Chapter 8
Crop Productivity in Changing Climate

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Abstract Climate change has been identified the major environmental constraint affecting the vegetation all over the globe. Environmental variations such as increase in temperature, carbon dioxide (CO_2), change in precipitation pattern and associated abiotic stresses such as heat, drought, salinity, soil nutrient status affect the growth and productivity of plants. Alterations in the growth and yield of crop plants limit agricultural productivity thus affecting the food production required to sustain growing human population. Models suggest that change in flowering pattern due to alterations in temperature and effects on other factors such as nutrient availability, carbon sequestration, microbial dynamics, and increased pathogen infestation are likely to affect growth and yield of agricultural crops. Abiotic stress due to climatic variations will cause disturbance in essential phenological, physiological and biochemical events in plants. Studies suggest differential responses of plants to changes in temperature and CO_2. Crop yields of both C3 and C4 species are expected to increase within the range of 5–20% under conditions of increasing CO_2 conditions, but supposed to decrease by about 10% with every 1 °C rise in temperature. Plants can minimize the effect of stress induced by various climatic factors by developing adaptive traits and tolerance mechanisms. Biotechnological approaches can also prove useful in developing crop plants with enhanced capacity for withstanding abiotic stresses such as drought, salinity and flooding. Transgenic crop plants developed by genetic engineering technology can grow under adverse environmental conditions.

Keywords Abiotic · Climate · Crops · Nutrition · Productivity · Salinity · Soils · Yield

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E. Lichtfouse (ed.), *Sustainable Agriculture Reviews 27*, Sustainable Agriculture Reviews 27, https://doi.org/10.1007/978-3-319-75190-0_8

8.1 Introduction

Crop plants occupy around 61% of the world arable area (Ewert et al. 2005). About two third of the world cropland area is cultivated with crop species such as wheat, maize, barley, rice, rye, millet, sorghum, cassava, potatoes, sugar beets, sugar cane, pulses, soybeans, groundnuts/peanuts, rapeseed/canola, sunflower, oil palm fruit, and cotton (FAO 2009; 2012) (Table 8.1). Most crop plants are C3 species but few crops such as maize, millet, sorghum, and sugar cane are C4 species (Fig. 8.1). Majority of the crop plants grown all over the world are annuals.

Intergovernmental Panel on Climate Change (IPCC 2007a) reported that increase in concentration of greenhouse gases and mean temperature has progressive increased since pre-industrial times. Predictions suggest increase in the earth's

Table 8.1 Major crop species of the world

Crop species	Global production (m/t)	Area occupied (million ha)
Cereals		
Maize	822,712,527	139
Wheat	689,945,712	211
Rice	685,013,374	146
Barley		54
Sorghum		42
Oats	–	13
Pulses		
Soybeans	262,037,569	79
Cowpea	–	9
Chick pea	–	11
Oil		
Groundnut	40,016,584	26
Rapeseed	–	23
Sesame	–	7
Coconut	–	11
Vegetables		
Beans	–	25
Sugar cane	1,743,092,995	20
Potatoes	314,140,107	19
Cassava	256,404,044	17
Sweet potatoes	–	9
Tomatoes	159,347,031	4
Peas	–	6
Yam	–	4
Fruits		
Grapes	69,093,293	7
Bananas	107,142,187	4

Source: FAOSTAT (2012)

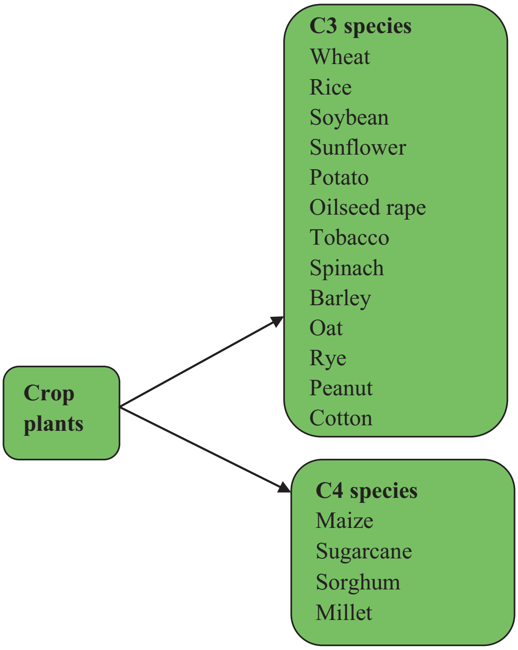

Fig. 8.1 Categorization of crop plants

surface temperature by 1.4 °C–5.8 °C by 2100 (IPCC 2007b). Increases in the CO_2 concentrations to 1000 ppm by 2100 have also been projected. Rise in temperature leading to global warming is expected to affect weather events such as increase in intensity of storms, altered rainfall pattern and other environmental stresses such as drought, salinity, and floods throughout the globe (Parry et al. 2004; Kang et al. 2009). The climatic variations are likely to produce negative effects on growth and productivity of crop plants, hence altering the agricultural output to a significant extent (Wheeler et al. 2000; Porter and Semenov 2005; Challinor and Whee'ler 2008; Challinor et al. 2009; Ahmed and Stepp 2016). Changes in the biotic factors such increase in disease outbreaks, pest and pathogens infestations/infection, weed invasion are also supposed to affect the agricultural productivity indirectly (Reynolds et al. 2015).

Impact of climate change on agricultural crop productivity is supposed to vary with the region. The response of crop plants is likely to depend upon the species and the extent of variation in climatic factors. The extent of damage from climate change depends on the developmental stage of the plant (Lobell and Gourdji 2012). Other factors that highly influence the response of crop species include fluctuations in day and night temperatures, timing of crop, frequency and intensity of cropping. Since many factors are contributing to growth and development of crop plants, hence it becomes difficult to suggest the exact trend of responses to climate change. According to recent surveys, El Niño Southern Oscillation phenomenon and associated cycles of droughts (water scarcity) and flooding events are expected to bring around 20–36% reduction in crop yield. Yield of major crops like wheat, oilseeds are expected to show significant variation of 15–35%. Increase in global temperature by 1°C is also likely to cause a decline in production of cereals such as wheat by 4–6%. Studies report reduction in maize yield by approximate 7% in the past few years (Lobell et al. 2011). Crop species such as corn, rice and soybean have also shown high vulnerability to changing climatic conditions. According to research studies, growth and productivity of both C3 and C4 crop species is likely to get equally affected by climate change (Menzel et al. 2006; Tao et al. 2006; Estrella et al. 2007; Sun et al. 2009; Hasegawa et al. 2013). The reduction in crop yields is likely to account for huge economic losses in agriculture sector (Garrett et al. 2006; IPCC, 2007a, b).

The decrease in yield and productivity of crop plants results from alterations in the e ssential physiological, phenological and metabolic events. Photosynthesis and respiration are the primary physiological events significantly affected in crop species. Alterations in time of flowering and delay in life cycle are the major phenological processes affected by climate change (Ziska and Bunce 2007).

Crop plants show variation in their distribution throughout different zones of globe (Lobell et al. 2008). Detailed studies need to be carried out to assess the effect of climate change on each crop distributed in various zones of globe with emphasis on each climatic variation. The data obtained from these studies help in predicting in overall change in cropping pattern. The results obtained from such studies can prove useful in developing strategies for the sustenance of crop yield and productivity in changing climatic conditions to ensure food security for humans at the global, regional, and local level.

8.2 Modeling Studies for Assessment of Climate Change in Crops

Effects of climatic variations on crop plants have been studied using various higher spatial resolution models. Climate models provide accurate predictions about impact of climate change on distribution of crop plants. They also prove as a valuable approach for assessing and analyzing the probable effects of climate change on crop yield under different scenarios. Some of the important models include General Circulation Models (GCMs), CERES (Crop Environment Resource Synthesis), SOYGRO, SWAP (Soil–Water–Atmosphere–Plant), and InFoCrop. Alterations in the growth and distribution pattern of major crop species such as wheat, rice, maize and soybean localized in different regions of the world have been studied using these models (Parry et al. 2004).

International Benchmark Sites Network for Agrotechnology Transfer (Rauff and Bello 2015) is a crop model that has been used to estimate alteration in yields of world crops at 112 sites in 18 countries. Crops such as wheat, maize, rice and soybean have been studied in response to increasing levels of carbon dioxide using this model. Effect of climate variables such as temperature, precipitation, water availability and changes in soil characteristics on crop growth have been evaluated using this model. The models have been validated for a range of soil and climate conditions. Both rainfed and irrigated lands have been taken into consideration for the study. The data collected from different regions and sites are clubbed. The data obtained is based on physiological events such as transpiration and photosynthesis.

Models have been developed for specifically for various crops. The models used to study wheat, maize, rice and soybean crop is CERES-Wheat, CERES-Maize, CERES-Rice and SOYGRO (Rauff and Bello 2015). The Basic Linked System of National Agricultural Policy Models (BLS) have been developed using around 35 national/regional models, 18 national models, 14 aggregate models of various countries involving European Union and former USSR. BLS models have been used to assess the changes in crop yields and agricultural productivity for the time period of 1990 to 2060.

8.3 Climatic Variations and Crop Production

Increase in temperature, CO_2 concentration, change in water availability/scarcity and associated stresses such as salinity, drought have been considered as the major environmental constraints affecting the productivity of crop species.

8.3.1 Increasing Temperature

Temperature regulates the essential physiological and metabolic growth events in plants. An optimum temperature is required for functioning of physiological and metabolic activities in plants. Temperature of around 15–20 °C is required for sustenance of C3 species, while 25–30 °C is essential for growth of C4 crops (Sage and Kubien 2007). Plant response to increased temperature varies among species. This is because each crop has a different optimal temperature requirement for growth and reproduction. The degree of damage depends on the species of crop plant and stage of development.

Changes in temperature cause severe damage to plant growth because of changes in physiological and metabolic events. Alterations in growth of crop plants have serious implications on agricultural productivity (Wollenweber et al. 2003). According to various models, growth of crops like soybean, maize, potato and beet is likely to get severely affected from alterations in temperature. Recent studies predicted that global food production will increase with slight rise in temperatures i.e. 1–3 °C but decrease at significantly higher temperatures (Gornall et al. 2010; Jaggard et al. 2010). Predictions suggest that for every one-degree increase in temperature crop yields will decrease by 10% (Zinn et al. 2010). Exposure to high temperature causes reduction in crop yield. The extent of decrease depends upon the duration of exposure and crop genotypes. Studies suggest that global warming might benefit production of crop plants such as wheat in some regions but reduce productivity in other areas.

Moderate warming proves beneficial to plants (Jin et al. 2011). Developmental events such as seed germination are promoted at moderate temperatures. Soil warming exerts positive effects on plant growth by increasing mineralization of nitrogen (Hungate et al. 2013). Agricultural production gets affected at extremely high temperature due to loss of soil organic matter caused due to warming. The damage to embryo affects germination of seeds in plants exposed to extremely high temperatures (Essemine et al. 2002; Prasad et al. 2006). High temperature (warming) enhances plant development by shortening life cycle and causing early maturity. Increase in soil temperature reduces the time required for emergence of seedlings and establishment of crop plants. The reduction in yield results from early maturity of pods and seeds (Ellis et al. 1995; Barnabas et al. 2008).

Reproductive development show greater sensitivity to heat stress in comparison to vegetative growth. Floral bud formation, development/differentiation of flower, pod set, grain filling and grain quality have been reported to be negatively affected in plants exposed to heat stress (Fuhrer 2003; Craufurd and Wheeler 2009; Bita and Gerats 2013). Premature degeneration of the tapetal layer result in formation of infertile pollen and cause/induce dehiscence of anther under warming conditions. Low pod production is caused by male sterility. Early development of pod increases leads to malformation of embryo, development of smaller pod with fewer seeds. The accelerated reproductive development negatively influences productivity. Reduction in kernel weight, grains/spike, grain yield has been reported in cereal crops exposed to high temperatures (45 °C and above). Research studies indicated that temperature leads to activation of *FT* (Flowering Locus T), and *PHYA* (Phytochrome A), phytochrome genes which promote flowering at high temperatures (Balasubramanian et al. 2006; Heschel et al. 2007). Apart from these, alterations in the assimilation and mineral uptake also affect the grain yield (Fuhrer 2003; Prasad et al. 2006). The reduction in translocation ability i.e. less sink activity also affects the productivity of crop plants to a significant extent (Maheswari et al. 1999; Al-Khatib and Paulsen 1999; Shah and Paulsen 2003). These responses are commonly noted in cereals crop species such as wheat, rice and maize.

High temperature induces decrease in vegetative growth. This correlates to decrease in leaf, shoot, seed and total biomass production in crop plants. Decrease in relative growth rate in response to high temperature has been well reported for crop species such as *Zea mays*, *Pennisetum glaucum, Saccharum officinarum, Glycine max* (Schlenker and Roberts 2009). Alterations in leaf structure, functioning and properties such as relative water content, water potential, osmotic potential and turgor potential has also been commonly reported in plants exposed to heat stress (Jin et al. 2011).

Photosynthesis is one of the major physiological processes affected by stress caused by high temperature (43 °C and above). The major cause for decrease in photosynthesis at high temperature is increase in the rate of transpiration, deactivation of RuBisco (enzyme involved in the fixation of CO_2). Stomatal closure (around 15–30%) noted in high temperature exposed plants limit the photosynthetic potential of plants due to less influx of CO_2 into leaves. Damage to components of photosynthetic machinery particularly photosystem II and membrane components are mainly responsible for decline in photosynthetic potential. Reduction in the production of photosynthetic pigments noted in these plants also restricts the photosynthetic capacity. The reduction in the production of photosynthetic pigments such as chlorophyll has been attributed to the inhibition of its biosynthesis, changes in ultra structure of chloroplast (Tewari and Tripathy 1998; Sage et al. 2008).

In contrast, increase in the photosynthetic capacity of plants noted under moderately high temperatures is attributed to the increase in stomatal density, number of chloroplasts and chlorophyll content (Jin et al. 2011). Research studies have reported an enhancement of 12% in chlorophyll content (Liu et al. 2013). Increase in size of mitochondria and need for more energy for cell growth and maintenance leads to increase in rate of respiration (Jin et al. 2011). According to estimates, 10 °C rise in temperature will increase the double the rate of respiration. The increase can be attributed to increase in the activity of enzymes.

Perennial plants are more susceptible to changes in temperatures than annual plants. Under warming conditions, fruit development gets restricted in perennial crops causing a decrease in yield (Hatfield et al. 2014). Decreases in fruit set have been reported for fruit crops such as cherries, citrus (*Citrus sinensis)* exposed to increase in temperature by 3 °C (Siebert et al. 2014).

High temperatures produce detrimental effects on crops by

- Faster crop development and shortening crop duration leading to lower yields.
- Alteration in essential processes such as photosynthesis, and respiration (Crafts-Brandner and Salvucci 2002).
- Exponential increase vapor pressure deficit (VPD) because of reduced water-use efficiency.
- Alteration in reproductive events such as sterility leading to low grain filling and crop failure (Teixeira et al. 2012).
- High susceptibility to attack of biotic agents such as pests and diseases (Ziska et al. 2011).
- Changes in the microbial dynamics due to increase in soil temperature and high root respiration.

In nutshell, warming (extremely high temperatures) results in severe heat and water stress, leading to acceleration in growing periods for crops and higher yield losses in crop plants (Hatfield et al. 2011; Hatfield and Prueger 2015).

8.3.2 Rise in CO_2 Concentration

Increase in atmospheric CO_2 concentrations (doubling) promotes growth of crop plants by exerting CO_2 fertilization effect (McGrath and Lobell 2013). Increased availability of CO_2 promotes rate of essential physiological processes such as photosynthesis by 30%. The response of crop plants to increasing CO_2 varies among C3 and C4 species (Tissue et al. 1995). Research studies have shown that C3 plants (temperate and boreal) are greatly affected by increase in CO_2 and show promotion in growth. In contrast C4 plants do not show any significant variation. Literature reports have shown that CO_2 concentrations of around 380 ppm increase yields of C3 and C4 crop species by about 10–20% and 0–10% respectively. An increase in CO_2 concentration by 50% accelerates the rate of photosynthesis by 30%–50% as reported in C3 plant species and 10%–25% in C4 species. Increase in the rate of photosynthesis in C3 occurs because of high optimum for CO_2 (Leakey et al. 2009). C3 species such as wheat, rice, barley, sunflower has been reported an average increase of 36% in photosynthesis with increasing CO_2 concentration. Research studies suggest that C_3 crops are likely to produce more harvestable products, while both $C_3$and C_4 crops are likely to use less water under conditions of rising atmospheric CO_2. An approximate increase of 21 and 28% has been noted in the above and belowground biomass. The production of belowground biomass is significantly higher (about 40%) as compared to aboveground biomass. Increased biomass production results from higher rate of photosynthesis and carbon input in soil through rhizodeposition (Kimball et al. 2002; Nowak et al. 2004; Ainsworth and Long 2005; Inauen et al. 2012). Studies have reported a decline in the yield of crop species such as rice, maize, soybean and wheat exposed to high CO_2 conditions (Erda et al. 2005; Yin et al. 2006; Yang et al. 2009). A significant decline of 63–70% in yield has been noted in crop species including wheat, corn, and cotton subjected to very high CO_2 concentrations (Schlenker and Roberts 2009).

In some plants exposure to high CO_2 leads to increase in vegetative growth evident from increase in parameters such as plant height, stem thickness, total dry weight (Lawlor and Mitchell 1991; Kimball et al. 2002; Ainsworth and Long 2005; Long et al. 2006; Ziska and Bunce 2007). Increase in productivity results from increased photosynthetic rates and improved water-use efficiency. Increases in atmospheric CO_2 concentration favor CO_2 fixing efficiency of Rubisco (Luomala et al. 2003; Ainsworth and Long 2005; Ainsworth et al. 2002, 2008a, 2008b). Increased CO_2 levels reduce stomatal conductance and transpiration rate. A significant reduction of 30% has been reported in the transpiration rate (Polley 2002; Tubiello and Ewert 2002). Crops plants are supposed to get benefitted from decrease in stomatal conductance and increased water-use efficiency (Ainsworth and Long 2005). Increase in leaf temperature support faster rate of plant development. Increased water potential stimulates growth by increasing leaf area (Ainsworth and Long 2005). Increase in leaf area can be attributed to changes in food partitioning, delayed leaf senescence and improved water potential resulting from closure of stomata (Ainsworth and Rogers 2007). The positive effect of rising CO_2 is reflected in high biomass and yield production (40–60%). Improved water relations and nutrient status support the growth of crop plants (Kimball et al. 2002; Long et al. 2006; Leakey et al. 2009; Ziska et al. 2012; Hussain et al. 2013). C4 plants including maize and sugarcane have reported a nominal increase in productivity (approx. 5–10%) under rising CO_2 conditions (Jablonski et al. 2002).

Very high CO_2 concentrations exert a negative effect on chlorophyll biosynthesis and PSII photochemistry thereby limiting the photosynthetic potential of cop plants

(Riikonen et al. 2005). High starch accumulation noted in leaves of plants grown under elevated CO_2 conditions occurs when carbohydrate supply from photosynthesis exceeds growth and respiratory needs (Kimball and Bernacchi 2006). Elevated CO_2 stimulates the respiratory breakdown of carbohydrates resulting in an increase in R:S ratio (Ainsworth and Long 2005; Ainsworth and Rogers 2007; Leakey et al. 2009; Hussain et al. 2013). Altered carbohydrate pools and carbon allocation result from increased carbon assimilation and enhanced carbon storage in the soil under elevated CO_2 conditions. The respiratory breakdown of carbohydrates provides increased energy and biochemical precursors for leaf expansion and growth under elevated CO_2 conditions (Ziska 2000; Ziska and George 2004).

Elevated CO_2 affects nutrient status in plants. High CO_2 lowers plant nutrient concentrations via carbohydrate dilution and increased nutrient use efficiency (Dijkstra et al. 2008, 2010a, 2010b). Increases in carbon and decreases in nitrogen content have been noted in above and belowground tissues in response to elevated CO_2 (Burkart et al. 2009). Allocation of carbon to root increases thereby altering C: N ratio leaves though show low levels of total nitrogen and protein (Gifford 2003; Leakey et al. 2009). The reduced nitrate assimilation and hence lower protein concentrations have been reported in harvestable parts of plants (Alagarswamy et al. 2006; Taub et al. 2008). Increase in soil microbial carbon, organic matter and microbial respiration supports plant growth under elevated CO_2 conditions (Kim et al. 2003; Morgan et al. 2004). Soil carbon contents increases, while nitrogen leaching decreases under elevated CO_2 conditions suggesting a positive effect on plant nitrogen uptake (Porter and Semenov 2005; Johnson 2006; Van Groenigen et al. 2006). Increase in root production or mycorrhizal colonization in response to CO_2 enrichment increases the efficiency for uptake of nutrients (Easterling et al. 2007; Ziska et al. 2012).

Increase in the level of various metabolites such as soluble sugar, starch, cellulose, structural carbohydrate, polyphenol and tannin contents have been noted in response to elevated CO_2. Increases in carbohydrates result from greater carbon reallocation from proteins to carbohydrates under elevated CO_2 conditions (Long et al. 2004). Increased synthesis of polyphenols, fructans and other secondary metabolites has been reported in crop plants exposed to high CO_2 concentrations. The increase can be attributed to increased shikimate metabolism and high carbon availability. The production of nitrogenous compounds increase in response to high nitrogen availability (Temperton et al. 2007).

Elevated CO_2 affect phenological and reproductive development of plants (Jablonski et al. 2002; He et al. 2005). Studies suggest that short-day and long-day species respond differently to increases in CO_2. According to studies short-day crop plants such as soyabean, rice, cowpea and long-day species such as barley, pea, faba bean showed earlier flowering, while delayed flowering response has also been reported in species such as maize, sorghum in response to exposed to increased CO_2 (Springer and Ward 2007). Open-Top Chambers (OTCs) and the Free-Air Carbon Enrichment (FACE) experiments suggest that high CO_2 conditions show slight changes in flowering and fruiting (Springer and Ward 2007; Craufurd and Wheeler 2009). Genes involved in flowering respond to changes in CO_2 concentration

(Blazquez et al. 2003; Lee et al. 2007). The down-regulation of *FLC* (Flowering Locus C) and up-regulation of *SOC1* (Suppressor of Overexpression Constans 1) and *LFY* (Leafy) gene has been noted in response to elevated CO_2. The delay in flowering is associated with up-regulation of *SOC1* and *LFY* expression (Welch et al. 2003, 2004).

CO_2-responsive genes that play a crucial role in cellular functions such as cell cycle, RNA regulation of transcription, DNA synthesis, and cell organization show higher expression under elevated CO_2 conditions. Up-regulation of genes has been indicated by increased transcript levels. Increased expression of transcription factors suggest increased synthesis of proteins such as ubiquitin-specific proteases, cysteine proteinases, and enzymes such as inositol phosphate, isoprenoid biosynthesis, nitrate transport and assimilation proteosome subunits. Genes involved in nitrogen (N), hormone and secondary metabolism get differentially expressed under elevated CO_2 conditions. It is supposed that under high CO_2 conditions, flow of carbon stock gets diverted into secondary metabolism i.e. cell wall, lignin, and fatty acid biosynthesis.

Improvement in growth of crop plants under elevated CO_2 conditions result from

- Stimulation in the photosynthetic carbon gain and net primary production.
- Improved nitrogen use efficiency
- Decrease in water use at both the leaf and canopy scale.
- Stimulation in dark respiration (Rogers et al. 1996; Kimball et al. 1999).

8.3.3 Rise in CO_2 and Temperature

Increase in temperature masks the positive effects of elevated CO_2 (Yin et al. 2006). The reduction in the positive effects of CO_2 has been noted in terms of reduction in yield parameters such as grain number, size, and quality (Drake et al. 1997; Boote et al. 2004; Hasegawa et al. 2013). In contrast, few studies have also reported no significant changes in plant growth when high temperatures exposure is accompanied by increase in CO_2 (Ziska and Bunce 2007; Wang et al. 2012).

8.4 Effect of Abiotic Stresses Induced by Climate Change on Crop Plants

Water scarcity/drought and salinity have been identified as the major abiotic stresses that can be indirectly induced by changes in climatic conditions such as warming.

8.4.1 Drought

Most of the agriculture practiced throughout the world comprises of about 40–45% of irrigated land. Global warming is expected increase the flow of water via melting of glaciers which could benefit to agriculture but increase risk of flooding to crop lands. In contrast, water scarcity due to drought and altered precipitation patterns can also prove detrimental to agricultural productivity (IPCC 2001a; b). Drought or water scarcity lowers water potential in plants but increases solute potential. It changes cell osmoticum and turgor pressure which affects growth negatively. Inhibition in cell elongation occurs due to low turgor pressure as mitosis gets impaired (Hussain et al. 2008). The decrease in soil water potential affects the production of leaves and reduces leaf size in plants. Stem diameter and root proliferation also get adversely affected in these plants. Impairment in growth-related traits affects the biomass production in crop plants (Farooq et al. 2009). Water scarcity reduces the soil microbial biomass which affects the availability of nutrients to plants and hence the crop quality.

Among the physiological processes, photosynthesis is the major event that gets significantly affected due to reduction in leaf area and premature leaf senescence (Anjum et al. 2011a, 2011b). Reduction in leaf area reduces light interception and hence causes inhibition of photosynthesis. Drought stress induced increase in leaf temperature alters the leaf water potential, relative water content and transpiration rate (Yang and Miao 2010). Stomatal closure induced by drought conditions restricts the supply of CO_2 thus reducing carbon assimilation and photosynthetic potential (Flexas et al. 2004; Samarah et al. 2009). Disruption of thylakoid membranes of the photosynthetic apparatus, decreased chlorophyll synthesis, structural changes in chloroplasts also lead to decline in photosynthesis. The decrease in chlorophyll content can be ascribed to photo-oxidation of pigments, chlorophyll degradation and structural deformities in chloroplast such as damage of chloroplast membranes, excessive swelling and distortion of the lamellae and vesiculation (Anjum et al. 2011c). Apart from these, non-stomatal mechanisms such as accumulation, transport, and distribution of assimilate also account for decrease in photosynthetic capacity (Manivannan et al. 2007a, 2007b).

Plants develop various adaptive strategies to withstand drought. These mainly include avoidance and tolerance mechanisms. Major adaptations noted in plants include

(a) Reducing the length of life cycle via changes in pre-flowering and/or post-flowering phases
(b) Formation of deeper roots to extract more water from soil and have better water supply (Salih et al. 1999)
(c) Reduction in canopy size i.e. smaller leaves limit water loss via transpiration (Salih et al. 1999)
(d) Accumulation of solutes viz. carbohydrates and dehydrins in basal tissues such as buds and meristems (Volaire 2002)
(e) Increased expression of aquaporins and stress proteins.
(f) Stomatal closure resulting from loss of turgor due to efflux of K^+ ions from the guard cells.

8.4.2 Salinity

Changes in the environmental conditions produce significant changes in soil profile. The change in soil properties affects the growth, sustenance and productivity of crop plants in the long run threatening the food security at global scale. Salinity has been recognized as one of the common factors influencing the crop production in a negative way. High uptake of sodium ions (Na^+) by plants roots leads to its accumulation in shoots and mature leaves. Salt accumulation followed by its sequestration in plant organs induces oxidative stress by production of reactive oxygen species (ROS). These ROS damage cellular components such as proteins, lipids, and DNA via interrupting vital cellular functions, essential physiological and biochemical events in plants (Hasegawa et al. 2000). Hyperosmotic stress induced by excessive uptake of Na^+ affects the physiological activities such as photosynthesis and respiration. The damage to chloroplast i.e. swelling of thylakoids, disintegration of grana and intergranal lamellae in plants exposed to high salinity (150 mM) conditions leads to reduction in photosynthetic rate thus causing a decline in biomass production. Nutrient imbalance resulting from uptake of high concentrations of Na^+ induces loss of turgor, growth reduction, wilting, leaf curling, epinasty, leaf abscission, loss of cellular integrity, tissue necrosis, and potentially death of the plant (Yamaguchi and Blumwald 2005).

The negative effects of salinity on growth and productivity of crop plants also result from reduced water absorption capacity of roots and water loss from leaves due to osmotic stress induced by high salt accumulation in soil and plants. The most common mechanisms operating in plants regulating the effects of salinity stress include sodium transport, cellular ion homeostasis, and salt response signaling (Hasegawa et al. 2000). The changes in the pollen viability and reduction in pod filling affect grain yield under saline conditions (Mohammadi-Nejad et al. 2010).

Salt Overly Sensitive (SOS) stress signaling pathway plays a significant role in ion homeostasis and salt tolerance in plants (Ji et al. 2013) (Fig. 8.2). It consists of three major components which include proteins namely SOS1, SOS2, and SOS3. *SOS1* encodes a plasma membrane Na^+/H^+ antiporter which regulates Na^+ efflux at cellular level and facilitates long distance transport of Na^+ from root to shoot. *SOS2* gene encodes a serine/threonine kinase which gets activated by salt stress elicited Ca^{2+} signals. SOS3 is a myristoylated Ca^{2+} binding protein. Interaction between SOS2 and SOS3 protein results in the activation of the kinase which then phosphorylates SOS1 protein thereby increasing its transport activity (Liu et al. 2000). Increase in the Na^+ concentration followed by a sharp increase in the intracellular Ca^{2+} level facilitates the binding with SOS3 protein. Ca^{2+} modulates intracellular Na^+ homeostasis along with SOS proteins. The SOS3 protein activates SOS2 protein by preventing its self-inhibition. The SOS3-SOS2 complex is loaded onto plasma membrane where it phosphorylates SOS1 (Gálvez et al. 2012). The phosphorylated SOS1 results in the increased Na^+ efflux, reducing Na^+ toxicity. Overexpression of these proteins confers salt tolerance in plants (Quintero et al. 2002; Guo et al. 2004).

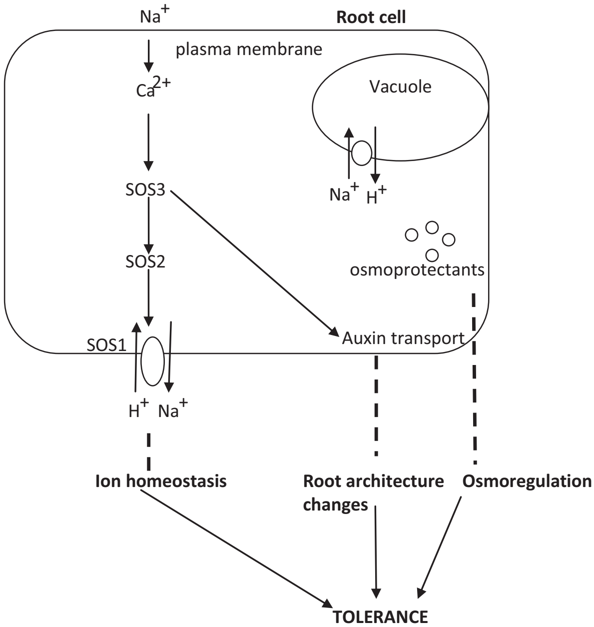

Fig. 8.2 Mechanism of salinity tolerance in plants

Various tolerance and adaptive mechanisms operate in plants exposed to high salinity stress. Tolerance mechanisms include ion exclusion mechanisms which restrict the entry of Na^+ ion into the cell. Vacuolar Na^+/H^+ antiporters, H^+-ATPase and H^+-translocating pyrophosphatase aid in pumping toxic Na^+ ions out of the cell and restricting the entry of Na^+ (Blumwald 2000). Increased expression of these vacuolar transporters including NHX1 (Na^+ H^+ exchanger 1) contributes to salinity tolerance (Fukuda et al. 2004). These transporters direct salt to vacuole where it gets sequestered in large quantities thereby protecting the plant machinery from salinity stress. A large number of genes and proteins such as HKT and NHX, encoding K^+ transporters and channels have been identified and cloned in various plant species. Class 1 HKT (histidine kinase transporter) removes excess Na^+ from xylem, thus protecting the photosynthetic leaf tissues from the toxic effect of Na^+. Sodium ion entering the cytoplasm gets transported to the vacuole via Na^+/H^+ antiporter. Class 1 HKT transporter removes excess Na^+ from xylem, thus protecting the photosynthetic leaf tissues from the toxic effect of Na^+ (Schroeder et al. 2013). Intracellular NHX proteins are Na^+, K^+/H^+ antiporters play a role in K^+ homeostasis. V-ATPase is another dominant H^+ pump that plays an important role in maintaining solute homeostasis and facilitates vesicle fusion during non-stress conditions present within the plant cell.

Physiological and biochemical tolerance mechanisms help in curtailing salinity conditions (Gupta and Huang 2014). These mainly include synthesis of compatible solutes which function as protector or stabilizer of enzymes or membrane structures (Flowers 2004; Saxena et al. 2013). They also play role in osmoprotection, carbon storage, and ROS scavenging (Munns 2005; Munns and Tester 2008). Amino acid such as proline and compounds such as glycinebetaine, sugar alcohols, polyamines increase in response to salinity stress and improve tolerance by increasing the activity of enzymes involved in antioxidant defense system, mitigation and protection of the cell. These compounds also assist in osmotic adjustment, stabilization of proteins, and reduction in ROS generation. Increased accumulation of carbohydrates such as sugars (glucose, fructose, fructans, trehalose) and starch has been reported in plants exposed to salt stress (Gupta et al. 2013, 2015; Hasanuzzaman et al. 2014). The role of proteins such as heat shock, pathogen-related proteins, protein kinases, ascorbate peroxidase, osmotin, ornithine decarboxylase in withstanding salt stress is also acknowledged. Antioxidant enzymes and antioxidant compounds combat salinity stress by detoxifying ROS generated. The genes involved in the biosynthesis of antioxidants, ion homeostasis show an upregulation in plants exposed to extreme salinity (Blumwald and Grover 2006; Zhao et al. 2006a, 2006b; Jiang et al. 2012; Kumari et al. 2013; Zhang and Shi 2013; Liu et al. 2014a; Rachmat et al. 2014).

8.4.3 Soil Nutrient Status

Soil nutrient status is greatly influenced by the environmental conditions. Water holding capacity, cation exchange capacity, soil nutrient content, organic matter are some soil properties that get severely affected by changes in temperature and water availability. Excessive soil warming and drying led to reduction in soil carbon. CO_2 enrichment conditions are supposed to increase the soil C: N ratio (Brevik 2013). Modeling studies predict that drastic changes in climatic conditions might cause decrease in soil organic carbon by 2–10% by the year 2100 (Dijkstra et al. 2010a; b). Soil nutrient content is also influenced by microbial dynamics. This is because microbes present in the soil help in the mineralization of nutrients essential for plant growth. Any changes in the biotic and abiotic factors affect the distribution of microbial communities (Pinay et al. 2007). Decline in the microbial population reduces the supply of nutrients such as nitrogen thereby limiting plant growth and productivity. Changes in the root symbionts such as rhizobia bacteria and mycorrhizal fungi alter plant nutrient status by influencing the rate of decomposition thereby altering carbon inputs which subsequently affects plant productivity (Clemmensen et al. 2013, 2015; Moore et al. 2015).

8.5 Indirect Effects of Climate Change on Crops

Climatic changes such as rise in atmospheric CO_2, temperature (warming), humidity, cyclones/hurricanes and drought alter the biotic components of the ecosystem. Changes in the climatic factors influence the distribution and biology of plant pathogens with positive, negative or neutral effects (Coakley et al. 1999; Fuhrer 2003; Newton et al. 2011). Studies predicted that climate change is likely to promote the survival and infestation of pathogens that cause disease in food crops such as wheat, rice, soybean and potato. Decreasing resistance and increased pathogencity affect the growth of crops to a significant extent hence limiting agricultural productivity. The rate of multiplication, sporulation, survival and vigor of pathogens is regulated by environmental conditions. The growth of pests and disease is promoted by warming, thus increasing the incidence of pest and disease outbreaks. Elevated CO_2 support the survival and infection of pests such as aphids (Newman 2004) and weevils (Staley and Johnson 2008). Increased temperatures reduce the mortality of aphids enabling their widespread dispersion. Elevated CO_2 also reduced expression of induced resistance (Pangga et al. 2004; Plessl et al. 2005). Enhanced growth of *Colletotrichum gloeosporioides, Fusarium pseudograminearum Candida albicans* has been noted at high CO_2 (Chakraborty and Datta 2003; Hall et al. 2010; Luck et al. 2011).

8.6 Climate Effects on Crop Nutritional Quality

Changes in precipitation, temperature, carbon dioxide levels, soil composition influence the production of various compounds contributing to the nutritional quality and secondary defense responses in plants (Baranski et al. 2014; Myers et al. 2014). Fruits, vegetables, cereals and nuts respond to climate variables and show changes in quality (Erda et al. 2005). High CO_2 and temperature conditions induce change in food quality as evident by changes in protein, lipid and mineral nutrient content.

Changes in temperature and CO_2 affect carbohydrate composition of cops plants though the response is variable and species/cultivar dependent. Increases in temperature are supposed to have a larger effect on carbohydrate content than elevated CO_2. Carbohydrate content changes significantly with increasing temperature. Most crops report increase in sucrose concentration, alteration in starch content but no effects on sugars such as glucose, raffinose and fructose in high temperature conditions. Increased CO_2 do not induce any change in carbohydrate content (Thomas et al. 2009), though alteration has been noted in plants exposed to combined effects of temperature and CO_2. Total soluble sugars and starch reported a decrease, while glucose concentration noted increase in plants exposed to increases in temperature and CO_2 (700 ppm). Wheat grains and sugar beet have shown minor alterations in carbohydrate composition in response to CO_2 enrichment (Porteaus et al. 2009). The changes in the developmental events such as flowering, grain maturity are responsible for reducing the accumulation of sugars such as starch in wheat and barley (Barnabas et al. 2008). Crops such as tomato show improved quality of fruits and increase in concentrations of sucrose, glucose and fructose in response to CO_2 enrichment (De Souza et al. 2008; DaMatta et al. 2010). Increase in sucrose concentration by approximate 29% has been reported in sugarcane plants grown at CO_2 concentration of 740 ppm.

Wheat and barley cultivars grown at elevated CO_2 concentrations show decreases in macronutrients and micronutrients, though the responses of plants to elevated CO_2 are species and cultivar dependent. The decrease in concentration of essential mineral elements of leaf has been reported (Idso and Idso 2001). Crops like rice and wheat show decrease in concentrations of nutrients in CO_2 enriched conditions. Concentrations of elements such as N, P, S, Fe and Zn showed a decrease in rice and wheat plants growing under elevated CO_2 conditions (Högy and Fangmeier 2008; Singh 2014). Decrease in essential elements in grains of major crops such as wheat and rice are likely to affect nutritional quality. The plant mineral deficiencies need fertilizer inputs in agricultural soils (Idso and Idso 2001).

Lipid profile of plants change under the influence of warming and increase in CO_2. Increased temperature exposure showed reduction in amounts of non-polar lipids. Oil content of crop plants such as soybean and sunflower increase in response to increasing temperature (Izquierdo et al. 2002). Increase in temperature by 4 °C changed oil composition in wheat, while rise in CO_2 have shown minimal effects on composition and quality of oil composition (Thomas et al. 2003). Increase in oleic acid and decrease in linolenic acid concentration has been reported in plants exposed to increasing temperature. Combined exposure of high temperature and CO_2 produce high yield of oil in soybean seeds (Thomas et al. 2003).

A meta-analysis (228 studies) suggested a reduction of 10% to 15% in protein concentration of major food crops such as wheat, barley and rice to study the effect of elevated atmospheric CO_2 (540–958 ppm) (Taub et al. 2008). Research studies suggested that nitrogen fertilizer application can minimize the effect of reduced protein production and may lead to high biomass and yield production in conditions of increased atmospheric CO_2 (Bloom 2006; Högy and Fangmeier 2008; Taub et al. 2008). Elevated CO_2 changes the amount and type of grain proteins in rice and wheat (Högy and Fangmeier 2008). In wheat, gluten storage proteins (glutenin and gliadin) show a significant decrease. Concentrations of these proteins have been shown to decrease at elevated CO_2 in open top chamber (OTC) experiments (Högy and Fangmeier 2008). The concentration and composition of protein in grains decreases as the concentrations of amino acids decline by 7–23% except for proline, glycine, tyrosine, histidine, and lysine. The proportion of the essential amino acids has shown an increase under elevated CO_2 conditions.

Secondary metabolites act as defense compounds and provide protection from various abiotic and biotic stresses, aid in pollination (Piasecka et al. 2015; Wink 2015). Climatic variations produce adverse effect on synthesis of secondary metabolites including phenolics, terpenoids, alkaloids, and fatty acids involved in nutrition, antioxidant, and anti-inflammatory properties (Wink 2015). Temperature variations affect anthocyanin accumulation in pomegranates (Borochov-Neori et al. 2011). CO_2 enrichment positively affects production of compounds such as tannin and terpene contents, vitamin C (Idso and Idso 2001).

8.7 Adaptations in Crop Plants

Crop plants develop certain morphological, biochemical traits that help them to survive in adverse environmental conditions. These mainly include morphological adaptations such as formation of deeper and proliferated roots that promote uptake of nutrients such as phosphorus, water from subsoil and aid in carbon sequestration. Changes in the leaf structure such as leaf thickness, leaf dry to fresh mass ratio has also been noted in plants in response to increased CO_2. This correlates to increased photosynthesis and accumulation of carbohydrates (Sakai et al. 2006).

The crop species having better adaptation to abiotic stress show anatomical changes such as decrease in stomatal density resulting from increased water use efficiency (Xu and Zhou 2008).

Changes in crop varieties and cropping pattern play a significant role in overcoming the effects due to climatic changes. Selection of varieties with appropriate thermal time and vernalization requirements, increased resistance to heat shock and drought can prove as an asset in overcoming stressful conditions. Alteration in the timing of cropping activities and extension of the growing season of short-season cereals such as wheat, rice, barley, oats and vegetable crops has been identified as the major strategies that can be followed to overcome adverse environmental conditions. Agricultural diversification by varietal and/or crop substitution, alteration in amounts and timing of irrigation help in sustaining growth of plants. Increase in soil inputs particularly fertilizers can help in maintaining grain or fruit quality.

Quarantine, pest, disease, and weed management practices, use of resistant varieties and species prove useful in sustaining crop plants in adverse growth conditions (Mtui 2011). Studies indicate that good irrigated agricultural lands are less susceptible to stress in comparison to dryland agriculture. Management of soil organic matter, carbon sequestration and organic agriculture through improvement of water allocation or irrigation increase efficiency of survival of plants under unfavorable conditions. Protective mechanisms such as upregulation of antioxidant pathways, curtail oxidative stress induced by alterations in abiotic factors. Synthesis of compatible solutes reduces tissue desiccation and protects macromolecules from stress (Almeselmani et al. 2009; Djanaguiraman et al. 2010). Biotechnological approaches such as raising abiotic and biotic stress tolerant plants also help in adapting plants to changing environmental conditions (Tester and Langridge 2010; Varshney et al. 2011; Bita and Gerats 2013).

8.8 Biotechnological Techniques

Biotechnological techniques such as genetic engineering assist in developing transgenic plants which possess higher resistance to abiotic and biotic stresses such as salinity, drought, heat, flooding, pests and diseases (Fita et al. 2015). Genetically modified plants raised by manipulating/introducing genes involved in metabolic pathways, enzymes, proteins and synthesis of various metabolites/osmolytes that play a major role in curtailing oxidative stress induced by stress can prove as an asset in combating changing environmental conditions. Marker-assisted approaches such as genes/quantitative trait loci (QTLs) developed to select genes desired for raising superior breeding line can also prove an effective way to overcome adverse conditions (Collard and Mackill 2008). Identification and mapping of major QTLs also prove as an effective way of identifying genes involved in tolerance against abiotic stresses (flooding, salinity, drought, heat).

Genes involved in stress response pathways overexpressed in transgenic plants confer tolerance to abiotic conditions (Budak et al. 2015). These mainly include activation of enzymatic and non-enzymatic antioxidant systems. Many genes responsive to abiotic stresses such as drought, salinity have been identified (Hu et al. 2008; Hussain 2015). These genes confer variable levels of tolerance in plants against drought, salinity, high temperatures, and/or other abiotic stresses (Ashraf 2009; Türkan and Demiral 2009). Transcription factors, protein kinases, receptor-like kinases, and osmoprotectants (Todaka et al. 2015) and dehydration-responsive element-binding factors such as OsDREB1A have been identified as some elements playing a major role in abiotic stress responses in plants (Chen et al. 2013; Liu et al. 2014b; Hussain 2015). Transgenic plants with capacity for increased production and vacuolar storage of solutes including proline, glycine-betaine, mannitol, and trehalose that help in maintaining water balance have been developed (Borrell et al. 2014). The genes responsible for synthesis of specific proteins such as heat-shock proteins (HSPs), late embryogenesis-abundant (LEA) proteins, osmotin have been overexpressed in plants. Genes encoding for ion transporters such as *AtNHX1* gene encoding a vacuolar Na^+/K^+ antiporter aiming at increased salt tolerance has been overexpressed in transgenic plants (*Arabidopsis thaliana)*(Shi et al. 2003). Transgenic alfalfa and tobacco plants with enhanced by expression of different antioxidant enzymes such as glutathione *S*-transferase/glutathione peroxidase or superoxide dismutase have also been raised (Kasuga et al. 1999; Fita et al. 2015). The genetic and biotechnological approaches can prove useful in raising crop plants with enhanced resistance for various abiotic stresses (heat, flooding, drought, salinity) induced by climatic variations.

8.9 Conclusions

Climatic changes such as rise in CO_2 concentration, temperature, alteration in precipitation and transpiration regimes affect the essential physiological and biochemical events in crop plants thereby altering the growth and productivity to a greater extent. Shortening of the growth period via early flowering and maturity is primarily responsible for reducing the yield at high temperatures. The changes nutrient availability, carbon sequestration and water scarcity have been identified as the major abiotic factors altering the dynamics of crop production. Changes in the microbial dynamics, increase in weed, pest and pathogen infestation are the biotic variables affecting the crop growth and agricultural output. Stress induced by climatic changes are supposed to affect quality of crops by altering nutritional content (proteins, carbohydrates, lipid, minerals) and induce loss in their active components or essential secondary compounds. Adaptive traits contribute to plants capacity to withstand various abiotic stresses induced by climatic variations. Biotechnological approaches also prove as an asset in developing plants robust varieties with enhanced capacity for tolerating abiotic and biotic stresses such as drought, salinity, flooding and pest infestations induced by climatic change. Research studies need to carried out to assess the impact of climatic variations on crop species growing in various regions of the world. Evaluation need to be done at both individual and landscape level with an emphasis on strategies and measures to develop crop plants that can survive/ withstand climatic alterations so that food security for human population can be ensured.

Acknowledgements The financial support from University Grants Commission (UGC), India to author is gratefully acknowledged.

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