Chapter 1

Impact of Climate Change on Agriculture Production, Food, and Nutritional Security

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Introduction

During recent years, worldwide heavy rains and floods, fire in forests, occurrences and spread of new diseases, as found in the new strains of different pathogens and viruses, and abnormal bacterial growth, higher incidences of insects pests are all direct indications of drastic environmental changes globally. It is now well established and documented that anthropogenic greenhouse gas (GHG) emissions are the main reason for the climate change at global level. It is also well recognized that agriculture sector is directly affected by changes in temperature, precipitation, and carbon dioxide (CO_2) concentration in the atmosphere. Thus, early and bold measures are needed to minimize the potentially drastic climate impacts on the production and productivity of various field crops. In most of the developing countries in Africa, Asia, and Asia Pacific regions, about 70% of the population depends directly or indirectly for its livelihood on agriculture sector and most of this population lives in arid or semiarid regions, which are already characterized by highly volatile climate conditions.

Food, from staple cereal grains to high protein legumes and oilseed crops, is central to human development and well-being (Misselhorn *et al.*, 2012); however, the complexity of global food security is becoming challenging and will be made more so under climate change. The world continues to face huge difficulties in securing adequate food that is healthy, safe, and of high nutritional quality for all (Redden *et al.*, 2011, 2014) and in an equitable and environmentally sustainable manner (Pinstrup-Andersen, 2009; Godfray *et al.*, 2010). With the growing demand of an expected 9 billion people by 2050, it remains unclear how our current global food system will cope with an ever-increasing demand for food, and how this supply can be maintained while ensuring minimal environmental impact (Tilman *et al.*, 2011; Foley *et al.*, 2011). Compounded with climate change, ecosystems and biodiversity under stress, ongoing loss of species and of crop genetic diversity, increasing urbanization, social conflict, and extreme poverty, there has never been a more urgent time for collective action to address food security (Hunter and Fanzo, 2013; Dulloo *et al.*, 2014).

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Despite considerable achievements to date in feeding a growing population, as of 2011–2013, a total of 842 million people, 1 in 8 worldwide still suffers from chronic hunger, struggling to obtain enough nourishment to lead an active and fulfilling life (FAO, 2013). Furthermore, micronutrient deficiencies, known as hidden hunger, continue to ravish and undermine the growth and development potential, health, and productivity of over 2 billion people worldwide(Micronutrient Initiative, 2009).

Reversing these trends in the context of ongoing global change, especially climate change, and finite available resources poses huge challenges to our current food production and food systems (Smith 2012). The response must permit more agricultural production from the same area of land through sustainable intensification (FAO, 2009a, 2009b, 2011a, 2011b; Garnett *et al.*, 2013). Foremost among the strategies to achieve this are significant efforts to reduce current "yield gaps," improve production efficiencies, reduce food waste and sustainable dietary change (Godfray *et al.*, 2012; Foley *et al.*, 2011; Tilman *et al.*, 2011).

The causes of climate change can be linked to the increased impact of human activities on the concentration of greenhouse including aerosols and changes in land use patterns. These effects influence the radiation balance of the earth, evaporation rate from the earth's surface, and patterns of heating and cooling around the globe (IPCC, 2007b). The negative effects of climate change on agriculture is most pronounced in developing countries (de la Peña *et al.*, 2011; IPCC, 2007b; Lobell *et al.*, 2011a, 2011b; Nelson *et al.*, 2009, 2010; Wassmann *et al.*, 2010; Müller *et al.*, 2011).

The impacts of climate change on agriculture are going to be particularly substantial, which also means that those countries still heavily reliant on agriculture will be disproportionately affected. Climate change is set to have significant impacts on crop, livestock, and pasture production including impacts on pest and diseases and water availability (Conway, 2012). Moderate temperature rises alone can significantly reduce yields of major food cereals, with Lobell *et al.* (2011a, 2011b) indicating that around three-quarters of Africa's maize crop would suffer a 20% yield loss with 1 °C rise in temperature. Climate change is also expected to impact heavily on livestock especially in arid and semiarid regions, especially on pasture species composition and forage quality. Likewise, more frequent and severe pest and disease attacks are anticipated. Bebber *et al.* (2013) highlight trends since 1960 in pole ward shifts of pests and pathogens to new areas. Further, soil-borne pathogens and diseases are expected to be an increasing problem under increasing temperature (Jaggard *et al.*, 2010).

It is likely that the impact of climate change on food security will be felt most in those parts of the world currently vulnerable to poverty, hunger, and malnutrition (Redden *et al.*, 2014). In a global review of scientific papers on climate change and food security, the authors found that 70% focused on food availability compared to the other dimensions of food security (accessibility, utilization, and stability). Climate change will certainly negatively impact crop and food production, with consequent effects on food prices, incomes, and trade, and sanitation may be affected if access to water is also affected. Climate change is likely to influence the stability of the food system through impacts on market volatility for both production and supply (Wheeler and von Braun, 2013). Clearly addressing food security is not just a matter of increasing food production and availability, though this is what concerns us most in this chapter.

The concerns and current evidence about climate change impacts support the urgent need for resources and efforts to be directed at mitigation (changing to climate change resilient crops, e.g., low toxin lathyrus) and adaptation (improvement of existing crops), to achieve what is sometimes referred to as "climate-smart agriculture" or even a "climate-smart food system" (Wheeler and von Braun, 2013). The strategy of most concern in this chapter is the importance of agricultural biodiversity, utilization, and maintenance of plant genetic resources for crop improvement and diversification of agricultural and food systems. Foley *et al.* (2011) point out important opportunities to improve crop yield and resilience, by improving “orphan crops” and conserving crop diversity. The important role here for crop wild relatives (CWR) cannot be overstated. CWR represent one of the most critical assets to address climate change, because they hold so much promise for crop improvement now and in the future (Ford-Lloyd *et al.*, 2011). The process of domestication has ensured that the level of genetic diversity in our commonly grown crops is much reduced compared to that available in CWR gene pools, which have novel pest resistances and tolerances to heat, drought, and salinity (Godfray *et al.*, 2010; Hodgkin and Bordoni, 2012). However, CWR are currently under threat from changing climate as well (Jarvis *et al.*, 2008).

Thus, it is important to understand and consider the availability of CWR of various field crops for utilization in regular crop breeding programs for the development of new varieties, which can stand well against the changing environmental conditions with high yields. It is also important to maintain and multiply these CWR under protected environments for creating a diverse gene pool in widely adapted popular cultivars.

This chapter reviews the current global food security context and the need to feed a growing global population with limited access to natural resources in the context of significant climate change. The possible impacts of climate change on the biodiversity of key crops are described, before examining the important roles of conservation and plant breeding and the diversification of farming systems through the better deployment of crop diversity.

Population versus food demand by 2050

The world population of 7.2 billion in mid-2013 is projected to rise by around 1 billion over the next 12 years, reaching a level of 8.1 billion by 2025. Continuing population increase is expected to see this figure reach 9.6 billion by 2050 and 10.9 billion by 2100 (United Nations, 2013).

The earth is undergoing changes unprecedented since the initiation of agriculture 11,000 years ago, with a vastly increased consumption of fossil fuels. The cost, however, of this extraordinary progress is increased levels of atmospheric CO_2, methane, sulfur, and aerosols, which have very complex interactions with the global atmosphere and ultimately on climate (IPCC, 2007a). The net result is a continuing increase in global temperature, which is unlikely to be mitigated in the short term as energy conservation measures are overwhelmed by a large increase in the polluting human footprint by 2050 (Redden *et al.*, 2011, 2014).

Temperature will increase globally by 0.8–1.0°C by 2050 and further increase by 2100, accompanied by more severe high temperature spikes during crop growth than previously experienced, severely affecting agricultural production systems and hence food security (Lobell *et al.*, 2011a, 2011b).

Global food production and food security

Considering the nature of this chapter, a brief summary of area, production, and productivity of major field crops is important. Feeding the increasing population is a big challenge especially in the developing countries. Importantly, although there is continuous increase in area, production, and productivity of various crop commodities; the increment is not proportionate to that of increasing global population. The major cereal crops are wheat, rice, maize, barley, sorghum, coarse grains, oats, and rye. Major pulses are chickpea, pigeon pea, dry peas, dry beans, lentil, and cowpeas. Likewise, among the oilseeds, the major crops contributing to global production are soybean, rape seeds canola and mustard, peanut, sunflower, and cotton seed. The production summary of major crops has been presented in Table 1.1.

Brief production details of major field crops

The present worldwide crucial food security challenges are to sustain the food production globally, sufficient availability of agroproducts in the international markets to meet the consumer demands, nutritional security with quality food products, and development of production technologies under changing climates. These are big challenges for agriculture professionals to meet with the present infrastructure available with them. Thus, extra resources and professional and technical innovations will be needed to accelerate the present production environment productivity so that the food and nutritional security can be sustained globally.

Each person now lives longer, consumes food above the subsistence level for 90% of the population, and is more demanding of both energy sources and manufactured goods. The challenge for agriculture is to at least double food production this century, despite increasing urban competition for land and water (Redden *et al.*, 2011).

The majority of food demand is usually met by local production as only about 5–10% of global staple crop production is traded, although certain countries are major exporters, such as the United States, Australia, and Canada for 50–70% of the wheat production (GIEWS, 2011). The leading countries in wheat production (653 million metric tons (m.mt)) in 2010/2011 were European Union (EU) (132 m.mt), China (126), India (91), and the United States (61) (IGC, 2012).

World rice production in 2010 was estimated at 700 m.mt corresponding to 466 m.mt of milled rice, led by China (200), India (141), Indonesia (66), and Bangladesh (51) (FAO, 2011a, 2011b). About 7.3% of world production is internationally traded, with major exports from Thailand, Vietnam, the United States, and India, and major imports to Bangladesh, Nigeria, Philippines, and Malaysia (FAO, 2011a, 2011b), although distorted by floods in South and Southeast Asia in 2010 and 2011.

Potato production in 2009 was 330 m.mt, mainly in China (75), India (37), Russia (21), and Ukraine (19) (Geohive, 2010). Two-thirds of production is used as food and one-third as animal feed.

Total world maize production was 866 m.mt in 2010/2011 (IGC, 2012, FAO 2012a), with about 11% being traded mainly for feed and industrial consumption including ethanol. The United States is a leading producer and exporter with 350 m.mt, while in China maize production (163 m.mt) for feed now exceeds that of wheat.

World sorghum production was projected at 65 m.mt in 2010, with Nigeria, the United States, and India being major producers with 7.5–10 m.mt (Agro stats, 2009). Sorghum is an important food security crop in the West African Savannah/Sahel, Ethiopia, and Somalia. There is a wide disparity in yield from 0.8 t/ha in Africa to 4 t/ha in North America (FAO and ICRISAT, 1966).

World cassava production was 91 m.mt in 2011, led by Brazil (27), Indonesia (11), Nigeria (10), and Zaire (9) (2.5) (FAO, 2012b). Cassava is a drought-resilient crop, with per capita consumption above 200 kg/year in Africa.

Pulses, with a world production of 56 m.mt in 2007 (Tata Strategic Management Group, 2012), provide an important source of high protein food in developing countries where diets consist mainly of high-carbohydrate staple foods. Ninety-five percent of pulses are cultivated in the developing world. The principal pulses are *Phaseolus* beans (46%), chickpea (22%), faba bean (10%), and (7%) each for lentil, pigeon pea, and cowpea. Leading producers are India for *Phaseolus* beans, chickpea, pigeon pea, and lentil, plus Brazil and Myanmar for

Table 1.1 Worldwide area, production, and productivity of major field crops in major countries during 2011–2012.

Major cereals and other field crops in 2011-2012	World/major country	Area in million ha	Production in million metric tons	Productivity in metric tons/ha
Major cereal crops				
Wheat	World	221.23	697.16	3.15
	India	29.07	86.87	2.99
	China	24.27	117.40	4.84
Corn	World	169.63	883.28	5.21
	United States	33.99	313.15	9.24
	China	33.54	192.78	5.75
Rice	World	159.23	465.83	4.36
	India	44.10	105.31	3.58
	China	30.06	140.70	6.69
Barley	World	49.61	134.29	2.71
Sorghum	World	39.42	54.05	1.37
Other coarse grains	World	312.81	1154.54	3.69
	United States	36.96	323.73	8.76
	China	35.61	199.30	5.60
Major oilseed crops	World	219.58	425.24	1.94
Soybean	World	102.93	239.15	2.32
	United States	29.86	84.19	**2.80**
Rapeseed mustard	World	33.45	61.17	1.83
	Canada	7.59	14.61	1.92
	China	7.35	13.43	1.83
Sunflower	World	25.56	40.64	1.59
	Russia	7.20	9.63	1.34
	Ukraine	5.80	10.50	1.81
Cotton	World	34.58	46.41	1.34
	China	5.40	12.97	2.40
Pulses*	World	103.67	71.35	0.69
Chickpea	World	12.34	11.63	0.94
	India	8.32	7.7	0.93
	Pakistan	1.06	0.29	0.28
Lentil	World	4.21	4.56	1.08
	India	1.6	0.95	0.59
	Canada	0.99	1.49	1.51
Dry peas	World	6.59	9.83	1.49
	Canada	1.31	2.81	2.14
	Russian Federation	1.16	1.66	1.43
Beans dry	World	53.67	23.59	0.44
	Brazil	27.09	2.79	0.11
	India	9.1	3.63	0.39
Dry cowpeas	World	11.29	5.71	0.51
	Niger	4.70	1.33	0.28
	Nigeria	3.20	2.50	0.78

Source: Foreign Agricultural Services/USDA (2011–2012), www.fas.usda.gov.
*http://faostat.fao.org/ (2012).

Phaseolus beans; Pakistan, Iran, and Turkey for chickpea; Myanmar, Kenya, and Malawi for pigeon pea; and Turkey, Iran, Nepal, and Syria for lentil. China is the leading faba bean producer followed by Ethiopia and Morocco. The major cowpea production is in West Africa, led by Niger and Nigeria. Soybean production is rapidly increasing above 240 m.m.t level for 2011-2012 (Table 1) notably in Brazil, Argentina and India which with USA are the major producers.

Minor crops

Interestingly, vegetable root and tuber crops have been under cultivation since ancient times indifferent continents and still they are essential components in daily dietary system of millions globally. These crops are very important in daily food chain because of their specialty in urban and rural areas worldwide. They hold great promise for vitamins and major and minor essential healthy nutrients and play important role in staple food including the nutritional value (Tekouano 2011). Interestingly, they have three to four times higher yield potential than other field crops and because of short duration, these crops fit well in to diverse and intensive cropping system globally.

Vegetables form a large and very diverse commodity group and include a wide range of genera and species, with a global production above 1 billion ton in 2010 mainly in Asia (FAOSTAT, 2012; Andreas and Roland, 2013). Root and tuber crops, including edible aroids, also are important for food and nutrition security (Rao *et al.*, 2010). Today, in population terms, 4 billion people rely on rice, maize, or wheat as their staple food, while a further 1 billion people rely on roots and tubers. About 100 other root and tuber crop species including sweet potato are significant (Rao *et al.*, 2010).

Sweet potato (*Ipomoea batatas* L. Lam) produces more edible energy on marginal agricultural land than any other food crop and has high nutritional quality (Mukhopadhyay *et al.*, 2011). Varieties rich in B-carotene (orange-fleshed sweet potatoes) address vitamin A deficiency in parts of sub-Saharan Africa and South Asia (Fanzo *et al.*, 2013). It tolerates adverse biotic and abiotic stresses. Production of sweet potato is greater than 82% in Asia, followed by Africa (14%) with global production of 108 m.mt on 8.5 million ha.

Yam (*Dioscorea* sp.) is a very important food in West and Central Africa where around 60 million people are dependent on it. Benin, Cote d'Ivoire, Ghana, Nigeria, and Togo are responsible for over 90% of the world production of 48 m.mt from 4 million ha (Asiedu and Sartie, 2010).

There are five edible species of aroid that are considered important for food security : giant taro (*Alocasia macrorrhizos* (L.) Schott); swamp taro (*Cyrtosperma merkusii* (Hassk.) Schott); cocoyam (*Xanthosoma sagittifolium* (L.) Schott); elephant foot yam (*Amorphophallus paeoniifolius* (Dennst). *Colocasia esculenta* (L.) Schott is an ancient root crop and the most scientifically studied. These edible aroid species play a significant role in marginalized agricultural lands, contributing to crop diversification and resilient farming systems. World production in 2010 was 9.3 m.mt of fresh produce from 1.3 million ha (100,000 ha in India) for the 55 countries as per official statistics (www.fao.org, 2011).

Neglected and underutilized species

Neglected and underutilized species refer to the many hundreds of crops and plants that have the potential to improve people's livelihoods, as well as food security, but are not being fully realized because of their limited competitiveness with commodity crops in mainstream agriculture. Their diversity and the range of adaptive traits represent an important resource for climate change adaptation (Padulosi *et al.*, 2011). They are of significant importance locally, being highly adapted to marginal, complex, and difficult environments, and contribute significantly to diversification and resilience of agroecosystems, for example, the legume bambara groundnut (*Vigna subterranea*) originating from West Africa is widely cultivated throughout sub-Saharan Africa and is well known for its drought tolerance and ability to grow in harsh ecosystems. The minor millets, grown mainly in South Asia, combine drought-resistant traits with excellent nutrition, and offer major opportunities for adaptation to water stress.

Remarkable frost tolerance is shown by cañihua (*Chenopodium pallidicaule*), an underutilized Andean grain, used around lake Titicaca in Bolivia/Peru to help cope with climate change. Sea buckthorn (*Hippophae rhamnoides*), a perennial species naturally distributed from Europe to Central Asia and China, is more tolerant to abiotic stresses like frost and cold than apple and pear, possibly associated with its high levels in ascorbic acid and myo-inositol.

Predicted impacts of climate change on global agriculture, crop production, and livestock

The agricultural sector is directly affected by changes in temperature, precipitation, and CO_2 concentrations in the atmosphere, but it also contributes about one-third to total GHG emissions, mainly through livestock and rice production, nitrogen fertilization, and tropical deforestation. Agriculture currently accounts for 5% of world economic output, employs 22% of the global workforce, and occupies 40% of the total land area. In the developing countries, about 70% of the population lives in rural areas, where agriculture is the largest supporter of livelihoods. This sector accounts for 40% of gross domestic product (GDP) in Africa and 28% in South Asia. However, in the future, agriculture will have to compete for scarce land and water resources with growing urban areas and industrial production (Hermann Lotze-Campen, 2011).

Creating more options for climate change adaptation and improving the adaptive capacity in the agricultural sector will be crucial for improving food security and preventing an increase in global inequality in living standards in the future (Smith 2012). Droughts and floods have always occurred at the local level, but they are predicted to increase in intensity and frequency over this century. Severe events can devastate agricultural environments, economies, and livelihoods of millions globally. Climate change and disaster risk management are not confined to only some geographic regions.

Wheeler and von Braun (2013) point out that the patterns of models on climate change impacts on crop productivity and production have largely remained consistent over the past 20 years, with crop yields expected to be most negatively affected in tropical and subtropical regions and to overlap with countries that already carry a high burden of malnutrition. Projections for the near term (20–30 years) predict that climate variability and extreme weather events will increase and affect all regions with increasing negative impacts on growth and yield, leading to increased concerns about food security, particularly in sub-Saharan Africa and South Asia (Burney *et al.*, 2010; SREX, 2012).

Major climate change impacts by 2030 are expected for maize with a 30% yield reduction in South Africa, and reductions in China, South, and Southeast Asia (Lobell *et al.*, 2008). Production of wheat, rice, millet, and *Brassica* crops is predicted to be reduced in these regions, by up to 5% in South Asia, with severe impacts in India because of less food per capita (Population Reference Bureau, 2007, Knox *et al.*, 2012).

The impact of climate change on food production in other regions will be crop specific, with reduced production of wheat, rice and soybean in Brazil, and of cassava and maize in the Andean region. Desert encroachment is expected in the West African Sahel with reduced production of sorghum, although millet and cowpea production may rise. In tropical West Africa, yields of peanuts, yams, and cassava are likely to decline. Central Africa may see reduced production of both sorghum and millet. East Africa may have an increase in yield for barley but a reduction for cowpea (Redden *et al.*, 2014).

In the Pacific Islands and other low-lying island areas, the impacts of erosion, increased contamination of freshwater supplies by salt-water incursion, increased cyclones and storm surges, heat and drought stress are all expected to have a negative toll on food production (Barnett, 2007).

The growing season is likely to lengthen at high boreal latitudes such as in Nordic Europe, Siberia, Greenland, and Canada. This will result in widening agricultural opportunities, albeit with possible extreme weather fluctuations. Such changes could provide opportunities for underutilized and semidomesticated local crops, for example, fruit species from Siberia will have the opportunity to be more widely grown in new cultivation niches and also provide benefits for their health food properties (Ebert and Schaffleitner 2015; Chapter 22 in this book). Such changes may result in the changing or developing of markets for novel crops and new utilization.

Possible impacts of climate change on food quality and food safety

To adapt to the new conditions of changing climate, one of the major strategies is the breeding of new varieties with the genetic traits for adaptation to these changes. However, care is needed to avoid compromising the nutritional quality of the crop or subsequent food products. Recent long-term studies of improved wheat production in the United Kingdom since the mid-1960s demonstrated that production gains were at the expense of lower levels of micronutrients (Fan *et al.*, 2008). Garnett (2008) highlights that future changed production methods in response to climate change could have implications for nutritional quality and food safety. This could include mitigation approaches to introduce high-sugar grasses into the diets of cows to reduce methane emissions.

As indicated elsewhere in this chapter, climate change will influence the incidence, intensity, and future distribution of pests and diseases (Bebber *et al.*, 2013). Lake *et al.* (2012) point out that this is likely to affect the use of herbicides and fungicides. In recent reviews, Tirado *et al.* (2010) and Lake *et al.* (2012) concluded that climate change could impact significantly on food contamination and foodborne diseases through elevated incidences of existing pathogens or the emergence of new pathogens in food.

Furthermore, predicted levels of atmospheric carbon dioxide for the next century will have major implications for plant physiology and growth and will most likely affect both agricultural production and food quality (Taub *et al.*, 2008; Taub, 2010). Panozzo *et al.* (2012) have highlighted that elevated carbon dioxide is likely to have a greater impact on grain protein levels under warmer and drier conditions. Given the many possible interactions between climate change factors and associated plant stresses, it is likely that future outcomes in terms of plant composition and food quality will be extensive.

CWR and climate change on a global basis

The exploitation of genetic diversity to develop stress-tolerant crops is of strategic importance to combat the negative impact of climate change on crop production (de la Peña *et al.*, 2011). Today, CWR are threatened in the wild and are only partially conserved in gene banks (Maxted *et al.*, 2012), but have been rediscovered as essential resource in crop improvement programs to adapt major crops to climate change.

Carbon dioxide (CO_2) concentrations

Changes in climate are associated with changing levels of GHGs in the atmosphere, namely,

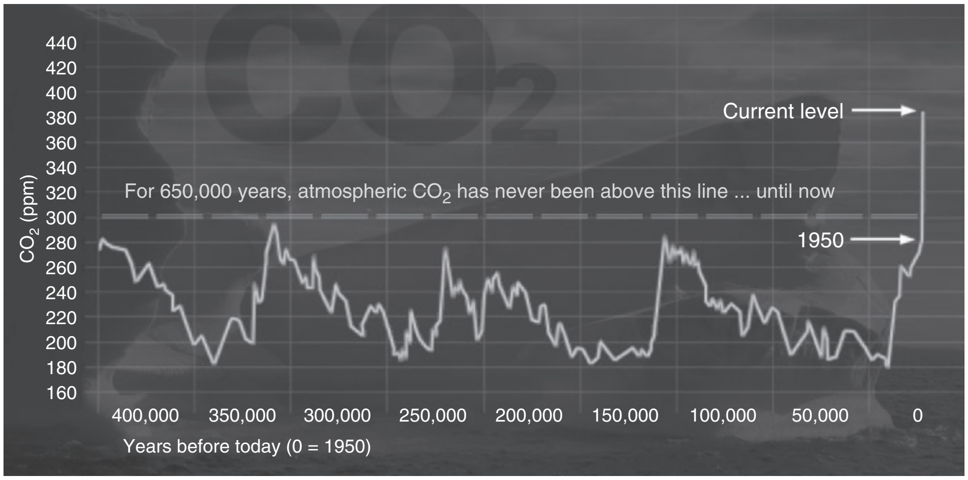

Fig. 1.1 Carbon dioxide (CO_2) concentrations in the atmosphere, 2013.

water vapor. There is an unmistakable increase in carbon dioxide (CO_2) concentrations in the atmosphere along with nitrous oxide (N_2O) and methane (CH_4) (IPCC, 2007a). These levels have now reached concentrations exceeding all recorded values in the history of cultivated agriculture. Such trends in carbon dioxide (CO_2) concentrations were summarized during the Forty-Ninth Annual AIARD Conference "Feeding the Future in a Changing Climate," Washington D.C. on June 4, 2013, which are presented in Figure 1.1 (Simpson, 2013).

Temperature and precipitation

Temperature and precipitation are two critical parameters affecting plant development. In terms of temperature change, Meehl *et al.* (2007) state that on a global basis, "it is very likely that heat waves will be more intense, more frequent, and longer lasting in a future warmer climate. Cold episodes are projected to decrease significantly in a future warmer climate. Almost everywhere, daily minimum temperatures are projected to increase faster than daily maximum temperatures, leading to a decrease in diurnal temperature range. Decreases in frost days are projected to occur almost everywhere in the middle and high latitudes, with a comparable increase in growing season length."

It is expected that by mid-century, 2040–2050, air temperatures will increase on average around the globe between 0.8 and 1.0°C and by the end of the century would have increased between 2 and 4 °C. In this context, the emerging trend is for a proportionally larger increase in average minimum temperatures than in average maximum temperatures with greater vulnerability for heat stress conditions occurring during the summer months. These trends have already begun to exhibit themselves in the climate record around the globe as reported by Lobell *et al.* (2011a, 2011b). Such temperature changes will have a significant impact on crop growth and development (Schlenker and Roberts 2009). Summaries of the global surface temperature changes are presented in Figure 1.2 as reported by Hansen *et al.* (2010), demonstrating that temperature is rising continuously over the years.

Many agree that climate change is one of the greatest threats facing the planet. Recent years show increasing temperatures in various regions and/or increasing extremities in weather patterns. The climate is changing, the earth is warming up, and there is now overwhelming

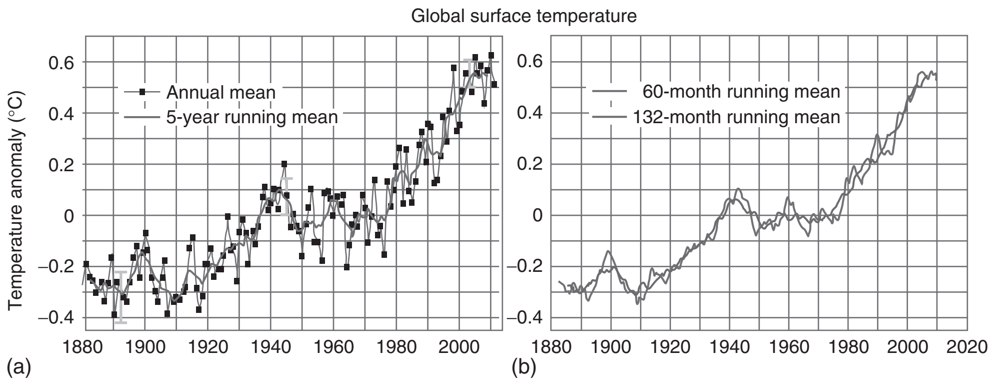

Fig. 1.2 The global surface temperature changes 2010.

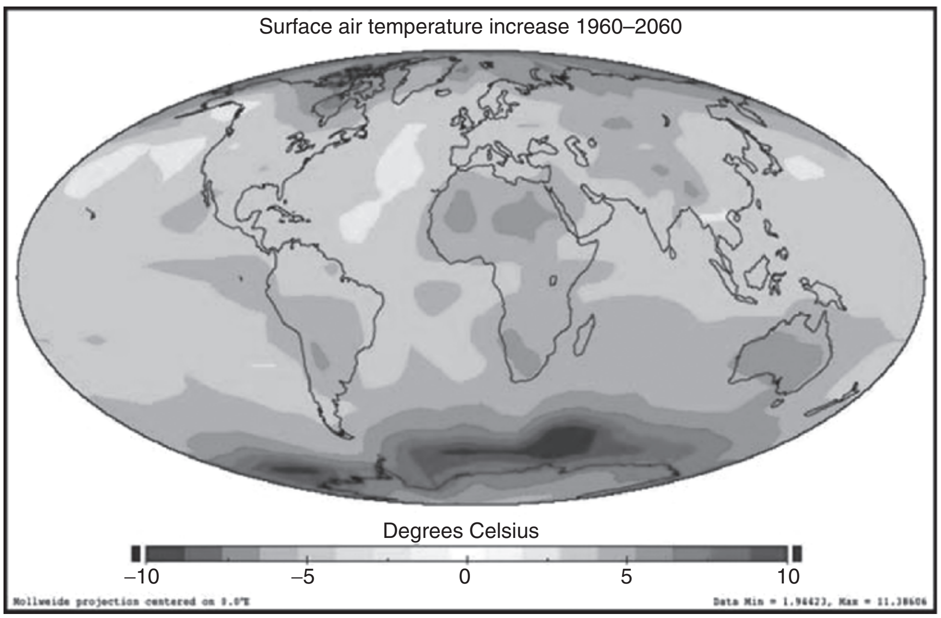

Fig. 1.3 Annual average global warming by the year 2060 simulated and plotted using EdGCM by NASA. *Source*: Climate Warming: http: www.greeniacs.com/ and http://newsjunkiepost.com/2010/02/22/climate-change-not-a-matter-of-faith/.

scientific consensus that it is happening and is human induced. With global warming on the increase, and species and their habitats on the decrease, chances for ecosystems to adapt naturally are diminishing (Figure 1.3).

In their assessment on future trends in precipitation, Meehl *et al.* (2007) stated: "For a future warmer climate, models indicate a general increase in regional tropical precipitation maxima (such as the monsoon regimes and over the tropical Pacific), general decreases in the subtropics, and increases at high latitudes due to a more intense global hydrological cycle. Globally averaged mean water vapour, evaporation, and precipitation are projected to increase." Precipitation changes are critical to agriculture, and shifts in both amounts and timing could have serious implications for agricultural production, disrupting all cultural operations from planting to harvesting.

The interaction of climate change factors on crop development

Better understanding of the interactions between climate change factors is critical to understanding the response of crops to changing environments. In particular, the interactions between elevated temperature and elevated CO_2 and water and nutrients need to be explored.

The interaction of rising temperature and CO_2

At low light, plant growth is strongly carbon limited and thus responds better to high CO_2. Elevated CO_2 decreases stomatal conductance, leading to decreased water loss, lower total water use, and increased water use efficiency. Thus, under water stress (drought) conditions, crops will survive longer under elevated CO_2. Water savings from lower transpiration will be offset by larger leaf areas and higher tissue temperatures in these conditions. Furthermore, the response of plants to elevated CO_2 is generally reduced at low levels of plant nutrition. An increase in the carbohydrate pool because of increased photosynthesis can stimulate growth only if crops can acquire more nutrients and use them more efficiently.

The beneficial effects of elevated CO_2 on growth and yield decrease at supraoptimal temperatures (Prasad *et al.*, 2002, 2003, 2006a). Less increase in air temperature would more than offset the water-saving effects of CO_2 from decreased stomatal conductance. Studies using rice, dry bean, and sorghum have shown that plants grown at elevated CO_2 displayed decreases in optimum and ceiling temperatures for seed set by about 2°C (Matsui *et al.*, 1997; Prasad *et al.*, 2002, 2006a).The rises in both carbon dioxide concentration and in temperature are increasing simultaneously globally (Hansen *et al.*, 2010) (Figure 1.4).

The interaction of high temperature and drought stress

High temperature and drought stress commonly occur in combination with field conditions. Under drought, leaf water potential is lowered and stomata close, thereby decreasing transpiration. Leaf water potential is also

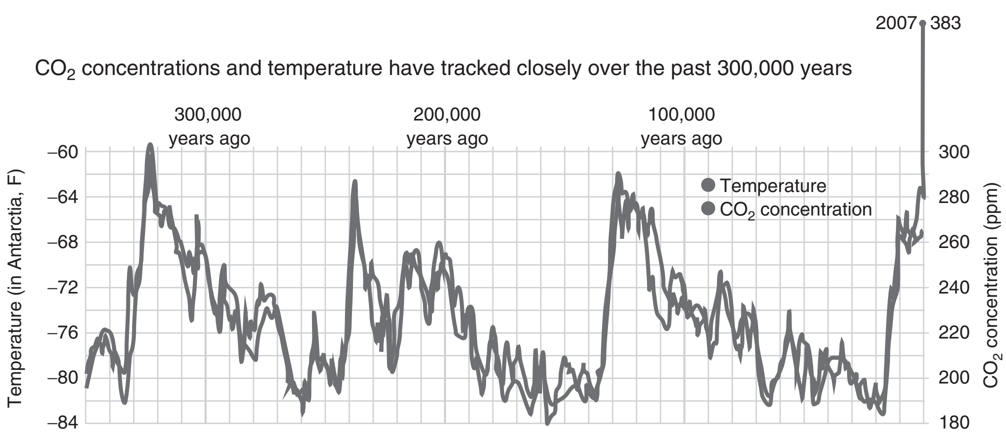

Fig. 1.4 The concentration and temperature of CO_2.

dependent on vapor pressure deficit (discussed in Section "Temperature and Precipitation"). High temperature increases evaporation from the soil surface and transpiration from the leaf surface because of higher vapor pressure deficits. Thus, high temperatures interact strongly with drought to exacerbate the effects of reduced available water (Machado and Paulsen, 2001).

The simultaneous effects of high temperature and drought stress on crop performance and yield may be different from the individual stresses alone. In wheat, the combined effect of high temperature and drought on leaf chlorophyll content, grain set, seed yield, and harvest index were more severe than additive effects of these individual stresses (Pradhan *et al.*, 2012a; Prasad *et al.*, 2000a, 2011). Differential effects between traits were, however, observed. Grain number was more sensitive to high temperature stress while grain weight displayed greater sensitivity to drought. There is a need to accurately model these interactive effects on crops so that realistic assessments of impacts and adaptive strategies can be made (Nuttall *et al.*, 2012). Such adaptation will involve genetic tolerance to very high temperatures under both irrigated and drought conditions.

The impact of temperature on crop water relations

More detailed physiological plant responses to temperature and to precipitation changes occur at both the leaf and canopy level and are expressed in responses ranging from photosynthetic and transpiration rates to leaf expansion (Hatfield *et al.*, 2008, Hatfield and Prueger, 2011).

Leaf or canopy temperatures of well-watered canopies are often 3–5°C less than air temperature because of evaporative cooling from transpiration through the leaf surface. Approaches to quantify crop water stress using canopy temperature are now well established.

The linkage between temperature responses of leaves and the thermal stability of metabolic enzymes has been studied (Burke *et al.*, 1988). Carbon assimilation in cotton peaked at a higher temperature than the optima for maximum yield (Conaty *et al.*, 2012). Linkages between air temperature, canopy temperature, and crop water status suggest that under well-watered conditions plants can maintain leaf temperatures near their optimal temperature range. But when soil water becomes limiting, leaf temperatures are no longer maintained within a plant's optimal range and stress will result. The management of crops at elevated temperature will therefore depend not only on the absolute climatic changes but also on the willingness of farmers to adapt their diverse farming systems to ones that conserve and utilize water more efficiently (O'Leary *et al.*, 2011).

Many of the predictions about the effect of increasing temperature on crops have focused on average air temperature. Increases in minimum air temperature changes may, however, be of greater consequence to plant growth and phenology (Hatfield *et al.*, 2011). Changes in minimum temperatures are more likely to occur over broad geographic scales when compared to maximum temperatures (Knowles *et al.*, 2006). Maximum temperatures are affected more by local conditions, and the role of soil water content and evaporative heat loss as soil water evaporates is particularly important (Alfaro *et al.*, 2006). The respiration rate of plants is directly related to minimum air temperatures, with increased respiration reducing biomass accumulation and crop yield (Hatfield *et al.*, 2011). The overall effect of changing maximum and minimum temperatures therefore has to be examined more closely than changes in the average temperature. Higher minimum temperatures in Asia reduced rice (*Oryza sativa* L.) yields, while higher maximum temperature raised yields (Welch *et al.*, 2010). It was further observed that maximum temperature seldom exceeded the critical optimum temperature for rice. Maximum temperatures were therefore predicted to decrease yields only if they rise substantially above a critical zone (Redden *et al.*, 2014).

In grain sorghum, high temperature can result in significant increases in leaf numbers, particularly when reproductive development is arrested without large decrease in leaf photosynthetic rates (Prasad *et al.*, 2006a). The length of time from floral initiation (panicle initiation) to anthesis (panicle excretion) is generally decreased by moderate increases in temperature, but severe high temperature stress delays panicle initiation, restricts panicle exertion, and potentially delays flowering (Prasad *et al.*, 2006b).

Early reproductive processes such as micro- and megasporogensis, anthesis, pollination, pollen tube growth, fertilization, and seed set development are all highly susceptible to increased temperature. Failure of any of these processes can decrease fertilization or increase early embryo abortion, leading to lower seed/grain production thereby limiting crop yield. High temperature stress prior to or at anthesis causes a significant increase in floral abortion and lower seed numbers in rice, wheat, groundnut, *Phaseolus* bean, and soybean (Jagadish *et al.*, 2007; Prasad *et al.*, 1999a, 1999b, 2002, 2006b, 2008a, 2008b; Saini *et al.*, 1983; Djanaguiraman *et al.*, 2013a, 2013b). Exposure to temperatures greater than 37°C for as short as 1 h during flowering has been shown to decrease seed set in rice (Matsui *et al.*, 2001). Similarly, exposure to temperatures greater than 33°C for 6 h after anthesis decreased seed set in peanut (Prasad *et al.*, 2000b). The timing of high temperature exposure relative to peak flowering is therefore critical (Wheeler *et al.*, 2000).

Prolonged high temperature stress shortens the reproductive development duration (period during which potential kernel or seed numbers are determined) and the grain-filling duration (during which the grain or seed weight are determined), leading to smaller seed size. For most crop species, yield capacity is mainly a function of seed numbers per unit area and seed-filling duration. Although there is often a slight increase in seed-filling rate under high temperature, it does not compensate for the reduction in seed-filling duration.

Global climate models predict that nighttime temperatures are expected to increase at a faster rate than daytime temperatures. High nighttime temperature has been shown to have a more pronounced negative effect than daytime temperatures on the yield of rice, with a 10% reduction in yield for every 1°C increase in nighttime temperature (Peng *et al.*, 2004). Studies have also shown that high nighttime temperature decreases pollen viability, spikelet fertility, and grain weight in rice (Mohammed and Tarpley, 2009; Morita *et al.*, 2002). Wheat yields have been observed to decrease linearly with increasing nighttime temperatures from 14 to 23°C (Prasad *et al.*, 2008b). Nighttime temperature greater than 20°C additionally decreased spikelet fertility, grains per spike, and grain size. Decreases in photosynthesis were observed at night temperatures greater than 14°C. High nighttime temperatures significantly decreased yields in soybean and grain sorghum by both increasing respiration rate and decreasing the photosynthesis rate (Prasad and Djanaguiraman, 2011; Djanaguiraman *et al.*, 2013a, 2013b).

Impact of climate change on crop wild relatives, conservation, and use

CWR contain unique genetic diversity that could better equip our future food crops with the traits to cope with expected food demand increases and climate change. CWR will be an important source of genes for breeding new cultivars adapted to the conditions of abiotic environmental stress that may be expected as a result of climate change (Hunter and Heywood, 2011). To date, the commercial value of CWR has been of major significance: the desirable traits of wild sunflowers (*Helianthus* spp.) are worth an estimated US$267–394 million annually to the sunflower industry in the United States; one wild tomato variety has contributed to a 2.4 percent increase in solid contents worth US$250 million; and three wild peanut varieties have provided resistance to the root knot nematode, which is a worldwide saving of US$100 million per year (Hunter and Heywood, 2011). Preserving the wild relatives of just 29 of the world's most important food crops alone, such as wheat, potato, rice and sugarcane, could be worth around $196 billion to the global economy (http://www.theguardian.com/environment/2013/jul/23/wild-crop-seeds-boost-economy).

However, CWR resources cannot be taken for granted. Jarvis *et al.* (2008) used current and projected future climate data for approximately 2055, and a climate envelope species' distribution model to predict the impact of climate change on the wild relatives of peanut (*Arachis*), potato (*Solanum*), and cowpea (*Vigna*). Climate change strongly affected all taxa, with an estimated 16–22% of these species predicted to go extinct and most species losing over 50% of their range size. Likewise, Lira *et al.* (2009) analyzed the effects of two scenarios in Mexico on the distribution patterns of eight Cucurbitaceae CWR, *Cucurbita argyrosperma* subsp. *sororia*, *Cucurbita lundelliana*, *Cucurbita pepo* subsp. *fraterna*, *Cucurbita okeechobeensis* subsp. *martinezii*, *Sechium chinantlense*, *Sechium compositum*, *Sechium edule* subsp. *sylvestre*, and *Sechium hintonii*. Most of these taxa have restricted distributions and many have critically important genetic traits for disease resistance. They found a marked contraction of the distributions of all eight taxa under both climate change scenarios, with maintenance of CWR in only 29 out of the 69 natural protected areas where they currently occur.

There is a recent Norwegian-funded initiative involving the Global Crop Diversity Trust, Millennium Seed Bank, and their partners to accelerate CWR collection and *ex situ* conservation (Guarino and Lobell, 2011). Conservation of CWR *in situ* in areas, or even outside protected areas, is little recognized and far from being guaranteed (Hunter and Heywood, 2011). Simply hoarding CWR in gene banks is not the complete answer as it halts the evolutionary process and the emergence of new genetic traits, an essential process given the uncertainty about what climatic and production environments we will face in the future.

Worldwide, even where protected areas (parks and reserves) did overlap with areas important for crop genetic diversity, little attention was given to CWR in the management of the area (Amend *et al.* 2008). Hunter *et al.* (2011, 2012) highlight the important obstacles and challenges with regard to the management of crop genetic diversity, especially CWRs, within protected areas with recommendations to address these. However, the majority of CWR are found outside already existing protected areas, and safeguarding their future *in situ* is far from given.

It is clearly a major challenge for a fixed system of protected areas to respond to global change, and significant rethinking in the design of such areas will be necessary if they are to survive and remain effective. More active management and monitoring is likely to be required to ensure greater connectivity, namely, corridors to facilitate migration and movement of species. Hodgkin and Bordoni (2012) suggest that ultimately *in situ* conservation may need to be replaced by *ex situ* conservation. How the two approaches may be most effectively combined will be an increasingly important question for research and conservation management.

Climate change mitigation, adaptation, and resilience

Never before in the history of humanity has there been such focus by the world scientists and farmers on securing future food production. Poor people and farming communities living in regions already being impacted by climate change are already developing effective community-based adaptation strategies (Ensor and Berger, 2009; IFAD, 2010; Conway, 2012).

In other areas identified as being at high risk from the effects of climate change, farmers, communities, and villages are being assisted in the development of Climate-Smart Villages (http://ccafs.cgiar.org/climate-smart-villages#.Uxl8JreYbcs), while yet others are working to achieve more resilient landscapes by strengthening technical capacities, institutions, and political support for multistakeholder planning and governance for Climate-Smart Landscapes (Scherr *et al.*, 2012). The challenge is to actively seek strategies to adapt to climate change and ensure that productivity can keep pace with the demand of a growing population within a finite natural resource base (Reynolds and Ortiz, 2010). This will require a holistic and integrated approach, which, among other things, will benefit from the availability of stress-tolerant germplasm (Pradhan *et al.*, 2012b, Ristic *et al.*, 2008). Such strategies need to be linked to more efficient and sustainable crop and natural resource management, enabled by effective policy support. This will require a worldwide concerted effort by scientists, farmers, development agencies, and donors, if we are to meet the growing demand for food by ensuring resilient agricultural and food systems (Smith 2012).

Closing the yield gap and increasing crop production will play a pivotal role, with greater access to the world's genetic resources and their enhanced utilization by farmers and breeders of genetic methods worldwide. A better understanding of crop physiology and genetic sequencing technology means that a more targeted approach to selection across multiple traits is now possible, leading to the development of new crop varieties for future challenging environments (Godfray *et al.*, 2010). This will necessitate much greater utilization and sharing of the plant genetic resources (PGR) that currently exists in the more than 1700 gene banks globally by the world's plant breeders (Guarino and Lobell, 2011; McCouch *et al.*, 2013a).

Mitigation

Reynolds and Ortiz (2010) and Cribb (2010) highlight that crop production mitigation strategies include improved soil management practices; mulch and cover cropping; conservation tillage; more efficient N utilization, improved rice cultivation techniques, and improved manure management practices that will reduce methane and nitrous oxide emissions. These will require new crop varieties and different crop combinations and management systems where agronomic practices have been modified (Hodgkin and Bordoni, 2012). Crop production systems may be able to mitigate climate change through the breeding of crop varieties with reduced carbon dioxide and nitrous oxide emissions (Reynolds and Ortiz, 2010).

Adaptation and resilience

The increased use of agricultural biodiversity, especially plant genetic resources, will play an important role in improving both adaptability and resilience of agricultural systems (Lin, 2011; Hodgkin and Bordoni, 2012).

Lin (2011) highlights that crop diversification can increase adaptation and resilience in a range of ways, including enhanced capacity to suppress pest and disease outbreaks, as well as buffering crop production from the impacts of greater climatic variability and extreme weather events. Areas with greater diversity were found to be more resilient and to recover more rapidly in Honduras following recent hurricanes (Hodgkin and Bordoni, 2012). A recent worldwide review of 172 case studies and project reports demonstrate that agricultural biodiversity contributes to adaptation and resilience through a range of strategies, often integrated, that include protection and restoration of ecosystems, the sustainable use of soil and water resources, agroforestry, diversification of farming systems, adjustments in cultivation practices, and the use of crops with various stress tolerances and crop improvement (Mijatovic *et al.*, 2013).

While certain levels of adaptation will be achieved by moving new crops and crop varieties to more favorable environments, crop improvement through plant breeding and the incorporation of new genes will be as important (Guarino and Lobell, 2011). Hodgkin and Bordoni (2012) highlight crop traits for adapting to changing climate and changing production environments: pollination and set seed under elevated temperatures and enhanced resilience and adaptability in the face of increasingly variable production conditions and increased frequency of extreme events.

We must make much better use of the genetic diversity that currently exists, both in gene banks and *in situ*. It will require global efforts to secure and safeguard the large amount of CWR (and other PGR) not already in storage and improved availability of prebreeding/germplasm enhancement efforts that can develop novel genetic material (with resistances to changing distributions and populations of insect pests/diseases and tolerances to drought, flooding, salinity, heat, and cold), with systems such as GENESYS to link gene banks and users so information on PGR is more readily available (Guarino and Lobell, 2011; Hodgkin and Bordoni, 2012).

Burke *et al.* (2009) have examined the likely future shifts in crop climates in sub-Saharan Africa and explore what might be the priorities for crop breeding and the conservation of crop genetic resources for agricultural adaptation. They conclude that most African countries will have novel climates in at least 50% of their current cropping area by 2050. Often, there will be analog climates already existing in the current climates of at least five other countries, which highlights the key role for international movement of germplasm in future adaptation. However, the few existing climate analogs for some countries were largely clustered in the Sahel.

Maxted *et al.* (2012) clearly stated that the growing concern over the potentially devastating impacts of climate change on biodiversity and food security, considered together with the growing world population, means that taking action to conserve CWR diversity is no longer an option – it is an urgent priority. CWR are recognized as a critical resource to sustain global food security; therefore, their systematic conservation is imperative (Maxted *et al.*, 2012). However, extending their conservation and promoting more systematic exploitation is hindered by a lack of understanding of their potential value and how their diversity might be conserved in practice.

Reliance on just three cereals (rice, maize, wheat) and a few other carbohydrate-rich staples might be sufficient to attain food security, but if nutritional security is to be addressed as well, diverse diets that include a range of grains, pulses, fruit, and nutrient-dense vegetables constitute a common-sense approach to good health (Keatinge *et al.*, 2011; Fanzo *et al.*, 2013).

The neglected and underutilized species diversity and the range of adaptive traits and characteristics they possess represent an important resource for climate change adaptation. Unfortunately, they remain largely ignored by researchers and policymakers. Increased efforts will be needed to secure diversity of crops and their wild relatives. Climate change threats posed to crop diversity and CWR will require enhanced complementary actions for both *in situ* and *ex situ* conservation, which will need to be adapted to face the growing threats posed by environmental and climate change (Hodgkin and Bordoni, 2012).

Interdependence on genetic resources and global treaties and conventions

Climate change and corresponding changes in crop production environments for better adaptation will require greater use of PGR, and this will mean increased movements of PGR both nationally and internationally of resources (Hodgkin and Bordoni, 2012). As these authors highlight, the demands arising from climate change for new or different traits in production systems and for more diversity will need to be reflected in changes in the conservation and utilization of PGR. Climate change is likely to alter the extent and distribution of crop diversity and CWR and to be a further driver of genetic erosion, placing further demands on already limited resources for conservation. Planning of strategies to safeguard CWR both *in situ* and *ex situ* will require enhanced collaboration and interconnected activities at national and international levels and including specific crop networks (Hodgkin and Bordoni, 2012).

Policies, incentives, measures, and mechanisms for mitigation and adaptation

It is likely that future international agreements and collaboration will become even more important between countries and their genetic resources. Future climate scenarios are likely to make countries even less reliant on their own national genetic resources and more dependent on those of other countries. The role of the International Treaty for Plant genetic resources for Food and Agriculture (ITPGRFA) and its Multilateral System (MLS) mechanism is therefore likely to become even more important in facilitating this interdependence and collaboration, though a major question remains as to whether the list of crops currently addressed by the treaty is sufficient under changing climate (Hodgkin and Bordoni, 2012). Further, although the treaty has been in force since 2004 and has 121 contracting parties, bottlenecks to facilitated access still remain and will need to be addressed if future access and sharing is expected to intensify (Bjornstad *et al.*, 2013).

Regulations and financial incentives to facilitate efforts to improve land management, maintain soil carbon content, and make more efficient use of agricultural inputs, especially fertilizers and irrigation, will be required (Cribb, 2010, Wreford *et al.*, 2010).

Lin (2011) points out improvements are urgently required to the policy realm if crop diversification strategies are to be adopted more widely, stressing that to date efforts to promote greater adoption of crop diversification has been slow and attributes this to market incentives only for a select few crops, the drive for biotechnology strategies, and a commonly held belief that monocultures are more productive than diversified systems.

Financing mechanisms to fund the response to climate change will run into billions of dollars requiring huge transformations in investments across many sectors (IFAD, 2010). Climate change will add dramatically to the cost of doing "development" with between US$49 billion and US$171 billion per year, estimated as required for adaptation alone by 2030. Carbon markets, relevant national policies, multilateral financial institutions, bilateral and multilateral aid agencies all have important roles to play in helping mobilizing the resources required (Wreford *et al.*, 2010).

Conclusions

Keeping in view the various situations of climatic changes and their implications on agriculture production and food and nutritional security at global level, it is evident that climate change will bring a major change around the world. Climate change will affect not only the food supply and nutritional availability to humans, but also the sustainability of crop production, standards in livestock production, and harmony of socioeconomic environments.

The increase in agriculture production, productivity, and profitability in future is extremely important to maintain harmonies among different stakeholders at village, district, province, national, and international levels. This can be achieved only when crop production can be suitably matched with the food demand globally.

Utilization of available genetic diversity in general and CWR in specific has not been used extensively and intensively to raise the genetic yield potential of different field crops globally. Importantly, CWR possess hardy gene pools for survival in adverse and harsh environmental conditions, and these novel genetic resources need to be utilized as a priority in crop breeding improvement programs internationally.

It is important to understand and consider the availability of CWR of various field crops for utilization in regular crop breeding programs for the development of new varieties, which may stand against the changing environmental condition with high yields. It is also important to maintain and multiply these CWR under protected environments for creating a diverse gene pool in widely adapted popular cultivars.

Climate change and biodiversity are closely linked and each impacts the other. Biodiversity is threatened by human-induced climate change, but biodiversity reduces the impact of climate change. The presence of healthy biodiversity builds natural resilience to climate extremes: for example, forests are nature's social security check in times of disaster and crisis; they also act as a sink for harmful GHG emissions.

In years to come, it is important that the increasing world population gets the sufficient nutritive food for the survival of mankind. It is possible only when the genetic yield potential of future varieties are increased significantly by crop professionals, sustained by farming communities, and supported by cropping managers globally. In this dynamic and innovative system, there is a need for strong linkages between national and international research organizations, crop improvement managers, policy makers, crop management specialists, national and international traders, and farming communities at global level.

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