Improving Vegetable Productivity in a Variable and Changing Climate

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The Impact of Climate Change on Tropical Agriculture

A significant change in climate on a global scale will impact agriculture and consequently affect the world's food supply. Climate change *per se* is not necessarily harmful; the problems arise from extreme events that are difficult to predict (FAO 2001). More erratic rainfall patterns and unpredictable high temperature spells will consequently reduce crop productivity. Developing countries in the tropics will be particularly vulnerable. Latitudinal and altitudinal shifts in ecological and agro-economic zones, land degradation, extreme geophysical events, reduced water availability, and rise in sea level and salinization are postulated (FAO 2004). Unless measures are undertaken to mitigate the effects of climate change, food security in developing countries in the tropics will be under threat.

***Vegetable production in the tropics*.** Vegetables are the best resource for overcoming micronutrient deficiencies and provide smallholder farmers with much higher income and more jobs per hectare than staple crops (AVRDC 2006). The worldwide production of vegetables has doubled over the past quarter century and the value of global trade in vegetables now exceeds that of cereals. In Asia, vegetable production grew at an annual average rate of 3.4% in the 1980s and early 1990s, from 144 million MT in 1980 to 218 million MT in 1993 (Ali 2000). In addition, the area under vegetable cultivation increased at an annual rate of 2.1%, from 12 million hectares in 1980 to 16.3 million hectares in 1993 with most of the increase coming from increased production in China. Amongst vegetable crops, tomatoes are the most important horticultural crop worldwide and grown on over 4 million hectares of land area (FAO 2006, Brown *et al.* 2005). Tomato, cabbage, onion, hot pepper and eggplant are particularly important in Asia and Sub-Saharan Africa (Brown *et al.* 2005). Yields in Asia are highest in the east where the climate is mainly temperate and sub-temperate. Most vegetables prefer cooler temperatures, thus productivity is lowest in the hot and humid lowlands of Southeast Asia (Ali 2000). In Sub-Saharan Africa (excluding South Africa) and tropical Asia, average tomato yields are only about 10 - 12 MT/hectare, well below the yields in temperate regions (FAO 2006). Vegetables are generally sensitive to environmental extremes, and thus high temperatures and limited soil moisture are the major causes of low yields in the tropics and will be further magnified by climate change.

Environmental constraints limiting vegetable productivity. Environmental stress is the primary cause of crop losses worldwide, reducing average yields for most major crops by more than 50% (Boyer 1982, Bray *et al.* 2000). The tropical vegetable production environment is a mixture of conditions that varies with season and region. Climatic changes will influence the severity of environmental stress imposed on vegetable crops. Moreover, increasing temperatures, reduced irrigation water availability, flooding, and salinity will be major limiting factors in sustaining and increasing vegetable productivity. Extreme climatic conditions will also negatively impact soil fertility and increase soil erosion. Thus, additional fertilizer application or improved nutrient-use efficiency of crops will be needed to maintain productivity or harness the potential for enhanced crop growth due to increased atmospheric CO^2. The response of plants to environmental stresses depends on the plant developmental stage and the length and severity of the stress (Bray, 2002). Plants may respond similarly to avoid one or more stresses through morphological or biochemical mechanisms (Capiati *et al.* 2006). Environmental interactions may make the stress response of plants more complex or influence the degree of impact of climate change. Measures to adapt to these climate change-induced stresses are critical for sustainable tropical vegetable production. Until now, the scientific information on the effect of environmental stresses on vegetables is overwhelmingly on tomato. There is a need to do more research on how other vegetable crops are affected by increased abiotic stresses as a direct potential threat from climate change.

- ***High temperatures.*** Temperature limits the range and production of many crops. In the tropics, high temperature conditions are often prevalent during the growing season and, with a changing climate, crops in this area will be subjected to increased temperature stress. Analysis of climate trends in tomato-growing locations suggests that temperatures are rising and the severity and frequency of above-optimal temperature episodes will increase in the coming decades (Bell *et al.* 2000). Vegetative and reproductive processes in tomatoes are strongly modified by temperature alone or in conjunction with other environmental factors (Abdalla & Verkerk 1968). High temperature stress disrupts the biochemical reactions fundamental for normal cell function in plants. It primarily affects the photosynthetic functions of higher plants (Weis & Berry 1988). High temperatures can cause significant losses in tomato productivity due to reduced fruit set, and smaller and lower quality fruits (Stevens & Rudich 1978). Pre-anthesis temperature stress is associated with developmental changes in the anthers, particularly irregularities in the epidermis and endothesium, lack of opening of the stromium, and poor pollen formation (Sato *et al.* 2002). In pepper, high temperature exposure at the pre-anthesis stage did not affect pistil or stamen viability, but high post-pollination temperatures inhibited fruit set, suggesting that fertilization is sensitive to high temperature stress (Erickson & Markhart 2002). Hazra *et al.* (2007) summarized the symptoms causing fruit set failure at high temperatures in tomato; this includes bud drop, abnormal flower development, poor pollen production, dehiscence, and viability, ovule abortion and poor viability, reduced carbohydrate availability, and other reproductive abnormalities. In addition, significant inhibition of photosynthesis occurs at temperatures above optimum, resulting in considerable loss of potential productivity.

- ***Drought.*** Unpredictable drought is the single most important factor affecting world food security and the catalyst of the great famines of the past (CGIAR 2003). The world’s water supply is fixed, thus increasing population pressure and competition for water resources will make the effect of successive droughts more severe (McWilliam 1986). Inefficient water usage all over the world and inefficient distribution systems in developing countries further decreases water availability. Water availability is expected to be highly sensitive to climate change and severe water stress conditions will affect crop productivity, particularly that of vegetables. In combination with elevated temperatures, decreased precipitation could cause reduction of irrigation water availability and increase in evapotranspiration, leading to severe crop water-stress conditions (IPCC 2001). Vegetables, being succulent products by definition, generally consist of greater than 90% water (AVRDC 1990). Thus, water greatly influences the yield and quality of vegetables; drought conditions drastically reduce vegetable productivity. Drought stress causes an increase of solute concentration in the environment (soil), leading to an osmotic flow of water out of plant cells. This leads to an increase of the solute concentration in plant cells, thereby lowering the water potential and disrupting membranes and cell processes such as photosynthesis. The timing, intensity, and duration of drought spells determine the magnitude of the effect of drought.

- ***Salinity.*** Vegetable production is threatened by increasing soil salinity particularly in irrigated croplands which provide 40% of the world's food (FAO 2002). Excessive soil salinity reduces productivity of many agricultural crops, including most vegetables which are particularly sensitive throughout the ontogeny of the plant. According to the United States Department of Agriculture (USDA), onions are sensitive to saline soils, while cucumbers, eggplants, peppers, and tomatoes, amongst the main crops of AVRDC - The World Vegetable Center, are moderately sensitive. In hot and dry environments, high evapotranspiration results in substantial water loss, thus leaving salt around the plant roots which interferes with the plant's ability to uptake water. Physiologically, salinity imposes an initial water deficit that results from the relatively high solute concentrations in the soil, causes ion-specific stresses resulting from altered K^+/Na^+ ratios, and leads to a build up in Na^+ and Cl^- concentrations that are detrimental to plants (Yamaguchi & Blumwald 2005). Plant sensitivity to salt stress is reflected in loss of turgor, growth reduction, wilting, leaf curling and epinasty, leaf abscission, decreased photosynthesis, respiratory changes, loss of cellular integrity, tissue necrosis, and potentially death of the plant (Jones 1986; Cheeseman 1988). Salinity also affects agriculture in coastal regions which are impacted by low-quality and high-saline irrigation water due to contamination of the groundwater and intrusion of saline water due to natural or man-made events. Salinity fluctuates with season, being generally high in the dry season and low during rainy season when freshwater flushing is prevalent. Furthermore, coastal areas are threatened by specific, saline natural disasters which can make agricultural lands unproductive, such as tsunamis which may inundate low-lying areas with seawater. Although the seawater rapidly recedes, the groundwater contamination and subsequent osmotic stress causes crop losses and affects soil fertility. In the inland areas, traditional water wells are commonly used for irrigation water in many countries. The bedrock deposit contains salts and the water from these wells are becoming more saline, thus affecting irrigated vegetable production in these areas.

- ***Flooding.*** Vegetable production occurs in both dry and wet seasons in the tropics. However, production is often limited during the rainy season due to excessive moisture brought about by heavy rain. Most vegetables are highly sensitive to flooding and genetic variation with respect to this character is limited, particularly in tomato. In general, damage to vegetables by flooding is due to the reduction of oxygen in the root zone which inhibits aerobic processes. Flooded tomato plants accumulate endogenous ethylene that causes damage to the plants (Drew 1979). Low oxygen levels stimulate an increased production of an ethylene precursor, 1-aminocyclopropane-1-carboxylic acid (ACC), in the roots. The rapid development of epinastic growth of leaves is a characteristic response of tomatoes to water-logged conditions and the role of ethylene accumulation has been implicated (Kawase 1981). The severity of flooding symptoms increases with rising temperatures; rapid wilting and death of tomato plants is usually observed following a short period of flooding at high temperatures (Kuo *et al.* 1982).

The Need for Adaptation to Climate Change

Potential impacts of climate change on agricultural production will depend not only on climate *per se*, but also on the internal dynamics of agricultural systems, including their ability to adapt to the changes (FAO 2001). Success in mitigating climate change depends on how well agricultural crops and systems adapt to the changes and concomitant environmental stresses of those changes on the current systems. Farmers in developing countries of the tropics need tools to adapt and mitigate the adverse effects of climate change on agricultural productivity, and particularly on vegetable production, quality and yield. Current, and new, technologies being developed through plant stress physiology research can potentially contribute to mitigate threats from climate change on vegetable production. However, farmers in developing countries are usually small-holders, have fewer options and must rely heavily on resources available in their farms or within their communities. Thus, technologies that are simple, affordable, and accessible must be used to increase the resilience of farms in less developed countries. AVRDC – The World Vegetable Center has been working to address the effect of environmental stress on vegetable production. Germplasm of the major vegetable crops which are tolerant of high temperatures, flooding and drought has been identified and advanced breeding lines are being developed. Efforts are also underway to identify nitrogen-use efficient germplasm. In addition, development of production systems geared towards improved water-use efficiency and expected to mitigate the effects of hot and dry conditions in vegetable production systems are top research and development priorities.

Enhancing Vegetable Production Systems. Various management practices have the potential to raise the yield of vegetables grown under hot and wet conditions of the lowland tropics. AVRDC – The World Vegetable Center has developed technologies to alleviate production challenges such as limited irrigation water and flooding, to mitigate the effects of salinity, and also to ensure appropriate availability of nutrients to the plants. Strategies include modifying fertilizer application to enhance nutrient availability to plants, direct delivery of water to roots (drip irrigation), grafting to increase flood and disease tolerance, and use of soil amendments to improve soil fertility and enhance nutrient uptake by plants.

- ***Water-saving irrigation management.*** The quality and efficiency of water management determine the yield and quality of vegetable products. The optimum frequency and amount of applied water is a function of climate and weather conditions, crop species, variety, stage of growth and rooting characteristics, soil water retention capacity and texture, irrigation system and management factor (Phene 1989). Too much or too little water causes abnormal plant growth, predisposes plants to infection by pathogens, and causes nutritional disorders. If water is scarce and supplies are erratic or variable, then timely irrigation and conservation of soil moisture reserves are the most important agronomic interventions to maintain yields during drought stress. There are several methods of applying irrigation water and the choice depends on the crop, water supply, soil characteristics and topography. Application of irrigation water could be through overhead, surface, drip, or sub-irrigation systems. Surface irrigation methods are utilized in more than 80% of the world's irrigated lands yet its field level application efficiency is often 40-50% (von Westarp 2004). To generate income and alleviate poverty of the small-holder farmers in developing countries, AVRDC – The World Vegetable Center and other institutions promote affordable, small-scale drip irrigation technologies developed by the International Development Enterprises (IDE). Drip irrigation delivers water directly to plants through small plastic tubes. IDE states that water losses due to run-off and deep percolation are minimized and water savings of 50-80% are achieved when compared to most traditional surface irrigation methods. Crop production per unit of water consumed by plant evapo-transpiration is typically increased by 10-50%. Thus, more plants can be irrigated per unit of water by drip irrigation, and with less labor. In Nepal, cauliflower yields using low-cost drip irrigation were not significantly different from those achieved by hand watering; however the long-term economic and labor benefits were greater using the low-cost drip irrigation (von Westarp 2004). The water-use efficiency by chili pepper was significantly higher in drip irrigation compared to furrow irrigation, with higher efficiencies observed with high delivery rate drip irrigation regimes (AVRDC 2005). For drought tolerant crop like watermelon, yield differences between furrow and drip irrigated crops were not significantly different; however, the incidence of Fusarium wilt was reduced when a lower drip irrigation rate was used. In general, the use of low-cost drip irrigation is cost effective, labor-saving, and allows more plants to be grown per unit of water, thereby both saving water and increasing farmers' incomes at the same time.

- ***Cultural practices that conserve water and protect crops.*** Various crop management practices such as mulching and the use of shelters and raised beds help to conserve soil moisture, prevent soil degradation, and protect vegetables from heavy rains, high temperatures, and flooding. The use of organic and inorganic mulches is common in high-value vegetable production systems. These protective coverings help reduce evaporation, moderate soil temperature, reduce soil runoff and erosion, protect fruits from direct contact with soil and minimize weed growth. In addition, the use of organic materials as mulch can help enhance soil fertility, structure and other soil properties. Rice straw is abundant in rice-growing areas of the tropics and generally recommended for summer tomato production. The benefits of rice straw mulch on fruit yield of tomato have been demonstrated in Taiwan (AVRDC 1981). In India, mulching improved the growth of eggplant, okra, bottle gourd, round melon, ridge gourd, and sponge gourd compared to the non-mulched controls (Pandita & Singh 1992). Yields were the highest when polythene and sarkanda (*Saccharum* spp. and *Canna* spp.) were used as mulching materials. In the lowland tropics where temperatures are high, dark-colored plastic mulch is recommended in combination with rice straw (AVRDC 1990). Dark plastic mulch prevents sunlight from reaching the soil surface and the rice straw insulates the plastic from direct sunlight thereby preventing the soil temperature rising too high during the day. During the hot rainy season, vegetables such as tomatoes suffer from yield losses caused by heavy rains. Simple, clear plastic rain shelters prevent water logging and rain impact damage on developing fruits, with consequent improvement in tomato yields (Midmore *et al.* 1992). Fruit cracking and the number of unmarketable fruits are also reduced. Elimination of flooding and rain damage, as well as the reduced air temperature, was responsible for the higher yields of the crops grown under plastic shelters. Another form of shelter using shade cloth can be used to reduce temperature stress. Shade shelters also prevent damage from direct rain impact and intense sunlight. Planting vegetables in raised beds can ameliorate the effects of flooding during the rainy season (AVRDC 1979, 1981). Yields of tomatoes increased with bed height, most likely due to improved drainage and reduction of anoxic stress. Additive effects on yield were observed when tomatoes were planted in raised beds with rain shelters.

- ***Improved stress tolerance through grafting.*** Grafting vegetables originated in East Asia during the 20th century and is currently common practice in Japan, Korea and some European countries. Grafting, in this context, involves uniting of two living plant parts (rootstock and scion) to produce a single growing plant.

It has been used primarily to control soil-borne diseases affecting the production of fruit vegetables such as tomato, eggplant, and cucurbits. However, it can provide tolerance to soil-related environmental stresses such as drought, salinity, low soil temperature and flooding if appropriate tolerant rootstocks are used. Grafting of eggplants was started in the 1950s, followed by grafting of cucumbers and tomatoes in the 1960s and 1970s (Edelstein 2004). Romero *et al.* (1997) reported that melons grafted onto hybrid squash rootstocks were more salt tolerant than the non-grafted melons. However, tolerance to salt by rootstocks varies greatly among species, such that rootstocks from *Cucurbita* spp. are more tolerant of salt than rootstocks from *Lagenaria siceraria* (Matsubara 1989). Grafted plants were also more able to tolerate low soil temperatures. *Solanum lycopersicum* x *S. habrochaites* rootstocks provide tolerance of low soil temperatures (10^{o}C to 13^{o}C) for their grafted tomato scions, while eggplants grafted onto *S. integrifolium x S. melongena* rootstocks grew better at lower temperatures (18^{o}C to 21^{o}C) than non-grafted plants (Okimura *et al.* 1986).

Vegetables generally are unable to tolerate excessive soil moisture. Tomatoes in particular are considered to be one of the vegetable crops most sensitive to excess water. In the tropics, heavy rainfall with poor drainage induces water-logged conditions that reduce oxygen availability in the soil thereby causing wilting, chlorosis, leaf epinasty, and ultimately death of the tomato plants. Genetic variability for tolerance of excess soil moisture is limited or inadequate to prevent losses. Research at AVRDC - The World Vegetable Center has shown that many accessions of eggplant are highly tolerant of flooding (Midmore *et al.* 1997). Thus, the Center developed grafting techniques to improve the flood tolerance of tomato using eggplant rootstocks which were identified with good grafting compatibility with tomato and high tolerance to excess soil moisture. Tomato scions grafted onto eggplant rootstock grow well and produce acceptable yields during the rainy season (Midmore *et al.* 1997). In addition to protection against flooding, some eggplant genotypes are drought tolerant and eggplant rootstocks can therefore provide protection against limited soil moisture stress.

Developing Climate-Resilient Vegetables. Improved, adapted vegetable germplasm is the most cost-effective option for farmers to meet the challenges of a changing climate. However, most modern cultivars represent a limited sampling of available genetic variability including tolerance to environmental stresses. Breeding new varieties, particularly for intensive, high input production systems in developed countries, under optimal growth conditions may have counter-selected for traits which would contribute to adaptation or tolerance to low input and less favorable environments. Superior varieties adapted to a wider range of climatic conditions could result from the discovery of novel genetic variation for tolerance to different biotic and abiotic stresses. Genotypes with improved attributes conditioned by superior combinations of alleles at multiple loci could be identified and advanced. Improved selection techniques are needed to identify these superior genotypes and associated traits, especially from wild, related species that grow in environments which do not support the growth of their domesticated relatives that are cultivated varieties. Plants native to climates with marked seasonality are able to acclimatize more easily to variable environmental conditions (Pereira & Chavez 1995) and provide opportunities to identify genes or gene combinations which confer such resilience.

- ***Tolerance to high temperatures.*** AVRDC - The World Vegetable Center has developed tomatoes and Chinese cabbage with general adaptation to hot and humid tropical environments and low-input cropping systems since the early 1970s. This has been achieved by developing heat-tolerant and disease-resistant breeding lines. The Center has made significant contributions to the development of heat-tolerant tomato and Chinese cabbage lines and the subsequent release of adapted, tropical varieties worldwide. Indeed, AVRDC - The World Vegetable Center's heat tolerant hybrids have resulted in the successful cultivation of Chinese cabbage in the lowland tropics. The key to achieving high yields with heat tolerant cultivars is the broadening of their genetic base through crosses between heat tolerant tropical lines and disease resistant temperate or winter varieties (Opena & Lo 1981). The heat tolerant tomato lines were developed using heat tolerant breeding lines and landraces from the Philippines (*e.g.* VC11-3-1-8, VC 11-2-5, Divisoria-2) and the United States (*e.g.* Tamu Chico III, PI289309) (Opena *et al.* 1989). However, lower yields in the heat tolerant lines are still a concern.

  More heat tolerant varieties are required to meet the needs of a changing climate, and these must be able to match the yields of conventional, non-heat tolerant varieties under non-stress conditions. A wider range of genotypic variation must be explored to identify additional sources of heat tolerance. An AVRDC - The World Vegetable Center breeding line, CL5915, has demonstrated high levels of heat tolerance in Southeast Asia and the Pacific. The fruit set of CL5915 ranges from 15% - 30% while there is complete absence of fruit set in heat-sensitive lines in mean field temperatures of 35^{o}C. Genetic studies at AVRDC - The World Vegetable Center indicated that heat tolerance in CL5915, based on fruit set and fruit number per cluster, is controlled by additive and dominant effects (Hanson *et al.* 2002). The average heritability for fruit set is 0.26. However, bimodality of fruit set distribution and recovery of tolerant lines in early backcross generations suggests that only a few major genes and modifiers may control the heat tolerance trait (Opena *et al.* 1990, 1992). Since then new breeding lines have been developed from CL5915 and other sources that exhibit increased heat tolerance. In Egypt, CL5915 lines were best combiners for percentage fruit set and total yield in hybrids developed from heat-tolerant and heat-sensitive lines (Metwally *et al.* 1996).

Germplasm evaluation for heat tolerance at AVRDC - The World Vegetable Center conventionally relied upon field screening during the hot and humid season, with measurement of fruit set and yield. Generally less than 1% of the screened lines or accessions exhibit a high level of heat tolerance (Villareal *et al.* 1978). Although field screening is effective, the accuracy and speed of the process could be improved through the use of molecular markers.

- ***Drought tolerance and water-use efficiency*.** Plants resist water or drought stress in many ways. In slowly developing water deficit, plants may escape drought stress by shortening their life cycle (Chaves & Oliveira 2004). However, the oxidative stress of rapid dehydration is very damaging to the photosynthetic processes, and the capacity for energy dissipation and metabolic protection against reactive oxygen species is the key to survival under drought conditions (Ort 2001, Chaves & Oliveira 2004). Tissue tolerance to severe dehydration is not common in crop plants but is found in species native to extremely dry environments (Ingram & Bartels 1996). Genetic variability for drought tolerance in *S. lycopersicum* is limited and inadequate. The best source of resistance is from other species in the genus *Solanum*. The Tomato Genetics Resource Center (TGRC) at the University of California, Davis has assembled a set of the putatively stress tolerant tomato germplasm that includes accessions of *S. cheesmanii*, *S. chilense*, *S. lycopersicum*, *S. lycopersicum* var. *cerasiforme*, *S. pennellii*, *S. peruvianum* and *S. pimpinellifolium*. *S. chilense* and *S. pennelli* are indigenous to arid and semi-arid environments of South America. Both species produce small green fruit and have an indeterminate growth habit. *S chilense* is adapted to desert areas of northern Chile and often found in areas where no other vegetation grows (Rick 1973, Maldonado *et al.* 2003). *S. chilense* has finely divided leaves and well-developed root system (Sanchez-Pena 1999). *S. chilense* has a longer primary root and more extensive secondary root system than cultivated tomato (O'Connell *et al.* 2007). Drought tests show that *S. chilense* is five times more tolerant of wilting than cultivated tomato. *S.*

pennellii has the ability to increase its water use efficiency under drought conditions unlike the cultivated *S. lycopersicum* (O'Connell *et al.* 2007). It has thick, round waxy leaves, is known to produce acyl-sugars in its trichomes, and its leaves are able to take up dew (Rick 1973).

Transfer and utilization of genes from these drought resistant species will enhance tolerance of tomato cultivars to dry conditions, although wide crosses with *S. pennellii* produce fertile progenies, *S. chilense* is cross-incompatible with *S. lycopersicum* and embryo rescue through tissue culture is required to produce progeny plants. Research at AVRDC - The World Vegetable Center and other institutions is in progress to identify the genetic factors underlying drought tolerance in *S. chilense* and *S. pennellii*, and to transfer these factors into cultivated tomatoes.

- ***Tolerance to saline soils and irrigation water.*** Attempts to improve the salt tolerance of crops through conventional breeding programs have very limited success due to the genetic and physiologic complexity of this trait (Flowers 2004). In addition, tolerance to saline conditions is a developmentally regulated, stage-specific phenomenon; tolerance at one stage of plant development does not always correlate with tolerance at other stages (Foolad 2004). Success in breeding for salt tolerance requires effective screening methods, existence of genetic variability, and ability to transfer the genes to the species of interest. Screening for salt tolerance in the field is not a recommended practice because of the variable levels of salinity in field soils. Screening should be done in soil-less culture with nutrient solutions of known salt concentrations (Cuartero & Fernandez-Munoz 1999). Most commercial tomato cultivars are moderately sensitive to increased salinity and only limited variation exists in cultivated species.

Genetic variation for salt tolerance during seed germination in tomato has been identified within cultivated and wild species. A cross between a salt-sensitive tomato line (UCT5) and a salt-tolerant *S. esculentum* accession (PI174263) showed that the ability of tomato seed to germinate rapidly under salt stress is genetically controlled with narrow-sense heritability (h^2) of 0.75 (Foolad & Jones 1991). Several studies indicate that salt tolerance during seed germination in tomato is controlled by genes with additive effects and could be improved by directional phenotypic selection (Foolad 2004).

In pepper, salt stress significantly decreases germination, shoot height, root length, fresh and dry weight, and yield. Yildirim and Guvenc (2006) reported that pepper genotypes Demre, Ilica 250, 11-B-14, Bagci Carliston, Mini Aci Sivri, Yalova Carliston, and Yaglik 28 can be useful as sources of genes to develop pepper cultivars with improved germination under salt stress. In Tunisia, the root system of salt tolerant cultivar 'Beldi' was unaffected by salt stress (van der Beek & Ltifi 1991). In addition, 'Beldi' significantly out-yielded other test cultivars at high salt treatments.

Related wild tomato species have shown strong salinity tolerance and are sources of genes as coastal areas are common habitat of some wild species. Studies have identified potential sources of resistance in the wild tomato species *S. cheesmanii*, *S. peruvianum*, *S pennelii*, *S. pimpinellifolium*, and *S. habrochaites* (Flowers 2004, Foolad 2004, Cuartero *et al.* 2006). Attempts to transfer quantitative trait loci (QTLs) and elucidate the genetics of salt tolerance have been conducted using populations involving wild species. Elucidation of mechanism of salt tolerance at different growth periods and the introgression of salinity tolerance genes into vegetables would accelerate development of varieties that are able to withstand high or variable levels of salinity compatible with different production environments.

Climate-Proofing though Genomics and Biotechnology. Increasing crop productivity in unfavorable environments will require advanced technologies to complement traditional methods which are often unable to prevent yield losses due to environmental stresses. In the past decade, genomics has developed from whole genome sequencing to the discovery of novel and high throughput genetic and molecular technologies. Genes have been discovered and gene functions understood. This has opened the way to genetic manipulation of genes associated with tolerance to environmental stresses. These tools promise more rapid, and potentially spectacular, returns but require high levels of investment. Many activities using these genetic and molecular tools are in place, with some successes. National and international institutes are re-tooling for plant molecular genetic research to enhance traditional plant breeding and benefit from the potential of genetic engineering to increase and sustain crop productivity.

- ***QTLs and gene discovery for tolerance to stresses.*** Genetic enhancement using molecular technologies has revolutionized plant breeding. Advances in genetics and genomics have greatly improved our understanding of structural and functional aspects of plant genomes. Combining new knowledge from genomic research with traditional breeding methods enhances our ability to improve crop plants. The use of molecular markers as a selection tool provides the potential for increasing the efficiency of breeding programs by reducing environmental variability, facilitating earlier selection, and reducing subsequent population sizes for field testing. Molecular markers facilitate efficient introgression of superior alleles from wild species into the breeding programs and enable the pyramiding of genes controlling quantitative traits. Thus, enhancing and accelerating the development of stress tolerant and higher yielding cultivars for farmers in developing countries.

Molecular marker analysis of stress tolerance in vegetables is limited but efforts are underway to identify QTLs underlying tolerance to stresses. QTLs for drought tolerance have been identified in tomato; Martin *et al.* (1989) identified three QTLs linked to water use efficiency in *S. pennellii* based on ^{13}C composition. Three independent yield-promoting regions were identified in *S. pennellii* when grown in both wet and dry field conditions in Israel (Gur & Zamir 2004), while Foolad *et al.* (2003) identified four QTLs associated with seed germination drought tolerance, two of which were contributed by *S. pimpinellifolium*. *S. pimpinellifolium* is also commonly investigated as source of salt tolerance. QTL mapping indicates that salt tolerance is quantitatively inherited (Foolad 2004). Only a few major QTLs account for the majority of phenotypic variation indicating the potential for marker-assisted selection (MAS) for salt tolerance. Lin *et al.* (2006) identified random amplified polymorphic DNA (RAPD) markers linked to heat tolerance in AVRDC - The World Vegetable Center's tomato line CL5915. A follow-up study is currently underway at the Center to fully understand the genetic mechanism of heat tolerance of CL5915. Studies indicate that stress tolerance is quantitatively inherited and in some cases tolerance is dependent on the developmental stage of the plant. Consequently, multiple genes are predicted to be involved with the expression of stress tolerance. Studies on QTL analysis of stress tolerance is limited, and may reflect the limited variation of these traits. Furthermore, the environmental influence on the expression of stress tolerance traits is high and makes phenotyping difficult. Identification of environmentally-stable surrogate phenotypes or component traits is necessary to effectively evaluate genotypes and genetic populations. This is a critical tool to identify the QTLs underlying tolerance to environmental stresses. Many genes associated with stress tolerance have recently been determined using high throughput expression assays. Integration of QTL analysis with gene discovery and modeling of genetic networks will facilitate a comprehensive understanding of stress tolerance, permit the development of useful and effective markers for marker-assisted selection, and identify candidate genes for genetic engineering.

- ***Engineering stress tolerance.*** Environmental stress tolerance is a complex trait and involves many genes (Wang *et al.* 2003). In response to stresses, both RNA and protein expression profiles change. Approximately 130 drought-responsive genes have been identified using microarrays (Seki *et al.* 2001, Reymond *et al.* 2000). These genes are involved with transcription modulation, ion transport, transpiration control and carbohydrate metabolism. *DREB1A* and *CBF,* and *HSF* genes are transcription factors implicated in drought and heat response, respectively (Sung *et al.* 2003, Sakuma *et al.* 2002). Cell wall invertase (*INV*) and sucrose synthase (*SUSY*) play key roles in carbohydrate partitioning in plants (Déjardin *et al.* 1999) and this regulation of carbohydrate metabolism in leaves may represent part of the general cellular response to acclimation and contribute to osmotic adjustment under stress. The *ERECTA* gene regulates plant transpiration efficiency in *Arabidopsis thaliana* (Masle *et al.* 2005), and the *NHX* and *AVP1* genes are associated with ion transport (Zhang & Blumwald 2001). There are many more genes implicated with stress response and the current challenge is to identify the ones that confer a tolerant phenotype in the crop of interest. Although the function of these genes has been elucidated, particularly in *A. thaliana*, only a few genes have contributed to a tolerant phenotype when over-expressed in vegetables (Zhang *et al.* 2004). Expression of *AVP1*, a vacuolar H+ pyrophosphatase from *A. thaliana*, in tomato resulted in enhanced performance under soil water deficit (Park *et al.* 2005). The engineered tomato has a stronger, larger root system that allows the roots to make better use of limited water. The control plants suffered irreversible damage after five days without water as opposed to transgenic tomatoes which began to show water-stress damage only after 13 days but recovered completely as soon as water was supplied. The *CBF/DREB1* genes have been used successfully to engineer drought tolerance in tomato and other crops (Hsieh *et al.* 2002). Orthologous genes of *CBF* have been found in most crop plants and functional tests indicate conservation of the pathway in these plant species. Constitutive over-expression of *CBF* genes results in salt, cold, or drought tolerance in several plant species. However, in addition to increased stress tolerance, the transgenic plants were dark-green and were stunted, with higher levels of soluble sugars and proline (Liu *et al.* 1998). The use of stress-inducible promoters that have a low background expression of *CBF* under normal growth conditions can achieve increased stress tolerance without plant growth retardation (Lee *et al.* 2003). Maintaining a low cytosolic Na^+ concentration is essential to achieve salt tolerance and can be achieved by restricting inflow, increasing outflow, or increasing vacuole sequestration of Na^+ (Zhang *et al.* 2004). Increased expression of the *A. thaliana* tonoplast membrane Na^+/H^+ antiporter, *AtNHX1*, under a strong constitutive promoter, was reported to result in salt-tolerant tomatoes (Zhang & Blumwald 2001). The transgenic tomato plants grown in the presence of 200 mM NaCl were able to flower and set fruit. While the leaves accumulated high concentrations of sodium, the tomato fruits continued to contain only low concentrations of sodium. The *NHX1* system seems to be highly conserved between many different plant species and manipulation of this system in crop species is likely to result in improved salt tolerance. Research on the physiology of stress tolerance has demonstrated that tolerance to a specific stress is determined by several component traits and controlled by corresponding genes. A combination of a genome-wide scan of expression, using DNA arrays, and QTL analysis could provide important information in identifying the major genes association with stress tolerance.

Prioritizing Vegetable Research to Address Impact of Climate Change

It is unlikely that a single method to overcome the effects of environmental stresses on vegetables will be found. A systems approach, where all available options are considered in an integrated manner, will be the most effective and ultimately the most sustainable, particularly for developing countries in the tropics under a variable climate. This holistic strategy will need global integration of efforts; the resulting synergies will produce impact more quickly than the individual institutions working in isolation could accomplish. For this to succeed, adequate and long-term funding is necessary, scientific results have to be delivered, best approaches utilized and effective methods sustained to deliver global public goods for impact.

AVRDC - The World Vegetable Center, as the world's leading international center focused on vegetable research and development, has expanded its research to further address the potential challenges posed by climate change. The Center's success in its major objectives of reducing malnutrition and alleviating poverty in developing countries through improved production and consumption of safe vegetables will involve adaptation of current vegetable systems to the potential impact of climate change. Vegetable germplasm with tolerance to drought, high temperatures and other environmental stresses, and ability to maintain yield in marginal soils must be identified to serve as sources of these traits for both public and private vegetable breeding programs. This germplasm will include both cultivated and wild accessions possessing genetic variation unavailable in current, widely-grown cultivars. Genetic populations are being developed to introgress and identify genes conferring tolerance to stresses and at the same time generate tools for gene isolation, characterization, and genetic engineering. Furthermore, agronomic practices that conserve water and protect vegetable crops from sub-optimal environmental conditions must be continuously enhanced and made easily accessible to farmers in the developing world. AVRDC-The World Vegetable Center has developed technologies on integrated crop management and many of these approaches directly provide solutions to mitigate the effects of climate change. Stressing the importance of effective delivery methodology to transfer technology and disseminate knowledge, AVRDC knows that for a technology to be successfully adopted, an effective extension strategy must be in place that includes technical, socio-economic, and political considerations. Finally, capacity building and education are key components of a sustainable adaptation strategy to climate change.

Enhancing adaptation of tropical production systems to changing climatic conditions is a huge undertaking. It requires the combined efforts of many national and international institutions and an effective and efficient strategy to be able to deliver technologies that can mitigate the effects of climate change on the diverse crops and production systems. The scientific information and technologies developed through these initiatives must be readily accessible, consolidated and utilized in a strategic way. This can only be achieved through collaboration, complementarity, and coordinated objectives to address the consequences of climate change on the world's crop production.

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