

Crop Genetic Engineering Under Global Climate Change

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Abstract: Climate change may bring an increased intensity and frequency of storms, drought and flooding, weather extremes, altered hydrological cycles, and precipitation. Such climate vulnerability will threaten the sustainability of farming systems, particularly in the developing world. Stress tolerant bred-germplasm, coupled with sustainable crop and natural resource management as well as sound policy interventions will provide means for farmers to cope with climate change and benefit consumers worldwide. This article reviews advances in genetic engineering for improving traits such as heat tolerance, water productivity, and better use of nutrients that may enhance crop adaptation to the changing climate of the twenty-first century.

Key words: Drought, genetic enhancement, global warming, plant breeding, transgenics.

Many crops are grown worldwide across a range of climates, soils, and vegetations. Farmers and scientists are aware of the influence of climate and weather on crop adaptations and yield stability. Furthermore, by using high-resolution paleo-climatic data, Zhang *et al.* (2007) showed that in both Europe and China long-term weather patterns were strongly linked to the frequency of wars from AD 1400 to 1900.

Increasing carbon dioxide (CO₂), rising global mean temperatures, gradual rainfall changes, more frequent intense weather extremes, and great weather variability are occurring due to climate change (FAO, 2008a). Such factors impact directly on the health and well-being of crops, thereby affecting small landholders, subsistence agriculture, and food security in the developing world (Tubiello *et al.*, 2007). Hence, research advances in agronomy and breeding should translate into crop yield gains to keep pace with predicted climate change.

Global Warming and Crop Yields

The total production of annual crops will be affected by increases in mean temperatures during the twenty-first century (Wheeler *et al.*, 2000). Seed yields are particularly sensitive to short periods of hot temperatures if they coincide with critical stages of crop development. Crop yield variation across years may depend on growing-season weather, which also influences how pathogens and pests affect crops and their host plant resistance. As indicated by Coakley *et al.* (1999) temperature is the single most important factor affecting insect ecology, epidemiology, and distribution, while plant pathogens will be highly responsive to humidity and rainfall, as well as to temperatures. CO₂ may further promote the rapid establishment of invasive insect species (Zavala *et al.*, 2008).

After analyzing spatial averages based on the locations of each crop, Lobell and Field (2007) indicated that temperatures and

precipitation account for approximately 30% or more of year-to-year variations in global average yields for the world's six most widely grown crops. For example, Argentina has had yield increases due to increases in precipitation, especially between October and March, decreases in maximum temperature and solar radiation, particularly during spring and summer, and increases in minimum temperature almost year round. Yield increases occurred especially in summer crops and in the semi-arid zone as shown by Magri *et al.* (2005), who quantified the impact of climate on crop yields in the last decades of the twentieth century. There was a negative response on global yields of wheat, maize, and barley to increased temperatures (Lobell and Field, 2007): warming since 1981 resulted in annual combined losses of about 40 million t or US\$ 5 billion per year, as of 2002, for these cereal crops. Peng *et al.* (2004) also showed that rice yields decline with higher night temperatures, as a result of global warming. Rice grain yield declined by 10% for each 1°C increase in growing-season minimum temperature in the dry season.

Each crop has a base temperature for vegetative development when growth commences, as well as an optimum temperature when the plant develops fast. Optimum mean temperatures for grain yields vary among the major crops [18–22°C for maize, 22–24°C for soybean, 15°C for wheat, 23–26°C for rice, 25°C for sorghum, 25–26°C for cotton, 20–26°C for peanut, 23–24°C for dry bean, and 22–25°C for tomato] (CCSP, 2008). An increase in temperature often accelerates crop phenological phases that may lead to shorter

life cycles associated with small plants and low yields. However, crop development slows beyond each species-dependent optimum temperature. Moreover, longer crop life cycles due to global warming will need more water. Higher temperatures at the reproductive stage may also affect pollen viability, fertilization, grain filling, and fruit development, thereby reducing crop yield potential. For example, by using projected low, mid, and high global warming scenarios, Anwar *et al.* (2007) indicated that median rainfed wheat yield may decrease by about 29% in southeastern Australia.

The negative impacts of warmer temperatures on crop yields may be countered by the increased rate of crop growth at elevated atmospheric CO₂ concentrations, at least when there is sufficient water (Wheeler *et al.*, 2000). C₃ crop species (e.g. rice or wheat) appear to be more responsive to CO₂ doubling than C₄ crop species (e.g. maize or sorghum). There are, however, serious doubts on projections that rising CO₂ will fully offset yield losses due to climate change (Long *et al.*, 2006). Crops may respond well to a CO₂ increase but the high temperature stress during the reproductive stage may erase such a benefit, which will depend upon other factors such as optimum breeding, irrigation, and nutrients. Hikes in surface ozone (O₃) can also be a threat to crop yields and will outweigh any benefits triggered by rising CO₂ levels (Giles, 2005) because O₃ creates reactive molecules that destroy Rubisco—a very important enzyme for photosynthesis, and makes leaves age faster. CO₂ and O₃ can also affect crop water-use because of

direct effects on crop growth and leaf area, alterations in leaf stomatal aperture (and consequently their conductance for water vapor loss), and physical changes in the vapor pressure inside leaves (CCSP, 2008). Furthermore, rising atmospheric CO₂ may contribute to shrubland expansion, which remains an important problem facing rangeland managers and ranchers (Morgan *et al.*, 2007). This process replaces grasses, the preferred forage of domestic livestock, with species that are unsuitable for domestic livestock grazing.

Nitrous oxide (N₂O) is a potent greenhouse gas generated through use of manure or nitrogen (N) fertilizer and susceptible to de-nitrification (several groups of heterotrophic bacteria use NO₃⁻ as a source of energy by converting it to the gaseous forms (N₂, NO, and NO₂). Thus, N₂O is often unavailable for crop uptake or utilization (Smith *et al.*, 1990). In many intensive cropping systems common N-fertilizer practices lead to high fluxes of N₂O and nitric oxide (NO) (Matson *et al.*, 1998). Reduced emissions (50% less) should be therefore a target for the intensive agro-ecosystems of the twenty-first century, but without affecting crop yields, e.g., through proper amounts and timing of N applications or by genetically enhancing crops with a better N use.

Targeting Priority Regions

Crop modeling shows that climate change will likely reduce agricultural production, thus reducing food availability (Lobell *et al.*, 2008) and affecting food security (Schmidhuber and Tubiello, 2007). For example, Jones and Thornton (2003) forecast for 2055 an overall 10% reduction

in maize production in Africa and Latin America; i.e., a loss in maize grain worth approximately US\$ two billion yearly.

Climate change impacts on agriculture will vary by region because these are influenced by the technologies used by farmers; i.e., technological sophistication determines farm productivity far more than climatic and agricultural endowments (Brown and Funk, 2008). The productivity of food staples, especially those grown in the developing world, will likely suffer without adaptation measurements to address global warming and water shortages. The magnitude of climate change will influence crop prices elsewhere, which depend also on global market changes, thereby affecting food affordability for poor people.

Recent estimates suggest an increase by about 5 to 8% (60-90 million ha) of areas with drought by 2080 in sub-Saharan Africa, which contributed very little to climate change (about 2% of the anthropogenic CO₂) (Fischer *et al.*, 2008). Southern Africa may be severely affected with about 11% of its land at risk of being lost to crop husbandry due to environmental constraints induced by climate change. Stige *et al.* (2006) suggest that maize yields in Southern Africa are affected by the El Niño Southern Oscillation, which may be a likely scenario with global climate change.

The favorable, high potential, irrigated Indo-Gangetic Plains, which account for most of the rice and wheat production in South Asia will be likely affected by possible climate shifts. For example 51% of its wheat-producing area might be reclassified as a heat-stressed, irrigated, short-season production environment (Ortiz *et al.*, 2008). This shift would also represent a significant

reduction in cereal yields, unless appropriate cultivars and crop management practices were offered to, and adopted by South Asian farmers.

As a result of climate change, there will be a decrease in water availability (expressed as runoff) of up to 40 mm per year in the Middle East and North Africa (MENA); there will be twice the runoff in the Anatolian Plateau (FAO, 2008b). The number of dry days will increase whereas the number of frost days should decrease and heat waves could increase in the region's more continental areas. The length of growing seasons should also decrease in MENA. Hence, crop yields in this region will likely suffer losses because of high temperatures, drought, floods, and soil degradation, thereby putting food security of the inhabitants under threat.

The Andes of South America are also highly vulnerable to climate change (Lagos, 2007), which will aggravate challenges for sustainable development of such a mountain region and will impact the ability of its farmers to adapt to changing conditions brought by global warming. By using a multi-model of global warming simulations and analyzing observed rainfall trends, Neelin *et al.* (2006) showed a significant drying trend in the Caribbean/Central-American region. Similarly, climate change scenarios suggest that the average annual temperature increase in China by the end of the twenty-first century may be between 3 and 4°C (Erda *et al.*, 2005). The models suggest that climate change without CO₂ fertilization could reduce the rice, maize, and wheat yields in the country by up to 37% in the next 20 to 80 years.

Adapting Agriculture to Climate Change through Plant Breeding

The Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report indicates that crop yields may slightly increase at mid to high latitudes for local mean temperature increases of up to 1 to 3°C depending on the crop, and then decrease beyond that in some regions (IPCC, 2007). For example, at lower latitudes, especially in seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1-2°C), which would increase the risk of hunger. The IPCC further states that crop and husbandry adaptations, such as altered cultivars and planting times, respectively, may allow low and mid to high latitude cereal yields to be kept at or above baseline yields for modest warming, whereas frequent droughts and floods will affect local production negatively, especially in subsistence sectors at low latitudes.

The Stern Review on climate change advocates for developing crops that can withstand heat, drought, and floods (http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/sternreview_index.cfm). A recent assessment of the World Bank report on climate change also points out that cultivars with enhanced tolerance to heat, and water or plus salinity stresses are essential for a long-term adaptation response to climate change (E. Pehu, World Bank, personal communication). Not surprisingly, worldwide research recently focused on generating plants with catch-all alterations involving the signaling pathways and their early responses that are common to several

abiotic stresses such as heat, cold, salinity or water scarcity, as pointed out by Tester and Bacic (2005).

Innovations in crop genetic enhancement will provide some of the best options for farmers, especially in the developing world, to cope with global warming and water scarcity, flooding, and salinity. Breeding research to develop crops for the twenty-first century should, however take into account the fact that production environments will be more variable and more stressful, yearly climate variation will be greater, and field sites and environments for testing and targeting crops will essentially be a rapidly moving target (Ainsworth *et al.*, 2008). Plant breeding, appropriate crop husbandry, sound natural resource management, and agricultural policy interventions will be needed to ensure food availability and reduce poverty in a world affected by climate change (FAO, 2007; Howden *et al.*, 2007; Slater *et al.*, 2007).

Research Agenda to Address Climate Change in Agriculture through Plant Breeding

To cope with the impacts of climate change, priority target breeding traits will address crop responses to temperature, water (drought and flooding) and nutrient stresses, and elevated CO₂ and O₃ (Ainsworth *et al.*, 2008). Breeding new cultivars with enhanced adaptation to high-temperatures, CO₂ and O₃, as well as cultivars that yield well with lower water and nutrient inputs will help farmers grow crops in stressful environments of the twenty-first century. Such farmers will also be affected by limited resources for farming. Genetic resources and breeding methods combining

conventional and molecular tools (including the transgenic approach) are needed to develop such cultivars. However, as indicated by Bonhert *et al.* (2006), abiotic stresses such as temperature extremes, water scarcity, and ion toxicity (e.g. salinity and heavy metals) are difficult to dissect because defense responses to abiotic factors require regulatory changes to the activation of multiple genes and pathways. Nevertheless, recent advances in genomics research address in a more integrated fashion the multigenicity of the plant abiotic stress response.

Crops with a better use of N can reduce surplus N-fertilizer inputs, saving farmers money and protecting the environment by reducing trace gas emissions, thus mitigating climate change. Biological nitrification inhibition (BNI) or suppressing nitrification by releasing inhibitory compounds from plant roots) may assist in this endeavor (Subbarao *et al.*, 2006). BNI genes are available in some tropical grasses (Gopalakrishnan *et al.*, 2007) and wild relatives of wheat (Subbarao *et al.*, 2007) and may pave the way for genetically engineered BNI ability in other major food crops.

Transgenic Crops for Farming under Climate Change

As a science-based technology, modern plant breeding brings innovations to farming systems as a result of new findings and ensuing knowledge from research on the genetic enhancement of crops. Crop improvement could be accelerated by the genetic engineering of new traits, particularly those that are not amenable to conventional breeding (Jauhar, 2006).

Transgenic alfalfa, canola, cotton, maize, papaya, soybean, and squash with herbicide and pest resistance have been successfully deployed elsewhere (James, 2007). Farmers grew about 114.3 million ha of transgenic crops in 2007 (with a growth rate of 12% vis-à-vis the previous year).

As indicated in the previous section, abiotic stresses exacerbated by climate change pose a serious threat to the sustainability of crop yields and account for substantial yield losses, particularly in rainfed agriculture. Various research domains including plant and cell physiology, molecular biology, genetics, and plant breeding will influence crop breeding in terms of how new cultivars can respond to environments with abiotic stresses (Bhatnagar-Mathur *et al.*, 2008).

Successes in crop breeding to adapt new cultivars to such abiotic stressful environments will depend on various research domains including plant and cell physiology, molecular biology, genetics, and plant breeding (Bhatnagar-Mathur *et al.*, 2008). The modern tools of cell and molecular biology have shed light on control mechanisms for abiotic-stress tolerance, and for engineering stress-tolerant crops based on the expression of specific stress-related genes. This could accelerate the breeding of new cultivars. Nevertheless, physiological knowledge of the processes of abiotic stress tolerance in crops continues to develop and guides conventional breeding and genetic engineering of new crop cultivars. Such physiological trait-based approaches to crop genetic enhancement will lead to target genetic manipulations (through crossing or transgenic approaches), thereby resulting in desired genotypes due

to an enrichment of stress-adaptive alleles in the breeding populations.

Drought stress

Climate change will also be associated with increased water stresses in many regions due to changes in rainfall distribution and because increased temperatures under low relative humidity will result in greater evaporative demand thereby reducing water-use efficiency, particularly in drought-prone environments. Bennett (2003) summarizes options for water productivity enhancement through crop breeding and biotechnology, whereas Ortiz *et al.* (2007) provide an overview of transgenic research for drought-prone environments. Some highlights of the most recent advances on genetically engineered crops for drought-prone environments are given below.

A model plant such as *Arabidopsis thaliana* became a useful research tool for functional genomics and also as a source of alleles for improving crops in stressful environments. For example, the *Dehydration-Responsive Element Binding* gene 1 (*DREB1*) and *DREB2* are transcription factors that bind to the promoter of genes such as the dehydration-responsive *Arabidopsis* gene *rd29A*, thereby inducing expression in response to drought, salt, and cold in some crop species (Ortiz *et al.*, 2007 and reference therein). Similarly, the expression of the *Arabidopsis* *HARDY* (*HRD*) gene in transgenic rice improved water-use efficiency and the ratio of biomass produced to the amount of water used, by enhancing photosynthetic assimilation and reducing transpiration (Karaba *et al.*, 2007). Rice

plants that consumed less water exhibited increased shoot biomass under irrigated conditions and an adaptive increase in root biomass under drought stress. This result shows the usefulness of research undertaken in a model plant such as *Arabidopsis* for improving water-use efficiency in a main staple such as rice.

Drought accelerates leaf senescence, leading to a decrease in canopy size and loss in photosynthesis, thereby reducing crop yields. A delay in drought-induced leaf senescence could therefore enhance crop tolerance to water scarcity. Rivero *et al.* (2007), using tobacco as the model plant, showed that the suppression of drought-induced leaf senescence led to outstanding drought tolerance as measured by the vigorous growth of the transgenic plants after a long drought period that killed the control plants. Furthermore, the transgenic tobacco plants maintained high water contents and retained, although reduced, photosynthetic activity during the drought period. Moreover, there was minimal yield loss in the transgenic plants when they were watered with only 30% of the amount of water used for the control plants.

Transgenic maize that expresses *Escherichia coli*'s glutamate dehydrogenase (*gdhA*) gene (Lightfoot *et al.*, 2007) will be another potential avenue for breeding drought tolerance. Germination and grain biomass production were increased in *gdhA* transgenic maize in the field during seasons with significant water scarcity. Water deficit tolerance under controlled conditions was also increased. Moreover, Castiglioni *et al.* (2008) indicate that expression of related cold shock proteins (CSPs) from bacteria,

CspA from *E. coli*, and CspB from *Bacillus subtilis*, promote stress adaptation in multiple plant species. They further stated that, expression of CSP proteins in maize is not associated with negative pleiotropic effects, indicating that stress tolerance does not come at a cost to crop yield under limiting water.

Phosphatidylinositol-specific phospholipase C (PI-PLC) plays important roles in various physiological processes that could be activated by several environmental stresses. A phospholipase C1 gene (*ZmPLC1*) cloned from maize encoded a PI-PLC and up-regulated the expression in maize roots under dehydration (Zhai *et al.*, 2005). Research results show that an enhanced expression of *ZmPLC1* improves drought tolerance in transgenic maize (Wang *et al.*, 2008). Under drought stress, the transgenic maize had higher relative water content, better osmotic adjustment, increased photosynthesis rates, lower percentage of ion leakage, less lipid membrane peroxidation, and higher grain yield than the control. Recently, Nelson *et al.* (2007) showed that an orthologous maize transcription factor (*ZmNF-YB2*) confers improved performance under drought. Transgenic maize plants with increased *ZmNFYB2* expression show tolerance to drought as measured by chlorophyll content, stomatal conductance, leaf temperature, reduced wilting, and maintenance of photosynthesis under limiting water. Such stress adaptations will contribute to grain yield, when this maize grows in drought-prone environments.

The new generation of traits to counter drought includes the use of RNA interference in which defense to stress will

still be maintained, but without impairing the growth of the plant. Bayer Crop Science report yield increases of up to 40% using this approach in transgenic canola after field testing in Canada (http://www.checkbiotech.org/green_News_Genetics.aspx?infoId=15836). Other scientists are investigating the ability of the South African resurrection plant, (*Craterostigma plantagineum*) for withstanding drought. In this plant, a number of genes are only read during a water shortage, while others are completely turned off at the same time. Researchers from the University of Bonn (Germany) isolated the detoxification enzyme aldehyde dehydrogenase (ALDH) from this resurrection plant and inserted it in *Arabidopsis*. The transgenic *Arabidopsis* withstood periods of drought longer (>40%) vis-à-vis wild-type plants.

High CO₂ and O₃

Rising atmospheric CO₂ and O₃ are broadly acknowledged as important to crop production, but little genetic research investments are given to improve crop responses to such factors. Ainsworth *et al.* (2008) provide an overview of potential biotechnological targets for improving yields in high-CO₂ and O₃ cropping systems. The main challenge for crop genetic enhancement will be to breed crops that maximize the advantages of rising CO₂. For example, Ainsworth *et al.* (2008) suggest that substituting current Rubisco for Rubisco from other species, particularly non-green algae, which has a markedly lower specificity and higher catalytic rate, could dramatically increase C gain at current and elevated CO₂ levels, whereas Zhu *et al.* (2004) indicate that further gains could be maximized by engineering plants to

express different types of Rubisco in sunlit and shade leaves.

A strategy to increase crop tolerance to O₃ might involve reducing stomatal conductance (Lin *et al.*, 2001), whereas other approaches for improving crop tolerance to O₃ may rely on improving detoxification of O₃-induced reactive oxygen species (Fiscus *et al.*, 2005). Ainsworth *et al.* (2008) also indicate that components of the O₃ sensing and signaling pathways are potential targets for crop engineering under high O₃. However, any attempts for breeding crop tolerance to O₃ by altering sensing, signaling, or regulatory pathways should not disrupt other vital processes in the plant.

Better N use

Improving the nitrogen-use efficiency (NUE) of crops will be a key factor for reducing N fertilizer pollution as well as for improving yields in N-limiting environments. Shrawat and Good (2008) give a brief summary of crop genetic engineering for enhancing NUE. Engineering plants with transport gene systems, glutamine synthetase and glutamate synthase gene systems, gene systems regulating N metabolism or manipulating N remobilization are among the ongoing NUE research undertakings. Research suggests it could be possible to enhance or manipulate N metabolism and crop growth. However, knowledge of the mechanisms involved in N remobilization during leaf senescence is still preliminary and further research will provide new insights for transgenic approaches to enhance NUE. In this regard, Yanagisawa *et al.* (2004) advocate that transcription

factor might be a powerful approach to modification of metabolism for a generation of crops having superior characteristics because a single transcription factor frequently regulates coordinated expression of a set of key genes for respective pathways. In their research the plant-specific Dof1 transcription factor induced the up-regulation of genes encoding enzymes for carbon skeleton production, a marked increase of amino acids, and a reduction of glucose in transgenic *Arabidopsis*. Furthermore, the N content increased in the Dof1 transgenic plants (~30%), which indicated the promotion of net N assimilation. The Dof1 transgenic plants exhibited improved growth under a low N.

Outlook

It takes about a decade and US\$ 100 million to breed a new transgenic crop cultivar and for it to become available to farmers (E. Sachs, Monsanto Co.). The development of a successful transgenic cultivar starts from trait discovery and undergoes, after the proof of concept, several development phases (including those needing field testing), and requires a regulatory phase for assessing risks to human health, the environment, and biodiversity. Some farmers and consumers are already planting and eating foods from these crops, while others are raising issues related to food and environmental safety. Lemaux (2008) provides updated responses to these issues using the most recent peer-refereed literature. As she points out, her article presents "as accurate a scientific picture as possible, although this does not imply that people possessing the same scientific understanding will necessarily

make the same choices about the advisability of genetically engineered crops for consumption, because different people have different values".

The authors of the International Assessment of Agricultural Science and Technology for Development (IAASTD) found that transgenic crops are appropriate in some contexts, unpromising in others, and unproven in many more (Kiers *et al.*, 2008). The potential of transgenic crops to serve the needs of the subsistence farmer was also recognized, but the IAASTD authors claim that this potential remains unfulfilled. As stated recently by the German Advisory Council on Climate Change (2007), "...without resolute counteraction, climate change...could result in destabilization and violence, jeopardizing national and international security to a new degree." Indeed, falling crop yields will block development and raise poverty, thereby escalating the risk of conflicts. Crop genetic engineering should therefore contribute to global security and peace by ensuring food security and improving the livelihoods of both farmers and consumers in the twenty-first century.

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