Impact of Climate Change on Crop Production: Effects and Management

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Introduction

One of the key challenges to agriculture in the twenty-first century is to feed the rapidly growing world population while adapting to the already deteriorating global climate (Lal 2005). Climate change has already affected crop productivity, water resources and food security globally but more severely in the developing world (Magadza 2000). Climate variabilities, for instance, high temperature, rise in carbon dioxide (CO_2) concentration in the atmosphere and changes in precipitation patterns, are causing year to year variation in crop growth and productivity, even in the areas with high-tech agricultural facilities (Reddy and Pachepsky 2000). The virtual conviction that earth's climate will continue to change raises many issues concerning agricultural productivity and crop quality. Hence, it is highly important and relevant to determine the influences of climate change on productivity and quality of crop plants in order to determine the feasible strategies to adapt to changing climate.

Climate change has fairly been rapid during the past few decades in many agricultural regions around the world. Climate change is affecting the crop productivity and expected to continue, if proper adaptation and mitigation strategies are not taken. There are four main climatic factors that represent climate change: rising atmospheric temperature, changes in precipitation patterns, elevated CO_2 concentration and increasing tropospheric ozone (O_3) level (Lobell and Gourdji 2012).

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The world temperature has been rising, with an average trend (rise) of 0.3 °C and 0.2 °C per decades for maximum and minimum temperature, respectively. The increasing temperatures are linked with high frequency of hot events and a low frequency of cold events, which influence crop growth and quality (Alexander et al. 2006). It is expected that global temperature could rise at the rate of 1 °C over the next 10-year period, which interprets as much as 2 °C increase in temperature in major agricultural regions, since lands heat up faster than oceans (Easterling and Wehner 2009). Temperature affects the crop growth and yield in many ways including its effects on photosynthesis, water use, crop duration, direct damage to plant tissues, and indirectly by increasing pest attacks (Ziska et al. 2011; Lobell and Gourdji 2012).

Changes in precipitation have direct consequences for crop production. Soil moisture as of direct relevance for crop growth is greatly influenced by variations in atmospheric temperature and seasonal precipitation. Generally, a substantial increase in drought and water scarcity has been projected for South and East Asia, Africa, Southern Europe and Eastern Australia (Sheffield and Wood 2008; Dai 2011). Increased drought events will lead to rise in agricultural crop water stress. Generally, plants respond to drought by closing their stomata, which reduce the net carbon uptake and increase the heat-related impacts, such as lower crop growth and quality. Water stress during the reproductive growth stage of crop plants severely affects the grain yield and quality. Alternatively, more intense rain events lead to flood and waterlogging, which destroy the crops and fertility of agricultural soils (Hatfield et al. 2011).

The atmospheric concentrations of CO_2 have been rising since industrial revolution, with an average rise of 2 ppm per annum in the 2000s (Peters et al. 2012). In 2018 atmospheric concentration of CO_2 (407.4 ppm) was 46.5% higher than at the begining of the industrial revolution (278 ppm). Atmospheric CO_2 concentrations are expected continue to increase in the next century at the rate of 25 ppm per decade, which will lead to a CO_2 level of 500 ppm by the mid of twenty-first century (IPCC 2001). The global rise in CO_2 concentration gives counteracting trends to the otherwise adverse impacts of rising temperature and increasing drought events. The expected increase in CO_2 concentrations will increase the global crop yield roughly by 1.8% per decade. At the same time, a rise in temperature is expected to decrease the crop yield roughly by 1.5% per decade. Elevated CO_2 may directly affect crop growth, development and quality, however, with different rates and magnitudes for different plant types (e.g. C_3, C_4) (Ainsworth and Long 2005; Taub and Wang 2008).

Air pollutants (e.g. nitrogen oxides, carbon monoxides, methane) form tropospheric ozone (O_3) by reacting with hydroxyl radicals in sunlight. The tropospheric O_3 concentrations have also increased from 10–15 ppm in the preindustrial age to over 35 ppm because of high emissions of pollutants from industrial activities. The predictions of the future O_3 level are uncertain due to improbability associated with ways of O_3 emission and pollutant control measures (Cape 2008).

In recent decades, significant studies have focused on enhancing our understanding of the impacts of climatic variables on crop production and mechanisms by which plants respond to these conditions (Kjøhl et al. 2011; Sangeetha et al. 2018).

The effects of climatic factors are complex, especially if multiple factors are combined. The interaction between climatic factors creates immense complexity that leads to either under or overestimation of the effects of an individual variable. In order to adapt to current and future climatic conditions, crop production strategies need to be modified. This chapter summarizes the most commonly known effects of changing climate on crop productivity and quality and management practices and technologies needed for adaptation to climate change.

Climate Change Effects on Crop Productivity and Quality

The primary climate variables that affect crop production and are associated with climate change are temperature, CO_2 and precipitation. Here, we briefly describe and discuss different ways by which these three major climatic variables affect crop productivity and quality.

Temperature

The increased climatic variability with a higher probability of occurrence of harmful weather events will make the conditions less suitable for crop production (Field et al. 2012). Climate change-induced changes in temperature dynamics can be multifaceted, that is, increased seasonal mean temperatures for certain crops and high-temperature episodes (heat waves), and to a lesser extent cold waves. Crops and crop growth stages that are sensitive to high temperature will become more vulnerable under such conditions. The main effects associated with the high temperature include leaf senescence, reduction in grain filling duration, perturbed leaf water relations and photosynthetic inhibition (Farooq et al. 2014). High temperature hastens crop development, ultimately shortening the crop duration. Higher than the optimum temperature during the post-anthesis period is particularly lethal for cereal crops where the grain-filling period is shortened, often resulting in lower yields (Asseng et al. 2015). Temperature also affects crop productivity by influencing the rate of photosynthesis and respiration. Photosynthesis is a complex process involving many enzymes and steps that have different temperature sensitivities. As such, the main enzyme involved in photosynthesis (rubisco) is very stable even at extreme high temperatures (Salvucci et al. 2001); however, rubisco activity declines under heat stress, because ‘rubisco activase’ (enzyme involved in activation of rubisco) is heat-labile (Salvucci et al. 2001; Salvucci and Crafts-Brandner 2004). Temperature effects on photosynthesis have also been observed in crops with a C_4 photosynthetic pathway (Crafts-Brandner and Salvucci 2000). Higher temperature also increases rates of respiration, which ultimately lowers the net carbon assimilation rate. The elevated temperature during the anthesis stage can cause pollen death and sterility, with a significant reduction in yields (Chavan et al. 2019).

Temperature-induced rise in vapour pressure deficit (VPD) is another aspect, which is often ignored in most studies; ultimately, it could lead to an exaggeration of temperature effects. It is known that as the temperature increases and absolute humidity remains constant, the leaf to air VPD increases exponentially. Increased VPD can have different consequences depending on crop response and microclimate. High VPD increases atmospheric deficit leading to an increase in evapotranspiration (ET). Moreover, the conditions in which soil water is limited, high ET may cause edaphic drought, thus, amplifying the overall effects of high temperature. Studies have shown that even a few degree increase in temperature can lead to plant death solely due to increased ET and water shortage (Will et al. 2013). Lobell et al. (2013) also indicated that temperature-induced rise in VPD acts as dual stress, because it not only increases water demand but also affects the water supply under rainfed agriculture, or at places where crop production depends on stored soil moisture. In a modelling study, they found that the high-temperature effects on maize through heat stress were non-existent and yield reduction was attributed to VPD-driven changes in water demand and supply. The VPD effects on ET are not straightforward and difficult to generalize. This is because plants tend to bring physiological changes in response to external stimuli, i.e. drought and VPD (Munns et al. 2010). It is known that high temperature reduces net photosynthesis (Law and Crafts-Brandner 1999; Monneveux et al. 2003); however, the photosynthetic inhibition could also be attributed to VPD-induced drought or stomatal closure and not just to direct heat effects. Further, increased VPD also lowers water use efficiency because more water is lost per molecule of CO_2 fixed.

Warming may also have a positive effect on crop yields in areas where crop production is restricted due to frost periods, and low temperature is a limiting factor to attain higher biomass and yields such as in North America (Izaurralde et al. 2003), Sweden (Eckersten et al. 2001), Northern Canada (Lesk et al. 2016) and China (Rashid et al. 2019). Higher seasonal mean temperature and reduction in the frost-free period may extend the cropping seasons in these areas. For example, low spring temperature slows the establishment of winter wheat in the north China plain, which can benefit from warming with fast establishment after overwintering (Rashid et al. 2019). Warming is also expected to help shifting crops towards those areas that are not suitable for crop production under current climatic conditions. For instance, warming would make the conditions suitable for maize production for grain purposes in Scandinavian countries.

Carbon Dioxide

Increasing atmospheric CO_2 concentration is a concern because it is one of the potent greenhouse gases responsible for global warming. Elevated CO_2 is likely to have significant direct effects on crop production through changes in physiology, growth, yield and even chemistry of plants. The magnitude and direction of these effects may also depend on other factors such as crop type and environmental conditions. Elevated CO_2 is expected to have fertilization-like effects. Net carbon assimilation rates are expected to increase with higher CO_2, through a reduction in photorespiration in C_3 crops (Ainsworth and Long 2005). Experimental evidence from free-air CO_2 enrichment (FACE) studies indicated that elevated CO_2 (500–600 ppm) for a number of crop species increases photosynthetic rate around 40% (Ainsworth and Rogers 2007).

The positive effect of elevated CO_2 through increased photosynthetic rate is much more pronounced in plants having C_3 than C_4 photosynthetic pathway. FACE and climate chamber studies have indicated that, in general, C_4 plants are less responsive to elevated CO_2 because the CO_2 concentration at the photosynthetic site is not a limiting factor even under the current ambient CO_2 level. The effects of elevated CO_2 on photosynthesis, biomass (Ainsworth and Long 2005) and yield of C_4 crops (Long et al. 2006) are much lower than for C_3 crops.

Legume crops are expected to benefit most out of elevated CO_2 (Rogers et al. 2009). Since, the positive effect of elevated CO_2 also depends on the availability and uptake of nitrogen, the effect is greater if nitrogen is not a limiting factor. Legumes have a specialized way to 'fix' atmospheric nitrogen through bacteria that live in nodules attached to plant roots. Therefore, legumes have been reported to have a greater increase in photosynthesis (Rogers et al. 2009) and less reduction in tissue nitrogen content at elevated CO_2 compared to nonleguminous crops (Taub and Wang 2008). Likewise, compared to rice, the photosynthesis and growth of soybean were significantly higher under elevated CO_2 in a FACE experiment (Long et al. 2006).

Another major effect of elevated CO_2 is regulation of plant stomata. Stomata are pore-like openings on plant surfaces, through which plants exchange gases (water vapour and CO_2) with the external environment. Among the stimuli affecting stomatal regulation, CO_2 is very crucial. Since stomata are the only gateway for CO_2 influx and water efflux, stomatal regulation to maintain CO_2 diffusion into leaves for photosynthesis and at the same time reducing water loss (transpiration) is a very delicate business. Elevated CO_2 has been shown to reduce stomatal conductance (a measure of stomatal openness) by an average of 22% across FACE experiments (Ainsworth and Rogers 2007). With the increase in CO_2 concentration, plants are expected to maintain higher photosynthetic rates even at low stomatal conductance. In general, lower stomatal conductance due to elevated CO_2 is expected to increase crop water use efficiency. Unlike the effects of elevated CO_2 on net photosynthesis, which are more pronounced in C_3 crops, its effects on stomatal conductance and water use efficiency are equally important for both C_3 and C_4 crops, and plant water use has been reported to decrease up to 20% (Leakey et al. 2009). Although, elevated CO_2 induced reduction in stomatal conductance has the potential to reduce water loss and in turn increase water use efficiency, the positive effect of elevated CO_2 on crop growth, e.g. leaf area and canopy size, could offset this effect. Higher leaf area and bigger canopy size could offer larger surface area for transpiration, thereby neutralizing the effect through reduced conductance. Lower stomatal conductance and transpiration can also affect leaf and canopy temperature. Cooler canopies are vital for saving plants from heat stress at high temperatures, thus, at elevated CO_2; reduced transpiration can jeopardize this heat tolerance mechanism. Moreover, lush green larger canopies and enhanced shading provide a suitable environment for pest proliferation, which could be another indirect effect under elevated CO_2.

The above-mentioned effects of elevated CO_2 on stomatal conductance and photosynthesis are clear; however, how much of these effects can actually translate into harvestable yield benefits is the main question. Literature indicates that these effects are highly variable, depending on other environmental conditions and crop types (Long et al. 2006). With higher photosynthetic rates and higher availability of photosynthates, plants tend to grow faster at elevated CO_2. The increased growth rate has been shown to increase average dry matter of plant by 17% for aboveground and 30% for belowground parts (De Graaff et al. 2006). Likewise, an increase in crop yield has also been reported at elevated CO_2 in FACE studies, where rice, wheat and soybean are the main candidates (Ainsworth 2008).

Crop Quality Under Elevated CO_2 and Temperature

Elevated CO_2 is also expected to affect the quality and chemical composition of plant organs. The main effects are the increase in leaf sugars and starch concentration and a decrease in leaf nitrogen concentration. FACE studies have indicated an increase in starch/sugars on average by 30–40% (Ainsworth 2008) and a reduction of leaf nitrogen concentration (per unit leaf mass) by 13% at elevated CO_2 (Ainsworth and Long 2005). Since tissue nitrogen status is closely related to protein concentration in plant organs, elevated CO_2 is likely to affect the nutritional quality and value of crops. The grain protein concentration of barley, rice and wheat has been reported to decrease at elevated CO_2 (Taub et al. 2008). Other than protein, elevated CO_2 has also reportedly a negative effect on the concentration of many other important minerals in plants such as phosphorus, magnesium and calcium (Loladze 2002). Elevated CO_2 also reduces iron and zinc concentration in edible legumes and grains (Myers et al. 2014). Likewise, higher temperature has been shown to negatively affect vitamin concentrations in horticultural crops (McKeown et al. 2006). Since the uptake of different minerals from the soil also depends on water uptake, higher CO_2 and temperature that can lead to higher VPD and reduced stomatal conductance, reduction in transpiration and water uptake may also affect mineral uptake, ultimately jeopardizing the quality of produce.

Precipitation

Climate change is expected to change the frequency, patterns and intensity of rainfall. These changes are critical for crop production in many ways including moisture stress (drought or flooding), especially if this happens during the critical stages of crop development. Particularly, the effects of drought are more important in the scenario of climate change where higher temperatures increase crop water demand. The direct effect of changes in rainfalls on crop productivity may vary, depending on the percent of agricultural areas under rainfall in different parts of the world. However, about 80% of total world cropped area is rainfed/dryland; therefore, any change in rainfall may have direct effects on global food security (Faurès et al. 2013). This is mainly because wet areas may become wetter and dry areas are expected to receive low rainfall (Liu and Allan 2013). Changes in rainfall patterns and increased variability may also create problems for individual farmers in a way that they cannot plan farming activities, as they would do under normal conditions. Changes in sowing and harvesting dates and seasonal length would ultimately result in yield loss (Linderholm 2006). Apart from the usual variations in precipitation dynamics, increased incidence of extreme weather events is another aspect of climate change that includes intensive heavy showers, flooding and hailstorms. Such events can destroy crops and may cause a delay in planting and harvesting activities, both of which can lower crop yields.

Generally, the direct effects of changes in precipitation are more relevant for areas where crops depend on seasonal rainfall or stored soil moisture. Interannual variation in rainfall patterns can cause uncertainty in farmers' minds and create problems in decision-making for farming activities. Changes in precipitation are also expected to affect crop production in irrigated areas by changing the overall hydrological cycle, mainly through its effects on the availability of freshwater in rivers, streams and groundwater reservoirs.

Interactive Effects of Climate Variables

The interactive effects of increasing temperature and elevated CO_2 are important in the context that both factors are vital for crop production and both factors can have negative and positive consequences. Elevated CO_2 is thought to have the potential to alleviate the effects of high temperature through increased photosynthesis and growth (Ainsworth and Long 2005). However, studies have indicated that, despite the fact that elevated CO_2 can mitigate the high-temperature effects on the physiology of plant processes, it may not recover the yield loss. A recent study on wheat involving elevated CO_2 and short-duration heat stress treatments during the anthesis stage concluded that elevated CO_2 mitigated the adverse effects of high temperature on photosynthesis and gas exchange; however, it does not compensate the yield loss due to direct damage of heat stress (Chavan et al. 2019). Higher crop leaf area and biomass under elevated CO_2 are also expected to increase crop water and nutrient demand. Thus, whether or not elevated CO_2 will increase crop yield depends on if the crop has access to other raw materials in a sufficient amount, especially water and nutrients. Larger canopies and higher leaf area also provide a larger surface area for transpiration loss, therefore, requiring more water.

The size and magnitude of the effects of climatic variables also depend on other non-climatic factors. Since elevated CO_2 has the potential to increase photosynthesis and crop biomass, the magnitude of this effect also depends on the availability of other raw materials, e.g. minerals (Ainsworth and Long 2005). The best example is nitrogen, where FACE experiments have indicated that the positive effects of elevated CO_2 on photosynthesis, biomass and yield are considerably lower under low than high soil nitrogen conditions (Poorter and Navas 2003; Ainsworth and Rogers 2007). Likewise, the negative effect of elevated CO_2 on the nutritional quality of plant tissues is also more pronounced under low soil N conditions (Taub and Wang 2008).

Changes in precipitation and thus the availability of water are even more important under high-temperature conditions because high temperature can be a stress itself, but, at the same time, it increases the crop water demand through increased VPD. Therefore, the two stresses at a time are definitely lethal and more difficult to manage.

Miscellaneous

Apart from changes in temperature, CO_2 and precipitation, increasing concentration of ozone and increasing threats from pest attacks are also associated with climate change. Ozone (O_3) is another environmental factor that can affect crop production by damaging the tissues, and it has been associated with climate change. Ozone is known to have negative impacts on crop yield, and its effects are likely to increase with climate change (Chuwah et al. 2015; Tai and Martin 2017). Elevated CO_2-led reduction in the stomatal opening has been shown to reduce the O_3 uptake by leaves, therefore, decreasing the exposure and minimizing its negative effects on photosynthesis, growth and yield of rice and soybean (Feng et al. 2008). Increases in temperature and humidity are likely to increase the attacks of pests such as insects and diseases. Moreover, elevated CO_2-led increase in crop growth and leaf area index would also provide suitable environments for the growth and spread of pests. The impacts of climate change on pests including diseases, insects and weeds are not well-known and require more research.

Management Strategies to Adapt Climate Change

Different management strategies have been demonstrated for adaptation of crop plants to changing climate and variability. Crop adaptations to climate change occur at different levels of agricultural association: use of quality seeds of improved varieties or species well-adopted to climate variabilities, diversification of cropping system, improved water use efficiency through irrigation and drainage systems and sustainable management of land and soil.

Development and Plantation of Plant Varieties Adapted to Climate Change

Planting material of well-adapted crop varieties is the basic requirement for high growth, quality and yields of crop plants. It is not possible to harvest a good-quality crop with low or bad quality of planting material (Gibbon 2012). Breeding efforts usually involve multilocation trials in order to develop the crop varieties that are resistant to climate-related phenomenon and more efficient to adopt the climate variabilities. For example, resistance to drought, salinity and flooding is a common climate trait for which crop varieties are bred. Other more location-specific factors include high temperature during grain filling stage, frost events at seedling or pollination stage, alternate high temperature and light rainfall which stimulate germination but obstruct seedling establishment. Increasing or maintaining the crop yield in the view of climate change largely depends on the capacity of breeders and geneticists to introduce adaptive traits found in crop plants to locally adaptive crop varieties (Jarvis et al. 2008). Active participation of farmers in the varietal development process is very important for successful adaptation of improved varieties (Efisue et al. 2008; Ashby 2009). Furthermore, introduction of resilient and adapted plant species in stress-prone areas could also be a strategy to adapt to climate change. For instance, an option includes replacing staple crops, such as maize with drought-resistant crops, such as millets and cassava. Such a shift in crop plantation can only become a viable climate-adaptive strategy, if farmers are willing to adopt new crops (Burns et al. 2010; Rezaei et al. 2015).

Conventional crop varieties are generally well-adapted to the present climatic conditions in the local crop production systems and are a potential source of adaptive genetic material for crop improvements (Mba et al. 2012; Lopes et al. 2015). However, these varieties may lose their adaptation with climate change (Bellon et al. 2011). The introduction of more suitable varieties from other places may not always be an option (Bellon and van Etten 2014). Therefore, development of new varieties through breeding seems a more viable option to adapt to climate change variations. The increased genetic vulnerability and homogeneity reduce the crop potential and make them more susceptible to the impact of climate change. This genetic vulnerability may be reduced by introducing novel traits (resistance to biotic and abiotic stresses) into the cultivars, traits often found in crop wild relatives (Lane and Jarvis 2007; Dwivedi et al. 2008). Table 1 shows some examples of the successful introduction of wild relative stress-tolerant traits into crop cultivars (Maxted and Kell 2009; Brozynska et al. 2016).

Development of climate-tolerant crop varieties required the use of a range of technologies, such as induced mutation, cell and tissue culturing, genetic engineering, marker-assisted selection and genome editing (Ahloowalia et al. 2004; Shu 2009). The development of climate-ready varieties for stress-prone areas is a key measure to deal with climate change extremes. For example, a flood-tolerant rice variety (Scuba Rice) was developed for flood-prone rice areas of Bangladesh, India and the Philippines (Singh et al. 2010). Farmers can only benefit from newly

Table 1 Examples of stress-tolerant traits obtained from wild relatives into the cultivated crop species

Cultivated crop species	Wild relatives	Traits
Rice (*Oryza sativa*)	Wild rice (*Oryza glaberrima*)	Water stress tolerance, nutritional and grain quality improvement
Oat (*Avena sativa*)	Wild oats (*Avena barbata*)	Water and heat stress tolerance
Peanut (*Arachis hypogaea*)	Wild peanuts (*Arachis cardenasii*)	Improvement in grain size, pest and disease resistance
Grape (*Vitis vinifera*)	Wild grapevine species (*Vitis amurensis*)	Cold stress tolerance in leaves
Cassava (*Manihot esculenta*)	Wild cassava (*Manihot rubricaulis*)	Adaptation to cool temperatures and high altitudes
Banana and plantain (*Musa acuminata*, *M. balbisiana*)	Wild plantain (*Musa balbisiana*, *M. nagensium*)	Drought resistance

developed climate-resistant varieties if they have timely access to the right quantity of quality seeds and planting materials. Therefore, it is important to include the effective delivery system to ensure the timely access of seeds to the farmers in the remote areas (McGuire and Sperling 2013; Westengen and Brysting 2014).

Diversification of Cropping Systems

Growing genetically diverse and improved crop varieties that are suitable for a wide range of farming practices and agroecosystems and resilient to climate variables is a valid strategy to develop the resilient crop production systems (Gibbon 2012). The level of diversification of crop species makes the difference between stressed and resilient agroecosystem. Generally, all major grain crops, for example, wheat, rice, maize, etc., are grown in monoculture systems that require significant management investment in terms of control of pests and diseases. In cropping systems, crop diversity in terms of different species and varieties is important to improve the resilience and stability of cropping systems (Folke 2006). The crop diversity also serves as an integrated pest and disease management, which has a direct impact on farm yield and revenue, since it saves a lot of external inputs and labour costs which are required for traditional management of pests and diseases. The diversity of cropping system also provides other environmental and social benefits to the society, for example, pollination and improved soil quality, and provides a wide variety of foods. Furthermore, increasing sustainable management of crop diversification will provide the food and nutritional security for the expanding urban population (Howden et al. 2007).

The diversification of cropping systems can occur at different levels, diversification of different crop varieties and species (i.e. intra- and/or inter-specific diversification), diversification at different spatial scales (i.e. individual field, farm or landscape) and diversification at different time frames. For the annual cropping system to better adapt to the climate change integration of perennial crops is a good strategy (Howden et al. 2007). Integration of perennial species in cropping system does not mean complete conversion of annual cropping system to perennial cropping or landscape dominated by perennial crops. Introduction of perennial species in annual cropping systems serves the multifunction in addition to increasing adaptability to climate change of annual crop production systems. The use of perennial crops in crop diversification gives multiple benefits, e.g. feed, food, fuel, fibre, medicines, pesticides, increased soil fertility, reduced soil erosions and serves as windbreaks. For example, integration of pigeon pea as a perennial crop with maize and soybean serves as an herbicide for weeds and provide two harvests per season (Schoeneberger et al. 2012).

At the individual farm level, the adaptability to climate change can be improved by mixing different crop varieties of the same species, for example, planting of different varieties of the same crop, which can be grown and harvested at the same time but have different responses to climate stresses (drought, heat, etc.). This strategy can successfully increase the crop adaptability to unpredictable raining season and heat; it also improves the crop stability and yields. The different management options where different varieties can intergrade together or grow one after the other to improve adaptability to climate change include relay cropping, intercropping and crop rotation (Scialabba and Müller-Lindenlauf 2010).

Improved Management of Water Resources

Sustainable management of water resources such as deficit irrigation, reduce unproductive evaporation losses and conservation measures for soil water can limit the risk of lower crop yield due to limited water. These management options are required to be adopted at different scales: at the farm field level, at the watershed or aquifer level, at the river basins level and at the national level. The farm-level adaptations are spontaneous and can perform in response to a specific change, but adaptations at other levels need advanced planning and financial support (Cooper et al. 2008; Mwongera et al. 2017).

At the farmer field scale, reduction of water losses and the soil capacity to restore rainwater can increase the resilience of cropping systems to water shortage. Different management options are adopted by farmers to improve water storage in soils, for example, on-farm water retention, on-farm water harvesting and enhanced water infiltration. These management options can be combined with efficient irrigation techniques (e.g. deficit irrigation) that was developed to reduce evaporation losses and increase crop yield per volume of water applied (Cooper et al. 2008). Selection and diversification of drought- and heat-resistant varieties will benefit farmers to cope with adverse climatic conditions. Furthermore, farmers need to be more systematic in developing drainage facilities to cope with heavy rainfalls and flood events to prevent crop damage and soil erosion (Mwongera et al. 2017). Habitat engineering and reintegration will be required to lower the impacts of flooding, provide essential nutrients to soil and control erosion.

Modern irrigation schemes are considered a step forward to adapt the climate change. Irrigation modernization requires a better mechanism for water allocation, timely alert for water scarcity for farmers, infrastructure development at local scale and management to allow more flexible and reliable water distribution (Renault et al. 2007). The establishment of the water market and water pricing are often promoted as a management tool to reduce water losses and improve water use efficiency. However, these options are difficult to implement in some places due to institutional and technical reasons. Improved weather prediction and hydrological monitoring can play a significant role in development of efficient adaptation strategies (Faurès et al. 2010). At present, weather prediction is limited to a few days. Though, better forecasting in terms of time and consistency over the season will provide the opportunity to the farming communities to better respond to climate variabilities. More efforts should be given to the timely delivery of information to farmers and increase their capacity to better utilize climate information (Gommes et al. 2010).

Sustainable Management of Land and Soil

Sustainable management of agricultural lands is important to reduce the climate change effects imposed by greenhouse gas emissions and to increase the soil carbon storage. Increasing crop productivity per unit area will eliminate the need for more land for crop production and will eventually reduce the overall emissions of greenhouse gases caused by the expansion of agricultural land. The more economical management strategies for sustainable land intensification comprise attaining the balanced nutrient cycling through protecting the soil on field and crop management (Scialabba and Müller-Lindenlauf 2010; Bitew and Abera 2018).

Soil protection can be achieved by implementing conservative tillage practices and sustainable management of crop residues in the fields. Conservation agriculture provides a strategic point for adaptation to climate change. Minimum soil disturbances, retaining the crop residues on soil and integrating different crops in rotation, reduce the soil erosion and restore the degraded soils (Farooq et al. 2011). Conservation agriculture allows to develop a more sustainable soil ecosystem and reduce the dependence on external inputs (Ghosh and Hazra 2014; Bitew and Abera 2018). Conservation tillage keep the crop residues on surface, which stabilize soil temperature, reduce moisture and nutrient losses from soil and help in the development of soil fertility. Adaptation of conservation tillage improves the growth and activities of soil microorganisms, e.g. earthworms, mites, millipedes, etc. The soil microorganisms perform the natural tillage operation, which improves the soil porosity and fertility. Organic matter accumulated by soil microorganisms improves the soil water storage capacity, which helps the crops to survive during the drought period (Lal 2004; Ghosh and Hazra 2014).

Reducing cultivation practices and retaining crop residues influence the soil carbon and nitrogen balances. Carbon is accumulated in the soil when the net nitrogen input (i.e. mineral fertilizers, organic sources, natural fixation) in the soil is greater than net removal (i.e. crop harvest, leaching, atmospheric emissions) (Corsi et al. 2012). Soil positive nitrogen balance can be attained through effective crop rotations. Keeping the soil evenly covered with crop residues with carbon to nitrogen ratio of 25–30 creates a positive residual fertilizer effect. The ideal carbon to nitrogen ratio (25–30) in crop residues can be achieved by rotating the crops high in carbon with crops high in nitrogen (Gál et al. 2007). This allows the carbon to be stored in the soil and nitrogen be released slowly to be available for the next crop (Al-Kaisi et al. 2008). Adopting the more complex crop rotation with the integration of leguminous crop increases the net carbon accumulation in soil. Crops with deep root systems accumulate carbon in the deeper soil layer which is not readily available for oxidation (Jarecki and Lal 2003).

Future Thrusts

The success of adaptation strategies to climate change depends on the participation of all key stakeholders including farmers in the development process. Interdisciplinary participatory approaches are required to develop more feasible adaptation strategies at farmers' field scale. Further, the development of targeted adaptation strategies is more important, since the adaptation strategies that are feasible at one place and for one community of farmers may not be feasible to adapt at other places. Similarly, farmers in poor and developing countries are more vulnerable to climate change. The development of adaptation strategies that are feasible for farmers under their local conditions and resources is far more important to deal with adverse impacts of climate change. The improvement in socio-economic conditions in rural areas will have a positive impact on adaptation to climate change, since it will increase the resilience of local communities to better cope the climate extremes and will reduce their vulnerability.

Technology transfer and knowledge sharing are appropriate ways to improve the adaptive capacity of resource-poor farmers. The availability of timely, accurate and easy-to-understand information about the weather forecast, pest or disease outbreaks, etc. in marginal areas will help the farmers to better prepare and plan their activities. Therefore, it is important that the information provided to the farmers are timely, up-to-date and in their local languages. In addition, availability of improved crop varieties (e.g. drought-resistant and heat-tolerant) and development of mechanization capacity of resource-poor farmers, who are more vulnerable to climate change, will increase their capacity to adapt the climate variabilities.

There is a need to advance our understanding about the interaction of two important climate variables (i.e. increasing temperature and elevated CO_2) on crop growth and quality. For example, how much of elevated CO_2 help to reduce the adverse effect associated with increasing temperature and drought stress? Similarly, how much of increasing temperature and water stress reduce the positive effect of increasing CO_2 due to direct damage to crop and decrease in crop quality (change in protein and mineral contents in grains).

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