Maize for Changing Climate - Chasing the Moving Target

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Introduction

The average annual growth rate of harvested maize area from 1993 to 2013 was 2.7% in Africa, 3.1% in Asia, and 4.6% in Latin America (FAOSTAT, 2018). Maize has emerged as the cereal with largest global production, which surpassed rice in 1996 and wheat in 1997, and its production is increasing at twice the annual rate of rice and three times that of wheat (Fischer et al., 2014). Among cereals, including rice, wheat and other coarse cereal, maize has recorded highest increase in area and productivity during 2006-2015 and is projected to keep the momentum during 2016-2025 (OECD/FAO, 2016). Asia, with its 31% share in global maize production from about 34.0% of the total global area harvested, is the second largest maize producer in the world. The current decade continued impressive growth in maize production, as all the sub-regions showed significant increase in maize production (Figure 1), including Southeast Asia - 10.8%, Southern Asia - 27.3% and East Asia - 30.6%, which resulted in an overall 27.7% maize production increase in Asia within a short period of 2010-2016 (FAOSTAT, 2018). These gains in maize production were contributed by increase in productivity per unit area and increase in maize growing areas in some countries.

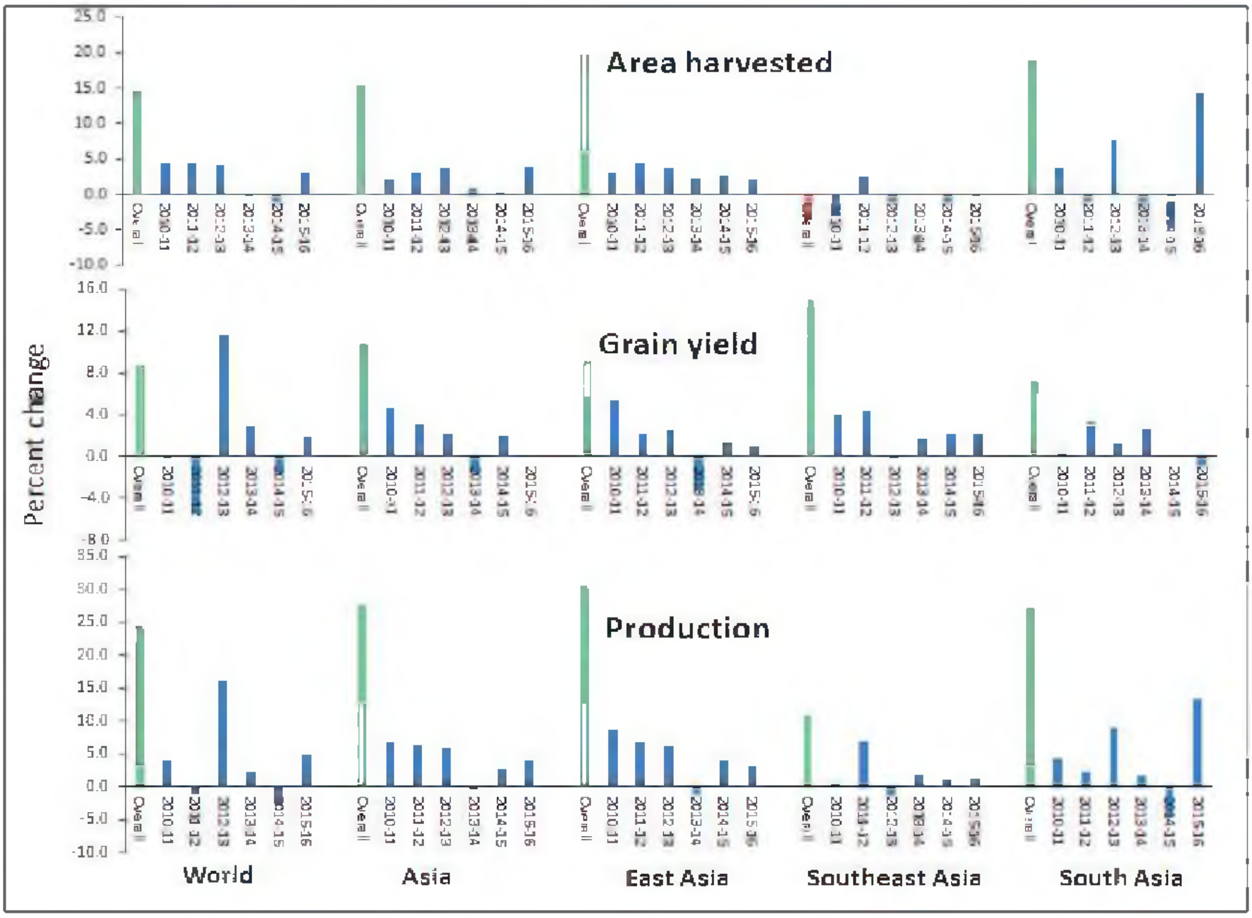


Figure 1. Maize trends in Asia – progress in current decade (2010-2016).

There has been an unprecedented increase in global maize demand at a rate faster than increase in global maize production. Maize has been identified as number one in the estimated global demand for cereals by 2020, with 45% increase in its demand (compared with 30% for wheat and 32% for rice). Increase in maize demand is projected to be acute in Asia, i.e. 87% rise by 2020 as compared with its demand in 1995 (IFPRI, 2003). Within Asian countries, the highest increase in demand for maize by 2020 is projected for the countries of East Asia, dominated by China that alone would require 252 million MT, followed by Southeast Asia requiring 39 million MT, and South Asia requiring 19 million MT (Figure 2, James, 2003). This has specific implications on Asian maize, where an array of factors contributing to a sharp increase in maize demand, including growth rate in per capita gross domestic product (GDP), changing diets, and a significant rise in feed use driven largely by a rapidly growing poultry sector (Shiferaw *et al.*, 2011). This indicated quite a challenge for most of the maize growing countries in the developing world which, except Latin America, all had to import maize to meet their demand as their net trade is projected to be in negative (IFPRI, 2003), ranging from about -1.0% in case of South Asia to as high as -43.0% for East Asia (IFPRI, 2003). By 2020, the global area of maize is expected to increase by only 12% compared to maize area in 2000. Thus, 88% of the necessary increase in maize production will have to be met from increased productivity per unit area of land (James, 2003). Meeting the projected maize demand is a daunting challenge for developing world maize farmers, who grow about two-thirds of the global maize area.

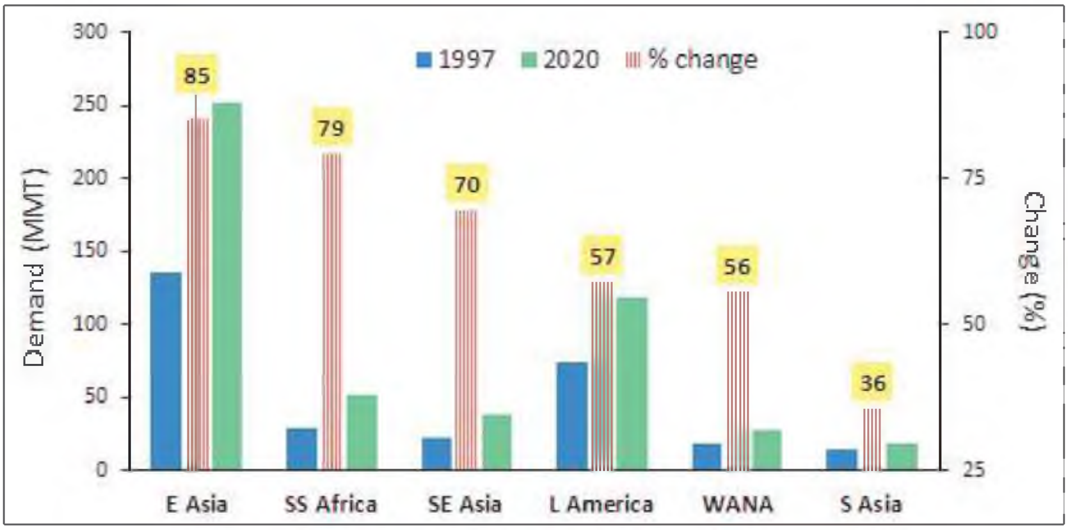


Figure 2. Maize demand projection during 1997-2020.

Maize in Asian tropics - a rainfed crop prone to array of stresses

Most of the maize in Asian tropics (about 70%) is grown in lowland tropics (<1000 masl), including both dry and wet lowlands, followed by sub-tropical/mid-altitudes and tropical highlands (Zaidi *et al*., 2014). Maize is largely (about 80%) grown as a rainfed crop, which is prone to the vagaries of monsoon rains and associated with an array of abiotic and biotic constraints. This is clearly reflected in the productivity of the rainfed system, which is usually less than half of the irrigated system (Zaidi *et al*., 2014). In general, there is considerable pressure on irrigation water, resulting in increased irrigation intervals thus subjecting the maize to stress and a consequent reduction in yield. Moisture availability is seldom adequate for rainfed maize. Erratic or un-even distribution pattern of monsoon rains occasionally causes drought or excessive moisture/ waterlogging at different crop growth stage(s) within the same crop season, which is probably the main factor responsible for relatively low productivity of rainfed maize. Due to the uncertainty of assured returns, farmers are often hesitant to invest in recommended cropping management practices, which results in low soil fertility, and eventually poor yields. Also, in recent years Asian tropics have experienced frequent and widespread severe drought years, for example - seven drought years in South Asia since 2000, coupled with increased day/night temperatures during major maize growing season (monsoon season) covering about 80% of the total maize area, apart from scattered drought/heat almost every year in one or the other country in South Asia (Zaidi *et al*., 2016).

Maize is highly vulnerable to reproductive stage drought and/or high temperature stress. Spring maize in Asian tropics grown during the hot summer period of the year (Feb-May) is invariably exposed to high temperature regimes during most of the critical crop growth period, starting from late vegetative stage until early grain filling. Also, in drought years in summer-rainy season (major maize crop season in Asia) the temperature (both T_{max} and T_{min}) increased close to or beyond their threshold limit, which resulted in even more severe stress condition to maize crop due to combined drought and heat stress at same time (Figure 3). Assessment of the impact of current and future heat stress on maize in South Asia clearly showed that heat stress affected areas will significantly increase under the future climates, particularly in the pre-monsoon (spring) and monsoon (rainy) seasons. The study also highlighted the potential yield advantage of heat tolerant maize varieties in both the spring and rainy seasons, relative to the current heat-vulnerable maize varieties that are extensively grown in the region (Tesfaye *et al*., 2016).

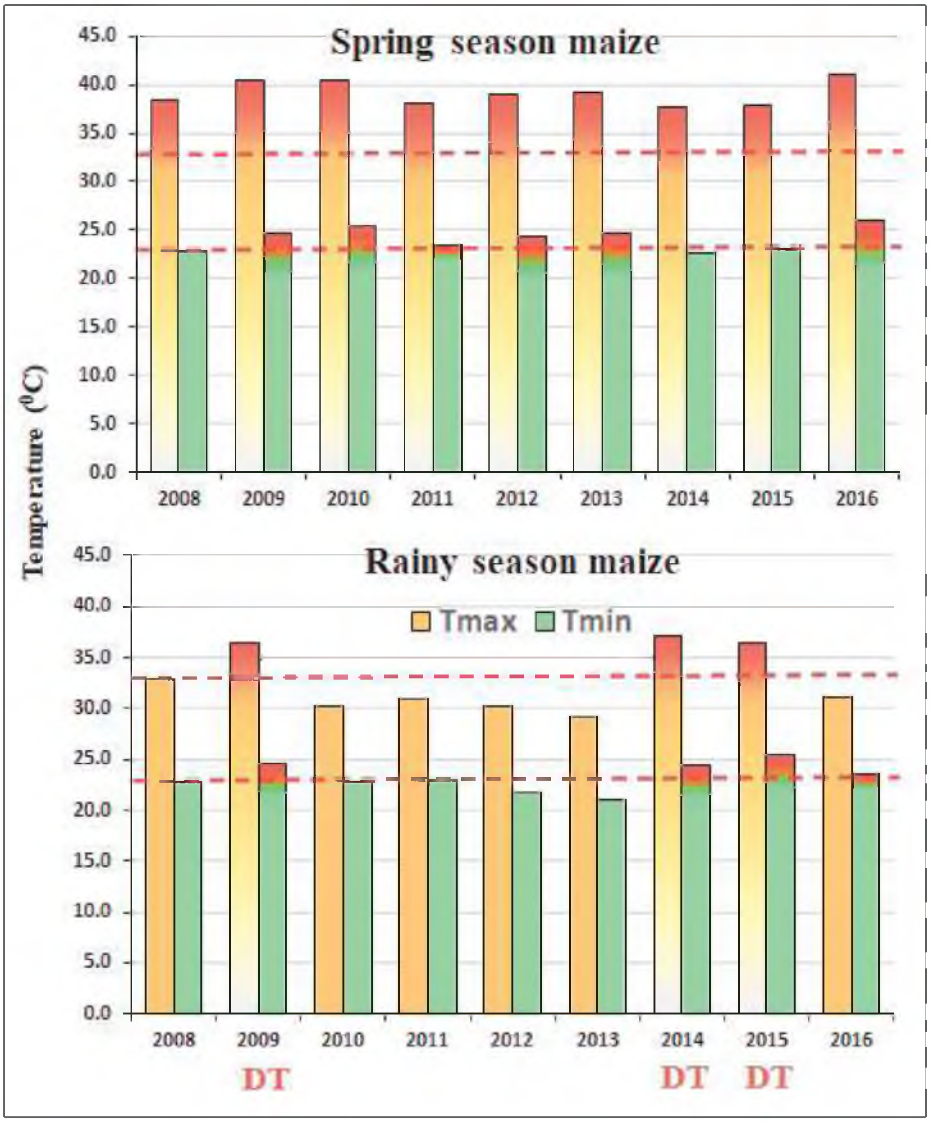


Figure 3. Temperature regime during flowering/grain-filling stage of maize crop in South Asia.

Lowland tropics, especially wet-lowland, are most congenial for biotic stresses, including diseases and insect-pests of economic importance. Turcicum leaf blight (*Exserohilum turcicum)*, Maydis leaf blight *Helminthosporium maydis*, Rust (*Puccinia polysora)* and Downy mildew (*Pernosclerospora spp.)* are the most common foliar diseases in Asian maize. Though reasonable sources of resistance to these diseases exist in Asian maize germplasm, new introductions and the evolution of more virulent strains are posing a major challenge to the longevity of such resistance. Therefore, host-plant resistance breeding programs require close monitoring of virulence changes in the pathogen and identification of new resistance sources to new virulent strains. Banded leaf and sheath blight (BLSB) is emerging as a major threat in most parts of Asian tropics, especially in the area where rice-maize rotation is followed. The main concern lies mainly in the lack of good sources of resistance to BLSB. Maize in Asian tropics is prone to several stalk rots, caused by range of causal organism. *Diplodia* ear rots are the most common, but *Fusarium* and *Aspergillus* ear and kernel rots are also found, especially after a dry spell or insect attack, and often lead to dangerous levels of mycotoxin in grain. Stem borers, including *Ostrinia furnicalis, Sesamia inferens* and *Chilo partellus,* are widely distributed in

Asia. Some partial resistance to these pests has been identified, which is largely dependent on inoculum load and intensity of infestation.

Climate-change effects – dealing with uncertainties

Rainfed systems, which represent a major part of maize mega-environments in Asian tropics, are more dependent on prevailing weather conditions, and therefore extremely vulnerable to climate change effects. Studies suggest that Asia will experience an increasing frequency of extreme weather conditions with high variability beyond the current capacity to cope up with (ADB, 2009; Cairns *et al*., 2012). Several climate modelling studies suggest sharper increases in both day and night temperatures in future, which could adversely impact maize production in the tropical regions (Lobell et al., 2011; Cairns et al., 2012). Such impacts are already being experienced in the region in several real and recognizable ways, such as shifting seasons and higher frequency of extreme weather events, such as drought, waterlogging and heat stress coupled with emergence of new/complex diseases. One of the major and well-realized effects of climate change has been the reduction in the number of rainy days (although there has been no significant change in total rainfall) in South (Kashyapi *et al*., 2012) and Southeast Asia (Manton *et al*., 2001). This has resulted in heavy rainfall events within a reduced number of days, thus extending the dry periods within same cropping season. The erratic distribution pattern in monsoon rains results in extremes of water regimes within the cropping season, causing contingent/intermittent waterlogging at some crop stage(s) and drought periods at other stages. Most of the Asian tropics is identified as a hotspot for climate change effects, and associated negative effects due to climate variability, including weather extremes (ADB, 2009). Climate change effects is a fact, well experienced in terms of weather extremes with increased frequency in recent years. One of the biggest challenges with climate change is the uncertainty in weather pattern, especially year-to-year variability and extremes with space and time. During most critical two months period, rainy season maize crop may be exposed to variable moisture regimes in the same area in different years (Figure 4).

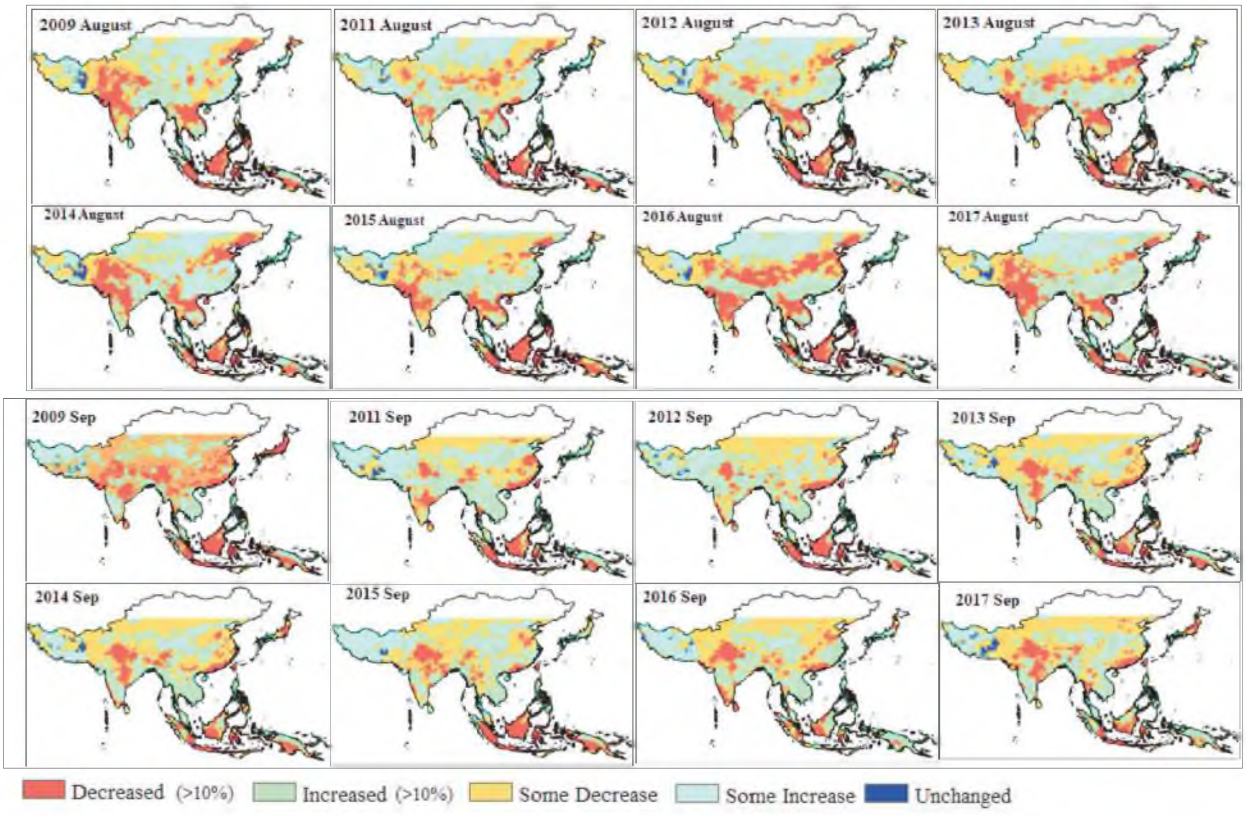


Figure 4. Variation in monsoon rains in Asian tropics during 2009-2017 in relation to 2010 (close to normal year.

With the increasing climate variability and uncertainties, current agricultural research - including development of crop varieties - needs to pay major attention to resilience towards variable weather conditions rather than tolerance to individual stress in a specific situation or crop stage. Plant breeders need to identify and deploy new genes and physiological mechanisms that contribute to climate-resilient varieties. Recent advancements in plant breeding and biotechnology are contributing efforts to engineer plants with tolerance to abiotic stresses; however, future plant breeding efforts must focus on integrating multiple climate adaptation traits in new cultivars to provide tolerance to a broad spectrum of adverse conditions. Drought and heat stresses often occur at the same time due to the integrated nature of these stresses in drought-prone environments. Drought is defined as a deficit of rainfall while heat stress is defined as an increase in temperature beyond a threshold level for a period enough to cause irreversible damage to plant growth and development. Plant breeding for heat stress tolerance in crop plants has lagged behind other abiotic stress tolerance research. Investigations into the genetic mechanisms influencing heat stress responses are underway. An extensive screen of lines developed for drought-prone environments in tropics indicated that very few of these lines combine heat and drought tolerance traits. Heat and drought stress tolerance were poorly correlated suggesting that heat and drought tolerance are controlled by different genetic mechanisms. As genetic sources of high-temperature tolerance are identified, it is hoped that inheritance studies will reveal a genetic architecture that can be manipulated to enhance crop productivity in a range of stressful environments.

Stress-resilient maize – an option for current and future climate

Challenged with growing problems of food security and climate change, Asian agriculture must become more productive, more resilient and more climate-friendly. Varieties with increased resilience to abiotic and biotic stresses will play an important role in autonomous adaptation to climate change (Fedoroff *et al*., 2010). Efforts to develop field crops with enhanced stress tolerance are of vital concern. Millions of smallholders in Asia grow maize under rainfed conditions for their subsistence. The future of maize production, and consequently, the livelihoods of several million smallholder farmers in such climate vulnerable regions are based on access to climate resilient cultivars.

C4 crops are known for their wider adaptability. However, recent trends in climatic conditions and associated variabilities seem to be challenging the threshold limit of even C4 crop, like maize. Maize production can be increased by the availability of invaluable genetic diversity which harbors favorable alleles for higher yield, biotic and abiotic stress tolerance (Prasanna *et al*., 2012). Maize varieties with increased resilience to abiotic and biotic stresses will play an important role in adaptation of climate change vulnerable farming communities in tropical Asia. Targeted crop improvement, aided by precision phenotyping, molecular markers and doubled haploid (DH) technology, offers a powerful strategy to develop climate change adapted germplasm. However, given the time lag between the development of improved germplasm and the adoption of the same by farmers in the targeted region(s), it is of utmost importance that necessary actions are initiated early in selected tropical Asian countries that are likely to be most affected by the changing climate (Cairns et al., 2012).

Using a crop growth simulation model for maize (CERES-Maize) Tesfaye *et al.* (2018) quantified the impact of climate change on maize and the potential benefits of incorporating drought and heat tolerance into the commonly grown (benchmark) maize varieties at six sites in Eastern and Southern Africa, and one site in South Asia. Simulation results indicate that climate change will have a negative impact on maize yield at all the sites studied but the degree of the impact varies with location, level of warming and rainfall changes. Combined hotter and drier climate change scenarios (involving increases in warming with a reduction in rainfall) resulted in greater average simulated maize yield reduction than hotter only climate change scenarios. Incorporating drought, heat and combined drought & heat tolerance into benchmark varieties increased simulated maize yield under both the baseline and future climates. While further evidence is still required to document the risk-reduction benefits of the climate-resilient maize on the numbers of chronically poor farmers, there is an increasing body of evidence confirming the benefits of climate-resilient maize to increase yields, reduce yield variability and, ultimately, increase food security (Cairns and Prasanna, 2018).

There is a myth that breeding for stress tolerance/resilience causes yield drag under optimal growing/high yield conditions. There are seldom optimal conditions in stress-prone ecologies in Asian tropics. Even if breeding and selection processes are planned using top-down approach, i.e. product design first followed by designing breeding and selection strategy accordingly, it is not impossible to develop hybrids with improved stable performance across un-stressed and stressed environments. In collaboration with national maize programs and private sector partners, CIMMYT-Asia maize program has initiated several projects largely focusing on saving achievable yields across environment by incorporating reasonable level of tolerance/resistance to key stresses, without compromising on yields under optimal conditions. Integrating the power of genomics with precision phenotyping, and focusing on reducing genotype x environment interaction effects, new generation of maize germplasm were developed with multiple stress tolerance that can grow well across variable weather conditions within season. These new generations of maize cultivars are being targeted to those stress-prone marginal environments where maize crop is invariably exposed to a wide range of challenging growing conditions, such as drought, heat, waterlogging and various virulent biotic stresses. The goal is to develop and deploy suitable maize germplasm for current climatic conditions and maintain a rich germplasm/product pipeline to effectively feed the requirement of emerging challenges due to future climatic situations in Asian tropics.

In CIMMYT-Asia maize program, we focused on enhancing resilience in maize germplasm for an array of climatic conditions. The overarching goal of the stress-resilience maize program has been to improve upside yield potential with downside risk reduction. This is achieved by focusing on and integration of the following key components:

- **Precision phenotyping** for key traits at several representative sites as well as under-managed stress screens.
- **Integration of novel breeding tools**, including genome-wide association studies (GWAS), genomic selection (GS), and double haploid (DH) technology to fast-track stress-resilience breeding pipeline.
- **Research collaboration** with committed NARS partners in the region for sustainable deployment and delivery of stress-resilient cultivars.

Phenotyping with precision

Irrespective of breeding approach, whether conventional or molecular breeding, high quality phenotyping is the key to success for genetic improvement for targeted traits. To realize true success of breeding program (or power of novel molecular breeding approaches), it is essential to appreciate the principles of phenotyping and apply them in practice (Zaidi *et al.* 2016b; Zaidi *et al.*, 2016c; Zaman-Allah *et al.,* 2016).

Managed stress screen

Precision phenotyping involves a detailed characterization of phenotype of test entries under well-defined conditions (for example - managed drought stress). The intent is to precisely study the overall phenology of the test entries, which is the foundation for establishing genotype-phenotype associations in a molecular breeding approach. Quality of phenotypic data is defined by the precision in phenotyping environment. Understanding the target population of environment and simulating similar but more precise and uniform conditions (managed stress) is a pre-requisite for generating useful phenotypic data. Phenotyping sites need to be carefully developed based on key information about the site, including:

- A minimum set of medium-term (past 10 years) weather data (daily maximum and minimum temperature, humidity, rainfall, and sunshine hours).
- Soil type - physical and chemical properties.
- Cropping history of the site.
- Field levelling, irrigation & drainage facility.

The overall purpose of these managed stress trials is to simulate the targeted stress with desired level of stress intensity and uniformity at critical stages of crop growth, in a way that the available genotypic variability is clearly expressed and could be recorded.

Trait-based selection along with yield under stress

In general, the major trait of interest is always grain yield. However, under abiotic stresses heritability of grain yield is usually low, whereas heritability of some secondary traits remains reasonably high, while the genetic correlation between those traits and grain yield increases significantly (Banziger et al., 2000). At times, selection only based on high grain yield under stress is misleading; for example, selecting a high yielding test entry with prolonged anthesis-silking interval (ASI; >5.0 days). Such an entry can produce high yield as it is fed by the synchronous availability of pollen from other test entries in the trial, a luxury that is not available in farmer fields where a single hybrid is grown in a large area.

In case of molecular breeding projects, detailed phenotyping is essentially required to support the huge volume of genotypic information generated and unearth the power of that valuable information. It is essential to dissect complex traits into components that can enhance understanding of the cascade of events involved in conferring tolerance and add value in genomic region discovery efforts. However, for a secondary trait to be considered in phenotyping portfolio, it must comply with some basic requirements (Edmeades *et al.*, 1998), such as:

- Significant genetic variability exists for the trait.
- Significant genetic correlation with grain yield in the target environment, i.e. relationship is causal, not casual.
- Heritability of the trait is higher than grain yield itself, i.e. less affected by genotype x environment interaction.
- Trait should not be associated with poor yields under optimal conditions, i.e. it must confer tolerance rather than avoidance.
- Rapid and reliable measurement, which is less expensive than measuring yield itself.

Recently, initiatives are being taken to establish field-based, high throughput phenotyping platform (HTPP) to increase the throughput, more detailed measurements with better precision (Makanza *et al.*, 2018). The target is to develop field-based HTTP using low cost and easy-to-handle tools, so that it becomes an integral and key component in the breeding pipeline of stress-resilient maize.

Developing stress-resilient maize

High yields under optimal conditions (yield potential) and reasonably good yields under stress conditions (adaptation to stress conditions) are not mutually exclusive. Therefore, we focus more on improved stable yields across stressed and non-stressed environments (i.e. resilience, rather than just tolerance to a particular stress). This is achieved by defining the phenotyping and selection strategy across a range of environments and select the progenies that have high-stable performance across stressed and non-stressed environments. To increase the efficiency of breeding pipelines, CIMMYT-Asia maize program uses a combination of approaches including index selection for stress-adaptive secondary traits along with grain yield, and modern molecular breeding approaches, e.g. genome-wide association studies (GWAS), rapid-cycle genomic selection (RC-GS) and double haploid (DH) technology. The strategies that helped in developing new Asia-adapted maize germplasm pipeline with enhanced stress tolerance for individual or across stresses, without compromising optimal condition performance, are described below.

Constitution of base germplasm

The constitution of base germplasm is a key factor in a stress resilience breeding program targeting products that perform across non-stressed and a set of stresses with varied intensity. In CIMMYT Asia and Africa maize programs, association mapping panels were constituted involving 300-500 maize inbred lines representing genetic diversity of tropical maize. These include, drought tolerant maize for Africa (DTMA) panel, CIMMYT Asia association mapping panel (CAAM) and heat tolerant association mapping (HTAM) panel. These panels were genotyped using various marker systems, including 1536 (Illumina-Golden Gate), 55K (Illumina-Infinium) and GBS (Genotyping by Sequencing - around 900K SNPs). Across-site phenotyping data was generated and through genome-wide association analysis (GWAS), major genomic regions associated with key biotic (Gowda et al., 2015; Zerka *et al*., 2018; Gowda et al., 2018) and abiotic stresses - including heat or drought (Babu *et al*., 2014; Cerrudo *et al*., 2018), waterlogging (Zaidi *et al*., 2015) and root traits (Zaidi *et al*., 2016d) - were identified. The study resulted in following major outputs:

- Identification of major genomic regions associated with drought, water-logging or heat tolerance.
- Introgression of those regions in elite but stress-susceptible, Asia-adapted maize inbred lines with established commercial value through accelerated back cross approach using molecular markers and doubled haploid technology.

New generation of stress-resilient maize hybrids

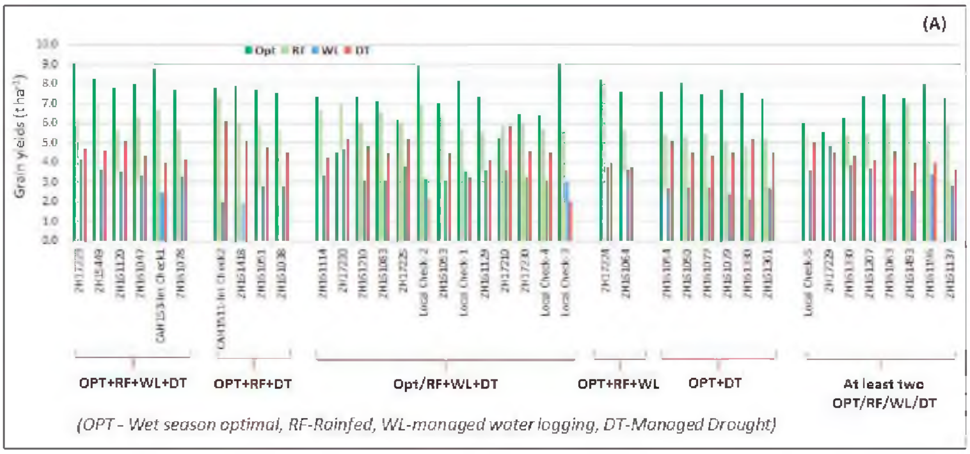
While introgression of major genomic regions identified is being executed, the large-scale robust phenotyping data helped in identification of highly promising donor lines for various complex traits (abiotic & biotic stresses). These promising trait donor lines for one or multiple stresses were used in various ways in breeding stress-resilient maize hybrids.

First generation hybrids

The first-generation maize hybrids were identified in two ways:

1. Promising test crosses from across site results of association mapping panel, as ready hybrid combination for individual stresses, and few hybrids, with stable performance across stresses and unstressed environments.
2. Elite donor lines identified after across site phenotyping of association mapping panel testcrosses with known heterotic pattern were crossed using north-Carolina design-II.

Hybrids from the above two sources were evaluated across range of stresses, including both biotic and abiotic stresses, as well as under optimal growing conditions. The best hybrids with combination of traits (and respectable yields under optimal trial) were identified based on across location trials results (Figure 5). These hybrids were licensed to partners (on semi-exclusive basis) and taken forward for deployment and scale-out in collaboration with public sector and seed company partners in the region.



(OPT - Wet season optimal, RF-Rainfed, WL-managed water logging, DT-Managed Drought)

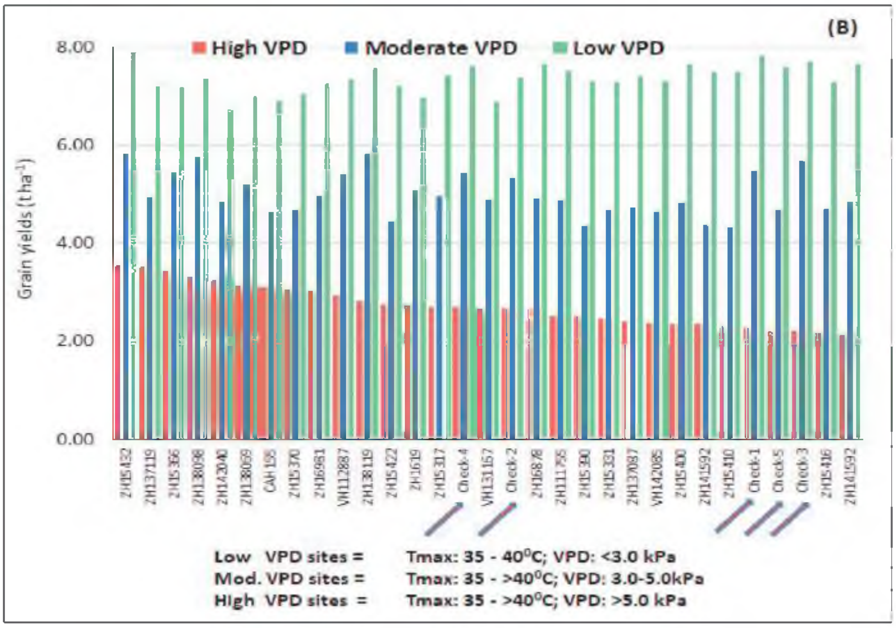


Figure 5. Stress-resilient maize hybrids –choice for various stress-prone ecologies (A) during rainy season prone variable moisture regimes and (B) spring season prone to heat stress.

Second generation hybrids

The inbred lines with promising performance in one or multiple stresses were used as trait donors in developing multi-parent synthetic populations (8-10 lines), which were used as base populations (Cycle-0 or C0) in stress-resilient breeding program. These populations were advanced through rapid-cycle genomic selection approach, C1 was constituted by inter-mating top 10% $F_{2:3}$ progenies based on their test-cross performance across several locations under stressed and non-stressed environments. Marker/haplotype/QTL effects were estimated by analyzing genotype of $F_{2:3}$ families and phenotype datasets from $F_{2:3}$ test-crosses. The C1 was subjected to next two cycles (C2 and C3) through rapid-cycle genomic selection (RC-GS) using genomic estimated breeding values (GEBVs) for grain yield (GY) across stressed and non-stressed environments. The advanced cycles were subjected to double-haploid (DH) induction, and these DH lines were used in developing new hybrid combinations for identification of new generations of stress-resilient hybrids for stress-prone target environments of South and Southeast Asia. These hybrids have gone through stage-1 testing across various stresses and optimal moisture conditions, along with promising 1st generation hybrids and popular commercial hybrids as check entries in the trials. Selected hybrids were advanced to stage-II, and are being tested to at least two more stages, i.e. stage-III and MLT (multilocation testing in larger plots), before finalizing best-bet hybrids for licensing to partners for deployment and scaling out.

Efforts have also started to follow genomic selection in the breeding pipeline which will help to dynamically create training populations and recalibrate GS models based on the breeding program; to effectively predict the breeding values bringing down time and cost, leading to enhancing genetic gains.

Productive partnership for efficient delivery of products and scale-out

In recent years, CIMMYT-Asia maize program has focused on developing strong partnerships and collaborations with a range of stakeholders, including public sector institutions, state agricultural universities, private sector and NGOs with required technical expertise and complementary strengths. Partnerships between public institutions actively engaged in maize R&D and private seed sector with good market share in the target countries are critical. Private sector partners play a key role in bringing products to a logical end through extensive multi-location testing of elite stress-resilient hybrids in target agro-ecologies/markets, multiplication of certified or quality declared seed, and marketing and delivery of the hybrids to the maize-based farming communities in Asian tropics.

The different types of partnership arrangements explored and developed, included:

i. Partnership through bi-laterals projects

CIMMYT-Asia program is implementing several bilateral projects in partnership with NARS and seed companies in the region; key among them Heat Tolerant Maize for Asia (HTMA) funded by USAID, Climate Resilient Maize for Asia (CRMA) funded by GIZ, Germany, Improved Maize for Asian Tropics (IMTA), and so on. Partnership in these projects is based on in-kind contribution by committed partners who are involved in all aspects of the project implementation - starting from research, development as well as product deployment and scale out.

ii. International Maize Improvement Consortium (IMIC)-Asia

IMIC-Asia is implemented in consortium mode, where willing private sector partners join the consortium on annual fee payment basis (public sector are honorary members). Consortium members jointly decide the R&D plan and product portfolio of IMIC then CIMMYT-Asia implements the breeding activities targeting the development of agreed type of germplasm, including early and advanced generation lines. These are then shared with partners through biannual IMIC-field days. Some ready hybrid combinations were also demonstrated in IMIC-field day, which were selected or largely preferred by SMEs with weak R&D capacity. IMIC also offers a platform for experimental hybrid testing, where partners can submit their pipeline hybrids, hybrid trials are constituted by CIMMYT, and evaluations done across locations on the sites shared by IMIC partners.

iii. Partnership with on-going developmental project in the region

There are different on-going developmental programs and projects in the region - supported by international donors – such as Nepal Seed and Fertilizer (NSAF), Nepal, Agriculture Innovation Project (AIP) funded by USAID, Pakistan, Cereal System Initiative for South Asia (CSISA) funded by USAID, and so on. Partnership with these projects helps in deployment of suitable products in targeted agro-ecologies. Partnership with developmental projects implemented by state governments (such as Stress Resilient Maize for Odisha (SRMO) supported by *Rashtriya Krishi Vikas Yojna* (RKVY), Government of Odisha, India, and *Rythukosham* project of Government of Andhra Pradesh, India), help in reaching remote areas where private seed companies may not have interest and/or reach.

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