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Maize ideotype breeding for changing environmental conditions

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The demand for corn in the developing world will double by the end of 2050. The challenges due to the climate change are real. Where extreme weather events will become more frequent and climate change projections suggest that large yield losses occur in many regions of the world. Corn is cultivated throughout the world and is a strategic crop: can tolerate high radiation intensities and exhibits high efficiency in the use of water. A framework is needed to design maize ideotypes for site specific condition with the definitions of past, present and future environmental history, and the response of the local material using empirical or mechanistic modeling. The ideotype is a combination of different types of biological traits or the genetic basis that confer enhanced performance for a particular biophysical environment, specific cropping system and end use of the crop. Studies of genotype performance under climate variability always shows that a single trait will never improve plant performance in all climatic scenarios and similarly a single genotype will not cope with all the existing climatic variability. In the past, ideotyping was based on visual and growth phenotypes, but future ideotyping trend will focused more on the knowledge of the genotype. In the future, the strategies for ideotipificación will be based on strong biotechnological techniques facilitated by the bioinformatics, filling gaps in the current knowledge and overcoming the climatic change challenges and increased the world population.

Key words: Maize, ideotype, climate change.

INTRODUCTION

Donald (1968) first time coined the term ideotype for the first time while Mark and Pearce (1975) proposed ideal plant type of maize. The later proposed ideal maize plant with small tassel size, low tillers, large cobs and angled leaves for good light interception. A maize ideotype that can utilize an optimum production environment should be a package of:

(1) Stiff, vertically-oriented leaves above the ear (leaves below the ear should be horizontally oriented);
(2) Maximum photosynthetic efficiency;
(3) Efficient conversion of photosynthate to grain;
(4) Short interval between pollen shed and silk emergence;
(5) Ear-shoot prolificacy;
(6) Small tassel size;
(7) Photoperiod insensitivity;
(8) Cold-tolerance in germinating seeds and young

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seedlings (for genotypes grown in areas where early-planting would require planting in cold, wet soils);
(9) As long as a grain-filling period is practically possible and;
(10) Slow leaf senescence (Mark and Pearce, 1975).

This environment should include optimum conditions of moisture, temperature, fertility etc. As ideal conditions do not always prevail, the aim is to ideotype for unpredictable stressed environment to escape any threat of food security in future. To identify maize ideotypes, a multi-disciplinary approach is essential (Cairns et al., 2012). Many scientists have made first hypothetical approaches to reach the idea of ideotype (Jonathan, 2012), and then identified the required source fitting the frame. A mathematical model of plant growth could be possibly used to design ideotypes and thus lead to new breeding strategies based on the guidance from optimization techniques. Certain optimization approaches relying on plant growth models, green lab model, source sink dynamics etc, may help improve breeding strategies and design ideotypes of high-yield maize (Rui et al., 2010). In crop modelling under climate change, quantitative trait loci (QTLs) can identify the best ideotypes as we need 5 to 15 years to breed a variety, and 2050 is only at two to eight cycles of breeding (Chapman, 2011).

Effect of climate change on the world maize production

According to a report (Annynomus, 2014), until 2050, extreme weather events will become more frequent and extreme. They will include mega-droughts, deadly heat waves and a year's rainfall in a month in some places. If greenhouse gas emissions continue to increase at the current rate, the average global temperatures could have risen more than 4°C. Climate change impacts will be worst in countries already suffering high levels of hunger. Extreme weather events are likely to become more frequent in the future and will increase risks and uncertainties within the global food system (Tim and Joachim, 2013).

Statistical studies of rainfed maize yields in the world and particularly in United States have an indication of strong negative yield response to temperatures above 30°C (David et al., 2013). Climate change has a universally negative effect on agriculture. In china, reduction of corn production in the Northeast region due to this negative effect is predicted (Xiang et al., 2014).

The average maize yield in the west and central regions in China is projected to decrease to 15% or more by 2050 as predicted by 90% of 120 projected scenarios. In the long run, the maize cultivars need to be introduced in line with the future warming climate (Meng et al., 2013). It requires advance regional policies and strategies until 2030 to mitigate this possible predicted reduction (Xiang et al., 2014).

Iowa's main corn growing state in the USA region represents the ideal climate and soils for corn production that contributes substantially to the world corn economy. The prediction is a decline in maize yields from the late 20th century to the mid and late 21st century, ranging from 15 to 50%. To maintain crop yields, farmers will need a set of adaptation strategies (Hong et al., 2016).

Climate change projections suggest that large yield losses will occur in many regions, particularly within sub-Saharan Africa and South Asia (Cairns et al., 2012). Agriculture "the pillar of economy" is also under threat in Malawi. This region of Africa is supposed to face 33% of losses in corn production due to 14% less rain and climate change at the end of the century. There is need to plan supplementary irrigation strategies, crop diversification and natural conservation methods (Kondwani et al., 2016).

The climate change is also of great concern in the Kingdom of Swaziland. The rainfall variability is a threat to their staple food "corn". The 60% rainfall is recorded in just two months of a year. This erratic rainfall results in a decrease in corn production. To mitigate climate change and increase family food security need is of soil conservation, intercropping, cultivation of short-season maize varieties / early maturation, diversification of crops such as millet and sorghum, etc. (Oseni and Masarirambi, 2011). Average temperature will negatively affect the corn crop in Pakistan, producing a 6% reduction in corn production until the year 2030. This scenario requires the key political intervention of the government to address climate change in agriculture and particularly in corn (Shakoor et al., 2017).

Climate change is the most serious environmental threat globally. The increasing global population with increase in earth mean temperatures (between 1.8 to 4.0°C) is a burning issue. Despite the technological success in the previous half of the 20th century, the agricultural production and economy is still highly susceptible to the predicted climate change (Rebolledo, 2014). Studies of genotype performance under climate variability always shows a single trait will never improve plant performance in all climatic scenarios and similarly a single genotype will not cope with all the existing climatic variability.

Root system

A maize root system efficient enough to absorb and store much water and N during hours of its availability before wasting into deeper soil strata should be breeder's aim. Ideotype root architecture for efficient N and water acquisition in maize should include:

(1) Deeper roots with high activity that are able to uptake

NO_3^{-1} nitrate and water before it moves downward into deep soil;
(2) Vigorous lateral root growth under high water and N input conditions so as to increase spatial N and water availability in the soil;
(3) Strong response of lateral root growth to localized N and water supply so as to utilize their uneven distribution especially under limited conditions;
(4) Being able to establish symbiotic relationships with soil micro- organisms (MI et al., 2010).

Moreover, it should compete with weeds. Exploit genetic variability for competitiveness and early coleoptilar node with extensive shoot born root (Hochholdinger et al., 2004). Lodging can be a major factor affecting grain yield. Vigorous root system with ideal root anchor is required to overcome root lodging under adverse environment. Rtcs (root hair less), Bk2 and Rth3 (mineral uptake) are the genes identifying the target for ideotyping (Hochholdinger and Tuberosa, 2009).

N uptake efficiency

N, a limiting and essential nutrient to plant growth leads to annual application of an estimated 10 million metric tons of N fertilizer to the maize crop worldwide (Anonymous, 2012, 2014). Although a much smaller amount of N fertilizer is absorbed by roots and very little amount is utilized by plant as compared to the N applied. Instead of increasing N application we should focus on an ideotype with very active N uptake efficiency. The extensive use of N fertilizer increases crop input costs and also have negative impact on soil, water and air quality at both local and ecosystem scales (Tilman et al., 2002). The manufacture of N fertilizer with natural gas is an energy-intensive process that is becoming increasingly costly. Reducing the amount of supplemental N used in maize production will have significant positive economic and environmental benefits to world agriculture. Indicating that more than half of the fertilizer N applied in maize crop production is lost to the environment. Thus, there is considerable opportunity for enhancing maize nitrogen use efficiency (NUE). The development of “N-fixing maize” is not far away as biotechnology has and will continue to play an important role in improving NUE (Alan and Brian, 2010).

Heat stress tolerance

Tolerance mechanisms help to fight plant tissues against dehydration. This type of tissue “hardening” occurs through the accumulation of proteins such as the dehydrins (hydrophilins) and heat shock proteins, and a wide range of compatible solutes (for example, polyols, glycine betaine, proline, inositol). By increasing the level and activity of enzymes and pathways, the plant can protect its tissues from the generation of potentially damaging reactive oxygen species (ROS) that are generated during periods of water limitation and stomatal closure (that is, ROS protective systems, GABA shunt, photorespiration).

Crassulacean acid metabolism (CAM) photosynthesis, variation of stomatal distribution and conductance, leaf cuticle properties (wax, hairs, boundary layers), hydraulic conductivity, leaf architecture (thickness, size, area, rate of appearance, leaf rolling, erectness), and canopy architecture are the set of traits that can modulate water utilization (Jordan et al., 1983). Maize crop is most sensitive to environmental stresses. Maize plants tend to experience extreme sensitivity to water deficit, during a very short critical period, from flowering to the beginning of the grain-filling phase. Maize crops tend to have the highest water requirement during the critical period, when the maximum leaf area index combines with the highest evaporative demand.

Drought avoidance traits have a significant impact on yield, because they help plants maintain good water status, allowing continued photosynthesis, growth, and development. Dehydration tolerance is important during seedling establishment for improved stand and maximum germination.

Traits that help plants avoid water deficit, such as the establishment of a deep rooting system have a greater impact on yield, assuming in the case of deep roots that water is available in the soil profile and soil water content is recharged annually (Sinclair and Muchow, 2001), (Sharp, 2002).

‘Staygreen’ trait in Sorghum has a vital impact on yield in water- limited environments because this response improves plant water status, photosynthetic activity, and N uptake in water-limited environments during the reproductive phase (Alan and Brian, 2010). Genes/traits contributing high grain yield and drought stress conditions can be identified in several ways for example, mutants with modified response to water limitation in field, QTL mapping and inserting the cloned genes into the desired germplasm, screening by comparative analysis and artificial stress.

Genes that show modified expression in response to water deficit are the easiest to identify. However, determining the importance of a specific inducible gene with regard to yield in water-limiting environment is challenging. One of these pathways starts with perception of water deficit through reduction of cell turgor, and this leads to accumulation of the plant hormone abscisic acid (ABA).

ABA in turn activates a signaling pathway that reduces stomatal aperture, contributes to differential root/shoot growth (Sharp, 2002) and modulates gene expression. Expression of putative stress tolerance genes using promoters that are activated in response to water deficit (or ABA) has been more successful in enhancing tolerance without secondary effects.

Sorghum closes its stomata in water deficient response but become nearly insensitive following anthesis. This change in sensitivity allows continued CO_2 fixation and grain filling even under drought stress. This can otherwise results in stomatal closer, inhibit photosynthesis, reduce sugar levels, and cause complete loss of reproductive structures. After identification of these traits and genes their optimization is essential in terms of tissue/cell- specific expression and expression during plant development (Alan and Brian, 2010).

Plant height

Crop yield potential may be increased by reducing plant height and selecting for erect leaves. Dwarf genes provided by the elite maize inbred line Shen5003 have been successfully exploited to develop several inbreeds and hybrids with reduced plant height. Recent genetic analysis and molecular characterization of dwarf mutants in maize revealed that mutations in dwarf genes including d1 (gibberellin-responding dwarf gene), d2, d3, d5, d8 (GA-insensitive dwarf genes), d9, An1, DWF1 and DWF4 (Jianfeng et al., 2011). Dwarf maize mutants are short, compact plants with shortened internodes, short wide leaves, and short erect tassels. Plant height, cob height and tassel size are important characters contributing towards stem lodging. Semi-dwarf with low bearing cobs and light tassels are attributes supporting lodging resistance (Janick, 2004).

Tassel and cob architecture

To ensure high quality F1 seed production, the ideal male parent should have a relatively large tassel with excellent amount of pollen viable for a longer period of time. The ideal female parent should be with large ear, producing a large number of kernels and relatively small tassel to direct more energy toward grain yield.

Ideotyping for grain yield should target smaller tassels, as tassel size, tassel weight, and tassel branch number are negatively associated with it. It is important that pollinators should have a very large tassel with excellent quality and quantity of pollens. Tassel branch length and spikelet pair density along with variation in branch angle are important as they determines the area, the pollen can be dispersed and also plays a role in shading of the flag leaf. This type of variation is associated with ra2 (Upadyayula et al., 2005).

The components of ear inflorescence architecture such as kernel row number, number of kernels per row, and kernel number density are positively correlated with grain yield. Previous quantitative genetic studies suggested indirect election for greater yield that involved selections of some ear traits could be more effective than direct selection for yield itself, because of lower heritability of yield. A long-term divergent selection for ear length indicated that grain yield did not increase with selection for longer ear length, but yield decreased significantly with selection for shorter ear length (Lopez-Reynoso and Hallauer, 1998).

Summarizing 20 cycles of divergent mass selection for seed size, reported that grain yield did not increase with selection for greater seed size, but grain yield decreased significantly with selection for small seed size. Significant positive correlations between grain yield and kernels per row and kernel rows per Ear is present. Fasciated Ear2 (FEA2) is responsible for more kernel rows per cob (18 to 20). Insertion of this gene through cloning into a wild type with 256 kernels yield increases of 13% with cob bearing 289 kernels (Bommert et al., 2013).

Prolific hybrids out-yield non-prolific types and are more drought stress tolerant. Larger grain weight per plant is due to more kernels per plant in the reduced-input system, and a combined effect of more kernels and heavier 1000-kernel weight per plant in the high-input system. Improved kernel number per plant for prolific hybrids was associated with kernels from secondary ears. Grassy tiller1 (gt1) suppresses the initiation of multiple ear per plant and only 1 or 2 ear will develop (Janick, 2004).

Quality traits

Majority of the seed phosphates are present in the form of phytic acid, digested only by rudiatary animals but remain undigested in poultry and human feed. Inorganic P is digest-able and is controlled by *lpa* alleles (Raboy, 2006). Similarly, quality protein maize (QPM) should be the priority. It contains nearly twice as much usable protein as other maize and yields 10% more grain than traditional varieties of maize. The deficient protein quality due to low lysine and tryptophan in maize grain can be improved by replacing normal Opaque2 (O2) alleles with nonfunctional mutant O_2 alleles (Prasanna et al., 2001). Similarly, waxy maize with recessive *wx* allele can increase maize industrial demand as a byproduct.

Transgenic corn

The first transgenic corn hybrid with insect resistance traits was commercialized in 1996 in the USA (Mendelsohn et al., 2003), (James, 2006). These products were targeted at lepidopteran pests of corn, particularly stem borers that are difficult to control using conventional insecticides. Now transgenic Bt corn hybrids have been adopted on tens of millions of hectares (James, 2006).

In addition, Bt corn hybrids containing coleopteran-active insecticidal proteins that control the larvae of the damaging corn rootworm complex (*Diabrotica* spp.) have been developed. Increasingly, corn farmers are purchasing hybrids with combinations of these insect resistance traits (both lepidopteran and coleopteran pest protection), along with herbicide-tolerance traits for improved weed control (The event MON 88017 also expresses Cry3Bb1 but combines a Roundup herbicide tolerance gene in the same expression cassette) (Brookes and Barfoot, 2007; James, 2006).

Even though these products have an obvious technical fit in many countries, the regulatory systems are not always in place to approve such products, and distributional and educational challenges exist when it comes to getting the products in farmers' hands (particularly in Africa and Asia). Ideotype may be benefited with transgenic technology but novel partnerships will be needed, along with broad governmental involvement and assistance from international organizations (Alan and Brian, 2010).

Trait inheritance pattern

The global gene pool is the base material for selection, especially for plant stature, maturity durations, leaf size and angle. For the incorporation of desirable traits, knowledge of the association between various characters is essential before starting hybridization program. Inheritance pattern in most of the agronomic important traits shows non-additive gene effects. Over-dominance gene effects for days from silking to physiological maturity, days from anthesis to physiological maturity, plant height, kernel depth, number of rows per ear and grain yield. The most appropriate strategy for the exploitation of these effects is to obtain hybrid cultivars, and to evaluate these characteristics in hybrid combinations. The gene effect for days from emergence to physiological maturity and number of kernels per row is complete dominance, suggesting that reciprocal recurrent selection will be effective. Ear leaf area and ear length are controlled by partial dominance, indicating that additive gene effects are more important than non-additive gene effects for controlling the inheritance of these traits. Therefore, improvement of these traits through selection of breeding materials is highly feasible. Broad-sense heritability ranged between 47.4 and 89.4% for days to physiological maturity and number of rows per ear; however, narrow-sense heritability varied between 7.3 and 50.6% for days from anthesis to physiological maturity and ear leaf area, respectively (Zare et al., 2011).

Conclusion

One who knows the success story of QPM and transgenic maize will always believe on heat and drought stress tolerant maize, growing in adverse conditions, ensuring food security of millions. All breeder's dreams and plans that target future threats will evolve a new ideotype. This will carry the genetic background of all favorable alleles along with additional developments that breeder will contribute time by time. History of ideotyping is the history of breeder's success while future of breeder and food security is ideotyping.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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