Maize in the Developing World: Trends, Challenges, and Opportunities

BM Prasanna

Director, Global Maize Program, CIMMYT (International Maize and Wheat Improvement Center), Nairobi, Kenya; Email: b.m.prasanna@cgiar.org

ABSTRACT. Maize is the basis for food security in some of the world's poorest regions in Africa, Asia, and Latin America. Together with rice and wheat, maize provides at least 30% of the food calories of more than 4.5 billion people in 94 developing countries. They include 900 million consumers with incomes of less than US$ 2 per day for whom maize is the preferred staple.

Globally, 765 million metric tons of maize was harvested in 2010 from just less than 153 million hectares. About 73 per cent of this area was located in the developing world, with again a predominant proportion of this area in the low and lower middle income countries. Maize is currently produced on nearly 100 million hectares in 125 developing countries and is among the three most widely grown crops in 75 of those countries. The crop provides over 20% of total calories in human diets in 21 countries, and over 30% in 12 countries that are home to a total of more than 310 million people.

Production of maize, especially in the tropical regions, is affected by a number of constraints, including an array of abiotic and biotic stresses, poor soil fertility, lack of access to key inputs (especially quality seed and fertilizers), low levels of mechanization, and poor post-harvest management. The result: maize yields in many of the sub-Saharan African countries, where maize is the most important staple food, are often extremely low, averaging approximately 1.5 tons per hectare—about 20% of the average yield in developed countries — and yields in several Asian countries are still below 3 tons per hectare. In addition, one-third of all malnourished children are found in systems where maize is among the top three crops.

Recurrent food price crises—combined with the global financial meltdown, volatile energy prices, natural resource depletion, and climate change—threaten the livelihoods and food security of millions of poor people. At the same time, demand for maize in the developing world is expected to double by 2050. By 2025, maize is expected to have become the crop with the greatest production globally and in the developing world. The growth in demand for human consumption of maize in the developing world is predicted to be 1.3% per annum until 2020. Moreover, rising incomes are expected to result in a doubling of consumption of meat across the developing world, leading to a predicted growth in demand for feed maize of 2.9% per annum. But harvests at current levels of productivity growth will still fall short of demand and millions of farm families will remain in poverty. Unless vigorous measures are taken the outcome will be less affordable food for millions of poor maize consumers, continuing poverty and childhood malnutrition, deforestation, soil degradation, reduced biodiversity, and accelerated depletion of water and fertilizer reserves.

Developing and deploying climate resilient germplasm adapted to the tropical/sub-tropical maize-growing regions, has become one of the topmost priorities. An equally important task is to enhance the adoption of such germplasm by the smallholder farmers. While breeding and delivery of quality seed are undoubtedly critical for the future of maize production, and consequently, the livelihoods of several million smallholder farmers worldwide, these efforts alone will not be adequate. Sustainable intensification of maize-based systems warrant complementation of improved cultivars with sustainable crop and natural resource management practices, as well as socio-economic interventions for maize futures (effective policies, institutions, technology targeting, and markets). "**MAIZE** – Global Alliance for Improving Food Security and the Livelihoods of the Resource-Poor in the Developing World" is the CGIAR Research Program (CRP) that aims to address the above-mentioned challenges of enhancing global food security, reducing poverty, and sustaining the environment in the maize-based systems. MAIZE, in essence, presents a new results-oriented strategy to fully exploit the potential of international maize research-for-development.

Besides breeding elite maize germplasm with tolerance to multiple abiotic stresses (especially drought, heat, waterlogging, acidity), another important challenge of adapting crops to the changing climate will be to maintain their genetic resistance to insect-pests and diseases. Although strategies to limit the effect of climate change on pests and diseases do not fundamentally differ from existing integrated pest management practices, there needs to be a much greater emphasis on modelling and forecasting systems, while host-resistance will continue to have a pivotal role.

Recent research has led to the development of a suite of soil and crop management practices for increasing resource use efficiency while maintaining soil health, and mitigating greenhouse gas emissions. Increased use of conservation agriculture practices is required to reduce climate change impacts. In addition to identifying/developing a new generation of maize cultivars suitable for conservation agriculture-based practices, achieving increased adaptation action will necessitate integration of climate change-related issues with other risk factors, such as climate variability and market risk, and with other policy domains. The above important researchable issues are being addressed by CIMMYT under the CCAFS (Climate Change, Agriculture and Food Security) CGIAR Research Program (CCAFS CRP).

More than 85% of the maize produced worldwide is used directly for food and feed; therefore, enhancing the nutritional quality of maize is an important breeding objective. 'Biofortification', or the improvement of nutritional quality in food crops, is a promising strategy to combat undernutrition, particularly among the rural poor in developing countries. The development of Quality Protein Maize (QPM) by CIMMYT, which contains almost double the amount of endosperm lysine and tryptophan as compared to the normal/non-QPM maize, is indeed a major milestone in maize breeding and biofortification. A range of hard endosperm QPM germplasm has been developed at CIMMYT, mostly through conventional breeding approaches to meet the requirements of various maize growing regions across the world. Many maize breeding programs operating in Africa, Latin America, and parts of Asia have deployed QPM varieties, for achieving a positive impact on the nutrition and health of local populations.

HarvestPlus, a multi-institutional Program on Agriculture for Improved Nutrition and Health, leads a global effort to develop and deliver biofortified staple food crops, including provitamin A enriched maize. Provitamin A biofortification of maize started seven years ago in CIMMYT-Mexico in partnership with IITA-Nigeria and several institutions/ Universities worldwide, and considerable progress has been achieved till date. In addition to provitamin A-enriched elite germplasm development, ongoing activities include assessment and validation of farmer and consumer acceptance of the promising hybrids, and to begin creating interest, demand and supply for seed of the best hybrids. Using marker-assisted selection for two key genes influencing provitamin A biosynthesis (*LycE* and *CrtRB1*), source lines with >15 µg/g of provitamin A carotenoids have been identified/developed, and now routinely used as parents for new crosses at CIMMYT.

New plant breeding strategies that utilize high-density genotyping based on next-generation DNA sequencing technology, coupled with precision phenotyping, genomic selection (GS) and doubled haploid (DH) technology, could significantly accelerate the development of stress-resilient and nutritionally enriched maize varieties. Genotyping-by-sequencing (GBS) has now become an integral component of CIMMYT's maize molecular breeding strategies. As whole genome molecular information builds up, new insights are being obtained into the maize genome organization and evolution, as well as strategies to utilize the rapidly expanding genomic information for maize improvement. Genome-wide association studies (GWAS), implemented through high throughput genotyping and precision phenotyping, has emerged as a powerful strategy for dissecting complex traits and identifying superior alleles contributing to improved phenotypes in maize. GWAS is being applied by CIMMYT-GMP for identification of genomic regions associated with an array of important traits, especially abiotic stress tolerance and disease resistance.

The doubled haploid (DH) technology offers powerful means to derive improved products through time- and cost-effective breeding. The *in vivo* haploid induction and subsequent doubling of maternal haploids to derive DH lines in maize is an important component of maize breeding strategy. However, adoption of DH technology by several of the maize breeding institutions under NARS, as well as small and medium enterprise (SME) seed companies, especially in the developing countries, is limited by the lack of inducers adapted to the tropical/sub-tropical conditions. CIMMYT-GMP, in collaboration with the Institute of Plant Breeding, Seed Science and Population Genetics of the University of Hohenheim, addressed this limitation and has developed tropicalized haploid inducers (with high haploid induction rate) that are now being shared with the interested institutions for research/commercial use. Thus, judicious combination of modern strategies like high throughput and precision phenotyping, GWAS, rapid-cycle GS, and DH-based breeding, coupled with conventional breeding wisdom, can accelerate development of elite, high-yielding, climate resilient and nutritionally enriched maize cultivars that can contribute to enhanced food security and sustainable intensification of maize-based systems.

Introduction

Maize provides food, feed and nutritional security in some of the world's poorest regions in Africa, Asia, and Latin America. Globally, 765 million metric tons (m t) of maize were harvested in 2010 from just under 153 million hectares (m ha). About 73 per cent of this area was located in the developing world, with again a predominant proportion of this area in the low and lower middle income countries. The crop provides over 20% of total calories in human diets in 21 countries, and over 30% in 12 countries that are home to a total of more than 310 million people (Shiferaw et al. 2011). For 900 million farmers and consumers in low- and middle-income countries, maize is a preferred crop or food.

The growth in demand for human consumption of maize in the developing world is predicted to be 1.3% per annum until 2020. Moreover, rising incomes are expected to result in a doubling of consumption of meat across the developing world (Naylor et al. 2005), leading to a predicted growth in demand for feed maize of 2.9% per annum. However, the average maize yields in several of the developing countries, especially in sub-Saharan Africa, where maize is a highly important staple food crop, are still below 1 t/ha, while many countries have only 1-2 t/ha, due mainly to poor soil fertility, frequent occurrence of droughts, high incidence of insect-pests, diseases and weeds, farmers' limited access to fertilizer, and lack of access to improved maize seed (Shiferaw et al. 2011). The importance of improving maize production and productivity in the developing world could be gauged from the fact that one-third of all malnourished children are found in systems where maize is among the top three crops (Hyman et al. 2008).

Asia's contribution to the worldwide harvested maize area as well as production has been significantly increasing. The major maize producers in Asia are China and D.P.R. Korea in East Asia; Indonesia, Philippines, Vietnam and Thailand in Southeast Asia; India, Pakistan and Nepal in South Asia; and Turkey and Iran in West Asia. It is notable that eight major maize-producing countries in Asia – China, India, Indonesia, Nepal, Pakistan, Philippines, Thailand, and Vietnam – taken together, now produce 98% of Asia's maize and 26% of global maize (Erenstein, 2010); in all these countries, maize is predominantly grown under rainfed conditions by the smallholder, resource-poor farmers.

The maize scenario in Asia is somewhat unique compared to the rest of the world. Firstly, 70% of the total maize produced in Asia is used for feed purposes, 23% as food, and 7% for other uses. By contrast, in sub-Saharan Africa, maize is mainly a food crop accounting for 73% and 64% of the total demand in Eastern and Southern Africa (ESA) and Western and Central Africa (WCA), respectively (Shiferaw et al., 2011). Although the maize feed market is rapidly growing, especially in countries such as China, India and Indonesia, maize is still an important staple food in many countries/areas in Asia, especially in the hills and tribal regions of Nepal, Bhutan, and India. Secondly, in terms of grain preference, unlike sub-Saharan Africa where white maize plays a highly dominant role as food, in almost all the Asian maize-growing countries, the demand is mostly for yellow maize. Despite these differences, the resource-poor maize farmers in Asia face many challenges that are shared by smallholders in sub-Saharan Africa and Latin America; among many, these include poor purchasing capacity, an array of abiotic and biotic stresses, poor soil fertility, and limited access to quality seed (particularly in the non-commercial maize belts).

The Growing Demand

During 2003-08, maize production increased annually by 6.0% in Asia, as compared to 5.0% in Latin America, and 2.3% in sub-Saharan Africa (FAOSTAT, 2010). However, between now and 2050, the demand for maize in the developing world will double, and by 2025 maize will have to become the crop with the highest production in the developing world (Rosegrant et al., 2009). This has particular implications to Asia, where an array of factors is contributing to a sharply increasing demand for maize, including the growth rate of per capita GDP (gross domestic product), changing diets, and a significant rise in feed use that is driven largely by the strongly growing poultry sector. Maize use for feed in the seven major Asian countries has more than tripled from 29 m t in 1980 to 109 m t in 2000 (Wada et al. 2008).

China's rapid economic growth, coupled with the booming maize feed and processing demand, has the potential to transform the global maize scenario. In 2010, China's maize area in 2010 (31.5 m ha) was quite comparable to that of USA (32.89 m ha). During the past four decades, China registered an impressive 3.4% annual average growth rate in maize yields, and by 2002 had become the world's second leading exporter of maize, after the USA (Dixon et al. 2008; Wada et al. 2008). However, China recently started to import maize, and to date has imported about 1 million metric tons of maize. Indonesia, the third biggest maize-growing country in Asia, imported 1.1 million metric tons of maize in 2010. Although predictions vary considerably in magnitude, there seems to be little doubt that the rate of increased demand will soon out-pace the rate of increased maize production in Asia, and that China, Japan, South Korea, Malaysia, Philippines and Thailand may import substantial amounts by 2025 (Gerpacio and Pingali 2007; Falcon 2008).

Both the area and production of maize in India have grown significantly in the past few decades. Maize grain production has increased from about 7 million tons in 1980/81 to about 21 million tons in 2010/11. The impressive growth of maize in India has been largely driven by the increasing demand for maize grain as feed for the rapidly expanding poultry industry (Hellin and Erenstein 2009). The adoption of maize in non-traditional areas, the strong role of the private sector in the maize seed industry, and the development and delivery of higher-yielding, single-cross hybrids, are some of the major factors behind this. Annual growth rates for production have been recorded as 1.9%, 3.3% and 5.3% for the decades 1980–1990, 1990–2000, 2000–2010, respectively. While growth in the first two decades (1980-2000) was driven mainly by the yield increases due to improved adoption of high-yielding cultivars, area expansion had constituted more than half the growth over the past decade (DAC 2010).

Simultaneous with these trends, maize prices have more than doubled over the past ten years, along with prices of other commodities, with consequent implications to maize-dependent countries and consumers in the developing world. What happens in the rest of the world, especially in the USA which is the largest producer and exporter of maize, affects the maize prices worldwide. Since prices are largely influenced by supply-and-demand, world maize prices are largely dependent not only on the weather in the US Corn Belt, but also the pattern of maize use (40 per cent of maize produced in US is used for producing ethanol).

Challenges to Maize Production

Despite the impressive growth in the last decade, the average maize yields in many of the Asian countries still remain low vis-à-vis the world average of 5.02 t/ha in 2010. Countries with sizable maize area but with less than 3 t/ha yields include India, Indonesia, Philippines, Pakistan and Nepal, while Vietnam and Thailand have registered maize yields in the range of 4-5 t/ha in 2010. China recorded an average yield of 5.33 t/ha in 2010. Although maize is grown in almost every province in China, approximately two-thirds of the maize in China is grown in temperate, high-potential production environments in the north, and the rest is grown in the subtropical and tropical environments of the south.

Drought is recognized as the most important constraint across the rainfed lowland and upland environments, covering about 70% of the maize production area in Asia. This situation is likely to exacerbate in the coming decades due to climate change, often leading to inadequate and/or uneven incidence of rainfall in the crop season alongside temperature changes (IPCC 2007). Alleviating the effects of drought alone could increase average maize yields by 35% across Asia-7 (excluding China), and by 28% in Southwest China (Gerpacio and Pingali 2007). At the same time, over 18% of the total maize production area in South and Southeast Asia is frequently affected by floods and waterlogging problems, causing production losses of 25–30 % annually (Zaidi et al. 2010).

By the end of this century, growing season temperatures will exceed the most extreme seasonal temperatures recorded in the past century (Battisti and Naylor 2009). Recent analysis of more than 20,000 historical maize trial yields in Africa over an eight year period, combined with weather data, showed that for every degree day above 30°C, maize grain yield was reduced by 1% and 1.7 % under optimal rainfed and drought conditions, respectively (Lobell et al. 2011). High temperature stress and drought are likely to aggravate in northern China (Piao et al. 2010) as well as in many tropical maize growing areas, especially in South and Southeast Asia. Spring maize is an important option for intensifying and diversifying cropping systems in South Asia, but is prone to severe heat stress during flowering/early grain filling stages, particularly in the upper and middle Indo-Gangetic plains. This highlights the importance of developing maize germplasm with tolerance to both drought and high temperature stress.

Biotic stresses that that have widespread effects in Asia include the downy mildews, post-flowering stalk rots (PFSR), grey leaf spot (GLS), banded leaf and sheath blight (BLSB), turcicum leaf blight (TLB), ear rots, mycotoxins, stem borers and weevils. Rising temperatures and variations in humidity also potentially affect the diversity and responsiveness of pathogens and insect-pests, and could lead to new and perhaps unpredictable epidemiologies (Gregory et al. 2009). For example, GLS is now becoming an important disease globally, with high incidences reported in Nepal, China, Bhutan, Colombia, Mexico, Brazil and several countries in Africa.

Poor soil fertility (including micronutrient deficiencies) and low nutrient use efficiency also rank among the most important factors limiting crop productivity and yield stability in both high potential–low risk environments as well as low potential–high risk environments. A common concern is imbalanced fertilizer use (i.e., very high use of N, less use of P, and negligible use of K, S, and micronutrients), which is particularly prevalent in the rice-maize systems that are distributed all over South Asia, but more so in Bangladesh, India, Nepal, and Pakistan (Timsina et al. 2010). Obviously, genetics and breeding alone cannot solve the complex challenge of enhancing productivity in smallholder farms. There is a distinct need for effective complementation of improved maize cultivars by suitable conservation agriculture practices. Availability of equipment for direct seeding or minimal tillage operations is a constraint that needs to be addressed in developing locally relevant options for conservation agriculture. In addition, agronomists and geneticists/breeders have to work in tandem to identify cultivars that respond best to such practices, and for generating better understanding of the complex interactions between genotype x environment x management practices.

Much has to be achieved also in terms of institutional and policy innovations that support maize growth and development in Asia. Also, an integrated approach that links the biophysical and the socioeconomic work is essential for success in improving productivity of maize and in enhancing adaptation to changing climate (Shiferaw et al. 2011). This includes understanding the smallholder farmers' affordability and access to quality seed, constraints in adoption of high-yielding, stress resilient and nutritionally enriched maize varieties, and partnerships and policies to significantly enhance seed production and distribution.

Climate Resilient Maize Cultivars

Drought Tolerance

Drought is undoubtedly a major cause of yield loss in maize worldwide (Bänziger and Araus 2007) and projections of decreasing precipitation and increasing evaporative demand within rainfed maize areas will further exacerbate losses (IPCC 2007). Understanding the environmental conditions that contribute to drought and the expression of genetic variation for drought tolerance is critical to the success of any attempts to breed for drought tolerance. CIMMYT's work on characterization of drought-prone environments (especially in sub-Saharan Africa and Latin America), identification of suitable secondary traits in breeding for drought tolerance, optimizing procedures for undertaking managed stress trials, developing drought stress tolerant germplasm through extensive multi-location experiments, and disseminating the stress tolerant cultivars in partnerships with various public and private organizations holds considerable significance for developing drought tolerant maize cultivars also in Asia.

The discovery, enhancement and delivery of useful germplasm to farmers is undertaken as a pipeline by CIMMYT, starting from identifying new sources of drought tolerance from among the world's genetic resources, through strategic germplasm enhancement targeted at smallholder farmers' maize production environments in the tropical agro-ecologies, to variety development, testing and release, and seed dissemination to target beneficiaries by the partner institutions. Substantial emphasis is placed on strengthening the regional/local capacity of both public and private institutions for continued improvement plus rapid and widespread dissemination of drought tolerant maize varieties in sub-Saharan Africa, Latin America and Asia. In recognition that a common constraint for SME seed companies and of rapid scale-up of new varieties is parental line maintenance and foundation (basic) seed production, CIMMYT also provides appropriate technical support for these activities, at least in the initial phases of variety commercialization, on a case-by-case basis. The basis for determining this support will be "seed road maps" that are developed with partner institutions for each product.

The CIMMYT-Asia Program, in collaboration with public and private institutions in South and Southeast Asia, is presently developing Asia-adapted, yellow maize germplasm with drought tolerance, through an array of projects.

Heat Tolerance

Maize is a C4 plant (a plant that generates a 4-carbon sugar as its basic photosynthetic sugar) and it is expected to tolerate erratic environmental changes much better than that of C3 plants. However, maize is particularly vulnerable to the reproductive stage heat stress. Relatively little research has been conducted on heat stress tolerance of maize as compared to other abiotic stresses. However, evidences are emerging in recent years that indicate the negative effect of high temperature on the performance of maize. A recent study showed that each degree day spent above 30°C reduced the final yield of maize by 1% under favorable growing conditions and 1.7% under drought stressed environments (Lobell et al. 2011). The most important effects of elevated temperatures on maize yield reduction include shortened life cycle, reduced light interception, and increased sterility (Stone 2001; Cairns et al. 2012).

Out of a total of approximately 6 million hectares of hybrid maize grown in South Asia, nearly a million hectares are highly vulnerable to high temperature stress especially during flowering. At the same time, spring maize has become an important option for intensifying and diversifying cropping systems in South Asia, especially in the upper and middle Indo-Gangetic plains, but the crop is prone to severe heat stress as well. Therefore, mainstreaming heat stress tolerance in elite tropical maize germplasm has emerged as an important breeding objective.

CIMMYT has started heat stress screening of its available germplasm under field conditions in South Asia. Initial experiments undertaken by the CIMMYT-Asia team to identify heat stress tolerant tropical maize lines among the elite, drought tolerant maize germplasm developed in Mexico, Asia and Africa revealed: (a) high vulnerability of most of the tropical maize germplasm, including commercial cultivars in South Asia, to reproductive stage heat stress; and (b) poor correlation between drought and heat tolerance, indicating that physiological mechanisms that contribute to heat stress tolerance in maize may be different from those that contribute to drought tolerance (Zaidi and Cairns 2011; Cairns et al. 2012).

Under the USAID Feed-the-Future initiative, CIMMYT is presently leading a project on "Heat Tolerant Maize for Asia" (HTMA) in collaboration with public and private sector partners in India, Bangladesh, Nepal and Pakistan, besides Purdue University, USA. The project aims to apply innovative technologies for accelerated development of heat stress resilient maize germplasm, with potential impact on the maize-dependent and climate change vulnerable regions in South Asia.

Waterlogging Tolerance

Waterlogging is a major problem for maize production in several maize agro-ecologies in South and Southeast Asia where rainfall is erratic and intense, and the soil drainage capacity is poor. The problem of waterlogging during the crop cycle is exacerbated due to climate change in some maize-growing regions in the developing world;

for example, the distribution patterns of rainfall rather than total annual rainfall are predicted to change in South Asia and in many areas in sub-Saharan Africa (IPCC 2007). Flood and waterlogging frequently affect more than 18% of the total maize production area in South and Southeast Asia causing production losses of 25–30% annually (Zaidi et al. 2010; Cairns et al. 2011, 2012). Erratic rainfall distribution pattern frequently could even cause severe drought and/ or waterlogging within a single crop season, as was the case in some regions of South Asia in 2009.

The development of improved germplasm with combined drought and excess-moisture tolerance is a major challenge, but is required in South and Southeast Asia. CIMMYT's phenotyping experiments in India showed genetic variation for waterlogging tolerance in maize, leading to identification of a few genotypes that can potentially offer tolerance to both drought and waterlogging stresses. However, there is a need to understand the physiological and molecular mechanisms that lead to tolerance, for which research is being undertaken through a project funded by GTZ-Germany.

Low Soil Nitrogen Tolerance

Declining soil fertility, expanding soil acidity, low phosphorus availability and aluminum toxicity affect yields on about 4 million hectares of land worldwide (Shiferaw et al., 2011). The problem of low soil fertility is particularly severe in sub-Saharan Africa where all maize mega environments are affected (Pingali and Pandey 2000). Use of fertilizer and restorative crop management practices remains relatively low and inefficient in many developing countries, particularly in sub-Saharan Africa (Smale et al., 2011). One of the most promising strategies, in this context, is the development of cultivars that are more efficient in taking up or using N, whether that nitrogen is supplied by chemical or organic fertilizers or through biological nitrogen fixation from legumes. CIMMYT has demonstrated that there is substantial genetic variation in maize for yield on severely N-depleted soils. This variation appears to result from genotypic differences in many physiological processes and morphological features, including root architecture, N assimilation enzymes, maintenance of photosynthetic area after flowering, and remobilization of N from vegetative tissue to the grain.

A retrospective analysis of 704 elite hybrid trials conducted by CIMMYT from 2001 to 2009 was used by Weber et al. (2012) to determine the relative ability of optimal, low-N, and managed drought trials to predict performance under the conditions of random abiotic stress and low-N fertility usually faced by African farmers. The study revealed that indirect selection under low-N and optimal conditions was more efficient than direct selection under random abiotic stress or indirect selection under managed drought, especially for early maturing genotypes, but direct selection was most efficient for predicting performance under low N.

The "Improved Maize for African Soils" (IMAS) Project, presently being led by CIMMYT in partnership with public and private sector institutions in sub-Saharan Africa, is focusing on developing and deploying low N tolerant maize varieties that can take up and use more efficiently nitrogen from severely depleted soils, as well as making better use of the little fertilizer African farmers apply.

Soil Acidity/Aluminum Toxicity Tolerance

Soil acidity is a major constraint limiting maize yields in several countries worldwide, ranging from Colombia in South America to Indonesia in South East Asia. The lower yield of crops grown in acid soils is because of combinations of low pH, toxicity of Al, Mn, and Fe, and deficiencies of N, P, Ca, and Mg (Velasquez et al. 2008). However, Al toxicity is the main factor inhibiting the root growth, reducing the water and nutrient uptake and interfering in different physiological process of crop development (Roy et al. 1988). About 20 million hectares of maize are estimated to be grown under acid soils in the world (Von Uexkull and Mutert 1995). Although different strategies have been suggested to improve the productivity of crops under such conditions, including application of lime, the development and deployment of acid soil tolerant cultivars (Welcker et al. 2005; Pandey et al. 2007) is the relatively cost-effective and environment-friendly option. Extensive work on the genetics and breeding for acid soil tolerance has been undertaken by institutions such as EMBRAPA in Brazil (Magnavaca et al. 1987), and CIMMYT's South America Maize Program located in Cali, Colombia (Pandey et al. 1995; Velasquez et al. 2008). Several populations, inbreds, and hybrids with high levels of tolerance to acid soils have been developed by these programs, including acid soil tolerant inbred lines CML530 to CML535 from CIMMYT.

Biotic Stress Resistance

Another important challenge of adapting crops to the changing climate will be to maintain their genetic resistance to insect-pests and diseases. Rising temperatures and variations in humidity affect the diversity and responsiveness of agricultural pests and diseases and are likely to lead to new and perhaps unpredictable epidemiologies (Gregory et al. 2009).

Significant progress has been made in the identification of stable sources of resistance to major maize diseases. CIMMYT undertakes multi-location phenotyping for several diseases including gray leaf spot (Kenya, Zimbabwe, Mexico, Colombia, Southern China and Nepal), Turcium leaf blight (Kenya, Zimbabwe, Zambia, Mexico and India), Maize streak virus (Zimbabwe), and ear rots (Zimbabwe, Mexico, and Kenya). Similarly, multi-location phenotyping is also undertaken for downy mildews, banded leaf and sheath blight (BLSB), and post-flowering stalk rots, all important diseases in tropical regions, in several countries in Asia, especially in India, Indonesia, Southern China.

Insect pests reduce maize production by attaching the different parts of the crop at both pre- and post- harvest stages. Average annual yield loss of 18, 80, and 44-55.9% was reported due to stem borers, grain weevils, and ear rots in several maize producing regions (Shiferaw et al. 2011). CIMMYT has been trying to develop technologies that reduce pre-and post-harvest losses from insects, especially through the Insect Resistant Maize for Africa (IRMA) Project, through conventional breeding. Through this project, elite lines and hybrids that offer resistance to stem borers, large grain borer (*Prostephanus truncates*) and maize weevil (*Sitophilus zeamais*) have been developed (Tefera et al. 2011a,b), and some of these hybrids have already been released by partner institutions in Africa. More than 16 donor lines that have resistance genes to stem borers and storage insects are being used by NARS in Eastern and Southern Africa to introgress new sources of resistance into their own materials in the process of developing hybrids through the IMRA project.

Nutritionally Enriched Maize

Quality Protein Maize (QPM)

CIMMYT scientists pioneered the development of QPM germplasm, which has 2-3 fold higher endosperm lysine and tryptophan, two of the essential aminoacids for human and animal diets (Prasanna et al. 2001). The QPM genotypes are homozygous for the *o2* allele (which enhances lysine and tryptophan content) and have endosperm modifiers that provide a grain texture similar to the normal (non-QPM) germplasm. CIMMYT's tropical and subtropical adapted populations, inbreds and hybrids of QPM have been widely used to develop QPM cultivars in several developing and developed countries (Prasanna et al. 2001; Atlin et al. 2011). Commercial QPM seed is currently available in more than 17 countries in the region, for achieving a positive impact on the nutrition and health of local populations (Atlin et al. 2011).

Nutritional studies in Ethiopia have demonstrated that QPM consumption can reduce or prevent stunted growth in young children whose diets are heavy in maize (Gunaratna et al. 2010). QPM also opened a new opportunity in animal nutrition. For example, pigs fed on QPM grew 2.3 times faster than those of the same age fed on same quantity of normal maize (Osei et al. 1994). Moreover, dietary replacement of normal maize by QPM significantly increased weight gain of broilers and greatly improved feed efficiency (Bai 2002). QPM also provides an ideal platform upon which a number of nutritionally important traits such as enhanced Fe and Zn, low phytate (for increased bioavailability of nutrients), high provitamin-A and high methionine could be combined to derive multiple benefits.

Provitamin A Enriched Maize

HarvestPlus, a multi-institutional program on Agriculture for Improved Nutrition and Health, leads a global effort to develop and deliver biofortified staple food crops with one or more of the three most limiting nutrients in the diets of the poor: vitamin A, zinc, and iron (Bouis and Welch 2010). CIMMYT leads the HarvestPlus-Maize Program, where the primary target is improving provitamin A concentration in the endosperm beyond 15 µg/g. Provitamin A biofortification of maize started seven years ago in CIMMYT, and considerable progress has been achieved till date at CIMMYT and IITA in active collaboration with several institutions/Universities worldwide.

The first-generation provitamin A-enriched maize hybrids developed at CIMMYT-Mexico have about 6 to 9 µg/g of provitamin A. Five of these hybrids have been evaluated during 2010-2011 in the Zambian National Performance Trials (NPT), and three of these hybrids have been released for commercial cultivation in September 2012. In addition to provitamin A-enriched elite germplasm development, ongoing activities in Zambia include assessment and validation of farmer and consumer acceptance of the promising hybrids, and to begin creating interest, demand and supply for seed of the released hybrids.

Many important lessons could be learned from the long experience of institutions such as CIMMYT in developing and disseminating nutritionally enriched maize germplasm, especially QPM. These include the need for: (a) assurance of competitive agronomic performance of the nutritionally enhanced germplasm (vis-à-vis normal maize); (b) high throughput, low-cost and easily accessible phenotyping/screening tools; (c) generating awareness and capacity building of national partners on the strengths and constraints (if any) of such germplasm; (d) effective seed production systems; and (e) strong partnership with national research programs, health and agricultural ministries for complementing the technologies with proper policy support and institutional innovations.

Integrating Novel/Advanced Technologies in Maize Breeding

The ability to develop and deliver maize germplasm combining tolerance to several abiotic and biotic stresses will be critical for the resilience as well as diversification of cropping systems. While conventional breeding has been successful in improving complex traits like drought tolerance, rapid advances in breeding climate change resilient cultivars is possible only by combining genetic analyses, high-throughput genotyping and phenotyping (preferably in the field) together with prediction models and molecular breeding.

Next-generation Sequencers and High-Density Genotyping

The genome sequencing of B73, a very popular inbred line in the US Corn Belt (Schnable et al. 2009), is a significant landmark in maize research. With next-generation DNA sequencing technology (Shendure and Ji 2008), it will be feasible to sequence any maize genotype of interest or undertake high-density genotyping (Metzker 2010). Genotyping-by-sequencing (GBS) has now become an integral component of CIMMYT's maize molecular breeding strategies. As whole genome molecular information builds up, new insights are being obtained into the maize genome organization and evolution, as well as strategies to utilize the rapidly expanding genomic information for maize improvement (Xu et al. 2012).

High-throughput and Reasonably Precise Phenotyping

High throughput and precision phenotyping protocols are now being developed and applied for an array of traits in crops like maize; this is extremely important in accelerated breeding for stress tolerance and improved nutritional quality. Of particular interest to CIMMYT is the development of relatively low-cost, field phenotyping platforms to overcome the limitation of greenhouse or growth chamber phenotyping like that of the High Resolution Plant Phenomics, Centre (http://www.plantphenomics.org/HRPPC). Such field platforms include placement of the remote sensing cameras in aerial platforms such as balloons, zeppelins or remote-controlled airplanes or "polycopters" (eg. http://www.mikrokopter.de/ucwiki/en/MikroKopter) or using light curtains and spectral reflectance sensors mounted on a tractor for evaluating crop performance under field conditions (Montes et al. 2011; Prasanna et al. 2013).

In addition to above, improving throughput and precision of field-based phenotyping, using low cost, easy-to-handle tools, is an area of research that is being intensively pursued, since many of the national agricultural research systems (NARS) and small- and medium-sized seed companies from developing countries cannot afford to establish and maintain expensive high throughout phenotyping platforms. CIMMYT Global Maize Program is making intensive efforts for characterizing field variability at the key phenotyping sites worldwide, and for improving field-based phenotyping. This includes approaches like non-destructive estimation of biomass using NDVI (Normalized Differential Vegetation Index), monitoring soil moisture using neutron probes/TDR, chlorophyll content using SPAD meter, canopy behavior using infrared thermography, etc. (Prasanna et al. 2013).

Doubled Haploid (DH) Technology

Cost- and time-effective development of homozygous lines is an important component of maize breeding. Traditionally, homozygous lines are obtained by repeated selfings of heterozygous material for 6-7 generations, which is a time-consuming and expensive process (Prasanna et al. 2012). The induction and subsequent doubling of maternal haploids is an efficient alternative to generate homozygous lines in quick timeframe (two generations). CIMMYT has adapted the DH technology, in collaboration with the University of Hohenheim (Germany), to accelerate the development of homozygous lines in diverse, elite, highly adapted genetic backgrounds (Prasanna et al. 2012).

The DH technology is a powerful means to accelerate the introgression of novel germplasm into elite maize breeding lines. It enhances "forward breeding" and provides an opportunity to have an earlier look at the potential of new lines, greater knowledge about their environmental adaptability before they are fully tested, and further used as parental lines for hybrid development and commercial cultivation. Use of DH technology can potentially enhance the efficiency of recurrent selection or genomic selection based schemes for traits with low heritability, particularly for breeding programmes without access to offseason nurseries (Bouchez and Gallais 2000). Furthermore, the DH technology enables shifting of resources from the labor-intensive task of repeated inbreeding to generate inbred lines, and spending more time on evaluation of the DH lines for yield and other adaptive traits, and using the identified lines for producing hybrids and synthetics.

In collaboration with University of Hohenheim, CIMMYT has recently developed tropicalized haploid inducer lines (Prigge et al. 2012; Prasanna et al. 2012) to meet the needs of the breeding programs especially in Africa, Latin America and Asia. These haploid inducers are being shared with public and private institutions worldwide through appropriate Material Transfer Agreements (MTAs).

Molecular Marker-assisted Breeding

Molecular marker assisted breeding provides tremendous opportunities for enhancing genetic gains and breeding efficiency in crops like maize (Prasanna et al. 2010; Xu et al. 2012). Moreover, marker-assisted selection techniques are free of the political and regulatory issues that have dominated the application of transgenic/GM technologies (Tester and Langridge 2010).

Microsatellite or simple sequence repeat (SSR) markers located within the *opaque2* (*o2*) gene, that confers the nutritional advantage of QPM, provided opportunities for accelerating the pace of QPM conversion programs through marker-assisted selection or MAS (Prasanna et al. 2010). CIMMYT scientists are also striving to develop reliable, easy-to-use markers for endosperm hardness and free amino acid content in the maize endosperm. Recent technological developments including high throughput, single seed-based DNA extraction, coupled with low-cost, high density SNP genotyping strategies, and breeder-ready markers for some key adaptive traits in maize, promise enhanced efficiency and cost effectiveness of MAS in QPM breeding programs (Babu and Prasanna 2013).

CIMMYT has also successfully employed marker-assisted selection (MAS) for specific genes in the carotenoid biosynthetic pathway in significantly enhancing provitamin A content in elite maize germplasm (Babu et al. 2012). With the discovery of useful allelic diversity for *LycE* and *CrtRB1* and development of molecular markers (Harjes et al. 2008; Yan et al. 2010), source lines with >15 µg/g of provitamin A carotenoids have been identified/developed, especially using MAS, and now routinely used as parents for new crosses at CIMMYT. This has led to the selection of lines with 40-250% higher provitamin A carotenoid concentrations than lines without the favorable allele (Babu et al. 2012).

In addition to the above, molecular markers have an important role to play in improving host-controlled resistance to some major diseases in maize. Some of the disease resistance traits in maize follow polygenic inheritance, governed by a few to many genes/QTL in each case, with low G x E, and reasonably high heritability. For such traits, the best possible strategy could be detection and validation of marker-trait associations, fine mapping for identifying breeder-friendly molecular markers (preferably SNPs), and pyramiding of the favourable alleles using such markers in the desired genetic backgrounds. CIMMYT is presently following this strategy for some of the important maize diseases, especially Maize Streak Virus (MSV), Grey Leaf Spot (GLS), and Turcicum leaf blight (TLB), as these diseases have significant impact on maize production and food security in several developing countries.

Genomic Selection (GS) Based Breeding

Complex traits are those which are governed by many genes/QTL, with high G x E and low heritability (e.g., drought stress tolerance). The genome-wide selection or genomic selection (GS) is a potential strategy for enhancing genetic gains in breeding for such complex traits. This approach could help in effectively avoiding issues pertaining to the number of QTL controlling a trait, the distribution of effects of QTL alleles, and epistatic effects due to genetic background (Bernardo and Yu 2007; Xu et al. 2012). GS also relies on MAS and is under evaluation for the feasibility of incorporating desirable alleles at many loci that have small genetic effect when used individually. In this approach, breeding values can be predicted for individual lines in a test population based on phenotyping and whole-genome marker screens. These values can then be applied to progeny in a breeding population based on marker data only, without the need for phenotypic evaluation. Modeling studies indicate that this method can lead to considerable increases in the rates of genetic gain by accelerating the breeding cycles (Heffner et al. 2009).

New breeding and selection strategies like GS rely on the availability of cheap, robust and reliable marker systems. Pilot projects on the implementation of rapid-cycling GS using much higher marker densities are being initiated by CIMMYT on new platforms based on next generation sequencing technologies, with the ultimate aim of its routine application across the CIMMYT and NARS maize breeding programs in Sub-Saharan Africa, Latin America and Asia.

Transgenic Maize Technology

Among the transgenic or genetically modified (GM) crops that are being grown worldwide, maize has an important place along with soybean, cotton and canola. GM crops occupied an area of 170.3 million hectares in 2012, up from 160 million hectares in 2011. Of the 28 Biotech/GM crop-growing countries in 2012, 17 countries had grown GM maize (James 2013). Several transgenic maize products have been developed and released by multinational companies not only in USA, but also in Africa and Asia, including the Bt maize, herbicide resistant maize, and those with stacked traits, mainly herbicide resistance + insect-resistance (Bt).

Despite the impressive progress, GM crops are not a "magic bullet" in providing solutions to all problems of agriculture. However, the developing world should have access to all cutting-edge technologies, including GM, to improve agricultural production. Research institutions need to judiciously utilize the GM technology in breeding improved maize genotypes for tackling some intractable problems, especially biotic and abiotic stress tolerance. Public-private partnerships are important for effective deployment of improved cultivars in the developing world, and to leverage cutting-edge technologies, such as transgenic technology, for development of novel products for the benefit of farmers and consumers.

Decision Support Tools

With the ongoing revolution in the Information and Communication Technology, there is a great opportunity for the public/private institutions in Asia to empower farmers and consumers even in the remote areas with up-to-date information on improved varieties, agronomic/conservation agriculture practices, markets, weather and pathogens/insect-pests. Information management systems, coupled with decision support tools, need to be adopted by the breeding programs in the public sector institutions, especially in the developing world, as these can significantly enhance genetic gains and breeding efficiency, especially through breeding information management. Such tools supporting breeding programs should include germplasm evaluation, breeding population management, genotype-by-environment interaction, genetic map construction, marker–trait linkage and association analysis, MAS and breeding system design and simulation, plant variety protection and breeding information management (Xu et al. 2012).

International Maize Improvement Consortium (IMIC) in Asia and Latin America

CIMMYT has recently established an International Maize Improvement Consortium (IMIC), which is now functional in Asia and Latin America. The underlying principles for establishing IMIC include research prioritization that is client-determined, a more focused, demand-driven approach, and better defined partner accountability. IMIC-Asia has been established in July 2010 to facilitate focused development and testing of inbred and hybrid maize with abiotic and biotic stress tolerance and high yield potential (germplasm developed by CIMMYT) through a collaborative testing network in Asia. The project also aims to strengthen the capacity of the breeders/technical personnel of the partner institutions in modern maize breeding and breeding informations. The Consortium now has nearly 30 private seed companies in Asia as partners.

IMIC-Latin America (IMIC-LA), established under the MasAgro initiative and supported by SAGARPA (Mexican Government), is a cooperation platform including national institutions like INIFAP, CINVESTAV, Colegio de Postgraduados, state programs, universities, and seed companies. IMIC-LA aims to improve maize productivity and increase the size and competitiveness of the seed production sector in Mexico and other Latin American countries that are dependent upon seed imports, through targeted delivery of germplasm and tools, and capacity strengthening of the local institutions. Mexico is ranked fourth among the most important maize producers in the world, and is the center of origin of maize. Yet, Mexican maize yields are low, only 30% of maize area is planted to hybrids, and most of the seed sown by Mexican producers does not come from national seed companies. Stronger research support for the Mexican maize seed sector is needed to ensure that yields increase at a rate needed to keep food prices low, that low-cost, productive, and stress-tolerant hybrids are accessible to farmers, and that the Mexican seed sector grows and remains competitive.

Future Perspective

Maize fields in many countries, especially in sub-Saharan Africa and Asia, are now increasingly experiencing rising temperatures, more frequent droughts, excess rainfall/ flooding, as well as new and evolving pathogens and insect-pests. Therefore, in addition to the challenge of improving productivity in the face of rising demand for maize, both as food and feed, developing and deploying climate resilient germplasm adapted to the tropical/sub-tropical maize-growing regions, has become one of the topmost priorities (Cairns et al., 2012). An equally important task is to enhance the adoption of such germplasm by the smallholder farmers. While breeding and delivery of quality seed are undoubtedly critical for the future of maize production, and consequently, the livelihoods of several million smallholder farmers worldwide, these efforts alone will not be adequate. Sustainable intensification of maize-based systems warrant complementation of elite, climate resilient cultivars with sustainable crop and natural resource management practices, as well as socio-economic interventions for maize futures (effective policies, institutions, technology targeting, and markets). "MAIZE – Global Alliance for Improving Food Security and the Livelihoods of the Resource-Poor in the Developing World" is the CGIAR Research Program (CRP) that aims to address the above-mentioned challenges of enhancing global food security, reducing poverty, and sustaining the environment in the maize-based systems. MAIZE, in essence, presents a new results-oriented strategy to fully exploit the potential of international maize research-for-development.

Judicious combination of modern strategies like high-density genotyping, high throughput and precision phenotyping, DH technology, molecular marker-assisted and genomic selection-based breeding, coupled with conventional breeding wisdom, can accelerate development of elite, high-yielding, climate resilient and nutritionally enriched maize cultivars that can contribute to enhanced food security and sustainable intensification of maize-based systems in the developing world.

References

Atlin, G.N., N. Palacios, R. Babu, B. Das, S. Twumasi-Afriyie, D. Friesen, H. De Groote, B. Vivek, and K.V. Pixley. 2011. Quality protein maize: progress and prospects. Plant Breeding Reviews 34: 83-131.

Babu, R. and B.M. Prasanna. 2013. Molecular breeding for quality protein maize (QPM). In: Tuberosa R, Varshney R K (Eds) Advances in Genomics of Plant Genetic Resources, Springer (In Press).

Babu, R., N.P. Rojas, S. Gao, J. Yan, and K. Pixley. 2012. Validation of the effects of molecular marker polymorphisms in LcyE and CrtRB1 on provitamin A concentrations for 26 tropical maize populations. Theoretical and Applied Genetics (Published Online DOI 10.1007/s00122-012-1987-3).

Bai, X-F. 2002. Nutritional evaluation and utilization of quality protein maize Zhong Dan 9409 in broiler feed. MSc Thesis. Chinese Academy of Agricultural Sciences, Beijing, PR China.

Battisti, D.S. and R.L. Naylor. 2009. Historical warnings of future food insecurity with unprecedented seasonal heat. Science 323: 240-244.

Bernardo, R. and J. Yu. 2007. Prospects for genome-wide selection for quantitative traits in maize. Crop Science 47: 1082-1090.

Bouchez, A. and A. Gallais. 2000. Efficiency of the use of doubled haploids in recurrent selection for combining ability. Crop Science 40: 23–29.

Bouis, H.E. and R.M. Welch. 2010. Bio fortification – a sustainable agricultural strategy for reducing micronutrient malnutrition in the global South. Crop Science 50: S20-S32.

Cairns, J.E., K. Sonder, P.H. Zaidi, N. Verhulst, G. Mahuku, R. Babu, S.K. Nair, B. Das, B. Govaerts, M.T. Vinayan, Z. Rashid, J.J. Noor, P. Devi, F. San Vicente, and B.M. Prasanna. 2012. Maize production in a changing climate: impacts, adaptation, and mitigation strategies. Advances in Agronomy 114: 1-58.

DAC. 2010. Agricultural statistics at a glance – 2010. Department of Agriculture and Cooperation, Government of India, New Delhi.

Dixon, J., L. Nalley, and J. Hellin. 2008. Asian maize trade and value chains. In: Gulati A., Dixon J. (Eds). Maize in Asia: Changing Markets and Incentives. Academic Foundation, New Delhi.

Erenstein, O. 2010. The evolving maize sector in Asia: challenges and opportunities. Journal of New Seeds 11: 1-15.

Falcon, W.P. 2008. The Asian maize economy in 2025. In: Gulati A, Dixon J (Eds). Maize in Asia: Changing Markets and Incentives. Academic Foundation, New Dehi, pp. 2435-456.

FAOSTAT. 2010. Food and agricultural organization of the United Nations Statistical Database, 2010; from http://faostat.fao.org: FAO.

Gerpacio, R.V. and P.L. Pingali. 2007. Tropical and subtropical maize in Asia: Production Systems, Constraints, and Research Priorities. CIMMYT, Mexico.

Gregory, P.J., S.N. Johnson, A.C. Newton, and J.S.I. Ingram. 2009. Integrating pests and pathogens into the climate change/food security debate. Journal of Experimental Botany 60: 2827-2838.

Gunaratna. N., H. De Groote, P. Nestel, K.V. Pixley, and G.P. Mccabe. 2010. A meta analysis of community based studies on quality protein maize. Food Policy 35: 202-210.

Harjes, C.E., T.R. Rocheford, and L. Bai. 2008. Natural genetic variation in lycopene epsilon cyclase tapped for maize biofortification. Science 319: 330-333.

Heffner, E.L., M.E. Sorrells, and J-L. Jannink. 2009. Genomic selection for crop improvement. Crop Science 49: 1-12.

Hellin, J. and O. Erenstein. 2009. Maize-poultry value chains in India: Implications for research and development. Journal of New Seeds 10: 245-263.

Hyman, G., S. Fujisaka, P. Jones, S. Wood, M.C. De Vicente, and J. Dixon. 2008. Strategic approaches to targeting technology generation: Assessing the coincidence of poverty and drought-prone crop production. Agricultural Systems 98: 50-61.

IPCC. 2007. Climate Change 2007: Synthesis Report. An Assessment of the Inter-Governmental Panel on Climate Change.

James, C. 2013. Global Status of Commercialized Biotech/GM Crops: 2012. Brief 44. ISAAA (http://www.isaaa.org).

Lobell, D.B., M. Bänziger, C. Magorokosho, and B. Vivek. 2011. Nonlinear heat effects on African Maize as evidenced by historical yield trials. Nature Climate Change 1: 42–45.

Magnavaca, R., C.O. Gardner, and R.B. Clark. 1987. Inheritance of aluminum tolerance in maize. In: Gabelman HW, Loughman BC (Eds) Genetic Aspects of Plant Mineral Nutrition. Martinus Nijhoff Publishers, Dordrecht, pp. 201-212.

Metzker, M.L. 2010. Sequencing technologies — the next generation. Nature Reviews Genetics 11: 31-46.

Montes, J.M., F. Technow, B.S. Dhillon, F. Mauch, and A.E. Melchinger. 2011. High-throughput non-destructive biomass determination during early plant development in maize under field conditions. Field Crops Research 121: 268–273.

Naylor, R., H. Steinfeld, W. Falcon, J. Galloway, V. Smil, E. Bradford, J. Alder, and H. Mooney. 2005. Losing the links between livestock and land. Science 310: 1621-1622.

Osei, S.A., D.B. Oaki, K. Ahenkora, B.D. Dzah, W. Haag, S. Twumasi-Afriyie, and A.K. Tua. 1994. Quality protein maize as a main source of energy and amino acids in the diets of starter pigs. Proc Ghanaian Animal Science Symposium 22: 31-36.

Pandey, S., H. Ceballos, and G. Granados. 1995. Registration of four tropical maize populations with acid-soil tolerance. Crop Science 35:1230-1231.

Pandey, S., L. Narro, D.K. Friesen, and S.R. Waddington. 2007. Breeding maize for tolerance to soil acidity. Plant Breeding Reviews 28: 59-100.

Piao, S.L., P. Ciais, and Y. Huang. 2010. The impacts of climate change on water resources and agriculture in China. Nature 467: 43–51.

Pingali, P.L. and S. Pandey. 2000. Meeting world maize needs: technological opportunities and priorities for the public sector, part I of the CIMMYT 1999-2000 world maize facts and trends. Mexico, D.F.: CIMMYT.

Prasanna, B.M., J.L. Araus, J. Crossa, J.E. Cairns, N. Palacios, G. Mahuku, B. Das, and C. Magorokosho. 2013. High-throughput and precision phenotyping in cereal breeding programs. In: PK Gupta, R Varshney (Eds) Cereal Genomics, 2nd edition, Springer (In Press).

Prasanna, B.M., V. Chaikam, and G. Mahuku (Eds). 2012. Doubled haploid technology in maize breeding: theory and practice. Mexico D.F.: CIMMYT, 50 pages.

Prasanna, B.M., K.V. Pixley, M. Warburton, and C. Xie. 2010. Molecular marker-assisted breeding for maize improvement in Asia. Molecular Breeding 26: 339–356

Prasanna, B.M., S.K. Vasal, B. Kassahun, and N.N. Singh. 2001. Quality protein maize. Current Science 81: 1308-1319.

Prigge, V., X. Xu, L. Li, R. Babu, S. Chen, G.N. Atlin, and A.E. Melchinger. 2012. New insights into the genetics of in vivo induction of maternal haploids, the backbone of doubled haploid technology in maize. Genetics 190:781-793.

Rosegrant, M.R., C. Ringler, T.B. Sulser, M. Ewing, A. Palazzo, and T. Zhu. 2009. Agriculture and food security under global change: prospects for 2025/2050. IFPRI, Washington, D.C.

Roy, A.K., A. Sharma, and G. Taludker. 1988. Some aspects of aluminum toxicity in plants. The Botanical Review 54: 145-147.

Schnable, P.S., D. Ware, and R.S. Fulton. 2010. The B73 genome: complexi ty, diversity, and dynamics. Science 326: 1112-1115.

Shendure, J. and H. Ji. 2008. Next-generation DNA sequencing. Nature Biotechnology 26: 1135-1145.

Shiferaw, B., B. Prasanna, J. Hellin, and M. Banziger. 2011. Feeding a hungry world: past successes and future challenges to global food security in maize. Food Security 3: 307-327.

Smale, M., D. Byerlee, and T. Jayne. 2011. Maize revolutions in Sub-Saharan Africa. Policy research working paper 5659: World Bank.

Stone, P. 2001. The effects of heat stress on cereal yield and quality. In: AS Basara (Ed) Crop Responses and Adaptations to Temperature Stress, Food Products Press, Binghamton, New York, pp. 243–291.

Tefera, T., S. Mugo, Y. Beyene., H. Karaya, and R. Tende. 2011a. Grain yield, stem borer and disease resistance of new maize hybrids in Kenya. African J Biotech 10: 4777-4783.

Tefera, T., S. Mugo, P. Likhayo, and Y. Beyene. 2011b. Resistance of three-way cross experimental maize hybrids to post-harvest insect pests, the larger grain borer (*Prostephanus truncatus*) and maize weevil (*Sitophilus zeamais*). Int J Tropical Insect Sci 31: 3–12.

Timsina, J., M.L. Jat, and K. Majumdar. 2010. Rice-maize systems of South Asia: current status, future prospects and research priorities for nutrient management. Plant Soil DOI 10.1007/s11104-010-0418-y.

Velásquez, J.C.P., C.L. de Souza Jr, L.A. Narro, S. Pandey, and C. De León. 2008. Genetic effects for maize traits in acid and non-acid soils. Genetics and Molecular Biology 31:89-97.

Von Uexkull, H.R. and E. Mutert. 1995. Global extent, development and economic impact of acid soils. In: Date

RA (Eds). Plant-Soil interaction at Low pH: Principles and Management. Klüwer Academic Publishers, Dordrecht, pp 5-19.

Wada, N., C. Feng, and G. Gulati. 2008. Introduction and overview. In: Gulati A, Dixon J (Eds). Maize in Asia: changing markets and incentives. Academic Foundation, New Delhi, pp. 28-75.

Weber, V.S., A.E. Melchinger, C. Magorokosho, D. Makumbi, M. Bänziger, and G.N. Atlin. 2012. Efficiency of managed-stress screening of elite maize hybrids under drought and low nitrogen for yield under rainfed conditions in Southern Africa. Crop Science 52: 1011-1020.

Welcker, C., C. Thé, B. Andréau, C. De Leon, S.N. Parentoni, J. Bernal, J. Félicité, C. Zonkeng, F. Salazar, L. Narro, A. Charcosset, and W.J. Horst. 2005. Heterosis and combining ability for maize adaptation to tropical acid soils: implications for future breeding strategies. Crop Science 45: 2405–2413.

Xu, Y., Y. Lu, S. Gao, J. Wan, and B.M. Prasanna. 2012. Whole genome strategies for molecular marker-assisted plant breeding. Molecular Breeding 29: 833-854.

Yan, J., C.B. Kandianis, and C.E. Harjes. 2010. Rare genetic variation at *Zea mays crtRB1* increases â-carotene in maize grain. Nature Genetics 42: 322–327.

Zaidi, P.H. and J.E. Cairns. 2011. Enhancing climate-resilience in tropical maize. In: PH Zaidi et al. (Eds). Addressing climate change effects and meeting maize demand for Asia. Book of Extended Summaries of the 11th Asian Maze Conference, Nanning, China, 7-11 November 2011. CIMMYT, Mexico, D.F., pp. 13-16.

Zaidi, P.H., P. Manislevan, A. Srivastava, P. Yadav, R.P. Singh. 2010. Genetic analysis of water-logging tolerance in tropical maize. Maydica 55: 17-26.