanced in Asia, although variability within the region was great; most of the seed sold in China (also parts of India) was seed of public varieties, while most of the seed sold in other countries was seed of private varieties.

The seed sales data provide direct evidence that CIMMYT germplasm is being used extensively. Of all the commercial maize seed sold during 1996/97 in developing countries and whose parentage could be determined, 57% was seed of varieties developed using CIMMYT germplasm. Focusing more directly on environments targeted by the CIMMYT Maize Program, of all commercial maize seed sold during 1996/97 in nontemperate areas (i.e., excluding Argentina and South Africa) and whose parentage could be determined, 63% was seed of varieties developed using CIMMYT germplasm.

In order to get a better sense of how the maize seed industry is changing through time, it is useful to examine longer-term trends in seed sales data. Figure 3 shows the evolution of total commercial maize seed sales during 1990–97. Summing across all three developing regions, the data show a slight upward trend. Although public seed agencies contributed slightly to this trend, the growth in commercial seed sales was driven mainly by increases in private-sector seed sales.

Adoption of Modern Varieties

How extensive is the area planted to modern maize varieties in the developing world? Respondents to the recent survey were asked to provide estimates of the percentage area under three categories of materials: (1) cultivars grown from farm-saved seed (including landraces, farmers' traditional varieties, and older OPVs and hybrids grown from advanced-generation recycled seed); (2) newer OPVs grown from commercial seed or from recycled seed emanating from recently purchased commercial seed; and (3) hybrids grown from newly purchased commercial seed.

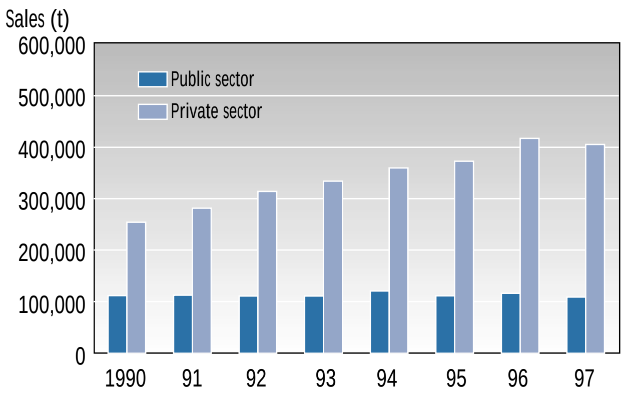

Figure 3. Total maize seed sales, all regions, 1990–97.

Table 5 presents estimates of the area under each of the three germplasm categories during the late 1990s. Overall, of the 70.0 million hectares planted to maize in the countries covered by the CIMMYT and IITA surveys approximately 36.0 million hectares (51.5%) were planted to modern varieties. Of the 63.3 million hectares planted to maize in nontemperate production environments (excluding Argentina and South Africa, where maize is grown mainly in temperate production environments), approximately 29.8 million hectares (47.0%) were planted to modern varieties.

How do these findings compare to those of the 1992 CIMMYT global impacts study? Since the geographical coverage of the earlier study was different, care should be taken in comparing the two sets of results. To make the results of the recent survey more directly comparable, it is necessary to drop countries from the current sample that were not included in the earlier survey (Argentina and South Africa).[7] Excluding these two countries, of the 55.0 million hectares planted to maize during the late 1990s, approximately 26.8 million hectares (48.7%) were planted to modern varieties. In percentage terms, this finding is slightly higher than the results of the earlier CIMMYT impacts study, which found that in 1990 approximately 43% of the developing world's maize area was planted to modern varieties (López-Pereira and Morris 1994).

Several conclusions can be drawn from the adoption data summarized in Table 5.

- Modern maize varieties have spread widely throughout the developing world.
- Adoption of modern maize varieties in nontemperate areas has been less extensive than in temperate areas.
- The area planted to hybrids is much larger than the area planted to OPVs.
- A significant proportion of the developing world's maize area continues to be planted to farm-saved seed.

Adoption of Modern Varieties Developed using CIMMYT Germplasm

Seed sales and varietal releases data can be combined with modern variety (MV) adoption data to derive estimates of the area planted to varieties developed using CIMMYT germplasm (Table 6). In 1996/97, of the 36.0 million hectares planted to modern varieties in the countries covered by the CIMMYT and IITA surveys about 18.0 million hectares (50.0%) were planted to varieties that had been developed using CIMMYT germplasm. Restricting the focus to nontemperate production environments targeted by the CIMMYT Maize Program, of the 29.8 million hectares planted to modern varieties in these environments, about 17.1 million hectares (57.5%) were planted to varieties that had been developed using CIMMYT germplasm.

Use of CIMMYT-derived varieties varied greatly by region. Nearly 10 million hectares were planted to CIMMYT-derived varieties in Latin America, compared to about 4.5 million hectares in Asia and about 3.7 million hectares in Sub-Saharan Africa.[8] These regional differences in the use of CIMMYT germplasm can be explained partly in terms of environmental factors. Since its inception, the CIMMYT Maize Program has invested more resources in breeding for lowland tropical environments than for other environments. Most of the maize grown in Latin America is grown in lowland tropical environments, so

Table 5. Maize area planted to improved OPVs and hybrids, developing countries, late 1990s[a]

	Total maize area[b] (million ha)	Area planted using farm-saved seed[c] (%)	Area planted using commercial seed		
			OPVs[d] (%)	Hybrids (%)	All MVs (%)
Latin America	27.1	55.1	5.0	39.9	44.9
excluding Argentina	*24.5*	*59.6*	*5.3*	*35.1*	*40.4*
Sub-Saharan Africa[e]	23.3	53.3	16.1	30.6	46.7
excluding South Africa	*19.2*	*63.9*	*18.9*	*17.2*	*36.1*
East, South, and Southeast Asia[f]	19.6	33.7	22.0	44.3	66.3
All regions	70.0	48.5	13.5	38.0	51.5
All nontemperate regions	63.3	52.9	14.6	32.5	47.1
Countries covered by 1992 impacts study, excluding Argentina, China, South Africa	55.0	51.3	11.8	36.9	48.7

Source: CIMMYT global maize impacts survey.

[a] Data refer to the following years: Latin America = 1996; Eastern and Southern Africa = 1997; East, South, and Southeast Asia = 1998.

[b] Includes only countries covered by the CIMMYT and IITA surveys.

[c] Includes landraces, farmers' traditional varieties, and older OPVs and hybrids grown from advanced-generation seed recycled more than three times.

[d] Includes area grown from commercial OPV seed that has been recycled up to a maximum of three times.

[e] Includes data for West and Central Africa.

[f] Excludes northern China.

---

[7] The geographical coverage is still not identical, because the earlier survey included a number of countries in northern, western, and central Africa.

[8] The figure for Sub-Saharan Africa includes an estimated 2.0 million ha in West and Central Africa.

Table 6. Maize area planted to MVs developed using CIMMYT germplasm, developing countries, late 1990s[a]

	Maize area[b] (million ha)	Maize area under MVs (%)	Maize area under MVs (000 ha)	Proportion with CIMMYT germplasm (%)	Maize area under MVs with CIMMYT germplasm (000 ha)
Latin America	27.1	44.9	12,171	80.1	9,842
excluding Argentina	*24.5*	*40.4*	*9,899*	*92.8*	*9,183*
Sub-Saharan Africa[c]	23.3	46.7	10,886	33.6	3,650
excluding South Africa	*19.2*	*36.1*	*6,941*	*49.8*	*3,454*
East, South, and Southeast Asia[d]	19.6	66.3	12,976	34.7	4,500
All regions	70.0	51.5	36,013	50.0	17,993
All nontemperate regions	63.3	47.1	29,816	57.5	17,138

Source: CIMMYT global maize impacts survey.

[a] Data refer to the following years: Latin America = 1996; Eastern and Southern Africa = 1997; East, South, and Southeast Asia = 1998.

[b] Includes only countries covered by the CIMMYT and IITA surveys.

[c] Includes data for West and Central Africa.

[d] Excludes northern China.

breeding programs in this region have been able to take advantage of some of CIMMYT's best materials. By contrast, much of the maize area in East and Southern Africa is located in subtropical and midaltitude environments, which until the mid-1980s received less emphasis from CIMMYT breeders. Similarly, before they can be grown successfully in Asia, materials developed in Mexico generally must undergo local adaptation. Breeding programs in Africa and Asia until recently thus had a more limited range of CIMMYT materials on which to draw. This situation has already started to change following moves by the CIMMYT Maize Program to strengthen its local breeding efforts in both regions.

Although this report includes information only on the use of CIMMYT germplasm by breeding programs in southern China, sources in the Chinese national maize breeding program recently reported that CIMMYT germplasm is also being used extensively in the breeding programs of northern China. These sources estimate that possibly as much as one-fourth of the total area planted to maize in China is planted to cultivars having CIMMYT parentage (i.e., as much as 6 million ha).

Future Directions for International Maize Breeding

These results confirm the findings of CIMMYT's original global impacts study conducted nearly 10 years ago: international maize breeding efforts have generated enormous benefits. Modern varieties currently cover nearly two-thirds of the area planted to maize in developing countries, bringing increased incomes to millions of maize producing households and lower food prices for even greater numbers of maize consumers. The widespread diffusion of modern maize varieties is especially impressive given the distinctive characteristics of maize, in particular, the open pollinating nature of the crop that requires farmers who grow modern varieties to replace their seed regularly. For this reason, modern maize varieties can disseminate only in the presence of an efficient seed industry.

The critical role of the maize seed industry has not gone unnoticed by policymakers. During the 1990s, liberalization measures introduced in many developing countries opened the door to increased participation by private companies, which responded by quickly capturing a large share of many national seed markets. The private sector now dominates commercial maize seed production throughout the developing world, with the notable exception of China, where private sector participation in seed production is still proscribed. Seed market liberalization has also had a pronounced effect on research. Recognizing that long-term survival in an increasingly competitive industry depends on the continued availability of superior products, private seed companies have significantly increased their investment in maize breeding research. The fruits of this increased investment are becoming evident in the steady stream of modern varieties emanating from private breeding programs, many of which have been developed using germplasm obtained from the public sector.

Increased privatization of national maize seed industries has brought generally positive results, but at the same time there are grounds for concern. The accelerating cost of genetic improvement research, coupled with the growing importance of IPR, is rapidly changing the rules of the plant breeding game. Fearful of conceding advantages to potential competitors, most of the large corporations that currently dominate the global maize seed industry are becoming less enthusiastic about sharing information, technology, and germplasm. As a result, maize breeding is rapidly being transformed from a collaborative activity undertaken for the common good into a competitive activity undertaken for individual profit. Since most public breeding programs depend heavily on the free exchange of germplasm and information, this trend raises questions about the future survival of the international breeding system.

Against a backdrop of declining public sector support for maize research, IARCs continue to play a vital facilitating role in support of international breeding efforts. The germplasm exchange network coordinated by CIMMYT has served as a particularly effective mechanism for promoting international flows of improved germplasm, as evidenced by the widespread use of CIMMYT materials in both public and private breeding programs. Yet despite the impressive progress achieved to date, considerable challenges remain to be overcome if modern varieties are to reach the poorest of the poor.

More than one-third of the developing world's maize area (nearly one-half of the maize area in nontemperate production environments) is still planted to farm-saved seed of uncertain genetic background and highly variable quality. In many instances, improved germplasm is available, but small-scale farmers located in isolated rural areas continue to use farm-saved seed because they are not attractive customers for profit-oriented commercial seed producers. As IARCs reposition themselves in the rapidly evolving global seed industry, they are being challenged to come up with creative approaches to reaching the millions of small-scale farmers who have not yet been integrated into the commercial farming sector.

Part 3

Current and Future Trends in Maize Production and Trade

Erika Meng and Javier Ekboir

Introduction

Total world maize production for 1999/2000 slightly exceeded 604 million tons, with approximately 11.5% of the total output traded internationally. Production for 2000/2001 is estimated to increase approximately 2%, due largely to a 9.5 million ton increase in production in the United States. The volume of trade forecast for the 2000/2001 marketing year is 70.8 million tons, which is the largest quantity traded during the last six years; this represents approximately the same percentage of total production as the previous year and, indeed, for the last decade (Table 1). A small number of countries are responsible for most exports, although not all of them are necessarily large producers. Table 2 lists the most significant maize producing countries of the last decade; information on maize importing and exporting countries is provided in Table 3 .

While the United States has continued to dominate world maize production, significant roles are also played by China, the nations of the Mercado Commun Sudamericano (MERCOSUR), and the European Union (EU). China alone has consistently accounted for more than 20% of world maize production during the last decade, while production in Argentina and Brazil together has averaged more than 8% over a similar period. In addition to being the largest maize producer, the United States is also the world's largest maize exporter. Argentina, likewise, is a major maize producer and exporter, but a high production level does not necessarily imply a large export role. For instance, all of Brazil's considerable output is consumed domestically, and nearly all of the EU's production is utilized by member countries. China is somewhat of an anomaly, having been both a significant maize exporter and importer during the last decade.

A closer examination of Asian maize imports reveals that they have consistently exceeded 30 million tons annually, primarily as a result of imports flowing into Japan and South Korea. Maize utilization and imports by Southeast Asian countries have also increased sharply in the last decade. Imports have largely been directed toward the expanding domestic livestock industries, which have been buoyed by higher income levels that have increased demand for meat products. Although

Table 1. World maize trade as percentage of total production ('000 t)

	1992/93	93/94	94/95	95/96	96/97	97/98	98/99	99/00	2000/01
World production	538,575	475,494	559,579	513,078	592,179	576,153	605,944	604,406	614,729
World trade	62,226	56,374	71,189	65,489	66,696	62,995	68,348	69,535	70,835
Percentage traded	0.116	0.119	0.127	0.128	0.113	0.109	0.113	0.115	0.115

Source: Constructed from USDA-FAS (2001a).

Table 2. World maize production ('000 t)

	1992/93	93/94	94/95	95/96	96/97	97/98	98/99	99/00	2000/01
United States	240,719	160,954	256,621	187,305	234,518	233,864	247,882	239,719	247,407
China	95,380	102,700	99,280	112,000	127,470	104,300	132,954	128,000	125,000
EU	30,242	30,487	28,298	28,952	34,794	38,522	35,295	37,241	38,765
Brazil	29,200	32,934	36,982	31,595	35,700	30,100	32,350	33,000	33,500
Mexico	18,631	19,141	17,005	16,000	18,922	16,934	17,788	19,000	19,000
Argentina	10,200	10,000	10,900	10,660	15,500	19,360	13,500	16,000	16,500
India	9,992	9,600	9,120	9,800	10,612	10,852	10,680	10,500	11,000
Romania	6,829	8,000	8,500	9,923	9,610	12,680	8,500	10,500	10,500
Canada	4,883	6,501	7,043	7,271	7,380	7,180	8,952	9,096	10,200
South Africa	9,990	13,275	4,845	10,200	10,136	7,693	7,700	9,700	9,500
Yugoslavia	6,650	5,912	7,500	8,300	8,300	10,500	8,700	9,500	9,300
Hungary	4,301	4,012	4,300	4,600	6,000	6,800	6,000	7,000	7,500
Indonesia	5,650	5,400	5,500	6,200	5,950	5,700	6,500	6,200	6,200
Egypt	4,500	4,980	5,650	5,738	5,825	6,010	5,605	5,678	5,800
Philippines	4,810	5,030	4,534	4,300	4,215	3,528	4,894	4,500	4,300
Thailand	3,400	2,900	3,800	3,700	3,900	3,700	4,300	3,800	4,100

Source: USDA-FAS (2001b).

Table 3. Major maize exporting and importing countries

	1992/93	93/94	94/95	95/96	96/97	97/98	98/99	99/00	2000/01
Exports (‘000 t)									
United States	41,766	33,148	58,645	52,500	46,633	37,697	51,886	46,500	49,500
Argentina	4,779	4,230	6,046	6,700	10,210	12,756	7,849	8,800	9,500
China	12,623	11,796	1,413	250	3,892	6,173	3,340	9,000	6,000
Hungary	222	18	370	500	1,122	1,250	1,766	1,700	2,000
South Africa	-	3,006	2,525	1,600	1,581	1,125	790	1,200	1,300
Romania	1	1	47	750	537	874	400	400	300
Ukraine	-	-	-	-	22	593	35	100	200
EU	1,256	1,722	347	350	243	382	100	100	100
Thailand	198	88	160	100	-	-	-	-	-
Imports (‘000 t)									
Japan	16,760	16,165	16,481	15,900	15,963	16,422	16,336	16,250	16,100
Korea, South	6,544	5,696	8,223	8,800	8,336	7,528	7,517	9,000	8,500
Taiwan	5,629	5,316	6,288	5,900	5,742	4,474	4,575	5,000	5,100
Mexico	396	1,691	3,166	6,400	3,141	4,376	5,615	4,600	5,000
Malaysia	1,957	1,977	2,415	2,300	2,332	2,195	2,388	2,500	2,600
EU	1,611	2,615	3,400	2,900	2,595	2,065	3,000	2,500	2,500
Brazil	1,170	1,134	1,435	150	514	1,491	968	1,600	1,400
Chile	395	439	551	425	783	851	1,268	1,200	1,300
Venezuela	1,126	945	1,170	1,200	1,494	1,161	1,500	1,250	1,300
Indonesia	357	962	1,738	900	895	516	475	450	600
Canada	1,190	585	1,108	650	879	1,418	903	800	500
Philippines	-	1	138	525	446	455	129	375	375
United States	166	519	245	385	285	126	388	325	325
Thailand	80	8	222	300	231	253	150	350	300
China	-	-	4,287	1,600	75	287	262	250	250

Source: USDA-FAS (2001a).

consumer demand for meat has slowed due to the Asian financial crisis of 1997/98, some gradual recovery in the region in the last few years has bolstered production and trade activity.

What can we expect to see in future trade patterns? Certainly they will continue to be determined by a complex interaction of many factors, including the domestic production environment and utilization trends, domestic and international trade policies, exchange rates, and commodity prices. Population growth and perhaps even more importantly, the rate of income growth, will also exert strong influences.

A reasonably good picture of future market development and activity can be obtained by looking at the pivotal roles played by three countries/regions: the United States, MERCOSUR, and Asia. We include the United States because of its indisputable role as a major player in international maize markets. The production and export potential of MERCOSUR, particularly Argentina and Brazil, also warrant serious consideration. Finally, the size, changes, and growth of the Chinese economy, as well as the potential of renewed growth of demand in other Asian countries, make Asia especially dynamic in terms of maize demand, production, and trade.

Changes in the U.S. Maize Market

Maize is cultivated throughout the United States, with most of the planted area in the nine neighboring Midwest states of the Corn Belt. Since maize yields have grown at slightly less than 2% per year during the last four decades, the greatest influences on U.S. maize production and trade are unlikely to come directly from changes in yield or area, despite some year-to-year variation due to weather and growing conditions. Rather, four other factors and their ramifications will heavily influence the production and trade environment: (1) changes in trade patterns and regulations; (2) ramifications of technical change, in particular, development of genetically modified (GM) maize and value-enhanced maize; (3) changes in domestic agricultural policy; and (4) changes in domestic demand for products containing maize, particularly for new products.

Changes in Trade Patterns and Regulations

In the last 15 years, U.S. trade and agricultural policies have become increasingly linked because of the growing share of agricultural output that is exported. Multilateral agreements aimed at reducing trade-distorting policies are further strengthening this linkage. Currently, more than 20% of U.S. maize output is exported. Negotiations in two specific areas will affect maize exports in the near future: (1) those carried out to create a freer trade environment, and (2) those for regulations on the trade of genetically modified organisms (GMOs).

In the area of freer trade, China's admission into the World Trade Organization (WTO) would have the greatest potential for affecting U.S. maize exports, possibly adding US$ 1.6 billion to annual U.S. exports of grains, oilseeds, oilseed products, and cotton by 2005 (USDA-ERS 2000e). The freer trade environment that is envisioned would increase Chinese imports of maize and boost demand for U.S. maize. The net effect will depend on domestic demand for food and feed maize in China and elsewhere, as well as the evolution of agricultural production.

The overall impact of regulations concerning genetically modified organisms (GMOs) on trade is still uncertain. Currently, importing countries may require approval of new GM crop varieties under their national laws and regulations. Once approval has been granted, trade is subject to the same regulations as for other bulk commodities. Most countries have not placed restrictions on maize imports from the United States. But a considerable conflict has arisen over official European acceptance of U.S. maize and maize product exports. Although some GM varieties (specifically those carrying *Bt* genes) have obtained final EU approval during the last two years, a de facto moratorium currently exists on additional approvals. At the macro level, this conflict could affect intercontinental trade; at the micro level, it could affect the decisions of maize growers and processors now exporting to the EU, who may respond to the EU constraints by growing only conventional maize.

European Union purchases represent less than 1% of U.S. maize exports, hence the conflict should have little impact on the country's maize exports, 94% of which are concentrated in Latin America (in particular, Mexico and Colombia), Japan, South Korea, Africa, and the Middle East (USDA-ERS 2000b). Nevertheless, it is possible that the GMO controversy could spread to more important U.S. export destinations in the future, making trade in these regions much more complicated. A counteracting force could be the adoption of GM maize by other large exporters, such as Argentina, in which case importers may not readily find alternative sources for large volumes of non-GM maize (USDA-ERS 2000b).

Negative impacts on U.S. trade are more likely to come from labeling requirements than from direct trade regulations. Mandatory labeling could hinder market adjustment by increasing the cost of market segregation and of voluntary labeling that may occur in response to differentiating demands. A likely solution is that two separate marketing channels, one for GM maize and another for non-GM maize, will continue to evolve. Such product differentiation would represent an extension of a trend already established for high-value products in grain and oilseed markets.

Unlike the sudden shocks the global maize market has experienced in the past (e.g., due to adverse weather or government policy changes), changes regarding GMO preferences will probably be comparatively gradual. In the near future, U.S. maize exports will almost certainly be affected more by international competitors than by regulation of GM trade (USDA-ERS 2000b; Riley 1998).

Technological Change

New seed technology for maize can be classified into two categories:
(1) technologies that generally reduce input use or lead to more effective input use, mainly developed through biotechnology; and (2) technologies that produce enhanced-value traits aimed at specific end-users (e.g., high oil maize, hard endosperm maize, waxy maize, and white maize), which are usually developed through conventional breeding. Herbicide resistant maize and *Bt* maize are the major products, to date, from the first category. Although the first wave of GM crops with built-in protection against pests and herbicides was rapidly adopted in the United States, adoption of the next wave of GM crops may proceed more slowly. Issues related to sharing the added value among different agents (producers, seed companies, storage elevators, and end-users), accommodation of specialized end-use characteristics, labeling controversies, and potential consumer resistance could all affect the next generation of GM goods (USDA-ERS 1999).

Expansion of value-enhanced maize will probably be less than that of GM maize. Area for the most widely grown product, high oil maize, was estimated in 1999 at slightly more than 900,000 acres, while total area of other value-enhanced products was estimated at less than 2 million acres, accounting for approximately 5% of output (USDA-ERS 1999). Although production has been hampered in the past by low yields, another important obstacle currently impeding the more widespread cultivation of value-enhanced maize is the lack of a widely recognized price mechanism for the specialty characteristics.

The growing emphasis on end traits, which require identity preservation (in some cases, segregation may be sufficient) and separate marketing channels, signals a departure from the traditional bulk commodity focus based on blending and large volumes. Future expansion of value-enhanced maize will likely require the evolution of completely segregated marketing channels. Niche markets for these non-GMO products may develop, similar to the present market for organic foods, which is characterized by separate identity-preserved marketing and premium prices (USDA-ERS 1999; Riley 1998).

Changes in Domestic Agricultural Policy

The 1996 FAIR Act had major consequences for U.S. agriculture and for maize, the nation's primary domestically grown feed grain. It eliminated set-aside programs and offered greater flexibility to farmers, thus acting as a catalyst to switch from wheat, barley, oats, and sorghum to more profitable crops (e.g., maize and soybeans). Because of the greater planting flexibility, maize and soybean planting decisions are now based on a wider set of variables than previous planting history and the soybean to maize price ratio (Lin and Riley 1998). Relatively rapid changes have been observed in the crop distribution of the overall cropping area that may reflect another significant ramification of the policy change: increased volatility in maize area due to greater substitutability among crops.

Domestic Demand

Domestic demand for maize continues to be largely driven by the evolution of traditional markets (e.g., feed and food markets), as well as by industrial use and the development of alternative uses for maize. Given relatively small income elasticity of food demand in the United States, traditional markets are expected to grow at about the same rate as population. Total U.S. maize usage in 1999 was 59% for feed/residual, 6% for high fructose products, 6% for ethanol, 21% for exports, and 8% for all other uses (USDA-ERS 2000d). Maize demand, particularly in the poultry, hog, and sweetener industries is currently strong with projections of a 3% increase in 2001 from the preceding year. Maize demand in the ethanol industry has also remained strong due to increases in the price of gasoline (USDA-ERS 2000c). Several public and private initiatives exist to increase the market for ethanol and alternative uses for maize, among them, a research and development effort for bio-fuels and bio-based products that is coordinated by the U.S. government and involves the government, academia, industry, and producers.[1]

Maize Potential in the MERCOSUR Countries of South America

Although MERCOSUR was created in 1991, its governing treaty did not take effect until January 1995. The agreement introduced an imperfect customs union among its full members (Argentina, Brazil, Paraguay, and Uruguay) and its associated members (Bolivia and Chile).[2] The member nations of MERCOSUR produce a diversified basket of outputs, including soybeans, maize, wheat, sunflower, sorghum, barley, beef, poultry, and pork (Ekboir 2000b). Production data

Table 4. Maize, soybean, and wheat production for selected MERCOSUR countries (t)

	1980	1981	1982	1983	1984	1985	1986
Argentina							
Maize	6,400,000	12,900,000	9,600,000	9,000,000	9,500,000	11,900,000	12,100,000
Soybeans	3,500,000	3,770,000	4,150,000	4,000,000	7,000,000	6,500,000	7,100,000
Wheat	7,780,000	8,300,000	15,000,000	13,000,000	13,600,000	8,700,000	8,700,000
Brazil							
Maize	20,372,080	21,116,910	21,842,480	18,731,220	21,164,140	22,018,180	20,541,230
Soybeans	15,155,800	15,007,370	12,836,050	14,582,350	15,540,790	18,278,590	13,333,360
Wheat	2,701,613	2,209,631	1,826,945	2,236,700	1,983,157	4,320,267	5,638,470

Source: FAO 1994.

Table 5. Maize area and yield for selected MERCOSUR countries

Maize area (ha)	1980	1981	1982	1983	1984	1985	1986
Brazil	11,451,290	11,520,340	12,619,530	10,705,980	12,018,450	11,798,350	12,460,130
Argentina	2,490,000	3,394,000	3,170,000	2,970,000	3,024,800	3,340,000	3,231,000
Paraguay	226,000	195,000	231,000	170,000	168,000	156,000	154,000
Chile							
Bolivia	293,480	313,110	285,780	260,844	321,731	348,929	294,000
Uruguay	131,923	146,202	94,948	93,094	83,191	89,491	76,262
Maize yield (t/ha)	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**
Brazil	1.779	1.833	1.7308	1.7496	1.761	1.8662	1.6486
Argentina	2.5703	3.8008	3.0284	3.0303	3.1407	3.5629	3.745
Paraguay	1.5531	1.6103	1.4892	1.5412	1.4345	1.6987	1.7013
Chile							
Bolivia	1.3063	1.6087	1.5733	1.2927	1.5436	1.5875	1.5554
Uruguay	0.9538	1.2365	1.025	1.114	1.3441	1.2066	0.9913

Source: FAO: FAOSTAT.

---

[1] An example is the recent announcement by Cargill/Dow about their plans to produce PLA, a plastic polymer made from maize that can be used in a wide variety of consumer products.

[2] The four full members form a customs union with free movement of goods within the union and a common external tariff. The associated members have agreed to a phased integration into MERCOSUR and temporarily maintain tariffs for certain products, the most important being agricultural products.

for selected crops are given in Table 4. Maize in MERCOSUR is produced mainly by commercial large-scale farmers and is part of a crop management package that includes soybeans, wheat, sunflower, and sorghum, the latter two being of comparatively less economic importance. Maize area and yields for MERCOSUR countries may be found in Table 5. The substitutability among these crops is very high and depends largely on expected relative prices. In the mid-1980s, the MERCOSUR countries embarked on major structural reforms that increased their competitiveness in world grain and meat markets. Reforms included reduced import tariffs and export taxes on agricultural products, privatization of key services, elimination of government controls, and imposition of greater fiscal discipline. Farmers responded quickly to the improved policy environment by adopting a new technological package based on zero tillage cropping systems. In the 1990s, maize production in the region grew 74%, while soybean output grew 61% (FAO 1999).[3]

Zero tillage solved the vexing problems of soil compaction and erosion while allowing continuous planting in traditional agricultural regions. In addition, the improved soil moisture characteristics achieved with zero tillage allowed the expansion of agriculture into previously uncultivated marginal areas. Most importantly, however, zero tillage simplified production technology and reduced production costs for commercial farmers, allowing grain production to rise to its current level (Ekboir and Parellada 2000). While the area under zero tillage in the early 1970s was negligible, it is estimated that by 1999, the technology had been adopted on approximately 20 million hectares (Derpsch 1998).

Maize Production Potential in MERCOSUR

Brazil

Maize is produced in every state in Brazil. Traditionally, it was considered a subsistence crop, however, the expansion of the feed and poultry industries induced a transformation of maize producers into specialized and commercial farmers. With the termination of government intervention in the early 1990s, maize producers became more market oriented and open to the adoption

---

[3] In the same period, maize production in the United States increased 20% and soybeans increased 39%.

1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
9,250,000	9,200,000	4,900,000	5,400,000	7,684,800	10,700,500	10,901,000	10,360,000	11,404,000	10,518,000	15,536,000	19,100,000	13,700,000
6,700,000	9,900,000	6,500,000	10,700,000	10,873,500	11,315,100	11,045,400	11,715,100	12,133,000	12,448,000	11,000,000	17,200,000	18,000,000
9,000,000	8,540,000	10,000,000	10,991,900	9,884,000	9,874,400	9,659,000	11,306,000	9,445,000	15,914,000	14,733,000	10,500,000	13,000,000
6,786,650	24,749,550	26,589,870	21,341,200	23,739,000	30,556,630	30,004,490	32,487,400	36,274,580	32,185,180	34,601,900	30,073,000	32,503,600
6,977,150	18,011,650	24,051,670	19,887,640	14,938,110	19,184,920	22,558,400	24,912,340	25,651,270	23,562,280	26,430,780	31,271,800	30,821,200
6,099,111	5,745,670	5,555,184	3,093,485	2,921,297	2,795,979	2,152,760	2,092,420	1,534,150	3,359,450	2,440,860	2,492,520	2,348,250

1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
13,499,440	13,181,990	12,918,980	11,390,650	13,109,840	13,388,950	11,868,030	13,747,740	13,960,020	13,415,350	13,556,100	10,802,000	11,755,100
2,900,000	2,437,500	1,683,700	1,560,330	1,900,100	2,365,440	2,503,010	2,445,040	2,522,000	2,603,720	3,410,000	3,183,000	2,587,000
161,000	183,000	185,000	191,000	243,215	258,000	249,081	218,385	330,961	324,601	384,114	385,000	410,000
302,100	293,360	278,988	256,317	273,483	283,032	285,902	287,830	272,567	286,568	309,600	253,000	
87,510	74,328	48,994	60,677	66,133	69,304	64,402	51,048	44,216	54,701	61,300	87,000	78,000

1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
1.9843	1.8775	2.0582	1.8736	1.8108	2.2822	2.5282	2.3631	2.5985	2.3991	2.5525	2.784	2.7651
3.1897	3.7744	2.9103	3.4608	4.0444	4.5237	4.3552	4.2371	4.5218	4.0396	4.556	6.0006	5.2957
1.8046	1.902	1.9889	2.1991	1.6501	1.743	1.7631	2.114	2.466	2.015	2.7483	2.4597	2.4
1.5912	1.5189	1.4353	1.5866	1.8657	1.5183	1.761	1.8658	1.9116	2.1395	2.1899	1.6443	
1.185	1.592	1.2278	1.851	1.751	1.6709	1.9922	1.629	2.452	2.171	2.6476	2.5931	3.109

of improved technologies (OECD 1997). Maize previously faced strong competition from soybeans because of the higher profitability of the latter and the greater availability of financing for soybeans from government export financing programs (USDA-ERS 1998). With the expansion of zero tillage, the competition between maize and soybeans decreased as both crops are needed in the rotation. Additionally, the shorter turnaround time allowed a third crop per year (known as *zafrinha*) in certain areas. The Empresa Brasileira de Pesquisa Agropecuaria's (EMBRAPA) Maize and Sorghum Center estimated that 7 million tons of maize were produced in the 1998 zafrinha (Ekboir 2000b).

During the last four decades, the area planted to maize in Brazil oscillated between 7 and 14 million hectares. In the same period, annual production increased from about 9 million tons to more than 30 million tons, due to yield gains that rose at an annual average rate of 2% between 1961 and 1995. The rate of yield growth accelerated in the late 1990s to 4.2%, based on FAO figures (1999), because of the introduction of new varieties. In recent years, private investment in the Brazilian seed industry has surged. However, since these investments are only replacing public research, it is expected that the rate of yield growth will eventually return to approximately 2% per year (Ekboir 2000b).

Expansion of the agricultural frontier in Brazil is hampered primarily by the lack of infrastructure, particularly in the *Cerrados*.[4] Should this area be developed, another 60 million hectares could be brought into production using currently available technologies. Even assuming that the maize area in Brazil remains relatively constant, production could reach 40 million tons by 2008 (USDA-ERS 1998).

Argentina

The area planted to maize in Argentina increased from 2.7 million hectares in 1961 to 4 million hectares in 1971, and then fell back to 2.6 million hectares in 1999. In the same period, annual production jumped from 4.9 to 13.7 million tons, after peaking at 19 million tons in 1998. Yields increased from 1.8 t/ha in 1961 to 6 t/ha in 1999, at a rate of about 1.6% per year (FAO 1999). During the 1970s and 1980s, maize production was displaced from the best agricultural land by soybeans, but it staged a comeback in the late 1990s because of a fall in soybean prices, better maize hybrids, greater demand by the cattle industry, and the expansion of zero tillage that requires maize in the rotation. The potential for area expansion in Argentina is more limited than in Brazil, but through a reduction of pastures and expansion into less favored environments, the crop area could be increased by at least 5 million hectares, given favorable conditions with respect to prices and costs of production. Future maize output growth in Argentina will also depend on the availability of new technologies that could either boost productivity or contribute to lower production costs.[5]

Paraguay

The pattern of land use in Paraguay changed rapidly in the 1970s and 1980s as foreign investment, favorable commodity prices, official settlement policies, and investment in new infrastructure all contributed to the penetration of its eastern region. The introduction of improved technologies, in particular new maize hybrids and modern management practices, contributed to a strong expansion of production (World Bank 1996). During 1995–99, average maize production reached 0.89 million tons. Maize yields in Paraguay have increased with the introduction of Brazilian hybrids. If these transfers continue, maize yields should increase at the same rate as in Brazil (approximately 2%). However, expansion of maize production has recently been hampered by marketing problems.

Uruguay

Between 1961 and 1994, the area planted to cereals and oilseeds in Uruguay decreased at an annual average rate of 3%; however, this reduced area was offset by a 3.1% increase in yield. Crop production area peaked in 1976 at 880,000 ha, with the ensuing decline reflecting increasing levels of competition from livestock, as well as declining profitability stemming from the termination of government crop subsidies. Maize production fell from 224,000 t in 1961 to 83,000 t in 1994. The last five years, however, have witnessed a surge in grain production with the largest increases coming in sunflower and maize, with the latter increasing to 243,000 t in 1999, despite a considerable drop in cultivated area. The dramatic increase in yields resulted from adoption of improved technologies, including new planting materials, and consolidation of small and medium-sized farms into larger units.

---

[4] The Cerrados is a vast savanna-like region that occupies the center, west and northern regions of Brazil. Loosely defined, the Cerrados accounts for between 180 and 207 million hectares, of which only 10% is planted to field crops. The Cerrados does not include the Amazon forest.

[5] Introduction of more intensive technologies for livestock and dairy could free substantial amounts of land for cultivation. However, it is impossible to forecast the magnitude of this shift, as it will depend on a number of factors such as relative prices of inputs and outputs, productivity of the new technologies, and economic policies both in Argentina and other exporting countries.

However, Uruguay's poor soil quality makes it the only country in the region with limited expansion potential (Ekboir 2000b).

Trade Impacts of MERCOSUR

The creation of MERCOSUR has realigned regional trade, with flows of goods and services within MERCOSUR expanding at the expense of nonpartner countries (Reca and Diaz Bonilla 1997; USDA-FAS 1998a). Maize imports, almost entirely attributable to Brazil, were 1.6 million tons in 1999/2000 compared to 479,000 t in 1989/90, representing a large part of total trade activity within MERCOSUR (USDA-FAS 1998a).

Domestic consumption of grains in Brazil between 1960 and 2000 increased faster than production, driven by the expansion of the poultry and hog industries.[6] These industries will continue to grow, but probably not at the strong rates they enjoyed during the last decade. Brazil is currently a major exporter of soybeans, beef, and poultry and a major importer of wheat and maize. The U.S. Department of Agriculture (USDA) estimates that feed demand in Brazil will continue to grow faster than production, implying that maize imports will increase to 2 million tons by the year 2007 (USDA-ERS 1998),[7] a position not universally held by others in the field. The Organization of Economic Cooperation and Development (OECD) estimates that Brazil could become a net maize exporter with a combination of higher yields, larger production area, and slower expansion of domestic demand (OECD 1997).

Domestic demand for maize in Argentina is satisfied by local production at a level close to saturation, meaning that any future output expansion must be exported. Per capita demand for maize for human consumption has remained stable for the last 40 years (Ekboir and Parellada 2000) and is not expected to grow substantially in the near future. The demand for feed grains in Argentina will depend on the evolution of the dairy and beef industries, but again, no dramatic increases are foreseen.

During the 1999/2000 marketing year, Argentina exported 8.8 million tons of maize, making it the world's second largest maize exporter. Argentina has exported an average of 57% of its annual production for the last decade and has seen its share of the international maize market increase from approximately 4% to almost 13%, with a peak of more than 20% in the 1997/98 marketing year. Brazil is a major export market, but Argentina also exports maize to approximately 50 other countries. Because of recent increases in storage capacity, Argentina has also become a year-round participant in the global market (USDA-FAS 1998b).

Argentina's current and future export potential, combined with Brazil's uncertain supply and demand situation and the possibility of expanding its maize area, mean that MERCOSUR could have a major impact on future international maize markets.

Maize Production and Utilization in Asia

Population and income growth have been the two most important catalysts for the recent rise in Asian demand for maize. The trend is expected to continue: the population of Asia is projected to increase by approximately 1.1 billion to 4.4 billion people by 2020, an increase of more than 33% over the estimated population in 1995. But the remarkable growth of maize demand in Asia goes beyond simple demographics to fundamental changes in diet and per capita income. Although maize utilization patterns across Asia vary greatly by country and region, generally maize used for direct human consumption is largely associated with subsistence households in relatively small areas of the region. Increases in income are unlikely to result in proportionate increases in demand for food maize. Rather, households with rising incomes are likely to substitute away from maize in favor of more refined grains such as rice and wheat (Falcon and Naylor 1998).

The most important component of the increased demand for maize in Asia has been indirect, through a growing demand for meat and livestock products. More than 50% of the maize grown in Asia is used for livestock feed (Falcon and Naylor 1998). The unprecedented increase in demand for meat results largely from the strong economic growth and rapid urbanization experienced by many of the continent's nations (Table 6).

Per capita consumption levels in several Asian countries approach those of western, developed countries (Table 7). However, the Asian financial crisis of 1997/98 seriously affected gross domestic product (GDP) and income levels, with negative consequences for consumer confidence and levels of meat consumption. The economic health of some countries (e.g., Japan, Indonesia, and Thailand) suffered very severely, while others, such as China, were able to escape relatively unscathed. In recent years, GDP levels appear to have

---

[6] Direct human consumption of maize is not significant (OECD 1997).

[7] The USDA import forecast is based on a production of 42.6 million tons of maize by 2007.

Table 6. Trends in real gross domestic product (GDP) for selected Asian countries (%)

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	1982-91	1992-2001
Japan	1.0	0.3	0.6	1.5	5.0	1.6	-2.5	0.3	0.9	1.8	4.1	1.1
Korea	5.4	5.5	8.3	8.9	6.8	5.0	-6.7	10.7	7.0	6.5	8.9	5.7
Singapore	6.6	12.8	11.4	8.0	7.5	8.4	0.4	5.4	5.9	6.0	6.8	7.2
China	14.2	13.5	12.6	10.5	9.6	8.8	7.8	7.1	7.0	6.5	9.6	9.8
India	4.2	5.0	6.7	7.6	7.1	5.8	4.7	6.8	6.3	6.1	5.4	6.0
Indonesia	7.2	7.3	7.5	8.2	8.0	4.5	-13.2	0.2	3.0	3.5	5.5	3.6
Malaysia	8.9	9.9	9.2	9.8	10.0	7.5	-7.5	5.4	6.0	5.8	6.3	6.5
Philippines	0.3	2.1	4.4	4.7	5.8	5.2	-0.5	3.2	4.5	4.5	1.3	3.4
Thailand	8.1	8.4	9.0	8.9	5.9	-1.8	-10.4	4.2	4.5	5.0	8.1	4.2
Vietnam	8.6	8.1	8.8	9.5	9.3	8.2	3.5	3.5	4.5	5.5	5.9	7.0

Source: IMF (2000).

stabilized and in several countries have begun once again to exhibit positive growth.

The IMPACT trade model of the International Food Policy Research Institute (IFPRI) projects 85% and 45% increases in global demand for poultry and pork, respectively, between 1995 and 2020. The model, which separates Asia into East, Southeast, and South Asia, projects large increases in annual per capita meat demand in East Asia (rising to 63.7 kg) and Southeast Asia (26.5 kg). In contrast, the projected growth rates and level of per capita meat demand in South Asia remain relatively low at 8.5 kg (IFPRI 1999).

China will be a particularly important player, accounting for almost 25% of the total 690 million ton increase in global cereal demand projected for 2020, and more than 40% of the 115 million ton increase in the demand for meat products (IFPRI 2000). India's projected impact, while considerable, is much smaller than China's, at one-half of the latter's increased demand for cereals and one-tenth of its increased demand for meat products (IFPRI 1999). Given its predominant position, our focus in this section is on China. However, Southeast Asia is also briefly addressed because of the rapid changes taking place in the economies and maize and livestock industries of the region.

Table 7. Per capita consumption, pork and poultry (kg)

	Poultry					
	1995	1996	1997	1998	1999	2000
China	7.3	8.2	8.8	9.0	9.5	9.7
Hong Kong	49.9	50.3	52.5	59.0	67.2	71.8
India	0.6	0.7	0.7	0.7	0.7	0.7
Indonesia	4.3	4.6	4.3	2.1	2.6	3.4
Japan	14.4	14.4	14.0	13.8	13.7	13.8
Korea, Republic of	10.0	10.8	10.8	9.5	10.4	10.7
Malaysia	32.2	33.1	34.0	29.4	29.1	30.1
Philippines	5.5	6.1	6.6	6.4	6.5	6.5
Singapore	33.7	34.0	33.7	34.7	37.7	37.8
Taiwan	29.4	31.1	34.1	33.6	34.8	34.3
Thailand	11.0	12.0	12.6	11.6	12.2	12.9

	Pork					
	1995	1996	1997	1998	1999	2000
China	30.1	25.8	29.2	31.3	31.4	32.3
Hong Kong	54.4	49.9	52.7	54.9	54.3	53.5
Japan	16.7	16.9	16.5	16.6	17.0	16.9
Korea, Republic of	18.4	19.2	18.9	20.3	20.9	21.3
Philippines	10.4	11.6	11.9	12.1	12.5	12.8
Singapore	31.9	30.2	31.4	28.1	13.9	11.2
Taiwan	40.2	41.7	39.6	44.3	42.5	42.3

Source: USDA-FAS.
Data for 1999 and 2000 are projected.

China

China's maize production has fluctuated in the last decade from a low of 95.4 million tons in 1992/93 to a record high of 133 million tons in 1998/99. The large variation in production is a result of fluctuations in both yields and area, largely due to weather and policy changes. Domestic maize consumption, meanwhile, has increased by more than 40% during the last decade (USDA-FAS 2000b), considerably exceeding the population growth rate and indicating that additional demand side forces are at work. China enjoyed a sustained period of strong economic growth with annual real GDP growth levels occasionally exceeding 10% over the last decade. Equally fortuitous, China was able to avoid many of the serious repercussions of the 1997/98 Asian financial crisis that afflicted other Asian countries.

A closer examination of meat consumption in China suggests that much of the recent maize demand has been largely driven by changes in economic well-being. China's domestic livestock industry, primarily consisting of poultry and pork production, represents a large factor in the domestic demand for maize. Approximately 75% of maize production in China is used for animal feed with the remainder used for human consumption and industrial purposes (USDA-FAS 2000b).

Although average growth in China's poultry industry slowed to 2% between 1997 and 1999, following double-digit growth between 1985 and 1995, it is currently the second largest poultry producer in the world. China is also simultaneously the world's largest poultry importer (USDA-FAS 2000a). Advances in breeding technology and continuing improvements in production efficiency are expected to maintain production growth for at least the next several years (USDA-FAS 2000c). The gradual evolution of the Chinese hog industry from backyard operations with an average of 1–4 head (accounting for approximately 80% of current pork output) to larger, commercial facilities producing leaner, grain-based meat reinforces expectations for long-term growth in demand for feed maize (Fang et al. 2000). Market reform and structural adjustments in the 1980s (Tuan and Peng 2001) have also played a large role in promoting the growth of the livestock industry. Growth in the production of selected livestock products is shown in Figure 1.

Although per capita consumption of all livestock products in China remains relatively low compared with that of other northern Asian countries (Crook 1998), per capita consumption of pork, the most widely consumed meat in China, is more comparable to that of developed countries. Figure 2 shows the trends in per capita consumption of livestock and fishery products in rural and urban communities. Both poultry and pork consumption have increased with economic growth and the rise of incomes. Reductions in Chinese exports to previously lucrative Asian markets and currency devaluations by other Asian countries hit by the financial crisis resulted in a decline in the GDP growth rate in 1998 and 1999. These effects combined with government downsizing and policy changes related to previously fixed housing and other benefits have resulted in a more cautious approach to consumer spending (Tuan et al. 2000).

There has also been uncertainty regarding the impacts of China's future role in international maize markets. The debate centers on China's ability to provide the food needed to sustain its population and the ramifications of alternative options for meeting this goal. Chinese political leaders have always considered food security to be a crucial policy objective, particularly in staple crops such as maize. The extent to which food security goals take on the guise of food self-sufficiency differs with political leaders and with the political landscape. Although agriculture's share of China's total trade figures has declined (from 21% in 1980–84 to 8.7% in 1995–97), the total value of China's agricultural trade averaged a growth rate of 6% per year from 1980 to 1997 and had increased to US$ 25.2 billion by 1997 (Huang et al. 2000).

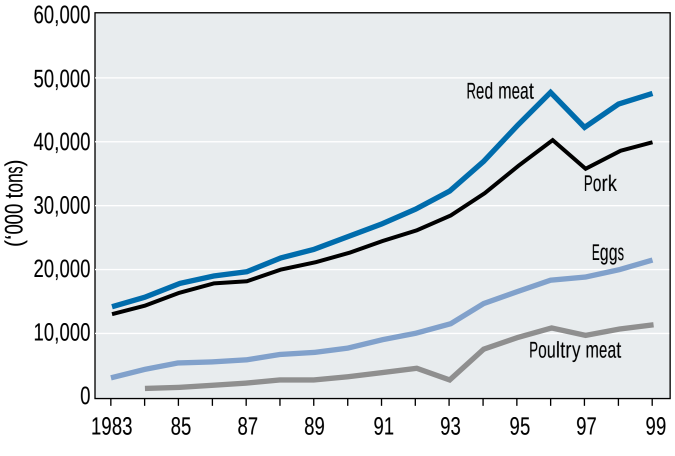

Figure 1. China's major livestock output, 1983-99.
Source: China *Statistical Yearbook* (various issues) as presented in Tuan and Peng (2001). All statistics after 1996 have been corrected by the National Bureau of Statistics according to China's agricultural census results.

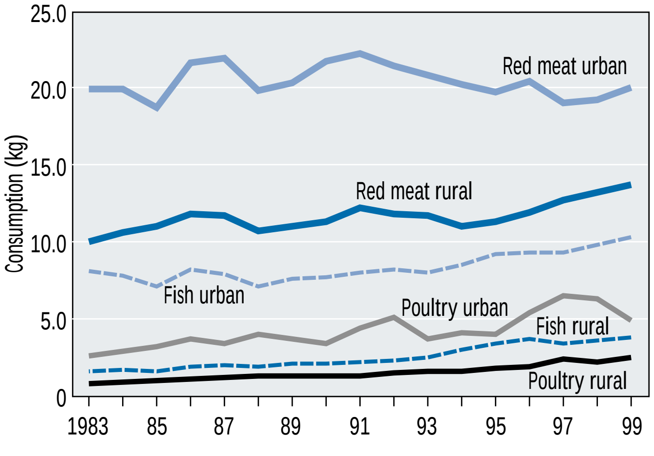

Figure 2. Per capita livestock and fish consumption, China, 1983-99.
Source: China *Statistical Yearbook* (various issues) as presented in Tuan and Peng (2001). All statistics after 1996 have been corrected by the National Bureau of Statistics according to China's agricultural census results.

China's involvement in global trade is likely to increase with its anticipated entry into the World Trade Organization (WTO). Access to China's import markets has historically been very restricted, with the China National Cereals, Oils, and Foodstuffs Import and Export Corporation (COFCO) controlling imports through a murky and ill-defined quota system. With a series of major reforms beginning in 1987, China's foreign trade sector has become more decentralized and market oriented; nevertheless, trade in agricultural products remains largely controlled by the state (Huang et al. 2000). In negotiating entry into the WTO, China has agreed to use a tariff-rate quota (TRQ) system and state trading for sensitive crops such as maize. Maize imports will be permitted at a low duty on a volume up to 4.5 million tons (to increase to 7.2 million tons after 2004), while imports above the quota level will be subjected to a much higher duty (USDA-FAS 2000a). Given total maize imports of 250,000 t in 1998, the WTO figures represent a very large potential increase in imports (USDA-FAS 2000a).

A free trade scenario simulated by Huang et al. (2000) goes beyond the anticipated impacts of WTO to project the maximum possible impact of trade liberalization on Chinese agriculture. In this scenario, the resulting grain deficit between domestic supply and demand totals 12% of China's 2005 grain consumption. With a fall in prices and large increases in demand for livestock feed, maize would be the most seriously affected grain. By 2005, maize imports would jump to 39.31 million tons, or one-fourth of the country's total consumption, making China the world's largest maize importer; increases in poultry and pork prices, combined with lower feed prices, would result in production and export growth in both industries (Huang et al. 2000). While other simulation models addressing this issue differ substantially in their assumptions (USDA-ERS 2000a; Zhou et al. 2001), they concur that China is unlikely to remain a maize exporter in the face of trade liberalization.

Southeast Asia

Economic growth, changing income levels, and rising demand for meat products also affect maize utilization, production, and trade in Southeast Asia. The strong growth in GDP experienced by the region during much of the previous decade contributed greatly to diversification in diet and to the increased ability of consumers to purchase meat products. Feed demand from the expansion of local poultry industries stimulated domestic maize production, local feed industries, and maize imports. The growth of the hybrid seed industry and the adoption of new varieties have been particularly rapid in the region. However, the financial crisis of 1997/98 resulted in negative growth rates for many of the region's countries. Higher unemployment and reduced consumer income and wealth created insecurity that effectively halted the growth in demand for meat with negative repercussions for local maize and feed industries.

The slight upturn in economic performance during 1999 and 2000 suggests that the worst of the transition may be over for these economies. However, continuing concerns regarding political instability in the region and the lack of meaningful structural reforms have dampened optimism. Growth is again slowing for Indonesia, the Philippines, and Thailand, which raises uncertainty about long-term income growth and stronger consumer demand for meat products.

Part 4

Selected Maize Statistics

Pedro Aquino, Federico Carrión, Ricardo Calvo, and Dagoberto Flores

Introduction

The following tables present statistics related to maize production, trade, utilization, experimental yield, type of maize seed, moisture regime, prices, and input use. These statistics reflect the latest information available at the time of publication.

Countries are classified as either "developing" or "high-income" based on the criteria used by the World Bank in its *World Development Indicators* (2000). Countries classified as "developing" had a per capita GNP lower than US$ 9,360 in 1998, whereas high-income countries had a per capita GNP exceeding US$ 9,361. Countries in Eastern Europe and the Former Soviet Union (FSU) are treated separately. Traditionally included as "developed" countries in FAO statistics, most of these countries would be classified as developing countries by World Bank criteria.

The first set of tables is divided into two sections, "Production Statistics" and "Consumption Statistics." Developing countries and those in Eastern Europe and the FSU are included in the individual country statistics if they consumed (or produced) at least 100,000 t of maize per year. Developing countries are classified as "maize producers" if they produce more than 100,000 t of maize per year, regardless of import and consumption levels. Developing countries that produce less than 100,000 t each year but that produced at least 50% of their total maize consumption are also classified as producers. Other developing countries that consumed more than 100,000 t per year are defined as "maize consumers." High-income countries are classified in the same way, using minimum levels of production or consumption of one million tons. A three-year average of the latest data available was used in the classification.

Unless otherwise indicated, the regional aggregates include data from all the countries in a particular region, including those countries for which data have not been reported individually. For a list of countries belonging to each region, see Appendix A. Regional means are appropriately weighted; thus they may not exactly equal the mean of the average values presented for each country. The former Czechoslavakia, former Yugoslavia, and the FSU were divided into separate countries, for which statistics were reported individually.

Notes on the Variables

The data source for all production and consumption statistics is FAO (1999, 2000).

Growth rates were calculated using the log-linear regression model:

$$ln\ Y = a + \beta t + e,$$

where $ln\ Y$ is the natural logarithm of Y, t is time period (year), a is a constant, β is the growth rate of Y, and e is the error term. The function describes a variable Y, which displays a constant proportional rate of growth ($\beta>0$) or decay (ß<0). β may be interpreted as the annual percentage change in Y.

Yield was computed by dividing three-year average production by the three-year average area harvested, which gives an average weighted by areas in the different years. The data source is the *FAOSTAT Production Statistics* (FAO 2000).

Net imports are defined as the amount of imports less exports. Data are taken from *FAOSTAT Trade Statistics* (1999).

Total consumption was calculated as the sum (in kilograms) of the amounts used for each type of maize utilization (i.e., food, feed, seed, processing, waste, and other uses). The data source is the *FAOSTAT Food Balance Sheets* (1999). The growth rate was calculated using the regression model given above.

Data regarding the type of maize seed, moisture regime, prices, and input use were collected through a general country survey of knowledgeable maize scientists. Data for experimental yields as of the year 2000 come from the CIMMYT International Maize Testing Historical Data System. The data for prices and input use refer to an important producing region within each country. The maize price is the average postharvest price received by farmers. The fertilizer price is usually the price paid by farmers for the most common fertilizers.

Production Statistics

	Average maize area, yield, and production, 1997-99			Growth rate of maize area (% / yr)			
REGION / COUNTRY	Harvested area ('000 ha)	Yield (t / ha)	Production ('000 t)	1951-65	1966-77	1978-87	1988-99 *
Eastern and Southern Africa	15436	1.5	23389	3.2	1.3	1.7	0.1
Angola	658	0.7	434	2.3	2.0	3.1	-2.9
Burundi	115	1.2	135	1.5	0.9	0.9	-1.2
Ethiopia	1606	1.7	2724	8.6	-1.2	1.5	8.9
Kenya	1502	1.5	2255	4.2	3.3	-0.1	0.2
Lesotho	134	1.0	128	-0.6	-5.2	2.2	-0.6
Madagascar	192	0.9	170	2.5	-2.1	2.2	2.7
Malawi	1342	1.4	1826	7.4	0.5	0.9	0.3
Mozambique	1221	0.9	1117	0.7	4.1	5.8	2.2
Somalia	200	0.7	141	16.7	-1.2	7.7	-0.5
South Africa	3691	2.3	8514	2.5	0.8	1.1	-2.1
Sudan	169	0.3	56	8.7	11.0	-4.4	8.1
Swaziland	63	1.8	115	8.8	-4.5	2.6	-3.7
Tanzania	1785	1.3	2362	3.7	1.8	3.6	-0.6
Uganda	615	1.2	763	2.3	5.1	-0.5	5.3
Zambia	553	1.5	818	1.0	1.1	-0.7	-4.1
Zimbabwe	1437	1.2	1710	5.7	1.8	3.8	2.5
Western and Central Africa	9223	1.2	11035	3.6	-0.5	7.6	1.5
Benin	607	1.2	738	1.7	-2.9	0.6	2.6
Burkina Faso	261	1.4	362	2.5	-6.3	4.3	1.1
Cameroon	392	1.5	583	7.9	2.7	-13.9	7.4
Central African Republic	94	0.9	89	18.6	8.3	-5.5	3.8
Chad	122	1.2	148	0.8	-6.6	5.9	13.5
Congo, Dem. Rep. of	1436	0.8	1161	3.2	2.4	4.2	2.2
Côte d'Ivoire	700	0.8	573	4.8	6.0	1.6	0.5
Ghana	683	1.5	1015	3.5	0.9	8.6	2.8
Guinea	85	1.0	88	4.7	0.2	1.3	2.2
Mali	195	1.7	324	0.7	-2.1	13.2	4.1
Nigeria	4111	1.3	5419	3.3	-5.3	23.9	0.6
Senegal	61	0.9	57	8.0	-0.8	5.3	-5.4
Togo	377	1.0	384	2.1	-5.6	6.9	4.0
North Africa	1192	5.4	6402	-1.2	0.5	-0.6	-0.8
Egypt	864	7.1	6164	-1.2	2.0	-0.6	< 0.1
Morocco	327	0.7	237	-1.1	-1.6	-0.7	-2.8
West Asia	1105	3.5	3876	1.3	-0.1	-2.2	1.4
Afghanistan	200	1.2	243	3.2	-0.3	-5.1	-3.2
Iran	148	6.3	932	5.1	2.7	-25.5	28.1
Iraq	61	1.9	118	-12.2	18.1	0.2	-0.6
Syria	75	3.2	244	-9.1	16.2	9.0	3.5
Turkey	573	3.9	2260	0.2	-1.3	-0.5	1.3
South Asia	8147	1.7	13660	2.1	0.8	0.6	0.7
India	6223	1.7	10694	2.4	0.8	-0.2	0.6
Myanmar	170	1.8	299	2.6	-1.0	5.8	3.9
Nepal	800	1.7	1343	-0.4	0.5	5.0	0.9
Pakistan	879	1.4	1251	1.8	0.7	2.4	0.3
Southeast Asia and Pacific	8185	2.4	19974	4.6	1.4	1.1	-1.2
Indonesia	3547	2.6	9358	3.0	-2.5	< 0.1	1.5
Philippines	2594	1.6	4266	4.9	4.0	1.3	-4.3
Thailand	1263	3.6	4483	21.3	6.7	2.7	-3.0
Vietnam	665	2.5	1668	4.2	3.1	0.5	3.7
East Asia	25592	4.8	122784	1.4	1.7	-0.6	2.2
China **	24996	4.9	121363	1.2	1.7	-0.6	2.3
North Korea	576	2.3	1338	7.5	2.5	-0.1	-1.8

* Data for 1993-97 (former Ethiopia and former Czechoslovakia) and 1992-97 (former Soviet Union and former Yugoslavia).

** Data for China include figures for Hong Kong.

*** Slovenia is a high-income country but is included here for greater geographical consistency with previous *Maize Facts and Trends*.

**** The world aggregates are not exactly equal to the FAO estimates because the method of aggregation may have differed.

n.a. not available

Growth rate of maize yield (% / yr)				Growth rate of maize production (% / yr)				Maize area as percentage of total cereal area (average), 1997-99 (%)
1951-65	1966-77	1978-87	1988-99 *	1951-65	1966-77	1978-87	1988-99 *	
1.8	2.8	-2.7	0.4	5.1	4.1	-1.0	0.5	41
1.3	-2.1	-6.0	9.3	3.6	-0.1	-2.8	6.3	76
0.4	0.7	0.4	-1.6	1.9	1.6	1.4	-2.8	56
2.1	3.3	0.8	3.4	10.7	2.1	2.3	12.3	23
1.8	2.5	3.6	-1.5	6.1	5.8	3.5	-1.3	79
0.5	2.4	-7.0	1.3	-0.1	-2.7	-4.8	0.7	71
2.4	0.5	1.4	-1.3	4.9	-1.5	3.6	1.4	14
1.0	0.9	-1.5	3.1	8.4	1.3	-0.6	3.4	89
1.5	-5.1	-7.6	12.3	2.2	-1.1	-1.8	14.5	62
0.4	0.5	6.7	-6.0	17.1	-0.7	14.4	-6.6	39
2.3	3.1	-5.7	1.6	4.8	3.8	-4.6	-0.5	74
-6.9	-0.7	-3.0	-2.9	1.8	10.3	-7.4	5.2	2
-11.0	11.6	3.3	4.4	-2.2	7.1	5.9	0.8	98
1.7	5.8	0.7	0.1	5.3	7.6	4.3	-0.5	56
1.2	2.5	-3.1	-1.1	3.5	7.5	-3.6	4.3	45
1.9	5.9	1.2	-2.0	2.9	7.0	0.4	-6.1	78
0.3	3.0	-2.6	-3.2	6.0	4.8	1.2	-0.7	75
-0.2	0.5	3.3	0.4	3.4	0.1	10.9	1.9	21
0.8	2.7	1.1	3.5	2.5	-0.2	1.7	6.1	73
1.2	1.6	-1.5	2.2	3.7	-4.6	2.8	3.3	9
-3.0	2.1	12.3	-2.1	4.8	4.8	-1.5	5.4	37
-2.0	-9.0	12.7	0.1	16.6	-0.6	7.2	3.9	62
0.9	1.4	-3.9	3.5	1.7	-5.1	2.0	17.0	6
-2.8	0.4	1.0	< 0.1	0.5	2.9	5.2	2.2	69
6.5	-4.2	4.1	1.5	11.4	1.8	5.7	2.0	43
-1.8	-1.9	0.5	1.5	1.7	-1.1	9.1	4.3	52
-2.2	-0.3	0.9	0.3	2.6	-0.1	2.2	2.5	12
2.3	-0.1	-2.6	1.3	3.0	-2.2	10.6	5.5	10
0.4	2.1	-0.5	-0.2	3.7	-3.1	23.5	0.4	22
-1.5	2.8	5.1	-2.8	6.5	2.0	10.5	-8.2	5
2.5	6.3	-5.1	-0.7	4.6	0.7	1.7	3.3	52
3.1	1.5	2.6	3.4	1.9	2.0	2.0	2.6	10
2.9	0.4	2.9	3.1	1.7	2.3	2.3	3.1	32
3.9	1.3	-0.1	-5.4	2.8	-0.3	-0.8	-8.1	6
1.6	2.5	5.7	1.4	2.9	2.4	3.6	2.8	3
2.7	0.8	0.5	-4.2	5.9	0.5	-4.6	-7.5	7
0.5	5.8	15.1	8.0	5.5	8.4	-10.4	36.1	2
1.9	8.5	-3.3	-0.9	-10.4	26.6	-3.1	-1.6	2
-2.1	2.5	-4.0	2.4	-11.2	18.7	5.0	5.9	2
1.2	3.6	7.9	-0.6	1.4	2.4	7.4	0.7	4
0.0	0.3	1.3	1.3	4.1	1.1	1.9	2.0	6
2.9	0.4	1.4	1.5	5.3	1.2	1.2	2.2	6
1.7	2.4	6.1	1.6	4.4	1.5	11.9	5.5	3
0.6	-0.7	-1.5	0.8	0.2	-0.2	3.5	1.6	25
0.5	1.4	0.8	0.3	2.4	2.1	3.2	0.6	7
1.6	1.9	3.0	3.6	6.3	3.3	4.0	2.4	19
1.1	2.6	4.3	2.7	4.2	0.1	4.3	4.2	24
0.2	1.7	2.5	3.4	5.1	5.7	3.8	-0.9	41
5.4	-0.2	1.0	4.0	26.7	6.6	3.7	0.9	11
-0.1	0.6	4.1	5.5	4.1	3.7	4.6	9.2	8
0.8	3.7	3.8	1.7	2.2	5.4	3.2	3.9	27
0.5	3.8	3.8	2.0	1.8	5.5	3.2	4.3	27
5.6	2.1	4.4	-12.0	13.1	4.6	4.2	-13.8	42

Production Statistics (cont'd).

REGION / COUNTRY	Average maize area, yield, and production, 1997-99			Growth rate of maize area (% / yr)			
	Harvested area ('000 ha)	Yield (t / ha)	Production ('000 t)	1951-65	1966-77	1978-87	1988-99 *
Mexico, Central America, and the Caribbean	9601	2.2	21084	2.8	-1.0	0.6	1.3
Cuba	100	1.3	129	-6.7	-2.0	0.1	3.1
El Salvador	317	1.8	579	0.4	1.9	-0.6	1.0
Guatemala	611	1.7	1013	2.2	-1.6	2.0	-0.8
Haiti	273	0.8	217	-2.1	-1.5	1.4	1.4
Honduras	409	1.3	519	0.1	3.4	-1.9	1.4
Mexico	7502	2.4	18145	3.8	-1.2	0.6	1.5
Nicaragua	266	1.1	287	2.3	-0.4	-2.9	3.4
Andean Region, South America	2082	1.9	4013	3.0	-1.8	2.9	-1.6
Bolivia	283	2.0	572	8.9	0.9	1.6	0.1
Colombia	528	1.7	902	-0.1	-3.5	-1.1	-3.9
Ecuador	456	1.2	527	7.9	-1.2	8.4	0.2
Peru	440	2.1	939	3.1	0.9	2.8	0.9
Venezuela	373	2.9	1069	4.8	-3.1	5.2	-3.5
Southern Cone, South America	15501	3.2	50107	3.8	1.2	1.4	0.4
Argentina	3035	5.3	16026	4.0	-2.2	1.7	4.6
Brazil	11929	2.7	32091	4.1	2.2	1.5	-0.5
Chile	93	8.7	816	4.5	2.9	-0.8	-1.4
Paraguay	383	2.5	971	2.9	5.2	-6.1	7.6
Uruguay	60	3.4	203	-3.1	-2.8	-6.5	-1.2
Eastern Europe and Former Soviet Union	9577	3.8	36617	1.1	-0.1	1.5	-1.3
Albania	58	3.4	197	1.9	-4.1	-2.5	-0.7
Bosnia and Herzegovina	165	3.7	612	n.a.	n.a.	n.a.	-8.4
Bulgaria	437	3.1	1354	-1.4	1.8	-2.7	-2.0
Croatia	378	5.6	2098	n.a.	n.a.	n.a.	0.4
Czech Republic	38	6.6	249	n.a.	n.a.	n.a.	5.2
Georgia	211	2.3	484	n.a.	n.a.	n.a.	12.7
Hungary	1067	6.3	6693	0.9	1.1	-1.9	-0.7
Kazakhstan	63	2.5	159	n.a.	n.a.	n.a.	-12.1
Kyrgyzstan	48	4.7	223	n.a.	n.a.	n.a.	1.0
Macedonia	39	4.2	166	n.a.	n.a.	n.a.	-1.8
Moldova	419	3.3	1400	n.a.	n.a.	n.a.	6.3
Poland	89	5.7	504	-11.2	17.9	-3.5	5.7
Romania	3033	3.4	10439	0.8	-0.1	-1.5	1.8
Russian Federation	816	1.9	1522	n.a.	n.a.	n.a.	1.2
Slovakia	128	5.8	745	n.a.	n.a.	n.a.	-1.4
Slovenia ***	46	7.3	332	n.a.	n.a.	n.a.	-4.9
Ukraine	1077	2.9	3124	n.a.	n.a.	n.a.	-3.8
Uzbekistan	47	3.8	180	n.a.	n.a.	n.a.	-14.3
Yugoslavia	1371	4.4	6071	n.a.	n.a.	n.a.	-0.9
Western Europe, North America, and Other High-Income Countries	34543	8.3	287335	-1.5	2.3	-1.1	1.2
Austria	179	9.7	1739	-1.2	9.6	1.9	-0.8
Canada	1097	7.7	8396	4.0	7.2	1.3	1.0
France	1807	8.8	15888	7.9	5.8	< 0.1	-0.5
Germany	358	8.4	3002	5.3	8.9	6.7	5.6
Greece	211	9.1	1914	-4.1	-1.3	8.4	-1.0
Italy	1013	9.6	9677	-1.4	-1.0	-1.6	2.5
Portugal	190	5.6	1070	-0.1	-2.3	-5.0	-2.1
Spain	447	9.3	4164	2.8	-1.0	2.0	-1.9
United States of America	29110	8.3	240489	-1.9	2.2	-1.4	1.3
Regional aggregates							
Developing countries	96062	2.9	276325	2.7	0.9	1.1	0.8
Eastern Europe and Former Soviet Union	9577	3.8	36617	1.1	-0.1	1.5	-1.3
Western Europe, North America, and Other High-Income Countries	34543	8.3	287335	-1.5	2.3	-1.1	1.2
World ****	140182	4.3	600277	1.3	1.1	0.6	0.7

* Data for 1993-97 (former Ethiopia and former Czechoslovakia) and 1992-97 (former Soviet Union and former Yugoslavia).

** Data for China include figures for Hong Kong.

n.a. not available

Growth rate of maize yield (% / yr)				Growth rate of maize production (% / yr)				Maize area as percentage of total cereal area (average), 1997-99 (%)
1951-65	1966-77	1978-87	1988-99 *	1951-65	1966-77	1978-87	1988-99 *	
2.5	1.2	1.5	2.5	5.4	0.2	2.1	3.8	70
0.4	2.8	-0.1	2.9	-6.4	0.8	0.0	5.9	41
1.2	2.7	0.5	-0.9	1.6	4.6	-0.1	0.1	71
1.0	5.0	0.8	-1.5	3.3	3.4	2.8	-2.3	91
3.0	-1.7	0.8	-0.1	0.9	-3.2	2.2	1.4	59
3.7	-1.7	4.5	-0.6	3.7	1.7	2.6	0.7	82
2.9	1.0	1.5	3.3	6.7	-0.2	2.2	4.7	71
-0.8	-0.5	2.9	-2.4	1.6	-0.9	0.0	1.0	69
-0.3	2.2	1.8	2.1	2.6	0.3	4.6	0.5	45
-0.1	0.2	2.1	3.1	8.8	1.1	3.7	3.2	37
0.5	2.3	0.3	2.1	0.4	-1.2	-0.8	-1.8	51
-4.2	4.1	1.0	1.3	3.7	2.9	9.4	1.5	52
0.6	1.2	2.6	0.8	3.6	2.0	5.4	1.7	43
-1.2	2.1	3.3	3.6	3.6	-1.0	8.5	0.2	53
0.8	1.7	2.5	4.3	4.7	2.9	3.9	4.7	53
1.3	2.5	0.7	4.3	5.3	0.3	2.4	8.9	30
0.5	1.9	3.3	3.8	4.6	4.1	4.8	3.3	68
4.6	-1.4	9.9	1.6	9.2	1.5	9.1	0.2	15
-0.1	2.0	2.4	2.9	2.8	7.2	-3.7	10.5	60
-2.3	6.2	2.7	8.4	-5.4	3.4	-3.8	7.2	10
4.8	2.9	0.5	0.3	5.9	2.9	2.0	-1.1	9
0.1	6.5	1.8	-0.5	2.0	2.3	-0.7	-1.2	27
n.a.	n.a.	n.a.	-3.2	n.a.	n.a.	n.a.	-11.6	55
7.1	0.7	-0.1	-1.9	5.6	2.5	-2.7	-3.9	23
n.a.	n.a.	n.a.	4.3	n.a.	n.a.	n.a.	4.8	58
n.a.	n.a.	n.a.	9.2	n.a.	n.a.	n.a.	14.3	2
n.a.	n.a.	n.a.	-0.9	n.a.	n.a.	n.a.	11.8	52
3.3	4.1	2.1	1.5	4.2	5.2	0.2	0.8	39
n.a.	n.a.	n.a.	-0.4	n.a.	n.a.	n.a.	-12.5	1
n.a.	n.a.	n.a.	1.2	n.a.	n.a.	n.a.	2.2	7
n.a.	n.a.	n.a.	7.8	n.a.	n.a.	n.a.	6.0	18
n.a.	n.a.	n.a.	2.0	n.a.	n.a.	n.a.	8.3	46
4.7	7.4	2.8	1.6	-6.5	25.3	-0.7	7.3	1
4.2	3.4	0.5	2.1	5.0	3.3	-1.0	3.9	53
n.a.	n.a.	n.a.	-10.0	n.a.	n.a.	n.a.	-8.9	2
n.a.	n.a.	n.a.	5.5	n.a.	n.a.	n.a.	4.1	16
n.a.	n.a.	n.a.	10.4	n.a.	n.a.	n.a.	5.6	48
n.a.	n.a.	n.a.	0.4	n.a.	n.a.	n.a.	-3.4	9
n.a.	n.a.	n.a.	2.4	n.a.	n.a.	n.a.	-11.9	3
n.a.	n.a.	n.a.	6.2	n.a.	n.a.	n.a.	5.3	59
4.6	1.5	2.0	2.6	3.1	3.8	0.8	3.7	25
4.5	2.5	2.3	2.0	3.3	12.0	4.1	1.1	22
2.8	0.5	2.2	2.5	6.9	7.7	3.5	3.5	6
4.3	-0.1	3.1	2.6	12.2	5.7	3.1	2.1	20
2.5	1.7	1.4	1.4	7.8	10.7	8.1	7.0	5
3.7	6.3	6.2	-0.7	-0.4	5.0	14.6	-1.7	16
3.7	5.2	1.2	2.6	2.3	4.2	-0.4	5.1	24
0.3	-0.4	7.9	7.4	0.2	-2.7	2.9	5.2	31
2.2	4.8	4.4	4.1	5.0	3.8	6.4	2.2	7
4.8	1.3	1.8	2.6	2.9	3.5	0.4	4.0	47
1.2	2.5	1.9	2.5	3.9	3.4	3.0	3.3	21
4.8	2.9	0.5	0.3	5.9	2.9	2.0	-1.1	9
4.6	1.5	2.0	2.6	3.1	3.8	0.8	3.7	25
2.4	2.4	1.2	2.4	3.7	3.5	1.8	3.1	20

*** Slovenia is a high-income country but is included here for greater geographical consistency with previous *Maize Facts and Trends*.

**** The world aggregates are not exactly equal to the FAO estimates because the method of aggregation may have differed.

Consumption Statistics

REGION / COUNTRY	Average net maize imports, 1996-98		Maize food		Maize consumption		Average percentage of maize used	
	Total (‘000 t)	Per capita (kg / yr)	Average per capita, 1995-97 (kg / yr)	Growth rate per capita, 1988-97 (% / yr) *	Average per capita, 1995-97 (kg / yr)	Growth rate per capita, 1988-97 (% / yr) *	Human consumption 1995-97 (%)	Animal feed 1995-97 (%)
Eastern and Southern Africa	-127	< 1	58	0.3	81	-0.4	72	17
Angola	147	13	36	3.7	42	3.1	84	5
Burundi	n.a.	n.a.	23	-3.6	25	-3.6	91	2
Ethiopia	25	< 1	39	2.0	45	2.9	88	5
Kenya	427	15	94	0.4	103	0.1	91	3
Lesotho	120	60	135	0.1	163	< 0.1	83	3
Madagascar	-4	< 1	11	0.3	12	0.2	86	5
Malawi	83	8	148	-0.3	182	0.4	82	6
Mozambique	109	6	53	2.8	58	2.7	93	++
Rwanda	163	27	25	8.0	42	12.0	61	++
Somalia	6	1	15	-13.3	17	-12.9	89	++
South Africa	-1200	-31	101	0.5	212	-1.0	48	39
Swaziland	10	11	60	7.1	150	-1.8	40	21
Tanzania	34	1	72	-2.1	85	-2.6	85	5
Uganda	-64	-3	25	3.7	39	3.6	64	11
Zambia	131	15	140	-1.4	165	-1.9	85	5
Zimbabwe	-260	-23	122	0.6	159	0.3	76	14
Western and Central Africa	184	1	28	0.9	43	0.5	66	13
Benin	2	< 1	66	2.4	102	2.4	65	3
Burkina Faso	n.a.	n.a.	26	1.3	28	1.2	91	
Cameroon	2	< 1	42	3.3	47	3.3	89	1
Central African Republic	< 1	< 1	21	3.4	25	3.1	83	
Chad	5	1	12	17.3	15	16.8	81	7
Congo, Dem. Rep. of	7	< 1	22	-0.4	25	-1.1	86	1
Côte d’Ivoire	-2	< 1	28	0.8	41	0.2	68	10
Ghana	29	2	42	3.0	56	2.6	75	6
Guinea	22	3	10	1.0	14	0.7	76	
Mali	1	< 1	25	1.9	28	1.8	91	++
Nigeria	n.a.	n.a.	34	0.3	62	< 0.1	55	20
Senegal	39	4	11	-6.1	13	-6.1	84	7
Togo	4	1	66	2.3	85	2.2	78	++
North Africa	4892	36	35	1.7	74	1.1	45	44
Algeria	874	30	5	22.1	34	-0.2	14	79
Egypt	2856	44	57	0.8	117	1.2	48	39
Libya	166	32	1	0.3	36	-7.7	2	93
Morocco	586	22	24	5.2	30	3.8	79	9
Tunisia	409	44	++	++	41	3.1	++	98
West Asia	4101	18	8	-0.2	34	1.9	23	69
Afghanistan	n.a.	n.a.	10	-12.7	14	-12.5	74	20
Iran	1068	17	1	9.5	30	9.5	3	92
Iraq	n.a.	n.a.	4	33.3	7	-20.7	50	45
Jordan	326	72	1	12.5	88	-2.6	1	95
Lebanon	260	83	1	3.1	85	4.5	2	95
Saudi Arabia	1062	54	< 1	2.3	62	15.9	1	96
Syria	418	28	2	2.4	38	9.0	5	91
Turkey	832	13	21	1.9	45	-0.1	47	39
Yemen	98	6	4	-1.6	8	-0.4	55	39

* Data for 1993-97 (former Ethiopia and former Czechoslovakia), 1992-97 (former Soviet Union and former Yugoslavia).

** Data for China include figures for Hong Kong.

*** Slovenia is a high-income country but is included here for greater geographical consistency with previous *Maize Facts and Trends*.

**** The world aggregates are not exactly equal to the FAO estimates because the method of aggregation may have differed.

++ Not applicable.

n.a. Not available.

Consumption Statistics (cont'd)

REGION / COUNTRY	Average net maize imports, 1996-98		Maize food		Maize consumption		Average percentage of maize used	
	Total ('000 t)	Per capita (kg / yr)	Average per capita, 1995-97 (kg / yr)	Growth rate per capita, 1988-97 (% / yr) *	Average per capita, 1995-97 (kg / yr)	Growth rate per capita, 1988-97 (% / yr) *	Human consumption 1995-97 (%)	Animal feed 1995-97 (%)
South Asia	24	< 1	7	-0.6	10	-0.4	75	5
India	-26	< 1	8	-0.8	10	-0.5	77	2
Myanmar	-71	-2	3	3.1	5	1.7	56	35
Nepal	3	< 1	52	0.8	61	-0.1	85	3
Pakistan	5	< 1	5	-1.7	9	-1.8	59	20
Sri Lanka	104	6	2	-3.9	7	7.3	32	63
Southeast Asia and Pacific	3080	7	22	2.6	50	3.0	43	46
Indonesia	453	2	39	4.7	49	4.4	79	5
Malaysia	2253	107	4	1.3	123	5.0	3	91
Philippines	393	6	9	-13.1	67	-1.9	14	74
Thailand	179	3	< 1	-5.4	67	4.7	< 1	96
Vietnam	-195	-3	13	7.9	17	7.0	74	20
East Asia	10326	8	12	-10.1	100	3.1	12	75
China **	1938	2	11	-11.1	97	3.5	11	76
North Korea	354	15	45	-1.3	84	-11.9	54	< 1
South Korea	8034	176	18	3.8	193	3.7	9	74
Mexico, Central America, and the Caribbean	6722	42	101	-0.9	166	0.8	56	28
Costa Rica	411	110	13	-8.0	106	3.5	12	82
Cuba	226	20	++	++	30	-11.8	++	94
Dominican Republic	700	87	8	7.0	93	5.2	8	88
El Salvador	227	38	92	-0.9	142	1.3	64	30
Guatemala	207	20	114	-1.4	131	-1.8	87	9
Haiti	7	1	29	2.0	33	1.9	87	5
Honduras	63	11	83	-2.2	125	0.7	67	25
Jamaica	185	73	12	-3.2	75	1.3	16	78
Mexico	4377	46	128	-0.8	222	1.1	58	25
Nicaragua	10	2	54	-3.4	74	-1.6	73	16
Panama	178	65	29	0.8	92	6.2	32	66
Andean Region, South America	3967	37	35	2.3	73	5.2	47	44
Bolivia	< 1	< 1	42	2.6	80	4.3	52	19
Colombia	1814	45	40	5.6	66	10.8	60	37
Ecuador	96	8	18	-1.5	48	0.7	38	50
Peru	947	39	12	0.0	69	2.0	18	77
Venezuela	1096	48	58	-0.1	105	4.3	55	31
Southern Cone, South America	-8744	-39	17	-1.2	190	3.1	9	77
Argentina	-9933	-278	6	2.1	133	0.6	5	59
Brazil	618	4	19	-1.8	216	3.3	9	80
Chile	652	45	9	10.9	99	4.4	9	87
Paraguay	-123	-24	43	1.9	127	4.3	34	49
Uruguay	41	13	18	-5.7	60	4.2	29	50

* Data for 1993-97 (former Ethiopia and former Czechoslovakia), 1992-97 (former Soviet Union and former Yugoslavia).

** Data for China include figures for Hong Kong.

*** Slovenia is a high-income country but is included here for greater geographical consistency with previous *Maize Facts and Trends*.

**** The world aggregates are not exactly equal to the FAO estimates because the method of aggregation may have differed.

++ Not applicable.

n.a. Not available.

Consumption Statistics (cont'd)

	Average net maize imports, 1996-98		Maize food		Maize consumption		Average percentage of maize used	
REGION / COUNTRY	Total ('000 t)	Per capita (kg / yr)	Average per capita, 1995-97 (kg / yr)	Growth rate per capita, 1988-97 (% / yr) *	Average per capita, 1995-97 (kg / yr)	Growth rate per capita, 1988-97 (% / yr) *	Human consumption 1995-97 (%)	Animal feed 1995-97 (%)
Eastern Europe and Former Soviet Union	-544	-1	8	8.8	88	-5.7	7	82
Albania	6	2	< 1	-105.6	67	-2.8	< 1	90
Belarus	99	10	++	++	8	-35.1	++	87
Bosnia and Herzegovina	6	2	45	-14.4	115	-15.1	39	43
Bulgaria	11	1	2	3.0	176	-7.7	1	83
Croatia	-18	-4	6	8.9	427	8.2	1	95
Czech Republic	113	11	< 1	-13.3	35	15.5	< 1	81
Georgia	1	< 1	81	24.8	100	23.6	81	13
Hungary	-1134	-112	1	-9.7	515	-2.4	< 1	77
Kazakhstan	-15	-1	1	-0.5	10	-40.3	6	84
Kyrgyzstan	12	3	++	++	38	-6.6	++	96
Latvia	14	6	< 1	50.8	6	17.2	3	97
Lithuania	49	13	< 1	12.7	12	14.3	2	77
Macedonia	64	32	26	14.9	108	12.4	24	58
Moldova	-79	-18	49	-2.8	286	13.7	17	75
Poland	487	13	++	++	20	4.2	++	77
Romania	-210	-9	39	2.7	420	3.6	9	87
Russian Federation	178	1	< 1	-20.4	24	-7.5	1	96
Slovakia	-117	-22	++	++	105	4.6	++	87
Slovenia ***	173	87	34	2.8	264	2.3	13	79
Ukraine	-55	-1	9	-1.7	55	-4.5	16	70
Uzbekistan	1	< 1	7	-10.9	10	-20.6	70	26
Yugoslavia	-147	-14	16	-0.3	560	12.0	3	84
Western Europe, North America, and Other High-Income Countries	-25749	-30	11	0.3	282	2.0	4	76
Austria	-103	-13	7	12.6	227	2.5	3	77
Belgium-Luxembourg	933	88	2	-1.9	118	-0.3	2	58
Canada	684	23	3	-0.5	267	1.4	1	78
France	-7091	-121	13	-0.5	129	0.6	10	72
Germany	606	7	7	0.4	45	0.5	16	63
Greece	236	22	2	2.9	206	-0.1	1	84
Italy	464	8	3	1.9	162	4.4	2	93
Japan	16050	127	22	-0.5	127	-0.5	17	76
Netherlands	1617	104	3	-0.2	87	-2.5	3	59
Portugal	1070	108	7	-2.3	180	4.3	4	91
Spain	2232	56	2	6.6	136	2.4	1	88
United Kingdom	1372	23	3	0.9	25	-1.5	14	11
United States of America	-45113	-166	14	0.9	652	2.1	2	76
Regional aggregates								
Developing countries	24426	5	20	-2.0	66	2.1	30	57
Eastern Europe and Former Soviet Union	-544	-1	8	8.8	88	-5.7	7	82
Western Europe, North America, and Other High-Income Countries	-25749	-30	11	0.3	282	2.0	4	76
World ****	—-	—-	18	-1	100	1.1	17	66

* Data for 1993-97 (former Ethiopia and former Czechoslovakia), 1992-97 (former Soviet Union and former Yugoslavia).
** Data for China include figures for Hong Kong.
*** Slovenia is a high-income country but is included here for greater geographical consistency with previous *Maize Facts and Trends*.
**** The world aggregates are not exactly equal to the FAO estimates because the method of aggregation may have differed.
++ Not applicable.
n.a. Not available.

Maize Area by Type of Seed and Moisture Regime (%)

	Maize area planted by type of seed as a percentage of total maize area, 1999 (%)				Maize area by moisture regime as a percentage of total maize area, 1999 (%)	
REGION / COUNTRY*	Improved seed	Hybrids	OPVs	Farm-saved seed	Irrigated	Rainfed
Eastern and Southern Africa	92	81	11	8	1	99
Kenya	87	85	2	13	0	100
Mozambique	9	3	6	91	4	96
South Africa	100	90	10	0	<1	100
Uganda	65	10	55	35	0	100
Zambia	65	62	3	35	1	99
Zimbabwe	100	91	9	0	2	98
South Asia	54	30	24	46	26	74
Bangladesh	44	25	19	56	80	20
India	58	36	22	42	23	77
Nepal	54	6	47	46	5	95
Pakistan	30	13	17	70	65	35
West Asia	82	67	15	18	100	0
Iran	100	100	0	0	100	0
Syria	45	0	45	56	100	0
Southeast Asia	72	35	36	28	9	91
Indonesia	80	24	56	20	n.a.	n.a.
Philippines	42	17	25	58	5	95
Thailand	100	90	10	0	5	95
Vietnam	90	60	30	10	30	70
East Asia	91	84	7	10	38	62
China	91	84	7	10	38	62
Mexico, Central America, and the Caribbean	23	15	8	77	18	82
El Salvador	80	34	46	20	0	100
Guatemala	9	8	<1	91	2	98
Haiti	1	0	1	99	n.a.	n.a.
Honduras	38	29	9	62	15	85
Mexico	22	15	7	79	20	80
Nicaragua	17	2	15	83	<1	100
Andean Region, South America	70	43	27	30	17	83
Bolivia	63	37	25	37	10	90
Colombia	59	36	23	41	22	78
Ecuador	89	52	37	11	<1	100
Peru	50	13	37	50	41	59
Venezuela	95	88	7	5	2	98
Southern Cone, South America	74	62	12	26	16	84
Argentina	100	80	20	0	3	97
Brazil	69	59	10	31	19	81
Paraguay	52	27	25	48	0	100
Western Europe	100	98	2	0	91	9
Greece	100	100	0	0	100	0
Italy	100	100	0	0	90	10
Netherlands [1]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Spain	100	90	10	0	90	10

* Regional aggregates include only countries that have been reported.

++ not applicable

n.a. not available

[1] Data for Netherlands correspond to silage maize and other types of maize.

Fertilizer Area and Use for Maize

REGION / COUNTRY*	Fertilized area as a percentage of total maize area (%)	Fertilizer applied per ha of maize harvested, 1999-2000 (kg / ha)			Ratio of farm-level fertilizer price to maize price, 1999-2000					
					Nitrogen		Phosphorus		Potassium	
		Nitrogen	Phosphorus	Potassium	Yellow maize	White maize	Yellow maize	White maize	Yellow maize	White maize
Eastern and Southern Africa										
Kenya	30	34	30	0	4	4	2	2	++	++
Mozambique	3	n.a.	n.a.	n.a.	6	7	29	35	59	70
South Africa	88	85	15	8	4	4	6	5	12	11
Sudan	n.a.	80	40	0	5	5	5	5	++	++
Uganda	15	70	35	0	++	29	++	78	++	140
Zambia	75	130	50	20	++	9	++	7	++	14
Zimbabwe	30	43	14	7	++	11	++	10	++	20
West Asia										
Iran	100	184	138	42	1	++	1	++	1	++
Syria	100	130	80	0	2	++	2	++	++	++
South Asia										
Bangladesh	95	256	55	139	2	++	12	++	2	++
India	50	100	60	40	2	2	8	8	1	1
Nepal	22	60	40	20	7	7	4	5	2	2
Pakistan	90	66	14	0	7	8	4	5	++	++
Southeast Asia										
Indonesia	n.a.	n.a.	n.a.	n.a.	7	7	++	++	++	++
Philippines	60	90	60	30	7	6	9	8	1	++
Thailand	98	83	31	n.a.	11	++	13	++	16	++
Vietnam	80	235	90	20	2	++	1	++	2	++
East Asia										
China	96	155	60	15	4	4	3	2	11	9
Mexico, Central America, and the Caribbean										
Salvador	80	n.a.	n.a.	n.a.	++	3	++	++	++	++
Guatemala	53	86	26	7	11	12	15	16	6	6
Haiti	n.a.	115	0	0	3	++	++	++	++	++
Honduras	53	105	43	22	9	9	5	6	13	14
Mexico	43	157	61	3	4	4	4	4	6	6
Nicaragua	21	61	27	14	++	5	++	4	++	5
Andean Region, South America										
Bolivia	40	40	40	0	5	3	++	++	++	++
Colombia	59	105	48	70	5	5	4	4	3	3
Ecuador	79	81	3	6	8	7	8	7	3	3
Peru	56	170	60	33	5	3	5	3	4	2
Venezuela	88	203	68	68	5	5	6	6	6	6
Southern Cone, South America										
Argentina	50	51	37	0	16	++	10	++	++	++
Brazil	61	35	65	37	11	++	13	++	22	++
Paraguay	35	18	46	0	5	1	++	++	++	++
Western Europe										
Greece	100	300	150	100	6	++	18	++	32	++
Italy	100	300	100	100	14	9	10	7	5	4
Netherlands [1]	100	250	n.a.	n.a.	52	15	65	19	33	10
Spain	100	270	150	150	5	5	9	8	7	6

* Regional aggregates include only countries that have been reported.

++ not applicable

n.a. not available

[1] Data for Netherlands correspond to silage maize and other types of maize.

Prices for Seed and Maize Grain

REGION / COUNTRY*	Farm price of maize (US$ / t), 1999-2000		Consumer price of maize (US$ / t), 1999-2000		Ratio of the price of improved seed to the price of grain, 1999-2000: Hybrids		Ratio of the price of improved seed to the price of grain, 1999-2000: OPVs		Farm wage in kg of maize per day, 1999-2000	
	Yellow maize	White maize	Yellow maize	White maize	Yellow maize	White maize	Yellow maize	White maize	Yellow maize	White maize
Eastern and Southern Africa										
Kenya	160	160	231	231	9	9	9	9	4	4
Mozambique	60	50	130	120	11	13	10	12	17	20
South Africa	84	93	n.a.	n.a.	18	16	7	6	75	68
Sudan	120	120	200	200	n.a.	n.a.	n.a.	n.a.	7	7
Uganda	++	65	++	327	++	22	++	12	++	13
Zambia	++	184	++	137	++	6	++	2	++	5
Zimbabwe	++	111	++	316	++	3	++	n.a.	++	14
West Asia										
Iran	120	++	145	++	8	++	++	++	20	++
Syria	170	++	183	++	++	++	2	++	11	++
South Asia										
Bangladesh	139	++	179	++	17	++	2	++	9	++
India	130	127	149	134	7	7	6	6	9	9
Nepal	146	139	175	168	8	8	5	6	7	8
Pakistan	130	111	157	148	29	33	2	3	14	17
Southeast Asia										
Indonesia	81	74	141	121	33	36	11	12	24	26
Philippines	131	153	283	278	16	13	5	4	21	18
Thailand	93	++	120	++	24	++	3	++	34	++
Vietnam	143	++	150	++	9	++	3	++	6	++
East Asia										
China	87	103	100	115	6	5	2	2	17	14
Mexico, Central America, and the Caribbean										
El Salvador	++	151	++	227	++	12	++	n.a.	++	20
Guatemala	153	147	201	195	9	9	7	8	23	24
Haiti	141	++	188	++	++	++	5	++	15	++
Honduras	154	142	228	206	11	12	6	6	21	23
Mexico	142	158	173	214	19	17	9	8	38	34
Nicaragua	++	172	++	203	++	11	++	5	++	13
Andean Region, South America										
Bolivia	200	400	300	600	11	6	5	2	21	10
Colombia	209	211	258	283	11	11	6	6	23	23
Ecuador	66	72	72	76	21	19	10	9	21	19
Peru	141	223	192	246	22	14	7	4	24	15
Venezuela	231	231	608	651	10	10	5	5	25	25
Southern Cone, South America										
Argentina	65	++	90	++	46	++	n.a.	++	308	++
Brazil	100	++	141	++	84	++	31	++	75	++
Paraguay	93	315	138	516	34	10	11	3	68	20
Western Europe										
Greece	120	++	149	++	65	++	1	++	190	++
Italy	130	190	145	205	58	39	n.a.	n.a.	346	237
Netherlands [1]	27	93	43	152	142	41	n.a.	n.a.	5000	1463
Spain	133	151	n.a.	n.a.	1	1	n.a.	n.a.	239	212

* Regional aggregates include only countries that have been reported.

++ not applicable

n.a. not available

[1] Data for Netherlands correspond to silage maize and other types of maize.

CIMMYT Average Maize Experimental Yield, 1997-99, Subtropical Trials (t/ha)

	CIMMYT experimental yield by grain color		CIMMYT experimental yield by type of seed		CIMMYT experimental yield
REGION / COUNTRY	Yellow	White	OPV	Hybrid	Quality Protein Maize
Eastern Africa [4]	**5.53**	**5.07**	**4.24**	**5.37**	**n.t**
Number of trials	18	122	28	112	
Ethiopia	**n.t**	**4.45**	**3.96**	**4.84**	**n.t**
Number of trials		34	14	20	
Madagascar [1]	**5.53**	**n.t**	**n.t**	**5.53**	**n.t**
Number of trials	18			18	
Tanzania	**n.t**	**6.15**	**n.t**	**6.15**	**n.t**
Number of trials		20		20	
Uganda	**n.t**	**4.75**	**4.55**	**4.91**	**n.t**
Number of trials		32	14	18	
Zimbabwe [1]	**n.t**	**5.45**	**n.t**	**5.45**	**n.t**
Number of trials		36		36	
North Africa [2]	**8.93**	**4.35**	**n.t**	**5.97**	**n.t**
Number of trials	18	23		41	
Egypt [2]	**n.t**	**4.35**	**n.t**	**4.35**	**n.t**
Number of trials		23		23	
Morocco [2]	**8.93**	**n.t**	**n.t**	**8.93**	**n.t**
Number of trials	18			18	
South Asia [3]	5.55	4.92	n.t	5.07	4.25
Number of trials	54	151		205	14
India	**5.55**	**5.02**	**n.t**	**5.17**	**4.25**
Number of trials	54	128		182	14
Pakistan [2]	**n.t**	**4.36**	**n.t**	**4.36**	**n.t**
Number of trials		23		23	
Southeast Asia	**6.30**	**n.t**	**n.t**	**6.30**	**n.t**
Number of trials	18			18	
Vietnam	**6.30**	**n.t**	**n.t**	**6.30**	**n.t**
Number of trials	18			18	
East Asia	**4.53**	**6.24**	**n.t**	**5.80**	**n.t**
Number of trials	18	60		78	
China	**4.53**	**6.24**	**n.t**	**5.80**	**n.t**
Number of trials	18	60		78	
Mexico and Central America	7.86	7.12	6.45	7.45	6.09
Number of trials	90	284	56	318	70
El Salvador	**n.t**	**2.34**	**n.t**	**2.34**	**2.34**
Number of trials	14		14	14	
Guatemala	**5.74**	**3.54**	**n.t**	**4.65**	**3.54**
Number of trials	18	14		32	14
Honduras	**n.t**	**4.45**	**4.45**	**n.t**	**n.t**
Number of trials		14		14	
Mexico	**8.50**	**8.12**	**7.28**	**8.36**	**10.04**
Number of trials	72	242	42	272	42
Andean Region, South America [1]	4.66	n.t	n.t	4.66	n.t
Number of trials	18			18	
Bolivia [1]	**4.66**	**n.t**	**n.t**	**4.66**	**n.t**
Number of trials	18			18	
Southern Cone, South America [2]	4.24	n.t	n.t	4.24	n.t
Number of trials	18			18	
Brazil [2]	**4.24**	**n.t**	**n.t**	**4.24**	**n.t**
Number of trials	18			18	
Western Europe and North America	3.42	2.47	n.t	2.99	n.t
Number of trials	54	38		92	
Greece	**5.40**	**n.t**	**n.t**	**5.40**	**n.t**
Number of trials	18			18	
USA	**2.73**	**2.47**	**n.t**	**2.59**	**n.t**
Number of trials	36	38		74	
Total trials	**5.63**	**5.65**	**5.61**	**5.65**	**5.75**
Total number of trials	306	678	84	900	84

n.t. = Not trial. [1] Data for 1997. [2] Data for 1998. [3] Data for 1998, and 1999. [4] Data for 1997 and 1999.

CIMMYT Average Maize Experimental Yield, 1997-99, Tropical Trials (t/ha)

	CIMMYT experimental yield by grain color		CIMMYT experimental yield by type of seed		CIMMYT experimental yield
REGION / COUNTRY	Yellow	White	OPV	Hybrid	Quality Protein Maize
Sub-saharan Africa [2]	**n.t.**	**3.92**	**n.t.**	**3.92**	**n.t.**
Number of trials		18		18	
Sudan [2]	**n.t.**	**3.92**	**n.t.**	**3.92**	**n.t.**
Number of trials		18		18	
Western Africa [2]	**n.t.**	**6.13**	**n.t.**	**6.13**	**n.t.**
Number of trials		36		36	
Ghana [2]	**n.t.**	**6.13**	**n.t.**	**6.13**	**n.t.**
Number of trials		36		36	
South Asia [4]	4.81	3.99	2.38	5.25	5.38
Number of trials	200	149	74	275	23
India	**4.71**	**3.99**	**2.38**	**5.19**	**5.38**
Number of trials	190	149	74	265	23
Myanmar [2]	**7.22**	**n.t.**	**n.t.**	**7.22**	**n.t.**
Number of trials	10			10	
Southeast Asia	**5.02**	**4.35**	**3.99**	**5.11**	**4.17**
Number of trials	190	218	156	252	92
Indonesia	**7.47**	**7.19**	**7.17**	**7.49**	**n.t.**
Number of trials	54	14	18	50	
Philippines	**5.11**	**4.85**	**4.61**	**5.22**	**3.80**
Number of trials	86	107	78	115	23
Thailand	**3.23**	**2.99**	**2.76**	**4.08**	**4.08**
Number of trials	32	51	60	23	23
Vietnam	**3.04**	**4.41**	**n.t.**	**3.97**	**4.41**
Number of trials	18	46		64	46
Mexico, Central America, and the Caribbean[4]	5.79	6.33	6.22	6.10	6.40
Number of trials	326	589	204	711	207
Costa Rica	**n.t.**	**7.44**	**7.25**	**7.68**	**n.t.**
Number of trials		51	28	23	
Cuba [2]	**6.91**	**n.t.**	**n.t.**	**6.91**	**n.t.**
Number of trials	10			10	
Dominican Rep [2]	**6.02**	**n.t.**	**n.t.**	**6.02**	**n.t.**
Number of trials	10			10	
Guatemala	**5.40**	**6.69**	**n.t.**	**6.21**	**6.80**
Number of trials	54	102		156	46
Honduras	**4.54**	**6.89**	**4.54**	**6.44**	**7.76**
Number of trials	46	93	28	111	23
Mexico	**6.02**	**5.82**	**6.48**	**5.68**	**5.82**
Number of trials	154	274	120	308	92
Nicaragua	**6.72**	**6.26**	**6.15**	**6.58**	**5.74**
Number of trials	32	51	28	55	23
Panama [2]	**6.50**	**6.74**	**n.t.**	**6.61**	**n.t.**
Number of trials	20	18		38	
Andean Region, South America [5]	5.15	7.02	n.t.	6.01	6.16
Number of trials	136	135		271	23
Colombia	**5.73**	**7.57**	**n.t.**	**6.85**	**n.t.**
Number of trials	54	98		152	
Ecuador	**4.25**	**5.75**	**n.t.**	**4.81**	**6.16**
Number of trials	54	37		91	23
Peru [2]	**n.t.**	**8.13**	**n.t.**	**8.13**	**n.t.**
Number of trials		10		10	
Venezuela [1]	**5.18**	**n.t.**	**n.t.**	**5.18**	**n.t.**
Number of trials	18			18	
Southern Cone, South America [2]	6.34	n.t.	n.t.	6.34	n.t.
Number of trials	28			28	
Brazil [2]	**6.34**	**n.t.**	**n.t.**	**6.34**	**n.t.**
Number of trials	28			28	
Total trials	**5.30**	**5.57**	**4.50**	**5.74**	**5.63**
Total number of trials	880	1,145	434	1,591	345

n.t. = Not trial. [1] Data for 1997. [2] Data for 1998. [3] Data for 1997 and 1998. [4] Data for 1998, and 1999. [5] Data for 1997, 1998, and 1999.

References

Alston, J.M., G.W. Norton, and P.G. Pardey. 1995. *Science Under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting.* Ithaca, New York: Cornell University Press.

Bänziger, M., S. Mugo, and G.O. Edmeades. 2000. Breeding for drought tolerance in tropical caize: conventional approaches and challenges to molecular approaches. In J.-M. Ribaut and D. Poland (eds.), *Molecular Approaches for the Genetic Improvement of Cereals for Stable Production in Water-Limited Environments.* A Strategic Planning Workshop held at CIMMYT, El Batan, Mexico, 21-25 June 1999. Mexico D.F.: CIMMYT.

Beck, D.L. S.K. Vasal, and J. Crossa. 1990. Heterosis and combining ability of CIMMYT's tropical early and intermediate maturity maize (*Zea mays* L.) germplasm. *Maydica* 35(3): 279–85.

Bellon, M.R. 2001. *Participatory Research Methods for Technology Evaluation: A Manual for Scientists Working with Farmers.* Mexico, D.F.: CIMMYT.

Bennetzen, J.L. 2000. Comparative genomics approaches to the study of drought tolerance. In J.-M. Ribaut and D. Poland (eds.), *Molecular Approaches for the Genetic Improvement of Cereals for Stable Production in Water-Limited Environments.* A Strategic Planning Workshop held at CIMMYT, El Batan, Mexico, 21-25 June 1999. Mexico D.F.: CIMMYT.

Berner, D.K., F.O. Ikie, and E.I. Aigbokhan. 1995. Some control measures for *Striga hermonthica* Utilizing critical infection period on maize and sorghum. In D.C. Jewell, S.R. Waddington, J.K. Ransom, and K.V. Pixley (eds.), *Maize Research for Stress Environments.* Proceedings of the Eastern and Southern Africa Regional Maize Conference, 4; Harare, Zimbabwe, 28 March–1 April 1994. Mexico, D.F.: CIMMYT. Pp. 267–74.

CIMMYT. 1999. *CIMMYT 1997/98 World Maize Facts and Trends. Maize Production in Drought-Stressed Environments: Technical Options and Research Resource Allocation.* Mexico D.F.: CIMMYT.

Crook, F.W. 2000. The effects of government policies on animal protein production and consumption. *International Agriculture and Trade Reports: China Situation and Outlook Series*, WRS-98-3. July 1998. Washington, D.C.: USDA-ERS.

CTIC. 1994. Definition of conservation tillage. *Conservation Impact* 12 (11): 6.

De Leon, C., and J.E. Lothrop. 1994. Lowland tropical germplasm development in Asia with emphasis on selection for downy mildew. In S.K. Vasal and S. McLean (eds.), *The Lowland Tropical Maize Subprogram.* Maize Program Special Report.. Mexico, D.F.: CIMMYT. Pp. 30–45.

Derpsch, R. 1998. Historical Review of No-Tillage Cultivation of Crops. In *Proceedings to the International Workshop Conservation Tillage for Sustainable Agriculture*, Harare, 22-27 June, 1998, Zimbabwe.

————. 1999. Expansion Mundial de la SD y Avances Tecnologicos. In *7o Congreso Nacional de AAPRESID*, Mar del Plata, 18-20 Agosto, 1999. Tomo 1, Conferencias y Disertaciones. AAPRESID/INTA.

Diallo, A.O., and Y. Dosso. 1994. Germplasm Development in sub-Saharan Africa with emphasis on streak resistance. In S.K. Vasal and S.D. McLean (eds.), *The Lowland Tropical Maize Subprogram.* CIMMYT Maize Program Special Report. Mexico, D.F.: CIMMYT. Pp. 47–58.

Edmeades, G.O., M. Bänziger, H. R. Mickelson, and C.B. Peña-Valdivia (eds.). 1997a. *Developing Drought- and Low N-Tolerant Maize.* Proceedings of a Symposium, March 25–29, 1996, CIMMYT, El Batan, Mexico. Mexico, D.F.: CIMMYT/UNDP.

Edmeades, G.O., S.C. Chapman, J. Bolaños, M. Bänziger, and H.R. Lafitte. 1995. Recent evaluation of progress in selection for drought tolerance in tropical maize. In D.C. Jewell, S.R. Waddington, J.K. Ransom and K. V. Pixley (eds.), *Research for Stress Environments.* Proceedings of the Fourth Eastern and Southern Africa Regional Maize Conference, 28 March–1 April 1994. Pp 94–100.

Edmeades, G.O., Bänziger, J. Bolaños, S.C. Chapman, A. Ortega C., H.R. Lafitte, K.S. Fischer, and S. Pandey. 1997b. Recurrent selection under managed drought stress improves grain yields in tropical maize. In G.O. Edmeades, M. Bänziger, H. R. Mickelson, and C.B. Peña-Valdivia (eds.), *Developing Drought- and Low N-Tolerant Maize.* Proceedings of a Symposium., March 25–29, 1996, CIMMYT, El Batan, Mexico. Mexico, D.F.: CIMMYT/UNDP.

Edmeades, G.O., J. Bolaños, and S.C. Chapman. 1997c. Value of secondary traits in selecting for drought tolerance in tropical maize. In G.O. Edmeades, M. Bänziger, H. R. Mickelson, and C.B. Peña-Valdivia (eds.), *Developing Drought- and Low N-Tolerant Maize.* Proceedings of a Symposium, March 25–29, 1996, CIMMYT, El Batan, Mexico. Mexico, D.F.: CIMMYT/UNDP.

Edmeades, G.O., J. Bolaños, and H. R. Lafitte. 1992. Progress in selecting for drought tolerance in maize. In D. Wilkinson (ed.), *Proc. 47th Annual Corn and Sorghum Research Conference*, Chicago, December 9–10, 1992. ASTA, Washington. Pp. 93–111.

Ekboir, J. 2000a. Innovation systems and technology policy: zero tillage in MERCOSUR. Paper presented at the XXIV Conference of the International Association of Agricultural Economists. *Tomorrow's Agriculture: Incentives, Institutions, Infrastructure and Innovations*, August 13-18, 2000, Berlin, Germany.

————. 2000b. *Can Mercosur Feed The World? An Assessment of MERCOSUR'S Agricultural Potential,* Economics Working Paper 00-04 Mexico D.F.: CIMMYT

Ekboir, J., and G. Parellada. 2000. Continuous complex innovation processes: public-private interactions and technology policy. Paper presented at the XXIV Conference of the International Association of Agricultural Economists. *Tomorrow's Agriculture: Incentives, Institutions, Infrastructure and Innovations*, August 13–18, 2000, Berlin, Germany.

Falcon, W.P. 2000. Globalizing germplasm: barriers, benefits, and boundaries. Paper presented at the XXIV Conference of the International Association of Agricultural Economists. *Tomorrow's Agriculture: Incentives, Institutions, Infrastructure and Innovations*, August 13–18, 2000, Berlin, Germany.

Falcon, W.P., and R. Naylor. 1998. The maize transition in Asia: Unlocking the controversy. *American Journal of Agricultural Economics* 80(5): 960–68.

Fang, C., F. Fuller, M. Lopez, and F. Tuan. Livestock production slowly evolving from sideline to principal occupation. *International Agriculture and Trade Reports: China Situation and Outlook Series*, WRS-99-4. March 2000. Washington, D.C.: USDA-ERS.

FAO. 1999. FAOSTAT database. WWW.FAO.ORG.

————. 1999. *FAOSTAT. Trade Statistics.* Rome: FAO.

————. 1999. *FAOSTAT Food Balance Sheets.* Rome: FAO.

————. 2000. *FAOSTAT Production Statistics.* Rome: FAO.

Gerpacio, R. (ed.). 2001. *Impacts of International Maize Breeding Research in Asia, 1966–1998.* Mexico, D.F.: CIMMYT. (in press).

Hassan, R.M., M. Mekuria, and W.M. Mwangi. *Maize Breeding Research in Eastern and Southern Africa: Current Status and Impacts of Past Investments by the Public and Private Sectors,* 1966–1997. Mexico, D.F.: CIMMYT. (in press).

Heisey, P.W., and G.O. Edmeades. 1999. Maize Production in Drought-Stressed Environments: Technical Options and Research Resource Allocation. Part 1 of *CIMMYT 1997/98 World Maize Facts and Trends; Maize Production in Drought-Stressed Environments: Technical Options and Research Resource Allocation.* Mexico, D.F.: CIMMYT.

Heisey, P.W., and W.M. Mwangi. 1996. *Fertilizer and Maize Production in Sub-Saharan Africa: Use and Policy Options.* Mexico, D.F.: CIMMYT.

Huang, J., C. Chen, S. Rozelle, and F. Tuan. Trade liberalization and China's food economy in the 21st century: implications to China's national food security. Paper presented at the International Agricultural Trade Research Consortium: China's Agricultural Trade and Policy: Issues, Analysis and Global Consequences. San Francisco, California, June 1999.

IFPRI. 2000. 2020 Projections. Washington, D.C.:IFPRI.

IMF (International Monetary Fund). 2000. *IMF World Economic Outlook.* May 2000.

Jensen, L. 2000. A Bio-Based Future: Blue Sky or Opportunity. Remarks made at the Agricultural Outlook Forum, February 25, 2000, Washington, D.C.

Khan, Z.R., K. Ampong-Nyarko, P. Chiliswa, A. Hassanali, S. Kimani, W. Lwande, W.A. Overholt, J.A. Pickett, L.E. Smart, L.J. Wadhams, and C.M. Woodstock. 1997. Intercropping increases parasitism of pests. *Nature* 388: 631–39.

Khan, Z.R., J.A. Pickett, J.van den Berg, L.J. Wadhams, and C.M. Woodcock. 2000. Exploiting chemical ecology and species diversity: stem borer and *Striga* control for maize and sorghum in Africa. *Pest Management Science* 56: 957–62.

Kanampiu, F.K., J.K. Ransom and J. Gressel.. Imazapyr seed dressings for *Striga* control on acetolactate synthase target-site resistant corn. (forthcoming)

Kumwenda, J.D.T., S.R. Waddington, S.S. Snapp, R.B. Jones, and M.J. Blackie. 1996. *Soil Fertility Management Research for the Maize Cropping Systems of Smallholders in Southern Africa: A Review.* Mexico, D.F.:CIMMYT.

Lafitte, H.R., and G.O. Edmeades. 1994a. Improvement for tolerance to low soil nitrogen in tropical maize. I. Selection criteria. *Field Crops Research* 39: 1–14.

————. 1994b. Improvement for tolerance to low soil nitrogen in tropical maize. II. Grain yield biomass production, and N. accumulation. *Field Crops Research* 39: 15–25.

Lin, W., and P. Riley. 1998. Rethinking the Soybeans-to-Corn Price Ratio: Is It Still a Good Indicator for Planting Decisions? *Feed Yearbook.* April 1998. Washington, D.C.: USDA

López-Pereira, M.A., and M.L. Morris. 1994. *Impacts of International Maize Breeding Research in the Developing World, 1966–90.* Mexico, D.F.: CIMMYT.

Morris, M.L. (ed.). 1998. *Maize Seed Industries in Developing Countries.* Boulder, Colorado: Lynner Rienner Publishers, CIMMYT.

————. 2000. *Impacts of International Maize Breeding Research in Developing Countries*, 1966–98. Mexico, D.F.: CIMMYT.

————. 2001 *Impacts of International Maize Breeding Research in Developing Countries.* CIMMYT Economics Program publication. Mexico, D.F.: CIMMYT.

Morris, M.L., and M.A. López-Pereira. 1999. *Impacts of Maize Breeding Research in Latin America, 1966–1997.* Mexico, D.F.: CIMMYT.

OECD. 1997. *Brazilian Agriculture: Recent Policy Changes and Trade Prospects.* Paris: Directorate for Food, Agriculture and Fisheries.

Pandey, S., H. Ceballos, and G. Granados. 1994. Development and improvment of lowland tropical maize populations by CIMMYT's South American regional maize program. In S.K. Vasal and S. McLean (eds.), *The Lowland Tropical Maize Subprogram.* Maize Program Special Report. Mexico, D.F.: CIMMYT.

Parker, C., and C.R. Riches. 1993. *Parasitic Weeds of the World: Biology and Control.* Wallingford, UK.: CAB International

Pingali, P.L. 2001. Population and technological change in agriculture. In N.J. Smelser and P.B. Baltes (eds.), *International Encyclopedia of the Social and Behavioral Sciences.* London: Pergamon.

Pingali, P.L., M. Hossain, and R.V. Gerpacio. 1997. *Asian Rice Bowls: The Returning Crisis?* New York: IRRI/CABI

Pingali, P.L., M. Hossain, S. Pandey, and L.L. Price. 1998. Economics of nutrient management in Asian rice systems: towards increasing knowledge intensity. *Field Crops Research* 56: 157–76.

Pingali, P.L., and S. Rajaram. 1997. Technological opportunities for sustaining wheat productivity growth. Paper prepared for the Illinois World Food and Sustainable Agriculture Program Conference, Meeting the Demand for Food in the 21st Century: Challenges, and Opportunities for Illinois Agriculture, 27 May 1997, Urbana-Champaign, Illinois.

Pinstrup-Anderson, P., R. Pandya-Lorch, and M.W. Rosegrant. 1999. World food prospects: critical issues for the early twenty-first century. *IFPRI 2020 Vision Food Policy Report.* Washington, D.C.: IFPRI.

Ransom, J.K., G.D. Odhiambo, R.E. Eplee, J.I. Ubero, D. Berner, and L.J. Musselmann. (eds.). 1996. *Proceedings of the 6th International Symposium on Parasitic Weeds, Cordoba. Spain.* Pp. 327–34.

Reca, L., and E. Diaz Bonilla. 1997. Changes in Latin American Agricultural Markets. Paper presented at the 19th International Policy Council, Full Meeting, Belo Horizonte, Brazil May 1997.

Ribaut, J.-M., G.O. Edmeades, J.F. Betran, C. Jiang, and M. Bänziger. 1999. Marker-assisted selection for improving drought tolerance in tropical maize. In O. Ito, J. O'Toole, and B. Hardy (eds.), *Genetic Improvement of Rice for Water-Limited Environments.* Proceedings of the Workshop on Genetic Improvement of Rice for Water-Limited Environments, 1-3 December 1998, Los Baños, Philippines. Los Baños, Philippines: IRRI.

Riley, P. 1998. The Impact of New Technology on the Corn Sector: 1998 Update and Prospects for the Future. *Feed Yearbook*, April 1998, Washington, D.C.: USDA

Rosen, S., and L. Scott. 1992. Famine grips Sub-Saharan Africa. *Agricultural Outlook* 191: 20–24.

Sanchez, P.A., K.D. Shepherd, M.J. Soule, F.M. Place, R.J. Buresh, A.-M.N. Izac, A.U. Mokwunye, F.R. Kwesiga, C.G. Ndiritu, and P.L. Woomer. 1997. Soil fertility replenishment in Africa: An investment in natural resource capital. In R.J. Buresh, P.A. Sanchez, and F. Calhoun (eds.), *Replenishing Soil Fertility in Africa.* SSSA Spec. Publ. 51. Madison, Wisconsin: SSSA. Pp.1–46.

Sharma R.C., C. de Leon, and M.M. Payak. 1993. Diseases of maize in South and South-East Asia: problems and progress. *Crop Protection* 12(6): 414–22.

Tuan, F., H. Colby, and Q. Cao. 2000. Demand for livestock stalls.*International Agriculture and Trade Reports: China Situation and Outlook Series*, WRS-99-4. March 2000.Washington D.C.: USDA-ERS.

Tuan, F., and T. Peng. 2001. Structural changes in China's livestock production and its trade implications. Paper presented at the 45th Annual Conference of the Australian Agricultural and Resource Economics Society, 23-25 January 2001, Adelaide, South Australia.

Turlings, T.C.J., J.H. Loughrin, P.J. McCall, U.S.D. Rose, W.J. Lewis, and J.H. Tumlinson. 1995. How caterpillar-damaged plants protect themselves by attracting parasitic wasps. *Proc. Nat. Acad. Sci.* (USA) 92: 4169–74.

UNICEF. 2000. *The State of theWorld's Children.* New York: UNICEF.

United Nations. 1999. *World Population Prospects: The 1998 Revision.* New York: United Nations.

USDA-Economic Research Service (ERS). 1998. The Future of Brazil's Agricultural Sector. *Agricultural Outlook*, May 1998. Washington D.C.: USDA.

————. 1999. Value-Enhanced Crops: Biotechnology's Next Stage, *Agricultural Outlook*, March 1999. Washington D.C.: USDA-ERS.

————. 2000a.China's WTO accession would boost U.S. ag exports and farm income. *Agricultural Outlook.* March 2000.Washington, D.C.: USDA-ERS.

————. 2000b. Biotechnology: Implications for U.S. Corn and Soybeans Trade, *Agricultural Outlook*, April 2000. Washington D.C.: USDA-ERS.

————. 2000c. "Corn Production and Use To Hit Record Highs. *Agricultural Outlook*, October 2000. Washington D.C.: USDA.

————. 2000d. *Feed Outlook.* January 2000. Washington D.C.: USDA-ERS.

————. 2000e. *Feed Outlook.* March 2000. Washington D.C.: USDA-ERS.

USDA-Foreign Agricultural Service (FAS) 1998a.*Foreign Countries' Policies and Programs*, circular, September 1998. Washington D.C.: USDA-FAS.

————. 1998b. *Argentina Driving Global Maize Market into New Era,* circular, 98-3, 1998. Washington D.C.: USDA-FAS.

————. 2000a. *The U.S.-China WTO Accession Deal: A Strong Deal in the Best Interests of U.S. Agriculture.* February 2000. Washington, D.C.: USDA-FAS.

————. 2000b. *Permanent Normal Trade Relations With China: What's at Stake for Corn?* May 2000.Washington, D.C.: USDA-FAS.

————. 2000c. *Selected Global Agriculture Information Network Reports.* September 2000. Washington, D.C.: USDA-FAS.

————. 2001a. *Grain: World Markets and Trade.* www.fas.usda.gov April 2001.

————. 2001b. World Grains by Commodity. *World Agricultural Production.* www.fas.usda.gov April 2001.

Woomer, P.L., A. Martin, A. Albrecht, D.V.S. Resck, and H.W. Scharpenseel. 1994. The importance and management of soil organic matter in the tropics. In P.L. Woomer and M.J. Swift (eds.), *The Biological Management.*

Waddington, S.R., and P.W. Heisey. 1997. Meeting the nitrogen requirements of maize grown by resource-poor farmers in Southern Africa by integrating varieties, fertilizer use, crop management and policies. In G.O. Edmeades, M. Bänziger, H.R. Mickelson, and C.B. Peña-Valdivia (eds.), *Developing Drought- and Low N-Tolerant Maize.* Proceedings of a Symposium, El Batan, Mexico, 25–29 March, 1996. Mexico, DF: CIMMYT. Pp. 44–57.

World Bank. 1996. *Trends in Developing Economies*, Washington, D.C.: World Bank.

World Bank. 2000. *World Development Indicators.* Washington D.C.: World Bank.

Zhou, Z.Y., W.M. Tian, X.A. Liu, and G.H.Wan. 2001. An issue of debate: China's feedgrain demand and supply. Paper presented at the 45th Annual Conference of the Australian Agricultural and Resource Economics Society, 23-25 January 2001, Adelaide, South Australia.

Appendix A

Regions of the World

Developing Countries

EASTERN AND SOUTHERN AFRICA

Angola
Botswana
Burundi
Comoros
Djibouti
Eritrea
Ethiopia
Kenya
Lesotho
Madagascar
Malawi
Mauritius
Mozambique
Namibia
Rwanda
Seychelles
Somalia
South Africa
Sudan
Swaziland
Tanzania
Uganda
Zambia
Zimbabwe

WESTERN AND CENTRAL AFRICA

Benin
Burkina Faso
Cameroon
Cape Verde
Central Africa Republic
Chad
Congo, Democratic Republic of
Congo, Republic of
Côte d'Ivoire
Equatorial Guinea
Gambia
Ghana
Guinea
Guinea-Bissau
Liberia
Mali
Mauritania
Niger
Nigeria
Sao Tome and Principe
Senegal
Sierra Leone
Saint Helena
Togo

NORTH AFRICA

Algeria
Egypt
Libya
Morocco
Tunisia

WEST ASIA

Afghanistan
Bahrain
Iran
Iraq
Jordan
Lebanon
Oman
Saudi Arabia
Syria
Turkey
Yemen

SOUTH ASIA

Bangladesh
Bhutan
India
Maldives
Myanmar
Nepal
Pakistan
Sri Lanka

SOUTHEAST ASIA AND THE PACIFIC

American Samoa
Cook Islands
East Timor
Fiji
Indonesia
Kiribati
Laos
Malaysia
Nauru
Niue Island
Norfolk Island
Papua New Guinea
Philippines
Samoa
Solomon Islands
Thailand
Tokelau
Tonga
Tuvalu
Vanuatu
Vietnam
Wallis and Futuna Island

EAST ASIA

China
Mongolia
North Korea
South Korea

MEXICO, CENTRAL AMERICA, AND THE CARIBBEAN

Antigua and Barbuda
Barbados
Belize
Costa Rica
Cuba
Dominica
Dominican Republic
El Salvador
Grenada
Guadeloupe
Guatemala
Haiti
Honduras
Jamaica
Mexico
Montserrat
Netherlands Antilles
Nicaragua
Panama
Saint Kitts and Nevis
Saint Lucia
Saint Pierre Miquelon
Saint Vincent
Grenadines
Trinidad and Tobago

ANDEAN REGION, SOUTH AMERICA

Bolivia
Colombia
Ecuador
Guyana
Peru
Suriname
Venezuela

SOUTHERN CONE, SOUTH AMERICA

Argentina
Brazil
Chile
Falkland Islands
Paraguay
Uruguay

Eastern Europe and Former Soviet Union

Albania
Armenia
Azerbaijan
Belarus
Bosnia Herzegovina
Bulgaria
Croatia
Czech Republic
Estonia
Georgia
Hungary
Kazakhstan
Kyrgyzstan
Latvia
Lithuania
Macedonia
Moldova Republic
Poland
Romania
Russian Federation
Slovakia
Slovenia
Tajikistan
Turkmenistan
Ukraine
Uzbekistan
Yugoslavia, Fed. Rep. of

Western Europe, Japan, and Other High-Income Countries

Australia
Austria
Belgium-Luxembourg
Brunei Darussalam
Canada
Cyprus
Denmark
Faeroe Island
Finland
France
Germany
Greece
Greenland
Iceland
Ireland
Israel
Italy
Japan
Kuwait
Malta
Netherlands
New Zealand
Norway
Portugal
Qatar
Singapore
Spain
Sweden
Switzerland
United Arab Emirates
United Kingdom
United States

ISSN: 0257-8743

CIMMYT®

International Maize and Wheat Improvement Center
Apdo. Postal 6-641, 06600 Mexico, D.F., Mexico
www.cimmyt.org