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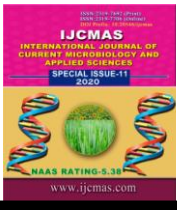

Review Article

Ideotype Breeding in Maize (*Zea mays L.*)-A Review

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ABSTRACT

Keywords

Ideotype, Climate change, Maize, Yield

In 21st century the whopping challenges are to gain food supply security under changing adverse climatic condition, the goal is to double the corn production by the end of 2050 at the world level. Future harvests are decreased by increased frequency and severity of extreme environmental events, i.e. heat waves and drought gives particular challenges to plant breeders and crop scientists. These extreme weather changes cause large yield losses in different regions of the world. Maize is cultivated throughout the world and is a strategic crop, i.e. it can tolerate high intensity radiations exhibits proper water use efficiency. Processbased crop models are developed to know the interactions between genotypes, environment and management are widely applied to gauge impacts of climate change on crop yield, water use efficiency etc. A frame work is needed to create maize Ideotype based on past, present and future environmental actions. The Ideotype is a combination of different types of biological characters that confer to enhance the performance of crop at particular environment, specific cropping system and end use of the crop. But this ideal genotype does not show same performance in all regions of climatic situations. In the pat the Ideotype was created based on visual and growth phenotypes, but in future the concept of Ideotype was concentrate on strong biotechnological techniques, by using this knowledge we can overcome the present demerits of Ideotype breeding and enhance the crop performance at all climatic diversities.

Introduction

The term Ideotype was introduced by Donald (1968), it means “a form denoting an idea”. He defined ideotype as “a biological model, which is expected to perform in a predictable manner within a defined environment”. An ideotype of maize for the optimal production environment was proposed by Mock and Pearce (1975). The environment is presumed to include adequate moisture, favourable temperature throughout the growing season, adequate fertility level, high plant density, narrow row spacing and early planting dates. The main traits of the proposed ideotype are as follows, Stiff vertically oriented leaves above and horizontally oriented leaves below the ears. Maximum photosynthetic efficiency. Short interval between pollen shed and silk emergence.

To have more than one cob per shoot.

Contain small tassel size, small tassel would show lower competition for nutrients.

To have photoperiod insensitivity.

Cold tolerance of germinating seeds and developing seedlings.

Grain filling period should be as long as practically possible.

In the environment we should observe optimum conditions of moisture, temperature, fertility etc. The ideal conditions do not always desirable, the aim is to create a ideotype which is ready to tolerate unpredictable stressed environment to escape any threat of food security in future. To create a maize ideotype we require a multidisciplinary approach is essential [1]. Many scientists have made first hypothetical approaches to reach the idea of ideotype [2] and then required source will be identifying and incorporate into that frame work. A mathematical model of plant growth could be possibly used to design ideotypes and thus leads to new breeding strategies based on the guidance from optimization techniques. Some of optimization approaches based on plant growth models, green lab models, source sink dynamics etc, it may lead to improve breeding strategies and design ideotypes of high yield maize [3]. In crop modelling under climate change, quantitative trait loci (QTLs) can identify the best ideotype as we need 5-15 years to breed a variety, and 2050 is only at 2-8 cycles of breeding [4].

Effect of climate change on the maize production

According to a report [5], until 2050, serious weather events occur more frequently. It includes droughts, deadly heat waves and a less than minimum 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 [6].

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 [7]. 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 [8]. 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 [9]. It requires advance regional policies and strategies until 2030 to mitigate this possible predicted reduction [8].

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 [10]. Climate change projections suggest that large yield losses will occur in many regions, particularly within sub Saharan Africa and South Asia [11]. 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 [12].

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 [13]. Swaziland is experiencing increasing reports of sexual exploitation and abuse, in particular rape. Conflicts over scarce resources increase during droughts putting women and girls at higher risks of experiencing sexual violence. Sexual intercourse in most cases is used as a commodity for food exchange, which can lead to physical injury, transmission of HIV/AIDS and other sexually-transmitted infections (STIs) and unwanted pregnancy [14].

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 [15]. 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 [16]. 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

The root system of maize has enough capacity to absorb and store nitrogen and water, when their availability before percolate into the deeper soil strata, it should be breeder aim. The ideotype root architecture of maize include:

Deeper roots with high activity that are able to absorb nitrate, water before they percolate into deep soil.

Vigorous lateral root growth under high water and N input conditions so as to increase spatial N and water availability in the soil.

Strong response of lateral root growth to localized N and water supply so as to utilize their uneven distribution especially under limited conditions.

Being able to establish symbiotic relationships with soil micro- organisms [17].

Moreover, it should compete with weeds. Exploit genetic variability for competitiveness and early coleoptile node with extensive shoot born root [18]. 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 ideotype breeding [19].

Nitrogen loss in maize fields

Nitrogen applied as various fertilizers is readily transformed into nitrate under suitable temperatures and water conditions for the growth of nitrifying bacteria. Ammonium, another inorganic N compound, is usually less common in soil. Nitrate can be further transformed into other compounds including NO2, NO, and N2O [20,21]. "Nutrient bioavailability" term coined by Barber. These forms of nitrogen will determine the nutrient availability. Basically ammonium is positively charged and soil particles are negatively charged, so soil particles are easily captured the ammonium at their surfaces. Due to these characters' ammonium is difficult to transport and is not easily leached. Vice versa the nitrate is negatively charged, so soil particles are cannot capture nitrate molecules easily. Due to this factor nitrate form of nitrogen can easily be transported by water in the soil, so nitrate molecules easily percolated into deeper soil. It is stated as the nitrate form of nitrogen fertilizer is positively correlated with nitrogen loss by leaching [22-24].

In china, due to less availability of labour, mechanization 2/3rd of the farmers follow one-time fertilization i.e. application of all fertilizers at the time of seed sowing. Result of this condition, the nitrate leaching is more than normal condition. Therefore, we need to improve nitrogen use efficiency by following optimum fertilizer application. In future prospect develop an efficient nitrogen uptake cultivar by improved root architecture, which can efficiently take up nitrate before it moves into deep soil [26–29].

Maize root growth regulated by nitrogen supply

It is well documented that N deficiency leads to relatively more photosynthates allocation to roots and therefore increases root to shoot ratios. The effect of N supply on root morphology is quite complex. Physiologically, maize roots respond to N supply in three ways. First, nitrogen deficiency increases root length, resulting in longer axial roots (including primary roots, seminal roots, and nodal roots) [30,31]. This helps roots to explore a wider soil space and thus increases the spatial N availability. Root elongation can be inhibited if N supply is too high. In maize, for example, root length was found to reduce when nitrate concentration in culture solutions was more than 5 mmol L−1 [32].

Second, when a plant is suffering from N deficiency and part of the root mass is supplied with nitrate locally, the growth of lateral roots in the supplied area is enhanced [33–35]. This helps plants to compete with other plant species and/or microbes for limited N resources [36]. Third, lateral roots grow well when external N supply is at optimum concentrations. Extremely low or high supply (exceeding 10 mmol L−1) of nitrate inhibits lateral root growth [37].

Plant nitrogen demand, thus requirement for fertilizer N input, is shown to increase with increasing yield. In reality, however, most fertilizers are applied no more than twice, at planting and at the stem jointing stage. Because of shortage of labour and/or machinery for fertilizer application, many farmers practice one-time fertilization, and apply all the fertilizer at planting.

As a result, nitrate levels in the soil are frequently higher than 10 mmol L^{-1} [38] during the early growth stages. As discussed above, the growth of roots, especially lateral roots, is depressed when nitrate levels are high. Root biomass and root to shoot ratio are known to decrease, and more roots are found in the topsoil layer [39, 40].

Ideotype architecture

Primary root system: a large diameter primary root with few but long laterals and tolerance of cold soil temperature. Three phenes are proposed for the primary root i.e. large diameter, few but long laterals, and the ability to grow into cold soil. Large diameter would be useful in increasing the ability to penetrate hard soil [41], and is also correlated with sink strength [42]. The frequency and length of lateral roots is important for two reasons. The first is that lateral roots are more metabolically demanding per gram of tissue than axial roots, and compete with each other for internal resources. An optimum level of lateral root development will balance the need for soil exploration and exploitation with the metabolic demands of these roots and their consequent effects on other plant processes, including the growth of other roots [43]. A clear illustration of this effect is the case in which abundant production of hypocotyl-borne roots in common bean decreases P acquisition by slowing the development of basal root branching [44]. Abundant lateral branching may also be associated with slower elongation of the root axis from which they originate, possibly because of differential response of axial and lateral roots to hormonal signals [45].

The second reason that the frequency and length of lateral branching is important is that they determine the balance between the capture of mobile and immobile resources. Mobile resources are captured more efficiently by fewer but longer laterals capable of exploring larger volumes of soil with greater spatial dispersion among roots. In contrast, immobile resources may be efficiently exploited by fine-scale foraging by dense branching. The overlap of resource depletion zones around roots of the same plant is inefficient [46] since depletion zones for mobile resources are larger, root phenotypes that optimize capture of mobile resources are more dispersed than phenotypes that optimize capture of immobile resources. Therefore, lateral root phenotypes to optimize water and N capture should be long and dispersed along the axial roots. Genotypic variation for lateral branching in maize genotypes was associated with greater P acquisition in the field [47]. In this context, the fact that branching density of a given axial root typically is greatest in surface soils that have the greatest P availability, and decreases in deeper soils which are usually enriched in nitrate in leaching environments, may be interpreted as a strategy to co-optimize acquisition of nitrogen and phosphorus. The ability to grow at cold temperatures would be beneficial for warm-season crops like maize grown in temperate climates where spring soil temperatures may be suboptimal [48, 49]. In isothermic and isohyperthermic soil temperature regimes as commonly found in the tropics this phene would not be needed. Resource allocation between primary root elongation and the development of seminal roots must be optimized, since capture of topsoil resources (which initially include N and water) by the seminal roots is important for early seedling growth, including elongation of the primary root.

Seminal root system: Shallow growth angles, thin diameter, many laterals and long root hairs or as an alternative seminal roots with steep growth angles, large diameter and few laterals coupled with abundant lateral branching of the initial crown roots.

Two alternative ideotypes are presented for the seminal root system depending on the phenotype of the initial crown roots. The general concept is that early in seedling development, as the primary root is penetrating deeper soil strata, it is advantageous to have a network of shallow roots to acquire topsoil resources, which include immobile resources such as P, K and ammonium as well as mobile resources such as water and nitrate that have not yet been subject to depletion from the topsoil by plant uptake, evaporation (including denitrification and volatilization) and leaching.

In the first case mesocotyl-borne roots are poorly developed as is often the case in the field and the seminal root system is responsible for topsoil foraging. Seminal roots should therefore be abundant, have shallow root growth angles, small diameter, many laterals and long root hairs. Shallow root growth angles are beneficial for topsoil foraging in maize and common bean [50]. Small diameter would be beneficial by reducing the metabolic cost of constructing and maintaining these roots [51] and, since shallow soils are typically not as hard as deeper soils, especially under tillage.

In the second case, rapid and extensive development of lateral roots arising from the initial crown roots are responsible for foraging for topsoil resources, permitting the seminal roots to grow at a steeper angle, resulting in more rapid development of deep root foraging. In this case, the seminal roots should have a larger diameter for penetration of harder soil at depth and reduced lateral branching, as rationalized above. The advantage of this phenotype is that seminal roots would contribute to foraging in deeper soil horizons. The utility of this phenotype would depend on the ability of the crown root laterals to exploit topsoil resources rapidly enough to capture topsoil resources before they are lost, which would in turn depend on environmental conditions. A benefit to either of these phenotypes is that the development of a seminal or crown root system capable of topsoil foraging would enhance P acquisition, which is useful, since P availability is generally low in many tropical soils [52] and P availability can be limited by low soil temperature in temperate maize production [53]. Topsoil foraging would also be important to capture ammonium and nitrate from recent fertilization or mineralization before it can be lost to volatilization, denitrification, leaching or weeds.

Crown root system: an intermediate number of crown roots with steep growth angles and few but long lateral branches

The crown root system is the most important part of the maize root system for soil resource acquisition during vegetative growth and remains important through reproductive development. As crown roots appear at successively younger nodes, their diameter and metabolic cost increases. The number of crown root axes may be too spatially dispersed to adequately exploit available soil resources, especially considering root loss to soil herbivores and pathogens, while at the high end the large number of crown roots may compete with each other for soil resources, as well as for internal metabolic resources, resulting in reduced elongation and wasted effort. An intermediate CN may be ideal. The optimum range of CN has yet to be determined, but is likely to be greater in low density maize plantings and soils of low P availability typical of low-input agroecosystems. The growth angle of axial roots is a primary determinant of root foraging depth. It is well established that the growth angle of axial roots is related to rooting depth in several crop species [54], which in turn is closely correlated with the depth of soil resource acquisition, with shallow growth angles being superior for topsoil foraging and therefore P acquisition [55] and steep growth angles being superior for water acquisition under drought [56].

Sparse lateral branching of crown roots should concentrate internal resources on axial elongation and thereby increase rooting depth and should reduce competition for nitrate among neighbouring lateral roots, as discussed above. Fewer, longer laterals would explore a greater volume of soil accessible via mass flow of water (and therefore nitrate) than a greater number of short laterals of equivalent total length. As N availability increases, or as the rate of leaching decreases, greater lateral branching would have value by increasing resource exploitation, whereas reduced lateral branching would favour soil exploration at the expense of soil exploitation.

Brace root system: one whorl of brace roots of high occupancy, a growth angle that is slightly shallower than the growth angle for crown roots, with few but long laterals

Brace roots arise from above-ground shoot nodes, appear later than crown roots, and function in mechanical support of the shoot as well as in mid-season topsoil exploitation. The successive appearance of maize root systems over time, beginning with the primary root, followed rapidly by the seminal roots, mesocotyl-borne roots, then crown and finally brace roots, represents successive flushes of roots originating in surface soil and descending into deeper soil over time. This is relevant to drought adaptation since, as noted above, steeply angled crown and brace root phenotypes that rapidly exploit deep soil resources may not have to sacrifice exploitation of topsoil resources, such as shallow water in intermittent drought, or N mineralization from topsoil organic matter, since successive root systems are passing through the topsoil throughout vegetative growth. This phenomenon may be more important for acquisition of water than N since, in agricultural soils, topsoil N resources may be fairly depleted by flowering [57], although in low-input systems, gradual release of mineral N from organic matter may make the topsoil a continuing source of N [58]. One whorl of brace roots is preferable to multiple whorls since brace roots from younger whorls appear later in development and arise farther from the soil, so are likely to be less useful for soil resource acquisition. The first above-ground node should have high occupancy, however, i.e. be fully occupied with brace roots that successfully reach the soil. These roots should have a steep growth angle but, to avoid direct competition with the crown roots, should be slightly less steep than the angle of crown roots. Intermediate rather than steep growth angles of brace roots may also be useful for physical bracing of the shoot. The rationale for few but long laterals on the brace roots is given above. In the field many brace roots branch profusely upon entering the soil – this phene may be counterproductive in cases where topsoil resources are depleted during vegetative growth, although it may aid in mechanical support of the shoot.

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 [59]. 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 [60].

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 [61]. 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 signalling pathway that reduces stomatal aperture, contributes to differential root/shoot growth [62] 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 CO2 fixation and grain filling even under drought stress. This can otherwise result 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.

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 [63].

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 [64].

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 determine 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 [65].

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 [66].

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 [67]. 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.

Quality characters

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 [68]. 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 non-functional mutant O2 alleles [69]. Similarly, waxy maize with recessive wx allele can increase maize industrial demand as a by product.

Transgenic maize

The first transgenic corn hybrid with insect resistance traits was commercialized in 1996 in the USA [70]. 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 [71]. 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) [72].

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.

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 favourable 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.

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