Improving Crop Adaptations to Climate Change: Contextualizing the Strategy

12

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Abstract

Climatic stresses have been affecting agricultural productivity and thereby present a major challenge for the food and nutritional security. The frequency and magnitude of these stresses are projected to increase and impact the crop yields at global level as well as in India. Genetic adaptation is identified as the most crucial factor for improving productivity in future climates. Contextualization of genetic improvement for changing climates is essential to improve the crop productivity as well as to conserve the natural resources. Serious reorientation of breeding efforts is required for a comprehensive genetic improvement programme that should address the challenges of changing climates and growing demand for food and nutritional quality. The approaches to be deployed for crop improvement should include characterization of projected climatic stresses, entire germplasm with projected climatic variability as background, utilization of entire genetic diversity and deploying multipronged approaches for genetic improvement. This chapter is aimed to contextualize the issues and approaches for breeding climate resilient varieties.

12.1 Introduction

Evolution has been the basis of species development. On the earth, about 1 million plant species exist, of which around 350,000 are accepted, while more than 240,000 are yet be resolved into 'accepted name' or 'synonym' (BGCI 2017). Out of these, only about 20,000 species are edible. Ever since settled agriculture was invented by

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human being over 10,000 years ago, numbers of species that are cultivated have been shrinking. Increase in population and demand for higher production of food grains led to expansion of area under agriculture on one hand while narrowing down the number of species to only a few on the other. Intensification of agriculture led to a further narrowing down of species that are being cultivated. Currently, only 20 species are providing over 90% of our food. Even among these, only a few varieties or hybrids are being cultivated causing extreme narrowing of gene pool in agroecosystems. Among the major species that are cultivated, probably rice is the only crop with larger diversity. Major cultivated crops have been subjected to improvement though human intervened conventional breeding or molecular breeding.

Natural selection has been the driving force for evolution of biological organisms on the earth. Organisms that could keep the pace of their evolution way ahead of the changing climatic conditions can dominate the ecosystems. Organisms that evolve at the pace of changing climates may sustain their existence till the time when the pace of climate change overtakes the pace of their evolution and eventually extinct. Other organisms which cannot keep the pace of evolution as that of the climate change will extinct. This basic principle is applicable to all organisms and cultivated species are no exception.

Climate, the mean state of weather over a long period (usually 30 years), of the earth has been dynamic and has been changing continuously. Out of 4.54 billion years of the earth's age, 3 million years has seen glacial and interglacial cycles. Last interglacial period occurred about 125,000 years ago. During this period the global mean surface temperatures were 1–2 °C warmer than present 15 °C. During the last glacial maximum, where the ice covered the earth's surface to the maximum extent about 21,000 years ago, the global mean surface temperatures were 4–7 °C cooler than present. The greenhouse gases (GHGs) are responsible for tapping of energy by the earth's atmosphere. Without GHGs, earth's surface mean annual temperature would have been −17 °C making earth unsuitable for living organisms. The presence of GHGs in the atmosphere and greenhouse effect causes warming of about 32 °C. This resulted in a global mean annual temperature of +14.84 °C in 2016 (NOAA 2017).

Human activities such as fossil fuel combustion and the GHG-emitting man-made technologies, on the one hand, and deforestation and land use change, on the other hand, have led to rapid accumulation of GHGs. All these GHGs have differential potential to warm the earth's surface, called global warming potential (GWP). The GWP is the measure of how much heat a greenhouse gas traps in the atmosphere relative to the amount of heat trapped by carbon dioxide. Carbon dioxide (CO_2), by definition, has a GWP of 1 regardless of the time period used, because it is the gas being used as the reference. The GWP of methane is 21 times and N_2O is 310 times of GWP of CO_2 in a 100-year period. The GWP of sulphur hexafluoride (SF6) (23,900), hydrofluorocarbons (HFCs, vary between 140 and 11,700 times depending the type of molecule) and perfluorocarbons (PFCs) (6500–9200) is extremely high for 100-year period. Collectively, their GWP is leading to increase in temperatures and climate change.

Climate change is projected to raise the global surface temperature in excess of 1.5 °C by 2100 relative to 1850–1900, and warming will continue beyond 2100 (IPCC AR-5 2013:2014). Increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to be 0.3 °C to 1.7 °C in GHG mitigation scenario (representative concentration pathway, RCP2.6); between 1.1 °C and 2.6 °C (RCP4.5) and 1.4 °C to 3.1 °C (RCP6.0) in GHG stabilization scenarios and by 2.6 °C to 4.8 °C (RCP8.5) in GHG emission intensive scenario. Concurrently the atmospheric CO_2 concentrations are projected to increase to 421 ppm (RCP2.6), 538 ppm (RCP4.5), 670 ppm (RCP6.0) and 936 ppm (RCP 8.5) by the year 2100. Further, climate change is projected to increase frequency of extreme temperature events, extreme rainfall events and skewed monsoon leading to increased risk of drought-related water and food shortage. Further, the report suggests that the risk level can be moderately minimized with current adaptation and risk level with high/intensive adaptation can be minimized.

Climate change impacts on crops are projected to vary with the type of species, location and season of crop growth. Several studies have projected that global production of many crops may reduce to the tune of 40–60% due to rise in temperature and climate change by the end of the century (Rosenzweig et al. 2014). The magnitude and direction of climate change impacts have significant spatio-temporal variation for a given crop, with some regions gaining yield while other losing it based on the current climatic conditions (Naresh Kumar et al. 2011, 2013). However, adaptation to climate change will not only reduce the negative impacts but also maximize the positive effects. Adaptation of agriculture to climate change involves managing current and future climatic risks. This can be achieved through an integrated approach of (1) anticipatory research efforts, (2) management of natural resources, (3) use of technology and (4) proactive development and policy initiatives. Several low-cost technologies can reduce the negative impacts of climate change (Easterling et al. 2007). Among the natural resources, genetic resource is the major factor that determines the performance of agricultural productivity. Growing suitable crop variety in changing climates is identified as one of the essential and easy-to-adapt strategy for not only minimizing the negative impacts but also for harnessing the beneficial effects (Braun et al. 1996; Chapman et al. 2012).

Historically, crop improvement has been aimed to achieve high yield, resistance to disease and pest and tolerance to abiotic stresses. Screening germplasm for identification of donors having specific traits and their utilization in developing resistant and tolerant varieties has been the convention in crop improvement (Ortiz 2002; Xin-Guang et al. 2010b). Breeders have been successful in achieving their targets. However, changing climates have been throwing new challenges for crop improvement.

12.2 Why Genetic Adaptation in Changing Climates?

The centre of origin of many crops falls in the region between Tropic of Cancer and Capricorn. Climate change has been changing the climatic conditions of these regions at a much faster pace resulting in new or novel climates (Williams et al. 2007). Since climate is the primary factor for species distributions and ecosystem processes, the new climates may pose challenge to the existing species, while new species may emerge. Novel climates are projected to develop primarily in the tropics and subtropics, challenging large portion of existent biodiversity to evolve faster. Species that evolve faster can survive, while those who are slow will eventually become extinct. This calls for an immediate action of conservation of all biodiversity in these areas, in general and in biodiversity hotspots, in particular. It is quite probable that lack of such efforts had led to the collapse of civilizations due to the late Holocene droughts between 6000 and 1000 years ago. Droughts resulted in the collapse of empires and societies like the Akkadian Empire of Mesopotamia, c. 6200 years ago; the Classic Maya of Yucatan Peninsula, c. 1400 years ago (Ceccarelli et al. 2010); the Moche IV–V transformation of coastal Peru, c. 1700 years ago (de Menocal 2001); and the early bronze society in the southern part of the Fertile Crescent (Rosen 1990), to name a few. Not just of historical events, these examples have current relevance as well, particularly in the current world where the food habits of regions are gradually merging.

Crop species gene pools are collected, conserved, catalogued and characterized for the use in crop breeding. As mentioned earlier, most of the genetic enhancements are made to achieve higher yield, resistance to specific disease and pest and tolerance to some abiotic stresses. Efforts to increase quality also have led to nutritionally enhanced varieties. While all these were done with focussed screening of germplasm to identify lines with ‘desirable’ traits, they ignored or overlooked to analyse its performance with climatic variability as the backdrop. Therefore, there is a need to contextualize the breeding efforts in changing climates to improve the crop yields as they are projected to reduce in the changing climates.

Climate change is projected to affect the yield of several major crops across the world. For instance, the global yield of maize, wheat, rice and soybean is projected to be affected up to 20% in 2020 (2010–2039) scenario, 20–35% in 2050 (2040–2069) and 40–60% in 2090 (2070–2099) (Rosenzweig et al. 2014). A global analysis on wheat production indicated a decrease of about 6% yield with every 1 °C rise in temperature (Asseng et al. 2015). The impacts are variable over space and time, e.g. more effects would be visualized in tropical regions (IPCC 2014). The projected climate change events and major impacts on crop productivity in different continents (Table 12.1) indicate a need for concerted effort to adapt to climate change. The IPCC reported that each additional decade of climate change is expected to reduce mean yields by roughly 1%, while the anticipated increase in productivity per decade needed to keep pace with demand is roughly 14% (IPCC 2014).

In Indian region, areas encompassed by climatic stresses and magnitudes of crop loss have been increasing recently. These risks are projected to increase in future affecting food production if agriculture is not adapted to changing climates. The

Table 12.1 Major climate-related risks and projected impacts on agricultural systems in different continents

Region	Projected climate-related risks	Major projected impacts on crops agriculture
Africa	Warming, extreme temperatures, drying trend, sea level rise and change in mean and distribution of rainfall	Reduction in the length of growing season
		Yield reduction of 8% in Africa by 2050 averaged over crops, with wheat, maize, sorghum and millets more affected than cassava and sugarcane
		Fall in crop net revenues by up to 90% by 2100
		75 to 250 million people at risk of increased water stress by the 2020s and 350 to 600 million people by the 2050s
Australia	Warming, droughts, water stress	Agricultural production may decline by 2030 over much of southern and eastern Australia, and over parts of eastern New Zealand, due to increased drought and fire
		Change land use in southern Australia, with cropping becoming non-viable at the dry margins
		Production of Australian temperate fruits and nuts will drop on account of reduced winter chill
		Geographical spread of a major horticultural pest, the Queensland fruit fly (*Bactrocera tryoni*), may spread to other areas including the currently quarantined fruit fly-free zone
Islands	Drying trend, sea level rise, change in mean and distribution of rainfall and damaging cyclonic events, sea level rise, ocean acidification	Coastal agriculture to be affected due to salinization and sea level rise
		Loss to plantations such as coconuts due to cyclonic storms
		Subsistence and commercial agriculture on small islands will be adversely affected by climate change
		In mid- and high-latitude islands, higher temperatures and the retreat and loss of snow cover could enhance the spread of invasive species including alien microbes, fungi, plants and animals
South America	Warming, extreme temperatures, drying trend, sea level rise, change in mean and distribution of rainfall and damaging cyclonic events, snow cover	Generalized reductions in rice yields by the 2020s
		Reductions in land suitable for growing coffee in Brazil and reductions in coffee production in Mexico
		The incidence of the coffee disease and pest incidence in Brazil's coffee production area
		Risk of *Fusarium* head blight in wheat is very likely to increase in southern Brazil and in Uruguay

(continued)

Table 12.1 (continued)

Region	Projected climate-related risks	Major projected impacts on crops agriculture
North America	Warming, extreme temperatures, drying trend, sea level rise, change in mean and distribution of rainfall and damaging cyclonic events	Increased climate sensitivity is anticipated in the southeastern USA and in the USA corn belt making yield unpredictable
		Yields and/or quality of crops currently near climate thresholds (e.g. wine grapes in California) are likely to decrease
		Yields of cotton, soybeans and barley are likely to change
		Risk of extinctions of important species
		By the 2050s, 50% of agricultural lands in drier areas may be affected by desertification and salinization
Asia	Warming, extreme temperatures, drying trend, sea level rise, change in mean and distribution of rainfall and damaging cyclonic events	Monsson aberration-related crop loss
		Reduction water availability
		Crop yields could decrease by up to 30% in Central and South Asia
		More than 28 million hectares (ha) in arid and semiarid regions of South and East Asia will require substantial (at least 10%) increases in irrigation for a 1 °C increase in temperature
		Crop yields to reduce (wheat, rice, mustard, maize)
		Loss in agrobiodiversity
		Increased incidence of disease and pests
		Water scarcity related food insecurity
Europe	Warming, extreme temperatures, drying trend, sea level rise, extreme precipitation events, ocean acidification	Crop productivity is likely to decrease along the Mediterranean and in Southeast Europe
		Differences in water availability between regions are anticipated to increase
		Much of European flora is likely to become vulnerable, endangered or to extinct by year 2100

Synthesized from IPCC (2014) and FAO (2010)

spatio-temporal variation in direction and magnitude of climate change impacts vary with the nature of crops, and therefore the crop-wise impacts and adaptation gains are summarized below.

Rice Climate change is projected to reduce irrigated rice yields by ~4% in 2020 (2010–2039), ~7% in 2050 (2040–2069) and by ~10% in 2080 (2070–2099) climate scenarios. Whereas rainfed rice yields are likely to be reduced by ~6% in the 2020 scenario, yields may reduce only marginally (<2.5%) by 2050 and 2080. However, spatial variations exist for the magnitude of the impact, with some regions likely to be affected more than others. The study indicated that growing improved varieties with efficient agronomy can lead to an increase in all-India irrigated rice yields by about 17% over current values in the 2020 scenario, by 14% and by 8% in the 2050 and 2080 scenarios, respectively. Similarly, rainfed rice yield can be increased by ~20% in the 2020 and by ~35–38% in the 2050 and later scenarios (Naresh Kumar et al. 2013).

Wheat Wheat yield in India is projected to reduce by 6–23% by 2050 scenario based on management, if no adaptation is followed. Adaption by timely sowing of suitable variety and with input (fertilizer and irrigation) management may be a practical low-cost adaptation strategy to increase the yield (by >10%) in future climates (Naresh Kumar et al. 2014a). Central India is projected to lose yield despite this adaptation strategy warranting development of varieties highly tolerant to early and terminal heat stress.

Maize Climate change is projected to reduce irrigated maize yield by 18% in kharif season, but adaptation is projected to increase the yield up to 21% in 2020 scenario (Naresh Kumar et al. 2012).

Sorghum Climate change is projected to reduce rainfed sorghum yield by 2.5% in 2020 (2010–2039). However, it is projected that adaptation can increase the productivity by 8% in 2020 (Naresh Kumar et al. 2012).

Mustard In India, mustard yield is projected to reduce by ∼2% in 2020 (2010–2039) if no adaptation is followed (Naresh Kumar et al. 2015). Adoption of a combination of improved agronomic management practices can improve the yield by ∼17% with current varieties (Naresh Kumar et al. 2014b). However, with improved varieties, yield can be enhanced by ∼25% in 2020 climate scenario.

Soybean Increase in soybean yield in the range of 8–13% under future climate scenarios (2030 and 2080) is projected (Naresh Kumar et al. 2012).

Groundnut The rainfed groundnut yield is projected to increase by 4–7%, except in the climate scenario of A1B 2080 under which yield is projected to reduce by −5% (Naresh Kumar et al. 2012).

Potato The potato yield is projected to reduce by ~2.5, ~6 and ~11% in 2020 (2010–2039), 2050 (2040–2069) and 2080 time periods, respectively, in the Indo-Gangetic Plains. Change in planting time is found to be the most important adaptation option for yield improvement by ~6% in 2020 (Naresh Kumar et al. 2015).

Cotton Cotton productivity in northern India is projected to marginally decline due to climate change, while in Central and southern India, productivity may increase implying that the overall productivity at the national level may not be affected (Hebbar et al. 2013).

Coconut Coconut productivity is projected to increase in western coastal region, Kerala, parts of Tamil Nadu, Karnataka and Maharashtra (with current level of water and management) while negative impacts are projected for Andhra Pradesh, Orissa, West Bengal, Gujarat and parts of Karnataka and Tamil Nadu due to climate change. On all-India basis, climate change is projected to increase coconut productivity by 1.9 to 6.8% in 2080 scenario. Adaptation can increase the productivity by ~33% in 2030, and by 25–32% in 2080 climate scenarios. Analysis further indicated that current productivity in India can be improved by 20% to almost double if all plantations in India are provided with location specific agronomic and genotype interventions (Naresh Kumar and Aggarwal 2014).

Horticultural Crops Climatic stresses such as extreme temperatures, hailstorms and heavy rainfall events damage horticultural crops. A 24 h flooding affects tomato crop and the flowering period is highly sensitive. In case of onion, bulb initiation stage is sensitive to flooding causing a 27 and 48% reduction in bulb size and yield, respectively (Rao et al. 2009). Productivity of temperate fruit crops such as apple is affected, and its cultivation is shifted to higher latitudes to 2500 mamsl from 1250 mamsl in Himachal Pradesh (Bhagat et al. 2009).

Climate change is projected to affect the quality in terms of reduced concentration of grain protein (under low fertilizer input conditions), and some minerals like zinc and iron due to elevated CO_2 (Porter et al. 2014). Elevated CO_2 caused reduction in the concentration of protein, secondary metabolites, while rise in temperature enhanced their concentration in pulse, several vegetable and fruit crops. Majority of studies indicate negative impacts; however, rise in temperature may decrease cold waves and frost events leading to reduced damage to frost-sensitive crops such as chickpea, mustard, potato and other vegetables.

12.3 Strategizing Crop Improvement for Adaptation

Crops have been adapting to external stresses; however, in the climate change scenario, the frequency of climatic stresses has been increasing posing serious threat to crop productivity. Several researchers have expressed concern that current breeding strategies will not be sufficient to meet the challenges of increased frequency of climatic risks. The basic strategy that has so far followed may need a thorough relook so that the climate resilient varieties are developed for meeting the ever-growing demand for food in changing climates (Rajeev et al. 2011; Stephen and Donald 2010a; Chikelu et al. 2012; Smith 2012). Only about 3% of the germplasm is being used for crop improvement. There is a need for involving wider germplasm pool for crop improvement. This implies that the germplasm characterization itself needs to be reoriented so that climatic stress responses are taken into consideration apart from other agronomic characteristics. Increased use of plant genetic resources is expected to play a major role in developing climate resilient agricultural systems (Lin 2011; Hodgkin and Bordoni 2012). Currently, the number of accessions of 612 genera and 34,446 agricultural species conserved ex situ worldwide has reached 7.4

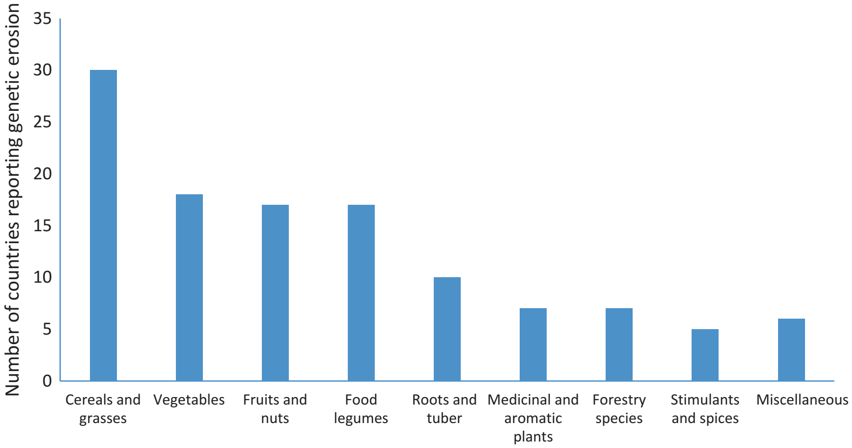


Fig. 12.1 Genetic erosion reported in agricultural species (Data used from The Second Report on The State of The World's Plant Genetic Resources for Food and Agriculture, FAO Report, 2010)

million. However, only less than 30 percent of the total numbers of accessions are estimated to be distinct. Though the number of accessions of minor crops and crop wild relatives (CWR) has increased, they are still generally underrepresented. Moreover, the germplasm erosion is reported from several countries from different types of agricultural crops (Fig. 12.1). Several breeding methods have been successfully employed for crop improvement. However, the use of crop wild relatives in crop improvement efforts is not optimized yet (Ortiz 2002). Genetic diversity available in crop wild relatives needs to be exploited for sustaining and improving the crop yield in dynamic biotic and abiotic stress events (Feuillet et al. 2008) in changing climates.

Under-exploitation of full genetic potential of edible species is a blessing in disguise as the demand for quantity and quality food will continue to increase in future. However, the rate of increase in biodiversity erosion is a major concern. As mentioned earlier, species which cannot adapt to the rate of climate change will become extinct immediately. Species that are able to adapt but at a rate slower than that of change in climate will extinct eventually. This implies that currently exploited species in agriculture and food production system must evolve faster. For this crop improvement, efforts need multipronged approach including conventional breeding, exploitation of full germplasm, molecular breeding, genetic engineering, distant hybridization and exploitation of crop wild relatives, among others. Among these, the use of currently available germplasm and crop wild relatives is of major concern because they are vulnerable to erosion causing serious loss of genetic diversity if extra care and precautions are not taken. Protecting areas of genetic diversity, national gene banks and ex situ and in situ conservation measures are being followed which help in conserving the genetic diversity.

A summary of the major climatic risks, crops in different regions and total germplasm available in different subregions indicate that major stresses and crops are almost common (Tables 12.1 and 12.2). Crops are being increasingly exposed to multiple stresses even in a crop season. Thus, exploiting the available entire germplasm is of utmost importance. Therefore, future crop improvement efforts need new initiatives and dimensions (Fig. 12.2) and some of them are briefly mentioned below:

- *Identification of current and anticipated climatic stresses and prioritizing the crops, traits and regions* for crop improvement. For instance, wheat is exposed to early and terminal heat stress in Central India and terminal heat stress in North India (Fig. 12.3). Simulation analysis indicated that timely sowing of

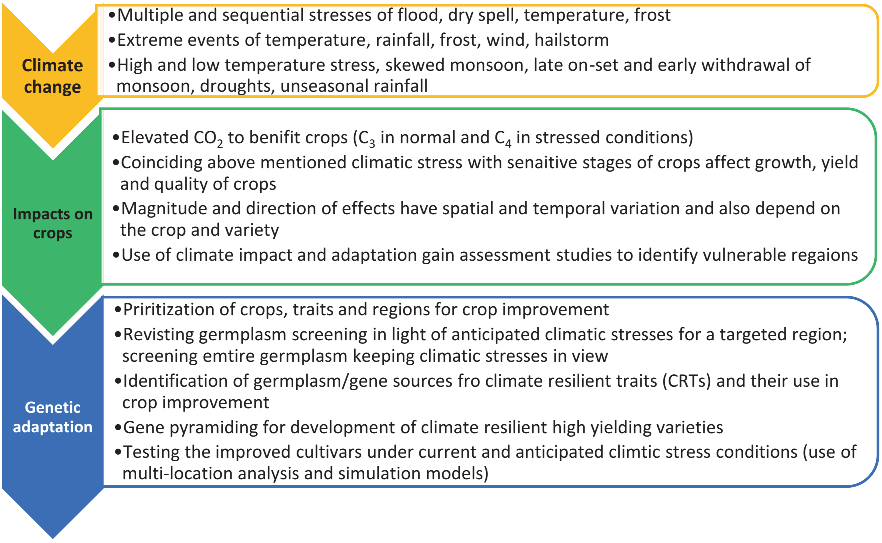
Table 12.2 Climatic stresses, major crops and number of total accessions in gene banks

Region	Climate-related risks	Subregion	No. of accessions	Major crops
Africa	Warming, extreme temperatures, drying trend, sea level rise and change in mean and distribution of rainfall	East Africa	145,644	Maize, sorghum, millets
		Central Africa	20,277	Sorghum, millets, maize, sugarcane, groundnuts
		West Africa	113,021	Sorghum, millets, maize, rice, cassava, groundnuts, pulses
		Southern Africa	70,650	Maize, millet, sorghum, cotton, pulses, sugarcane
Islands	Drying trend, sea level rise, change in mean and distribution of rainfall and damaging cyclonic events, sea level rise, ocean acidification	Indian Ocean Islands	4604	Rice, cassava, maize
America	Warming, extreme temperatures, drying trend, sea level rise, change in mean and distribution of rainfall and damaging cyclonic events, snow cover	South America	687,012	Maize, rice, sugarcane, soybean
		Central America and Mexico	303,021	Maize, rice, cassava, sorghum, sugarcane
		Caribbean	33,115	Sugarcane
America	Warming, extreme temperatures, drying trend, sea level rise, change in mean and distribution of rainfall and damaging cyclonic events	North America	708,107	Wheat, maize, soybean, cotton, sorghum, pulses

(continued)

Table 12.2 (continued)

Region	Climate-related risks	Subregion	No. of accessions	Major crops
Asia	Warming, extreme temperatures, drying trend, sea level rise, change in mean and distribution of rainfall and damaging cyclonic events	Pacific East Asia	1,036,946	Rice, wheat, groundnut, sugarcane, maize, soybean, potato
		Asia Pacific	252,455	Rice, maize, groundnut
		Pacific South Asia	714,562	Rice, wheat, soybean, maize, pulses, groundnut
		Pacific Southeast Asia	290,097	Rice, maze, oil palm, coconut
		Near East Central Asia	153,849	Wheat, barley, cotton
		Near East West Asia	165,930	Wheat, maize, pulses
		Near East South/ East Mediterranean	141,015	Maize, wheat, pulse
Europe	Warming, extreme temperatures, drying trend, sea level rise, extreme precipitation events, ocean acidification	Europe	725,315	Wheat, maize, potato, barley, rapeseed



- Multiple and sequential stresses of flood, dry spell, temperature, frost
- Extreme events of temperature, rainfall, frost, wind, hailstorm
- High and low temperature stress, skewed monsoon, late on-set and early withdrawal of monsoon, droughts, unseasonal rainfall

- Elevated CO_2 to benifit crops (C_3 in normal and C_4 in stressed conditions)
- Coinciding above mentioned climatic stress with senaitive stages of crops affect growth, yield and quality of crops
- Magnitude and direction of effects have spatial and temporal variation and also depend on the crop and variety
- Use of climate impact and adaptation gain assessment studies to identify vulnerable regaions

- Prioritization of crops, traits and regions for crop improvement
- Revisting germplasm screening in light of anticipated climatic stresses for a targeted region; screening emtire germplasm keeping climatic stresses in view
- Identification of germplasm/gene sources fro climate resilient traits (CRTs) and their use in crop improvement
- Gene pyramiding for development of climate resilient high yielding varieties
- Testing the improved cultivars under current and anticipated climtic stress conditions (use of multi-location analysis and simulation models)

Fig. 12.2 Basic steps in development of climate resilient cultivars

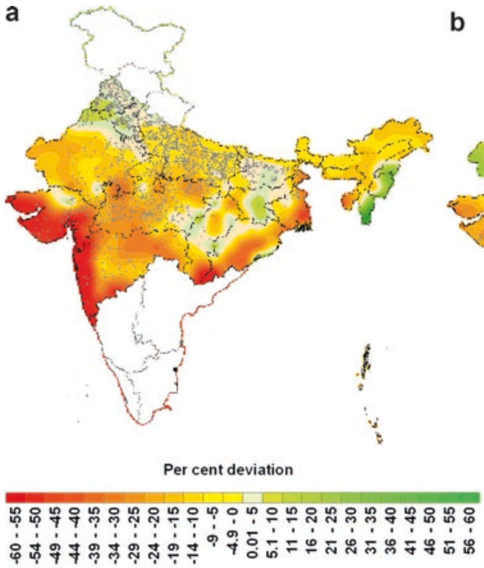


Fig. 12.3 Impact of climate change on wheat (**a**) without and (**b**) with adaptation in 2050 scenario (Naresh Kumar et al. 2014a)

wheat with suitable cultivars can improve the wheat yield despite climate change (Naresh Kumar et al. 2014a). However, yield in Central India is projected to be reduced if suitable cultivars are not developed. As per this analysis, development of short-duration and heat stress-tolerant varieties for Central India should be prioritized. Since development of a variety of an annual crop takes at least 8–15 years, it is essential to initiate concerted efforts immediately as by 2050 one may get about only 3–7 breeding cycles.

- *Characterizing entire germplasm of a species* in the backdrop of current and anticipated climatic stresses and conditions. There is a need to exploit all available genetic variability within a species with climatic stresses as backdrop. Targeted breeding, as is done in case of droughts, floods, high temperature and salinity stress, also needs to be extended to other types of climatic stresses (Table 12.3). Further, the traits that contribute to reduced GHG emission and enhanced CO_2 sequestration need to be identified. In addition to these, there is also a need to identify the climatic threshold for every sensitive phase of crop for developing climate resilient varieties. For instance, a rice analysis for India indicated that in areas with current seasonal (June–September) mean minimum temperatures of >23 °C, as in parts of Central, North and northeast regions of India, future temperatures constrain higher productivity of irrigated rice (Naresh Kumar et al. 2013). Moreover, high as well as low temperature stress coinciding pollination affects the pollen viability eventually reducing the rice yield. Similarly, in case of spring wheat varieties, yield would reduce in areas with mean seasonal

Table 12.3 Some climate-resilient traits (CRTs) for different types of abiotic stresses

Major target	Component traits	References
Drought-adaptive traits	Root architecture	Hammer et al. (2009)
	Accumulation and partitioning of water-soluble carbohydrates to storage organs	Steele et al. (2013)
	Abscisic acid concentration, stay green, canopy temperature, carbon isotope discrimination, stay green, ABA signalling for stomatal regulation	Rebetzke et al. (2008)
		Kholova et al. (2010)
		Lopes et al. (2014)
		Borrell et al. (2014)
		Ren et al. (2007)
Salinity tolerance	Na + accumulation via Na + exclusion	James et al. (2006)
Flooding tolerance	*Sub1* QTL	Xu et al. (2006)
Water logging tolerance	QTLs for submergence tolerance	Septiningsih et al. (2013)
	QTLs for adventitious root formation at the soil surface in maize	Mano et al. (2005)
Terminal drought	Early flowering	Hegde (2010)
Flowering time	Vernalization requirement (*VRN* genes), photoperiod sensitivity (*PPD* genes)	Bentley et al. (2011)
		Faure et al. (2007)
Developmental plasticity	Root elongation in water deficit condition and inhibition of shoot elongation	Spollen et al. (2008)
Cold tolerance	Winter hardiness	Pan et al. (1994)
	Vernalization response and frost tolerance	Galiba et al. (1995)
Heat stress tolerance	Pollen viability, starch accumulation during terminal heat stress in wheat, dehydration tolerance	Bita and Gerats (2013)
CO_2 sequestration	Fast-growing trees and perennial grasses	Garten et al. (2011) and Jansson et al. (2010)
Low greenhouse gas emission	Rice cultivars with low vascular transportation of methane	Gogoi et al. (2005); Nirmali et al. (2008); and Dubcovsky and Dvorak (2007)
	Nitrogen-use efficiency: NAM-B1 gene	

maximum and minimum temperatures more than 27 and 13 °C, respectively (Naresh Kumar et al. 2014a). Wheat is identified as the most important crop that needs to be focussed for crop improvement to beat climatic stress effects in South Asia (Lobell et al. 2008). In case of mustard, regions with mean seasonal temperature regimes above 25/10 °C are projected to lose yield due to temperature rise. As climatically suitable period for mustard cultivation may reduce in the future, short-duration (<130 days) cultivars with 63% pod-filling period will become more adaptable (Naresh Kumar et al. 2015). There has been a lot of literature available on this front with specific examples.

- In horticultural crops, the challenge is to retain and improve quality despite climatic stresses. For instance, breeding plantation crops need visionary approach as the plants live for up to 70 years, and one should take the anticipated future climatic stresses, technological improvements, land use change and socio-economic demand for quantity and quality into account. Thus, evaluation of germplasm taking into consideration the response to climatic extremes apart from other criteria becomes essential. Genotypic improvement strategies include population improvement through identified stress-tolerant plants, breeding for temperature stress tolerance of pollen and stigma, high retention of set fruits under climatic risks and improved source-sink balance and identification of multiple stress-tolerant cultivars. In addition, there is a need to understand the change in quality of produce with respect to climate change. Further, the biotic stresses that are anticipated to increase or emergence of new pests must also be taken into consideration while breeding climate resilient cultivars:

- *Identification of climate smart varieties* which can meet the challenges of future climates. For example, some of the major challenges include breeding:
  - Low-methane-emitting rice cultivars.
  - Rapid nitrogen uptake and its use efficient varieties for reducing the N_2O emission.
  - High water-use efficient varieties.
  - High carbon sequestration varieties for perennial crops, deep and high root volume varieties of annual crops.
  - Stress-tolerant varieties with high revival capacity.
  - Stress avoidance by phenological plasticity.
  - Multiple abiotic and biotic stress-tolerant/stress-resistant varieties.
  - Retaining quality of produce despite climate change.
  - In rice, low-methane-emitting cultivars, cultivars suitable for flood situation, water stagnation and salt tolerance become more important. In maize, cultivars with flood tolerance and endless gap between silking and tasselling gain importance. The farmers' varieties can be of immense source of tolerance gene pool for use. In plantation crops, identification of in situ tolerant trees (Naresh Kumar et al. 2002) and their use in population improvement programme becomes very important as they have been exposed to climatic stresses during their life cycle and still performed better in terms of physiological parameters and economic yield, indicating the presence of desirable genetic composition.
- *Utilization of crop wild relatives* in breeding programme for incorporating desirable genes for climatic stress tolerance. Though crop wild relatives may fail to adapt to new climatic conditions of their native habitats (Jarvis et al. 2008), they possess a gene pool which can be exploited for crop improvement. A number of reviews have taken stock of use of crop wild relatives in crop improvement for tolerance to abiotic stresses and quality (Radden et al. 2015).
- *Identification and utilization of genotypes from climate analogue analysis* for a quick intervention. The climate analogue analysis is a concept which is based on identification of areas where either the today's climate of a location corresponds to the future climate projected at another location or the projected future climate corresponds to the current climate of another site (Ramírez-Villegas et al. 2011).

Using this concept, testing the performance of genotypes in climate analogue sites can lead to identification of suitable genotypes for future climates. In addition, germplasm collection can also be rationalized suing climate analogues.

- *Geospatial analysis-based germplasm collection* to minimize the gaps in germplasm collection and also to minimize the duplication. Further, geospatial tagging and characterizing germplasm is possible in this approach. Geospatial software such as DIVA is extensively used for this purpose (Hijmans et al. 2001).
- *Distant hybridization* using interspecific and intergeneric breeding strategies (Liu et al. 2014).
- *Molecular breeding* helps in targeted crop improvement and is relatively faster than conventional breeding. In molecular or marker-assisted breeding, DNA markers are used as a substitute for phenotypic selection and to accelerate the release of improved cultivars.
- *Genetic engineering* has to be exploited for gene pyramiding to develop climate resilient varieties (Varshney et al. 2009; Scheben et al. 2016).
- *The use of omics science platforms* for crop improvement includes genomics, phenomic platform data, molecular data and bioinformatics tools. The growing number of available high-quality reference genomes and advances in population-level genotyping has contributed to improved understanding of genomic variation. These developments are leading towards plant pangenomics (Scheben et al. 2016).
- *The use of simulation models* in climate change research is indispensable for testing the performance of a cultivar in future environments. Several crop models such as DSSAT, InfoCrop, APSIM and Crosyst are being used for quantifying the impacts of climate change on crops (Assenge et al. 2013; Rosenzweig et al. 2014; Naresh Kumar et al. 2012, 2013, 2014, 2015). Further, combining the eco-physiological modelling and genetic mapping is becoming important approach in 'plant breeding through design' to predict the performance of genotype and recombinant inbred line population in terms of phenology and physiological traits (Yin et al. 2005).
- *Engineering agroecosystem genetic composition by varietal diversification* becomes essential in view of projected increase in climatic stresses and consequent biotic stresses. Varietal diversification can improve the horizontal resistance agroecosystems to climatic and consequential stresses.
- *Engineering agroecosystem genetic composition by crop diversification*: Out of over 20,000 species of edible plants in the world, fewer than 20 species provide 90% of our food. A quick analysis indicated that crop diversity ranged from 23 to 80 in major states of India (Fig. 12.4).

Diversification of food basket and food production systems helps in sustainable food and nutritional security systems in changing climates. There is a need to focus on socio-economic research to delineate the effects of globalization, markets, food habits, policy initiatives and crop diversification.

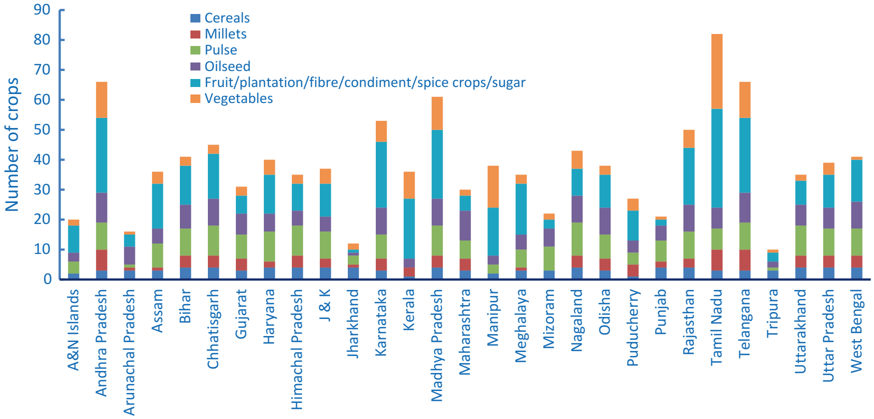


Fig. 12.4 Crop diversity in Indian states

12.4 Some Recent Examples of Breeding for Climate Change

- Common bean biodiversity has been used in plant breeding to develop both heat- and cold-tolerant varieties grown from the hot Durango region in Mexico to the cold high altitudes of Colombia and Peru.
- Corn genetic resources have been used in breeding varieties adapted to cultivation from sea level to over 3000 mamsl, as in Nepal.
- Protection of farmers' varieties as is done for varieties of millets and rice.
- Cultivar that can tolerate excessive heat during pollination for cowpea and corn and flooding early in the growing season for soybean and rice.
- Maize hybrids that show better synchronization of pollination and flowering under heat and water stress.
- Genome sequences are available for many crop species such as rice (Goff et al. 2002; Yu et al. 2002; IRGSP 2005), poplar (*Populus trichocarpa*) (Tuskan et al. 2006), sorghum (*Sorghum bicolor*) (Paterson et al. 2009), maize (Schnable et al. 2009), soybean (*Glycine max*) (Schmutz et al. 2010), cucumber (*Cucumis sativus*) (Huang et al. 2009), pigeon pea (*Cajanus cajan*) (http://www.icrisat.org/gt-bt/IIPG/home.html), wheat (http://www.genomeweb.com/sequencing/wheat-genome-sequenced-roches-454) and barley (*Hordeum vulgare*) (http://barleygenome.org/).
- Transgenic rice plants overexpressing *Arabidopsis* CBF3/DREB1A or ABF3 TF showed improved tolerance to drought and salinity without growth retardation (Oh et al. 2005).
- Using integrated biotechnology approaches, drought-tolerant maize cultivars were developed with about 20–50% higher yields under drought than the current cultivars. Several of them have already reached farmers' fields in Africa. The high NUE maize cultivars are also being developed (Varshney et al. 2011).

- To enhance adaptive phenotypic plasticity or yield stability of sorghum and pearl millet in variable climates, traits such as photoperiod-sensitive flowering, plastic tillering, flooding tolerance, seedling heat tolerance and phosphorus efficiency are identified for inducting into the cultivars for West Africa (Haussmann et al. 2012).
- Diagnostic markers for photoperiod sensitivity gene (*Ppd-D1*) and vernalization genes (*Vrn-A1*, *Vrn-B1* and *Vrn-D1*) were used for adaptation of wheat in Australia (Eagles et al. 2010).
- The *Sub1* rice tolerant to flood can survive total submersion for more than 2 weeks, with great benefits to farmers.
- Introduction of *Sub1* QTL resulted in rice varieties that can tolerate flooding for 12–14 days, and these varieties such as Swarna *Sub1* are cultivated in over one million hectares.

12.5 Conclusion

The strategy for adaptation to climate change has to be multidimensional with crops and cultivars as the central themes. There is a need for serious reorientation of breeding efforts to a comprehensive genetic improvement programme for sustaining the crop productivity in changing climates. Characterization of projected climatic stresses, characterization of entire germplasm with projected climatic variability as background, utilization of entire genetic diversity and deploying multipronged approaches for genetic improvement will ensure the enhanced crop production and quality to meet the demands of future climates and population.

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