

Climate change, its impact on crop production, challenges, and possible solutions

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Abstract

Climate change poses serious threats to agriculture and food security, and extreme weather events have reduced crop productivity worldwide. Future projections predict that the average global temperature will rise by 2.0 to 6.4 °C and the increase in sea level will be 59 cm by the end of 21st century. The unprecedented rise in temperature has led to an increase in the incidence of heat waves, droughts, floods, and irregular patterns of precipitation. These changes have a dramatic impact on prevailing agricultural cropping systems, productivity, and food security of people regionally and globally. The change in climatic parameters have substantial effects on weeds, diseases, insect, and pests in different ways, and can result in an increase of their geographical distribution, number of generations, and survival during winter. Thus, to sustain the crop production on the eve of climate change is the main challenge. Therefore, adaptation measures are prerequisites to reduce the effects of climatic changes on production of agricultural crops. In this review, a brief insight has been given in the impact of climate change on agriculture and, the future challenges of climate change on the production of crops. In addition, integrated approaches, or recent developments for the improvement of crops such as breeding, transgenic approaches to biotechnology, and functional genomics, agronomic practices, cultivation of climate resilient crops, and nanotechnology for abiotic stress such as drought stress, temperature, heat, and salinity tolerance have also been discussed.

Keywords: abiotic stress; crop production; cereals; challenges; climate change

Introduction

Climate change is a major persistent challenge that the world is facing constantly, and it has changed the world dramatically or further will lead to significant global changes in the future (Zhao *et al.*, 2017; Seleiman and Kheir, 2018). Although, global climate change is an ongoing process, however in recent times, in the last 100 years, the pace of this change has increased exponentially. Due to anthropogenic activities, the average temperature of the globe has increased by 0.9 °C since the 19th century (Zhao *et al.*, 2017), mostly because of greenhouse gas emissions into the atmosphere. As predicted, this increase in temperature is expected to reach 1.5 °C or more by 2050 (Calicioglu *et al.*, 2019). The unprecedented rise in temperature has led to an increase in the incidence of drought, floods, irregular rainfall patterns, heat waves, decrease in glaciers, high intensity of typhoons and hurricanes, changes in animal habitats, northward movement of plant habitats, and other

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extreme events in the world (Korea Meteorological Agency, 2008; Zhao *et al.*, 2017; Calicioglu *et al.*, 2019; Mukhtar *et al.*, 2020; Dindaroglu *et al.*, 2023).

The impact of climate change on yields of main crops in the world is expected to be negative (Roudier *et al.*, 2011) while, the exact impact remains highly uncertain when elevated temperatures, higher atmospheric CO₂ and changed rainfall occur simultaneously (Roudier *et al.*, 2011). If no specific actions are taken and the world continues to consume its current level of fossil fuels (for example, oil and coal), the Earth's average temperature will rise by 2.0 to 6.4 °C by the end of the 21st century. In fact, the average global temperature has increased by 0.74 °C over the past 100 years (1906 ~ 2005) (Korean Meteorological Agency, 2008; Rasul *et al.*, 2012; Bokhari *et al.*, 2017; Abbas *et al.*, 2017). Thus, it is expected that climate change and variability will have a dramatic impact on the future of cropping systems worldwide (van Ogtrop *et al.*, 2014; Ahmad *et al.*, 2015; Abbas *et al.*, 2017; Liu *et al.*, 2018). If the current changes in climate and greenhouse gas emissions continues (Hassan *et al.*, 2022), then by 2100, the production of wheat (*Triticum aestivum* L.) will decrease by 5-50%, rice (*Oryza sativa* L.) by 20-30% and maize (*Zea mays* L.) by 20-45%. There is rising opinion that current agricultural practices are unsustainable, as they tend to waste valuable resources and damage the environment (FAO 2016). These observations have altered the philosophy of plant research and the direction of demand-led plant breeding to emphasis more on the processes and mechanisms that enable the plants to grow healthy on limiting resources. Next-generation crops need to be nutrients and water use efficient, and have sustainable yields over a wide range of environmental conditions (Porfirio *et al.*, 2018; Pareek *et al.*, 2020).

Future predictions indicate that on a global scale, an expansion in land use of ~100 M ha with three times the volume of international trade is required by 2050 to meet the future demand of 9.8 billion people, without significant changes in current agricultural land area (Pastor *et al.*, 2019). Extreme climatic events can cause massive damage to crops production, thus, mitigation measures are needed to address the impact of such extreme events (Dhankher and Foyer, 2018; Schewe *et al.*, 2019; Nutan *et al.*, 2020). The concept that recent developments in technology and plant sciences may address the challenges faced by agriculture and can improve crop production and resilience to climate change (Bailey-Serres *et al.*, 2019). The aim of this paper is to provide an overview of the impacts of climate change on agriculture, and to explore possible ways to reduce adverse effects through adaptation and resilience.

Impacts of climate changes on agriculture

Climate change and increasing extreme weather events pose serious threats to crops yield (Table 1) and their stability worldwide (Reyes *et al.*, 2021). The increase in atmospheric CO₂ level and the predicted climate change could impact the future of agriculture worldwide by changing the plant growth and development, respiration, transpiration and photosynthesis rate (Wang *et al.*, 201; Crawford *et al.*, 2012; Rezaei *et al.*, 2015; Mall, 2017). Declining soil fertility, water quality, changes in groundwater table and increasing salinity in some parts of the world are now major concerns of existing agriculture. Short growing season, water scarcity, high temperature and heat stress at important reproductive phases of crops can cause massive yield reduction (6-18%) in arid and semi- arid regions of the world (Ullah *et al.*, 2017).

Climate change is posing threats to the strategic reservoir of crops and their genetic resources. As climatic conditions change, farmers may abandon some varieties and do not grow them, and consequently these varieties may be lost forever (Gitz *et al.*, 2016). Catastrophic extreme weather events (high temperature, heat stress, drought and floods) are predicted to occur more frequently due to climate change, and could pose severe threats to the survival of plants varieties that cultivated only in particular small geographical regions of the world. According to predictions of major agricultural model inter-comparison projects, many major

agricultural areas at low and high latitudes will face yield changes, however strong negative impact on production will be at low latitudes areas (Gitz *et al.*, 2016).

Table 1. Predicted impact of climate change on agriculture over the next 50 years (Brijesh *et al.*, 2017)

Climatic elements	Expected changes by 2050's	Effects on agriculture
CO ₂ level	Increase in CO ₂ level from 360 ppm to 450-600 ppm	Good for some crops and can enhance photosynthetic process, decrease water use
Temperature	Rise of temperature by 1-2 °C. Increased frequency of heat waves. Winters warming more than summers	High risk of heat stress, more evapotranspiration in some part of world. Short and earlier growing seasons, range moving north and to higher altitudes
Precipitation	Seasonal changes by ± 10%	Drought stress in some parts of world while flooding in some areas, impacts on soil workability, irrigation supply, transpiration
Sea level rise	Increase in sea level by 10-15 cm in south and offset in north by natural subsistence	Flooding, coastal erosion, loss of land and increase soil salinity and salinization of groundwater
Storminess	More intense rainfall events, high frequency of wind speeds particularly in north	Lodging of crops, increased soil erosion, decreased infiltration of rainfall
Variability	Increases across most climatic variables. Predictions uncertain	Changing risk of damaging events such as droughts, floods, heat waves, frost that affect the crops and timing of farm operations

Table 2. Estimated impact of climate change on agricultural production (Ruosteenoja *et al.*, 2003; Giorgi *et al.*, 2004; Christensen *et al.*, 2007)

Region/area	Temperature	Precipitation	Effect on agriculture
Latin America	Increase by 1–7.5 °C by 2070–2099.	Change by up to –40% to +12% by 2080	Change in grain yield between –30% to +5% by 2080. For instance, wheat production in rain-fed area is to decrease by –12 to –27% by 2080
North America	Increase by 2–5 °C by 2080	Precipitation to change by –20% to +20% by 2080–2099	Increase in yields by 5 to 20% in wheat, rice, maize, soybean, cotton, fruits and common forage
Europe	Increase by 1–5.5 °C by 2070–2099	Change in precipitation by –30% to +30% by 2071–2100	Increase cereal yields (rain-fed wheat) in northern Europe by 10 t 30%, while yield reduction in southern Europe by 2080
Sub-Saharan Africa	Increase by 3–7 °C by 2080–2099.	Decrease in Precipitation up to –30 to –40% in most parts of southern Africa, however increase by 7% in eastern and tropical regions by 2080–2099	Decrease yield of rain-fed cereals (rice, wheat, maize) by –12% (net loss) by 2080
South Asia	Increase by 2.3–4.5 °C by 2070–2099	Increase in precipitation by 10–17% by 2070–2099	Overall cereals production to decrease by –4 to –10%, while rain-fed wheat production is to decrease by –20 to –75% by 2080
South-East Asia	Increase by 2–3.8 °C by 2070–2099	Increase in precipitation by 3–8% by 2070–2099	Overall cereals production to increase by 30%, while decrease in rain-fed wheat by –10 to –95% by 2080

Production of agricultural crops

The world climate change is a key threat to agriculture due to the negative impact on agricultural systems and crop–weed–pest interactions owing to hostile climatic conditions.

Increasing temperature and CO₂ concentrations can lead to significant impacts on plant growth and long-term effects on agriculture (Varanasi *et al.*, 2016). The effects of climate change on crop production may vary according to the nature of climate variability factors. For example, increase in CO₂ level can be useful for some C3-crops such as barley (*Hordeum vulgare* L.), rice (*Oryza sativa* L.), wheat, cotton (*Gossypium hirsutum* L.), soybean (*Glycine max* L.), however, the benefits from climate change can only be achieved when other conditions of crop growth are better and at optimum levels. For instance, doubling the CO₂ level increases the yield of some crops such as wheat and soybean by 30%, while other crops such as maize may respond very low (<10%). Thus, if the increase in carbon dioxide (CO₂) level is accompanied by high temperature above the optimum level of crop requirement or if there is a shortage of water and nutrients availability, yield increases can be reduced or reversed (Varanasi *et al.*, 2016). Climate change indicates about 60% variability in crop yield, and it thus a critical factor affecting the production of foods and farmers' income worldwide (Ray *et al.*, 2015; Matiu *et al.*, 2017; Aryal *et al.*, 2019). Climate change affects the length of crop growing season (Lemma *et al.*, 2016) by imposing temperature, heat and water stress in agricultural production systems (Saadi *et al.*, 2015; Schauburger *et al.*, 2017).

The changes in precipitation and temperature will bring changes in land suitability and crop growth. The expected net impact will be an increase in land area in upper latitudes suitable for crops production owing to mild and short winter, while a reduction in land suitability and crop production in semi-arid and arid regions (Rosenzweig and Hillel, 2015). The land area in the highlands of East African countries is becoming unsuitable for wheat due to higher temperature, however may result in more suitable for other grains crops. There may be some gain crops in tropical highlands where currently there is constraint of cold temperature (Aryal *et al.*, 2019). Alike, in India, wheat yield has been reduced by 5.2% from last 30-years (1981 to 2009) due to global climate change (Gupta *et al.*, 2017). It is predicted that global warming would further decrease the wheat and maize yield in rain-fed areas by 5.2-12.2% in 2050 while in irrigated areas; yield reduction will be 5-14% by 2050 if the growers continue to grow current crop varieties (Tsfaye *et al.*, 2017). Despite crop management and variability in input use to crops, there is an adverse impact of both terminal heat stress and season-long wheat and rice, nevertheless wheat is relatively more sensitive than rice (Arshad *et al.*, 2017). Current evidences indicate that the trend of increasing wheat yield in different countries of the world has slowed down in recent past decades (Wiesmeier *et al.*, 2015; Chen *et al.*, 2017; Gouis *et al.*, 2020; Cassman *et al.*, 2020). In south Asia, wheat and rice are main staple foods, and the largest decline in yield will be in both the crops due to rising temperature and water scarcity. Reports indicate that if the current rate of global warming persists, then wheat yield will reduce up to 50% by 2050. The maximum decline in wheat yield, 60%, will be in Bangladesh and India (40%) followed by Pakistan (27%) by 2050 (Knox *et al.*, 2012; Bandara, and Cai, 2014; Aryal *et al.*, 2019). Similarly, rice yield will decrease up to 40% in India followed by Nepal (32%) and Bangladesh at 10% (Knox *et al.*, 2012). In addition, maize, coarse grains, sunflower, millet, soybean, cotton and sugarcane yields will also be influenced by global climate change (Table 3).

Crop simulation models can be used to evaluate the optimization of different resources for a specific agroecological zone (Kheir *et al.*, 2021; Khan *et al.*, 2022). The decrease in crops yields can be perhaps due to long-term variation in precipitation patterns and temperature that is more expected to shift cropping seasons, suitability of crops cultivation, and high incidence of pests and diseases (Aryal *et al.*, 2019). As per FAO (2016), if the current climate changes continue then there will be severe yield reduction in major cereals (5–50% in wheat yield, 20–45% in maize and 20–30% in rice) by the year 2100. Similarly, recent comprehensive study conducted in framework of Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) and Agricultural Model Intercomparison and Improvement Project (AgMIP) on the effect of world climate change and its

impact on agriculture found that by 2100, wheat yield will be reduced by 5 to 50%, rice yield by 20 to 30%, maize yield by 20 to 45% and soybean yield by 30 to 60% (Müller and Elliott, 2015). If assuming full CO₂ fertilization, climate change effects would then range between +5 to -15% for wheat, 5 to 20% for rice, 10 to 35% for maize and 30% for soybean. Main agricultural producers in temperate zones, such as the USA for maize or the European Union for wheat can be predicted to strong negative effects of climate change because of low water availability during the crops growing seasons, more frequent heat waves at flowering stage of crops and accelerated phenology that can lead to low biomass production (Müller and Elliott, 2015; Aryal *et al.*, 2019).

Table 3. Impacts of climate change on the yields of major crops in different regions of the World

Country	Crop	Yield reduction	Reference
Bangladesh	Rice	-10% by 2080	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Bhutan	Rice	-4% by 2080s	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
India	Rice	-40% by 2080	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Asia	Rice	-6.3% by 2030	Masutomi <i>et al.</i> , 2009
Indonesia	Rice	-11% by 2030	Naylor <i>et al.</i> , 2007
Nepal	Rice	-24% by 2030	Khanal <i>et al.</i> , 2018
Italy	Rice	-12% by 2030	Bregaglio <i>et al.</i> , 2017
Pakistan	Rice	-1.9% by 2080	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Japan	Rice	-11.3%	Iizumi <i>et al.</i> , 2011
Sri Lanka	Rice	-0.41% by 2030	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
South Asia	Rice	-17% by 2050	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Bangladesh	Wheat	-60% by 2050	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
India	Wheat	-5.2% by 2030	Gupta <i>et al.</i> , 2017
Nepal	Wheat	+8.6 to 18.4%	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Turkey	Wheat	-20% by 2030	Özdoğan, 2011
Australia	Wheat	-32% by 2030	Luo <i>et al.</i> , 2005
Pakistan	Wheat	-27% by 2080s	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014
Iran	Wheat	-37% by 2030	Valizadeh <i>et al.</i> , 2014
Sri Lanka	Wheat	-4.10% by 2030	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Mexico	Wheat	+25% by 2030	Lobell <i>et al.</i> , 2005
South Asia	Wheat	50% by 2050	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Ethiopia	Wheat	-36 to 40% by 2050	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
China	Wheat	-17.5% by 2030	Yang <i>et al.</i> , 2017
Worldwide	Wheat	-5.5% by 2030	Lobell <i>et al.</i> , 2011
Asia	Wheat	-7.7% by 2030	Asseng <i>et al.</i> , 2017
Ethiopia	Maize	-2.0% by 2050	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019

USA (South and Central)	Maize	-45% by 2050	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
South Africa	Maize	-3.6% by 2050	Estes <i>et al.</i> , 2013
USA	Maize	-50% by 2030	Xu <i>et al.</i> , 2016
Bangladesh	Maize	Negative	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Portugal	Maize	-17% by 2030	Yang <i>et al.</i> , 2017
Ghana	Maize	+12% by 2030	Srivastava <i>et al.</i> , 2018
India	Maize	-20% by 2030	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014
China	Maize	-2.92 to 3.11% by 2070	Basche <i>et al.</i> , 2016
China	maize	-30% by 2030	Xiao <i>et al.</i> , 2016
Nepal	Maize	-9.3% to -26.4% by 2050	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Panama	Maize	-0.1-0.5% by 2050	Ruane <i>et al.</i> , 2013
Pakistan	Maize	-27% by 2030	Ahmed <i>et al.</i> , 2018
South Asia	Maize	-6% by 2050	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Ethiopia	Maize	-4.7% by 2030	Araya <i>et al.</i> , 2015
Brazil	Sugarcane	+15% by 2030	Marin <i>et al.</i> , 2013
Bangladesh	Sugarcane	-1.6% by 2030	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Switzerland	Sugarcane	-9% by 2030	Knox <i>et al.</i> , 2013
India	Sugarcane	-30% by 2030	Kumar <i>et al.</i> , 2014
Australia	Sugarcane	+20% by 2030	Singh <i>et al.</i> , 2011
Nepal	Sugarcane	-5.69% by 2030	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
USA	Sugarcane	-40% by 2030	Zhao <i>et al.</i> , 2015
Pakistan	Sugarcane	-2.2% by 2050	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Sri Lanka	Sugarcane	-6.61% by 2030	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Bangladesh	Cotton	-7.94% by 2030	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
India	Cotton	-7.01 % by 2030	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Nepal	Cotton	-9.21% by 2030	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
Pakistan	Cotton	-5.23% by 2030	(Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019)
Sri Lanka	Cotton	-9.71% by 2030	Knox <i>et al.</i> , 2012; Bandara, and Cai, 2014; Aryal, <i>et al.</i> , 2019
China	Cotton	-5.5% by 2030	Rahman <i>et al.</i> , 2018
USA	Cotton	-17% by 2030	Adhikari <i>et al.</i> , 2016
Africa	Cotton	-7% by 2030	Amouzou <i>et al.</i> , 2018
Burkina Faso	Cotton	-13% by 2030	Diarra <i>et al.</i> , 2017
Australia	Cotton	-17% by 2030	Williams <i>et al.</i> , 2015

Germany and United Kingdom	Rapeseed	-5.30% by 2030	Donatelli <i>et al.</i> , 2015
India	Mustard	Decrease by 2050	Banerjee <i>et al.</i> , 2014
South Asia	Sorghum	-11% by 2050	Naresh <i>et al.</i> , 2015
India	Sorghum	Decrease by 2050	Naresh <i>et al.</i> , 2015
India	Potato	Decrease by 2030	Dua <i>et al.</i> , 2013

High temperature reduces the grain filling duration in cereal crops that is the major reason of crop reduced crop productivity in cereal in changing climatic conditions (Farooq *et al.*, 2015). Each degree (1°C) increase in global mean temperature would reduce the average global yield of maize by 7.4%, rice by 3.2%, wheat by 6% and soybean by 3.1% (Asseng *et al.*, 2015; Gamal *et al.*, 2021). Projected decline in wheat yield for France (-6.0 ± 4.2% per 1 °C rise) and USA (-5.5 ± 4.4% per 1 °C rise) and are comparable to the global average, while those for Russia (-7.8 ± 6.3% per 1 °C rise) and India (-9.1 ± 5.4% per 1 °C rise) are more vulnerable to rising temperature (Liu *et al.*, 2016; Zhao *et al.*, 2017). However, for China, the largest producer of wheat in the world, the projected estimate show that only 2.6±3.1% of wheat yield would be reduced for 1°C rise in global average temperature (Zhao *et al.*, 2017). Using the MAGICC/SCENGEN model, the projected decrease in maize and wheat yield will be between 19-23% (Grassini *et al.*, 2017). However, RCP6.0 and CCSM4 global climate model indicate that projected losses in wheat yield will be 10–12% and for maize 13–15% by 2030 (Morsy *et al.*, 2015). Knox *et al.* (2012) estimated maize yield reduction by 5% in African countries while 16% reduction in South Asian regions by 2050. In southern, eastern and northern regions of France, rise in global temperature and heat wave have been considered as the key variables that affect the maize yields in these areas (Ceglar *et al.*, 2016; Wu *et al.*, 2021). A negative correlation between maize yield and mean seasonal temperature has been recorded for major maize growing countries such as USA, Brazil, China and African countries (Tao *et al.*, 2008; Sakurai *et al.*, 2011).

Future challenges of climate change on crop production

The threats of climate changes to current agricultural systems and food production are interconnected and multidimensional. Global climate change is influencing the fundamental basis of agriculture through changes in precipitation pattern, temperature, intensifying heat waves, droughts, floods, pests and diseases. High temperature declines the crops yields through increased evapotranspiration, decreased moisture content of soil, and by developing favourable conditions for pest and weeds infestation. Simultaneously, change in precipitation patterns enhances the chance of crop failure and decreases crops yield particularly in rain-fed areas. Overall, climate change has led to a socio-economic inconsistency among the farmers by negatively influencing the agricultural systems, declining water resources, soil fertility, and increased emission of greenhouse gases and pollution. Therefore, the first and main challenge to world's agriculture is ensure food security to feed the growing population followed by wise utilization of natural resources by maintaining socio-economic balance and integration of traditional knowledge and resources (Kumari *et al.*, 2019). The future challenges of climate change on agriculture are elaborated in the following sub-sections:

Biotic stresses

Plants encounter several biotic stresses that results in major economic losses in agriculture every year. An estimated, 10–16% of global harvest (US 220 billion dollar) is lost due to pests each year (Chakraborty and Newton, 2011). Climate change influences the crops susceptibility to pests and diseases, and these changes in climate can cause modification in farming practices as to cope with pests to prevent a decline in productivity. Weeds cause maximum yield losses, estimated at 36%, in agricultural crops (Oerke, 2006; Chauhan, 2020).

The projections predict that climate changes will favor spread of pests and diseases in high-latitude areas (Uleberg *et al.*, 2014). Consequently, negative impacts can be expected due to increased vulnerability of crops to pests and diseases (Pautasso *et al.*, 2012; Abdelmoteleb *et al.*, 2023). The brief descriptions of biotic stresses on crops production are described as under:

Weeds

Unlike the outbreak of diseases and pests, weeds cause severe problems in crop production. If the weeds left uncontrolled, they can cause significant yield losses in agricultural crops. Chauhan (2020) estimated a loss of 200 million metric tons of grains (US \$100 billion annually) worldwide due to weed competition and pressure within cropping systems. However, yields losses due to weeds can fluctuate according to weed species in crops, type of crops, and agricultural or farming practices (Chauhan, 2020). Crops yields losses resulting from weeds will be maximum when weeds germinate and grow in high density with or prior to crop emergence (Jabran *et al.*, 2015; Chauhan, 2020). Some of the most troublesome weeds in different major crops and yield losses due to weeds competition are given in Table 4. Weeds directly decline crops yield by competing for essential resources such as nutrients, water, light and space etc. In addition, weeds deteriorate the quality of produce by contaminating the seeds/grains and, thus decreasing the value of harvested crops (Jabran *et al.*, 2015; Chauhan, 2020). Weeds also delay or interfere with soil operations, crop harvesting process of crops, produce harmful allelochemicals, and act as hosts or refuge for pests and diseases (Jabran *et al.*, 2015; Gharde *et al.*, 2018; Rao *et al.*, 2020), hence, weeds control is a key factor for successful crop production. Climate changes, CO₂ concentration, temperature and precipitation have substantial impact on weeds, and it is projected that climate changes will increase the distribution of invasive weeds and their competitiveness against crops (Ramesh *et al.*, 2017). The variations in temperature can result in changes in geographic ranges of weeds and facilitate overwintering. Some weed species could therefore enhance their geographic distribution range towards the poles and to high altitudes regions (Porter *et al.*, 2014; Svobodová *et al.*, 2014). For example, the temperature increase in the Mediterranean region allows the establishment of tropical weed species that were not able to flourish in the region so far. Likewise, water hyacinth (*Eichhornia crassipes*) established recently in Sardinia (Italian island), while it was supposed to be confined to regions with higher temperatures.

Table 4. Yield loss estimates due to major weeds of field crops (Bunce and Ziska, 2000; Gianessi and Sankula, 2003; Gharde *et al.*, 2018; Chauhan, 2020)

Crop	Yield losses	Troublesome weeds
Maize	20-25%	<i>Abutilon theophrasti</i> , <i>Sorghum bicolor</i> , <i>S. halepense</i> , <i>Chenopodium arvense</i> , <i>C. album</i>
Rice	53%	<i>Leptochloa fascicularis</i> , <i>Heteranthera limosa</i> , <i>Cyperus esculentus</i> , <i>Brachiaria platyphylla</i> , <i>Echinochloa crus-galli</i>
Wheat	19-25%	<i>Allium vineale</i> , <i>Bromus secalinus</i> , <i>Lolium multiflorum</i> , <i>Cirsium arvense</i> , <i>Convolvulus arvensis</i>
Sorghum	26%	<i>Brachiaria platyphylla</i> , <i>Panicum dichotomiflorum</i> , <i>Xanthium strumarium</i> , <i>S. halepense</i> , <i>S. bicolor</i>
Soybean	26-31%	<i>Cassia obtusifolia</i> , <i>A. theophrasti</i> , <i>Xanthium</i> , <i>C. album</i> , <i>S. halepense</i>
Sugar beet	29%	<i>Polygonum lapathifolium</i> , <i>P. arenastrum</i> , <i>Rumex crispus</i> , <i>X. strumarium</i> , <i>A. theophrasti</i>
Sunflower	16%	<i>Amaranthus retroflexus</i> , <i>Amaranthus palmeri</i> , <i>Kochia scoparia</i> , <i>C. arvense</i> , <i>Artemisia biennis</i>
Cotton	27%	<i>E. indica</i> , <i>Cynodon dactylon</i> , <i>Cyperus rotundus</i> , <i>C. esculentus</i> , <i>X. strumarium</i>
Sugarcane	25-35%	<i>Saccharum spontaneum</i> , <i>Cyperus rotundus</i> , <i>Parthenium hysterophorus</i> , <i>Amaranthus viridis</i>

Canola	45%	<i>Sisymbrium Sophia</i> , <i>Rapistrum rugosum</i> , <i>Capsella bursa-pastoris</i> , <i>Artemisia tilesii</i> , <i>Sinapis arvensis</i>
Peanut	36%	<i>Trichodesma indicum</i> , <i>Portulaca oleracea</i> , <i>Cyperus rotundus</i> , <i>C. dactylon</i> , <i>Celosia argentea</i> , <i>Chloris barbata</i> , <i>Boerhaavia diffusa</i> , <i>Amaranthus viridis</i>

Pests and diseases

Like all plant's species, pests and diseases have specific tolerance to or requirement for specific ecological and environmental conditions (Chaloner *et al.*, 2020; Chaloner *et al.*, 2021). This tolerance range describes their ecological niche, which defines the geographical areas and periods of the year that allows the pests and diseases to thrive/flourish and attack on crops (Chaloner *et al.*, 2020). As climate changes, suitable environments for pests and diseases outbreaks shift in time and space, developing the threats for farmers, necessary management practices are required for their control (Bebber, 2015; Chaloner *et al.*, 2021). Climate change affects the crops and their corresponding diseases and pests directly or indirectly. Direct effects are on the reproduction of pests and diseases, their survival, development and dispersal (Skendžić *et al.*, 2021). Whereas indirect effects include the relationships between pests and/or diseases to their environment, and with other species of insect such as vectors, predators, competitors, natural enemies and mutualists (Prakash *et al.*, 2014; Skendžić *et al.*, 2021). Climate change can enhance the effect of pests and diseases to allow their establishment in regions where they could not establish previously or allow them to come earlier in the season due to high temperature (Figure 1).

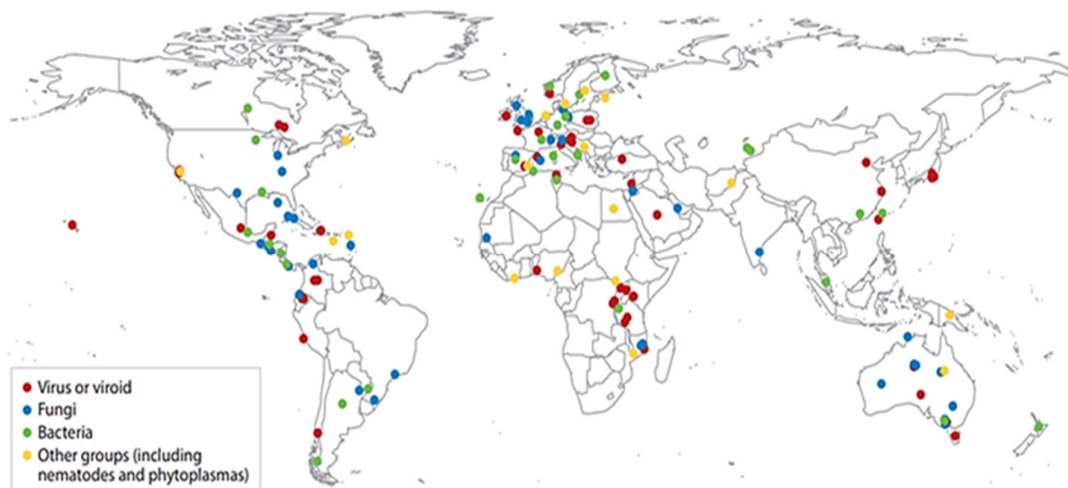


Figure 1. First reports of crop pests and disease in 2010–2015 from ProMED email alerts. Hot spots of new reports include Europe, Central America, East Africa, and Australia (Bebber, 2015)

Figure 1 shows the establishment of pests and diseases and their arrival in regions where they were not arriving before 2010. As the planet warms, the latitudinal range of pests and diseases can be increased, and pests follow their suitable preferred temperature zones (Bebber, 2015). For instance, the change in precipitation, temperature and wind patterns, East African countries have been facing severe swarms of desert locusts since 2020 (Cressman, 2013; Salih *et al.*, 2020; FAO, 2020). According to FAO (2020), the existing situation can be further aggravated due to new breeding of locust that will invade in Somalia, Kenya and Ethiopia, and possibly further damage to agricultural crops. In Finland, more epidemics of late blight of potato have been observed that appear now on average 2-4 weeks earlier than over past 70 years (Hannukkala *et al.*, 2007). In USA, over 70 years, attack of potato leaf hopper (*Empoasca fabae*) appears now one week earlier compared to early 1950s (Baker *et al.*, 2015), and its infestation is more frequent and severe in warmer years (Oszako and

Nowakowska, 2015). The earlier arrival of potato leaf hopper causes millions of dollars of losses each year in USA alone. Climate change favored the reproduction of potato leaf hopper and more than 200 plant species have been observed as potential hosts for this pest (Baker *et al.*, 2015). Likewise, in California, studies show an increased number of generations of walnut pests due to climate change (Luedeling *et al.*, 2011) and similar in case of coffee root-knot nematode (*Meloidogyne exigua*) in Brazil (Ghini *et al.*, 2008), as well as for many crops pest species in Europe (Svobodová *et al.*, 2014).

Many regions of northern and central Europe could become more susceptible to different pests and diseases such as Karnal bunt of wheat and Colorado beetle of potatoes as they increased their range to north regions (Baker *et al.*, 1999). In subtropical regions of Australia, the increase of temperature up to 2 °C would favor the outbreak of Queensland fruit fly (*Bactrocera tryoni*) (Sutherst *et al.*, 1999). In 2002-2003, the severe epidemic of sugarcane woolly aphid (*Ceratovacuna lanigera*) in sugarcane growing areas of Maharashtra and Karnataka states of India resulted in 30% yield losses (Pareek Abhisek, 2016; Shrestha, 2019). Thus, climate changes can create new ecological niches that offer opportunities for insect pests and diseases to spread and establish in new geographic areas and shift from one area to another (Kocmánková *et al.*, 2010; FAO, 2020). The complexities of physiological impacts imposed by increasing global temperature and CO₂ can significantly affect the interaction between crops and their pests and diseases (Skendžić *et al.*, 2021). Therefore, growers can expect to face new and intense pests and diseases problems (Table 5) in decades due to climate change. The spread of pests and diseases across physical and political boundaries threatens crops productivity and food security, and is a common problem to all regions of all the (Skendžić *et al.*, 2021).

Table 5. First reports of pests and diseases

New areas under invasion of pests and diseases	Name of pests and disease	Reference
Mozambique, Uganda, Rwanda, Tanzania	Maize lethal necrosis	Lyytinen <i>et al.</i> , 2009
Kenya	Maize dwarf mosaic virus	Wangai <i>et al.</i> , 2012
Kenya	Maize chlorotic mottle virus	Wangai <i>et al.</i> , 2012
Kenya	Wheat streak mosaic virus	Wangai <i>et al.</i> , 2012)
Minnesota and Manitoba	Goss's Wilt (<i>Clavibacter michiganensis</i> subsp. <i>nebraskensis</i>)	ProMED-mail, 2013
Argentina	Stewart's Wilt (<i>Pantoea stewartii</i> subsp. <i>stewartii</i>)	ProMED-mail, 2013
Uganda and Kenya	Maize rough dwarf virus	ProMED-mail, 2011
Mozambique and Jordan	Panama disease (<i>Fusarium oxysporum</i> f. sp. <i>cubense</i>)	ProMED-mail, 2013
Caribbean states	Black Sigatoka (<i>Mycosphaerella fijiensis</i>)	ProMED-mail, 2011
Australia	Freckle disease (<i>Phyllosticta</i> sp.)	ProMED-mail, 2013
Peninsular Malaysia Ecuador	Moko disease (<i>Ralstonia solanacearum</i>)	Zulperi and Sijam 2014, Delgado <i>et al.</i> , 2014
Burundi	bacterial wilt (<i>Xanthomonas campestris</i> pv. <i>musacearum</i>)	ProMED-mail, 2011
Benin	Banana bunchy top virus	Lokossou <i>et al.</i> , 2012
across Central and South America, with a single report from California	Citrus greening disease (<i>Candidatus Liberibacter asiaticus</i>)	ProMED-mail, 2012
Spain	African psyllid (<i>Trioza erytreae</i>)	ProMED-mail, 2015
Italy and France	Xylella leaf scorch (<i>Xylella fastidiosa</i>) of olives	ProMED-mail, 2014
Australia	<i>Septoria tritici</i> blotch (<i>Zymoseptoria tritici</i>) of wheat	ProMED-mail, 2014

Michigan.	Cercospora leaf spot (<i>Cercospora beticola</i>) of sugar beet	ProMED-mail, 2012
Guatemala, Central America	Coffee leaf rust (<i>Hemileia vestatrix</i>)	ProMED-mail, 2014
Tokyo	Plum pox virus	Maejima <i>et al.</i> , 2010
Veracruz, Mexico	Leaf stripe and stem rot of maize (<i>Burkholderia gladioli</i>)	Gijon-Hernandez <i>et al.</i> , 2011
Australia	Beet western yellows virus	ProMED-mail, 2014

Temperature is an important factor of climate that plays a vital role in metabolism, metamorphosis, mobility, and availability of hosts, which governs the possible potential changes in pests' population and dynamics (Shrestha, 2019). Species that cannot acclimate adjust and evolve themselves to rising temperature conditions usually have difficulties to maintain their populations, while other species can thrive, flourish and replicate or reproduce quickly (Figure 1). The distribution and behavior of present pests show that the rising temperature can change their growth rate and increase herbivory (DeLucia *et al.*, 2008; Deutsch *et al.*, 2018). Thus, the pests in temperate zones are projected to increase their growth and development due to climate change (Deutsch *et al.*, 2018). However, pests' population and growth rate in tropical zones are predicted to be decreased as a result of climate warming because the current increase in temperature is reached on the brink of the optimum level for pests' growth and development (Deutsch *et al.*, 2018). The same authors studied the deviations in growth of pests' population by using three major cereal crops (maize, rice and wheat) under climate change scenario. They reported that for wheat, which is usually planted in temperate zones, global warming will enhance the growth of pests' population. For rice, which is grown in tropical climates, warming will result in a reduction in the growth of pests' population whereas for maize that is planted in both tropical and temperate zones, mixed response of pests growth could be expected (Deutsch *et al.*, 2018). Thus, overall impacts of climate changes on pest dynamics include, the increase of geographic areas or ranges, better survival rates of populations during overwintering, higher risk of establishment of invasive pests' species, maximum chances of insect pests-transmitted plants diseases because of expansion in range and fast reproduction of insect pests vectors, decreased efficiency of natural enemies (biological control agents) and predators, etc. (Skendžić *et al.*, 2021).

In European countries, invasion of indigenous fungus is increasing with increase in length of time and amount of rainfall (Desprez-Loustau *et al.*, 2010). Santini *et al.* (2013) documented that in Europe, number of invasive forest pathogens and powdery mildews (*Erysiphales*) has increased rapidly. The increase in invasions of pests and diseases in Europe might be due to climatic suitability, favorable temperature and host availability (Bacon *et al.*, 2014). For example, the Colorado potato beetle (*Leptinotarsa decemlineata*, Chrysomelidae) has extended its range to Northern Hemisphere (Alyokhin *et al.*, 2013), and this latitudinal expansion of Colorado potato beetle is linked with global climate warming. Wheat blast disease (*Magnaporthe oryzae Triticum*), which is a drastic disease of wheat and limiting factor for wheat production, was identified in Brazil but recently observed in Bangladesh and successively extended to neighboring Indian states. The severe invasion of *Magnaporthe oryzae Triticum* is linked with abnormal climate warming and increased conditions before harvest of crop (Islam *et al.*, 2019). Similarly, stripe rust (*Puccinia striiformis*) and stem rust (*Puccinia graminis*) are serious threat to wheat production in the Eastern and Northern Africa, Central Asia and Near East causing severe outbreaks and decreasing wheat yield (FAO, 2017; Islam *et al.*, 2019). Thus, pests and diseases are likely to be more severe and expand their ranges to new areas due to climatic conditions (FAO, 2017).

Abiotic stress

Drought stress

Plants growth and yield is strongly affected by water availability (Seleiman *et al.*, 2021). Higher temperature and variability in precipitation pattern has resulted in low water availability, and future projections

indicate further decline in water availability, while agricultural water consumption is expected to rise by 19% in 2050 (UN-Water, 2013). Climate change, economic and agricultural activities and population growth are leading to water scarcity (Ayt Ougougdal *et al.*, 2020). For example, increasing dependence of Indian farmers on groundwater to deal with climate-induced water scarcity has resulted in a rapid reduction in the groundwater table, and it may extreme further due to more variability in climatic conditions in future (Fishman, 2018). In South Asia, it is projected that annual average increase in temperature may rise by 2.1–2.6 °C in 2050, which could result in 21% increase in heat-stressed areas in the region by 2050 (Tesfaye *et al.*, 2017). Predictions claim that more than half of the Indo-Gangetic Plains, the main food production area of the India, Pakistan, Bangladesh and Nepal, may decline wheat production (–4% to –36%) by 2050 due to increasing temperature, drought stress and heat stress (Ortiz *et al.*, 2008; Daloz *et al.*, 2021). The magnitude of impact of extreme climatic events on agricultural production is already high. Further even a small increase in global warming, variability in rainfall and glacial melt can result in severe impacts on stability of water resources and water availability, thus threatening the future agricultural production (Vinke *et al.*, 2017). According to FAO's recent analysis, 25% of all economic losses in 48 developing countries during 2003 to 2013 were due to medium- and large-scale climate threats such as drought stress, floods, heat waves and storms that affected the agriculture sector adversely (FAO, 2015). It is assessed that out of total crop production, more than 80% depends on rainfall, and therefore variability in rain fall pattern or its total seasonal amount is very vital for crop production (Olesen and Bindi, 2002; Skendžić *et al.*, 2021). Emadodin *et al.* (2021) documented that variability in precipitation pattern has strong impact on agriculture particularly in arid and semi-arid regions where dry season can be a limiting factor for crops cultivation.

Climate change has created substantial uncertainties about water availability in future in different regions of the world. Drought prone areas are increasing in Northern and Southern Africa, Southern Europe, Australia and parts of Latin America (Lickley and Solomon, 2018). Moreover, the various models of climate predict considerable drying, 10% increase in drought and moisture deficit of 200 mm per year, in these areas as well as for some parts of North America by mid-century. In tropical and temperate latitudes, precipitation is expected to decrease significantly (Meehl *et al.*, 2007; Reyes *et al.*, 2021). Spring and summer rainfalls are projected to be declined by 30% by the end of 21st century (Vautard *et al.*, 2014; Forzieri *et al.*, 2014; Reyes *et al.*, 2021) in North African and southern European countries (Toreti and Naveau, 2015). Similarly, fresh water availability is decreasing rapidly in the low latitudes regions such as China, India, South and East Asia, East Australia, Africa and Egypt as a result of climate change (Elbehri and Burfisher, 2015), consequently will lead to large reduction in share of irrigated to overall agricultural production. Cereal production is declined severely in Mediterranean countries due to and short grain filling duration because of drought stress, high temperature and heat waves. In Mediterranean, permanent crops such as citrus grapevine and olives have great importance however, extreme climatic events such as storms and hail affected these crops significantly, which can decrease or completely destroy yields (Olesen and Bindi, 2002). Decreased precipitation and low water availability in the soil can affect physiological and biological functions of plants, and plants become even more vulnerable to pests and diseases (Zayan, 2019). Further, limited precipitation and high evapotranspiration impair the crop productivity by causing salt accumulation in soils, nutrients immobilization, unhealthy, saline soil and subsequently infertile soils. Such barren soils become unsuitable for crops with passage of time, and finally left by growers leading to financial loss and social issues (Arora, 2019). Therefore, due to limited rainfall and high evapotranspiration, attention should be given to the improvement of existing agronomic practices and development of innovative irrigation techniques that enable effective and efficient use of available water resources to improve crops productivity (Kirda *et al.*, 2007). Drought stress affects the plant growth and development but reproductive stage particularly flowering and grain formation stages in cereal crops are the most critical ones (Pradhan *et al.*, 2012). For instance, wheat yield declined by 1-30% when mild drought stress was imposed at anthesis stage whereas 92% reduction in yield was observed for mild water stress during grain formation stage (De Oliveira *et al.*, 2013). Similarly, drought stress at flowering stage of mash bean (*Vigna*

mungo L.) decreased the grain yield by 31-57% (Baroowa and Gogoi, 2014). Maleki *et al.* (2013) documented that drought stress in soybean at rain filling stage decreased the seed yield by 42%. Similarly, water stress in maize and cowpea decreased the grain yield by as much as 40% for maize and 34- 68% for cowpea (Farooq *et al.*, 2011; Daryanto *et al.*, 2016). Thus, decrease in crop productivity will be further intensified due to global climate changes in future.

Floods

Floods are the most common type of natural disasters caused by heavy rains, rapid snowmelt, or storm surges caused by tropical cyclones or tsunamis in low-lying and coastal areas. Precipitation changes and rising temperature are rising sea levels, and increasing the frequency and intensity of flooding in coastal and low-lying areas in many countries around the world (Alexander *et al.*, 2006; Reyes *et al.*, 2021). European Academies' Science Advisory Council (EASAC, 2018) reported that extreme weather events, including flooding, have increased by 50% over the past decade and are now four times more frequent than two decades ago. Severe floods in 2018 in Kerala, India are striking examples to showcase this. These floods have resulted in the loss of top soil and nutrients from the soils leading to low production over the next few years unless and until curative and preemptive remediation practices and strategies are implemented (EASAC, 2018). The higher intensity of rainfall events can increase soil erosion and decrease soil moisture due to increased runoff. In addition, floods can cause large scale damages to agricultural lands, livestock, even loss of life, and devastations to people properties and critical public health infrastructure (WRI, 2015). Reports indicate that about 21 million people around the world are affected by various types of floods per year, and this number could reach to 54 million in 2030 due to climate changes (WRI, 2015). Figure 2 shows the 15 countries of the World where maximum people face the river floods due to changes in climate events.

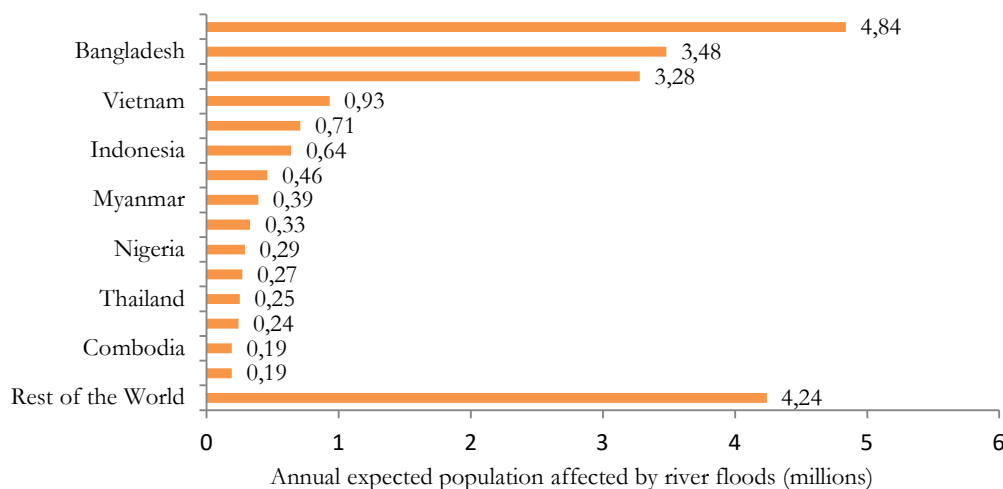


Figure 2. The top 15 countries of the World with greatest population exposed to river floods risks due to natural disasters and climate change (Ward *et al.*, 2013; Jongman *et al.*, 2015)

Rising sea levels could result in increase in soil salinity in coastal areas, decline in agricultural lands and consequently poor crop production (Shrivastava and Kumar, 2015) and high food insecurity in these areas. Climate models predict an increase in average precipitation, rivers runoff and water availability in regions of high latitudes and some regions in the tropics, while decline in lower mid-latitude and subtropical regions that would increase flooding and drought stress (Tabari, 2020). The increase in sea levels would be 50 cm high by 2100, increasing floods threats in most regions of South and East Asia (Gommes *et al.*, 1998). Aquaculture

production system will be threatened by saltwater intrusions. Likewise, coastal fisheries that depend on spawning ground in coastal wetlands and in mangrove swamps are threatened by sea level rise, and will be further worsen in future. The frequency and intensity of tropical cyclones will increase, and extreme storms and high-water events will occur and penetrate further inland. Nicholls *et al.* (1999) documented that maximum number of people (5 time more) will be vulnerable to sea flooding by 2080 than those vulnerable to rise in sea levels. Large and high intensity cyclones from Arabian Peninsula occurred in recent past decade (Mekunu, 2018). The strongest and high intensity 8 tropical cyclones occurred in Indian Ocean during 2019 that affected vast area in Asia and East Africa. In March 2019, the strongest tropical cyclones (Kenneth and Idai) on record, affected vast area of Mozambique (Eline and Hudah). East Africa experienced one of the wettest rainy seasons from October to December 2019 due to one of the strongest Indian Ocean Dipoles (IODs). In Djibouti city, more than 336 mm of rainfall occurred in just 4 days, comparable to 2 normal years' rainfall of city. Such extreme positive IODs events are expected to increase twice in the future due to 1.5 °C rise in temperature and global warming (Cai *et al.*, 2018). The increased frequency of cyclones and higher climate variability could enhance the pests and diseases outbreaks (Salih *et al.*, 2020) and decrease the crop production.

Temperature and heat stress

Temperature and heat stresses are key abiotic stresses that decrease crops yields and productivity leading to lower income for farmers. Plants need an optimum level of temperature to carry on their normal physiological process, growth and development. The increase in average global temperature poses considerable threats to plant growth and production (Priya *et al.*, 2019). The expected changes in temperature during the next fifty years are estimated in range of 2–3 °C that would result in extreme temperature and more frequent heat waves events (Meehl *et al.*, 2007). Faster development of growth stages in crops such as maize, wheat, rice etc. can results in a shorter life cycle leading to small plants, short reproductive durations, and low final yield. Extreme low or high temperature poses detrimental impacts on crop development particularly during critical growth stage such as seed germination, anthesis, grains development (Luo, 2011; Hussain *et al.*, 2019), and decrease the crop productivity. Studies revealed the negative correlation between crop yields and average increase in temperature from optimum level. According to Asseng *et al.* (2015), each 1 °C rise in global average temperature, 4–6% decrease in wheat yield is predicted. Each crop has specific temperature for growth and development, above or fall below specific thresholds level can considerably affect the yield of crops. Wheat (Brown, 2009) and maize (Lobell *et al.*, 2007) yields reduced by 10% and 8.3%, respectively, with each 1 °C increase in temperature beyond the optimum temperature level. Likewise, Ray *et al.* (2015) reported wheat yield reduction by 3–4% for each 1 °C rise in temperature beyond optimum level. Easterling *et al.* (2007) documented that 2 °C increase in temperature from optimum growth level caused 7% declined in wheat yield while further temperature increase to 4 °C reduced yield up to 34%. Alike, 2.6% decreased in rice yield was observed by for each 1°C increase in temperature (Easterling *et al.*, 2007). The reproductive organs of plants and reproductive functions are highly susceptible to increasing temperatures that adversely disturbs the source–sink relationship, and lowers final economic yields (Rehman *et al.*, 2015; Abdelrahman *et al.*, 2020). High temperature has been linked to yield reduction in wheat, maize, rice, sorghum, barley and soybean crops, with predictions estimating yield losses up to 70% by end of 21st century (Asseng *et al.*, 2015; Mistry *et al.*, 2017). Rising temperature has also been considered key cause of yield slow down or stagnation in Europe and other countries of the world (Brisson *et al.*, 2010), and further temperature increase will continue to reduce crop yields, despite adaptation efforts of farmers. However, northern regions of the world are predicted to get benefits of temperature increase during spring–summer season where length of planting period is a limiting factor (Tubiello *et al.*, 2002). The impacts of temperature increase are usually linked with other climatic factors such as availability of water, duration and intensity of sunlight, and occurrence of winds (Rehman *et al.*, 2015). The direct negative impact of temperature on crop yields could be furthermore wedged by indirect temperature effects on these climatic factors. For instance, the increase in temperature enhances the atmospheric water

demand, which can result in further moisture stress due to high water pressure deficit that consequently decreases soil water content and finally reduces crop yields (Asseng *et al.*, 2011; Zhao *et al.*, 2016; Zhao *et al.*, 2017). Other indirect impacts of high temperature include frequent and intense heat waves and outbreaks of pests and diseases (Tack *et al.*, 2015; Lesk *et al.*, 2016; Zhao *et al.*, 2017). In 2018, from March to August, Eastern, Northern and Central Europe experienced unusual high temperature and extreme dry conditions simultaneously whereas numerous regions in Southwestern Europe faced high rainfalls (Beillouin *et al.*, 2020).

Salinity stress

Salinity is more obvious in coastal agriculture land, semi-arid and arid areas of the world (Hashem *et al.*, 2018; Badawy *et al.*, 2021). In past 25 years, rise in sea levels has resulted in 33% increase in salinity level in coastal areas (Rahman *et al.*, 2018). Recent data have revealed that 1125 million hectares of land area in the world is salt affected (Hossain *et al.*, 2019) out of which one-fifth is irrigated lands area, and 1.5 million hectares in each year are degraded by high salinity levels and unsuitable for agricultural production (Hossain *et al.*, 2019). Climate changes and high temperature have increased the frequency of recurrent drought or precipitation above the average values in different parts of the world (Ayanlade *et al.*, 2018). The higher evapotranspiration in areas with shallow water tables and intrusion of sea water in coastal areas has resulted in root zone salinity. Bannari and Al-Ali (2020) reported that the long-term impacts of higher temperature and low precipitation for three decades resulted in increased soil salinity significantly in arid regions because of less salts leaching in the soil. Due to low precipitation, saline water irrigation and high evapotranspiration, agricultural lands is converting in to saline soil at a rate of 10% per year. If soil salinization continues then > 50% of arable land area will be salt-affected by 2050 (Jamil *et al.*, 2011; Hasanuzzaman *et al.*, 2014). Salt affected land area of different countries is given in Table 6 and Figure 3.

Table 6. Irrigated land area affected by soil salinity in different countries

Country	% of the irrigated land area into saline area	Reference
China	15	Zaman <i>et al.</i> , 2018
India	20	Mann <i>et al.</i> , 2020
Soviet Union	18	Hussain <i>et al.</i> , 2019; Hossianet al 2019
United States	23	Zaman <i>et al.</i> , 2018
Pakistan	25	Sharif <i>et al.</i> , 2016
Iran	29	Zaman <i>et al.</i> , 2018
Thailand	10	Zaman <i>et al.</i> , 2018
Egypt	33	Zaman <i>et al.</i> , 2018
Australia	32	Sahab <i>et al.</i> , 2021
Argentina	34	Hussain <i>et al.</i> , 2019; Hossianet al 2019
South Africa	9	Hussain <i>et al.</i> , 2019; Hossianet al 2019
Russia	21	Dobrovol'skii and Stasyuk, 2008

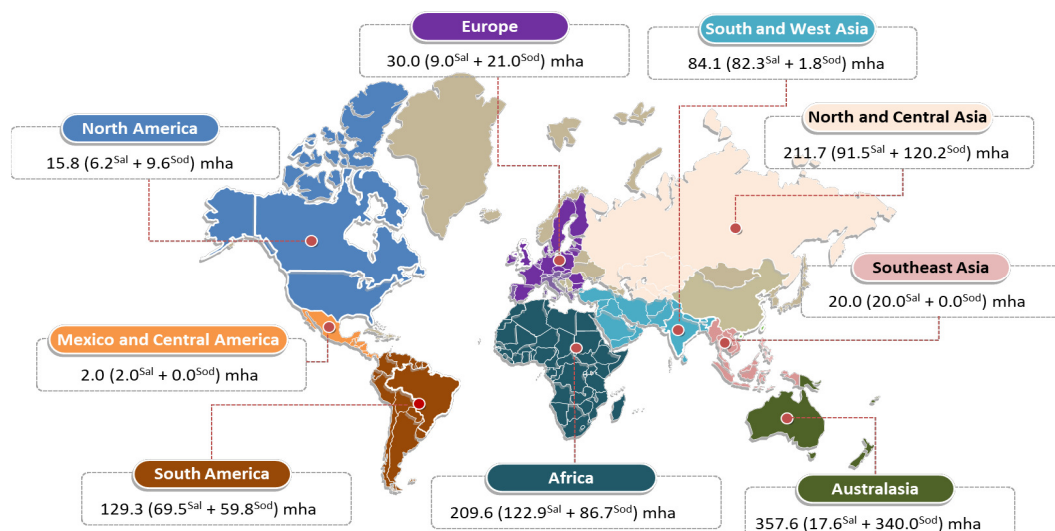


Figure 3. Distribution of salt-affected land area in different countries (FAO 2015; Butcher *et al.*, 2016; Zaman *et al.*, 2018)

Increase in salt-affected agricultural lands has arisen severe threats to food security of the world (Munns and Tester, 2008; Farooq *et al.*, 2015; Farooq *et al.*, 2017; Al-Ashkar *et al.*, 2019; Seleiman *et al.*, 2019; Taha *et al.*, 2021b). The threats of climate change-induced salinity are also expected to increase in drylands regions of northern Algeria, Morocco and Spain. Similarly, climate change multi-modal predict that drylands regions of central India, North of China, South-East Mongolia, and Western and Southern Sahara Desert will become some extent saltier by 2100 due to climate change. In contrast, the range of soil salinity will decrease or remain constant in the drylands areas of the Horn of Africa, West Kazakhstan, North-West United States, Turkmenistan and Eastern Europe by 2100 (Hassani *et al.*, 2021).

Saline soils contain higher concentration of soluble ions such as sodium (Na^+) and chloride (Cl^-), and low concentration of potassium (K^+), calcium (Ca^{2+}), and nitrate (NO_3^-) (Munns and Tester, 2008; Farooq *et al.*, 2015; Alkharabsheh *et al.*, 2021). The high concentration of these ions leads to hyper ionic salt stress that induces oxidative stress and metabolic damage, and production reactive oxygen species (Farooq *et al.*, 2015; Petrov *et al.*, 2015; Caverzan *et al.*, 2016; Taha *et al.*, 2021a; Ullah *et al.*, 2021). Soil salinity poses adverse impacts on crop yield, morphological, physiological, and biochemical parameters (Figure 4). All growth stages of plants from germination, seedling emergence to reproductive stage are adversely affected by soil salinity (Farooq *et al.*, 2015; Farooq *et al.*, 2017; Ullah and Bano, 2019). Salinity reduces the phytohormones production in plant body, and impairs seedling growth and establishment (Egamberdieva and Kucharova, 2009; Farooq *et al.*, 2017). If seeds are sown in salt affected soils, it results in impairment in germination and reduced shoot growth in later stages (Wakeel *et al.*, 2011; Farooq *et al.*, 2015). Salinity affects different physiological functions in the plants such as reduced stomatal conductance, CO_2 -fixation, limited activities of catalytic enzymes, destroys photosynthetic pigments (Omoto *et al.*, 2012) and finally results in low yield (Kalhor *et al.*, 2016; Genc *et al.*, 2019).

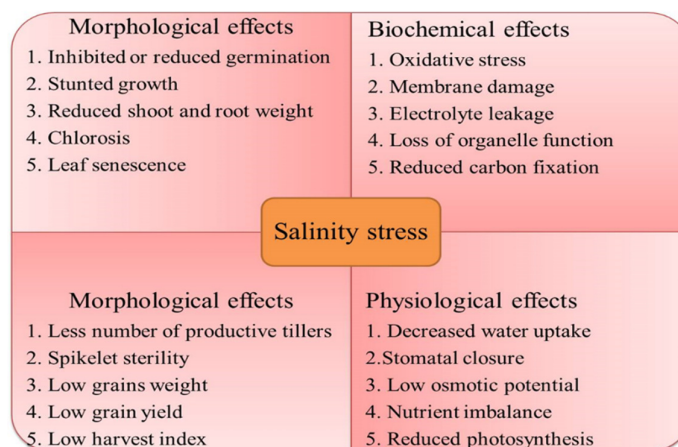


Figure 4. Effects of salinity stress on crop yield, morphological, physiological and biochemical traits

Management strategies to cope with climate change

On the eve of climate change, different adaptation measures and actions are prerequisite to mitigate and decrease the crops' vulnerabilities in response to climate change. Adaptation measures involve any activity or practice intended to decrease vulnerability and increase the resilience of system (Vogel and Meyer, 2018). Adaptation strategies give opportunities to address the challenges of climate change and to sustain agricultural production system (Ahmed *et al.*, 2019). Use of biotechnology, improvement in breeding and selection, development of climate resilient varieties, steps to words climate smart agriculture, water and nutrient management practices are some of the adaptation techniques and practices that are being talked about.

Breeding and selection

The breeding of improved crop cultivars such as short stature and early maturing, temperature, heat and drought tolerant cultivars are indispensable to increase and sustain the yield under changing climate (Vogel and Meyer, 2018; Ahmed *et al.*, 2019). The new crop varieties can perform well and enhance the yield in per unit area under extreme temperatures and drought stress (Deressa *et al.*, 2009). To breed drought and salt tolerant cultivars, an integrated approach comprising use of current genetic varied traits, exploitation of new and diverse sources to generate new variant, and use of historic breeding technique with compound traits can be useful (Sharma *et al.*, 2013; Duc *et al.*, 2015; Smýkal *et al.*, 2015; Farooq *et al.*, 2017). Increasing crop yield in salt and drought affected regions through selection and breeding is an also proven strategy (Tariq *et al.*, 2013; Farooq *et al.*, 2015; Farooq *et al.*, 2017). Mass screening and selection of genotypes for useful traits under water and salinity stress to improve the yield has been demonstrated in different cereal crops such as wheat, rice, maize, sorghum, and legume crops (Jat *et al.*, 2016; Farooq *et al.*, 2014; Farooq *et al.*, 2017). For salt tolerant, different traits such as seedling emergence, fresh and dry weight of plants, leaf $\text{Ca}^{2+}/\text{Na}^{+}$ ratio, leaf $\text{K}^{+}/\text{Na}^{+}$ ratio, nodule formation in legumes, number of tillers, number of grains, grains weight etc. have measured in plants (Jat *et al.*, 2016; Farooq *et al.*, 2017). Likewise, Farooq *et al.* (2014) and Ranjith and Rao (2021) documented various agronomic and genetic traits (Table 7) such as rooting depth, leaf area, dry weight of plant, number of grains per spike, 1000-grains weight, early flowering, stay-green character, presence of awns, canopy temperature, stomatal resistance, source sink relationship, stem reserve mobilization, partitioning and translocation of starch during embryo development, grain filling rate, grain filling duration and final yield in wheat genotypes selection under terminal drought stress. Meanwhile the final criteria for salt and drought stress is economic yield, the parameters used for evaluating salt or drought tolerance and resistance must be correlated with economic yields of crops (Flowers *et al.*, 2010; Farooq *et al.*, 2017). Sharma *et al.* (2013) carried out direct selection of legume

genotypes for salt tolerance by conducting trails at multiple locations. Similarly, Sehwat *et al.* (2014) evaluated 117 legume (mungbean) cultivars for salt tolerance by observing suitable traits during early growth stage. Salt sensitive cultivars had low germination, fresh and dry weight while salt tolerant cultivars had higher value of these traits. They categorized the cultivars as susceptible, highly susceptible and tolerant on the basis of their growth performance. Thus, for salt and drought tolerance, mass screening and selection can be carried out on the basis of plant dry and fresh biomass, osmotic adjustment, Ca^{2+}/Na^+ ratio, leaf K^+/Na^+ ratio, homeostasis, number of grains, grains weight and final economic yield.

Table 7. Parameters related to selection of genotypes for drought tolerance (Farooq *et al.*, 2014; Ranjith and Rao, 2021)

Category	Parameters
Morphological and Anatomical	Greater root length, root fresh and dry weight, root volume and thickness, leaf area of plant, canopy structure, stay-green character of leaves, fresh and dry weight of plant, number of grains per spike or pod, grain weight, harvest index and economic yield.
Phenological	Seedling vigor, early to flowering, anthesis and maturity, less silking interval, synchronization of silking and tasseling, weed competitiveness.
Physiological and Biochemical	Leaf water potential, stomatal conductance, osmotic adjustment, stay-green, carbon isotope discrimination, stem reserves mobilization, specific leaf area, presence of awns, ABA content, heat-shock protein, wax coating, leaf rolling, electrolyte leakage, water use efficiency, nutrient use efficiency, osmoprotectants, aquaporins and dehydrins.

Functional genomics

Genome-based approaches help to reveal the biological processes and genetic information of crop plants. Molecular plant breeding is very important technique to improve or increase crops yield under different abiotic and biotic stresses. In agriculture, various types of molecular markers are used to study the genomics of population or individual plant to find out novel suitable genes that can function in particular environment (Stinchcombe *et al.*, 2008; Raza *et al.*, 2019). With the progress and improvement in plant genomics, different DNA markers are identified that are suitable for marker-assisted breeding program to speed up the breeding for particular environment (Da Silva Dias *et al.*, 2015). For example, in Colorado, Haley *et al.* (2017) applied QTL (quantitative trait locus) mapping and successfully produced a wheat variety called “Ripper” that withstands in drought stress conditions without negative effects on grain yield. Similarly, Badu-Aparku and Yallou (2009) used QTL mapping for maize plants to screen out best maize lines that can be grown successfully drought prone areas. Merchuk-Ovant *et al.* (2016) carried out experiment on durum wheat (*Triticum turgidum* L.) bread wheat and selected the particular wheat traits for drought stress through marker assisted selection. Thoen *et al.* (2017) identified three vital points (7D, 7B, and 2B) on bread wheat genome that will improve the wheat growth under high temperature stress conditions. Tahmasebi *et al.* (2016) executed QTL mapping for wheat inbred lines under various stresses such as heat, drought and flooding and combination of these stresses (heat + drought) simultaneously. QTL mapping revealed 19.6% diversity among the wheat lines for grain yield under these stresses. Chopra *et al.* (2017) documented several genes in *Sorghum bicolor* associated with cold and heat stresses. Thus, molecular markers and QTL should further be exploited to identify the distinctive variations in agricultural crops to increase the potential against abiotic or biotic stresses.

Biotechnology and transgenic approach

In agriculture, biotechnology and transgenic approaches are very useful techniques used for genetic modification to improve the desired traits for particular environment such as heat, temperature drought, salinity, and cold stress (Raza *et al.*, 2019). Crop varieties resistant to different abiotic and biotic stresses are being produced successfully after the identification of stress-responsive transcription factors (TFs). These TFs can control the phenotypes of genes in genetically modified or engineered crops related to different stresses

(Reynolds *et al.*, 2015). There are many transgenic plants are produced by genetic engineering to cope with abiotic or biotic stresses. For example, DREB (dehydration-responsive element-binding protein) TFs have important regulating ability in different cold and water stress conditions (Stockinger *et al.*, 1997). Likewise, *DREB1* genes have been purified from rice, maize, wheat and oilseed crops, and then transformed to produce the transgenic crops resistant to biotic and abiotic stresses (Dubouzet *et al.*, 2003; Qin *et al.*, 2004). Transgenic *Arabidopsis* with high resistant against drought stress was produced by isolating the *ZmDREB2A* gene from maize (Qin *et al.*, 2007). Likewise, Chen *et al.* (2007) reported that the *GmDREB2* gene taken from soybean displayed substantial tolerance against drought salt stress conditions. Transgenic rice plants possessing *OsDREB2A* gene showed considerable tolerance against drought and salinity (Mallikarjuna *et al.*, 2011).

Agronomic management practices

Agriculture production systems can be made more productive and resilient to changing climate by applying system-specific management measures (Seleiman and Hafez, 2021). Many options are available nutrient, water and soil management practices or technologies, which are helpful to mitigate and reduce adverse impacts of climate change. The important practices or technologies for rainwater harvesting, in situ moisture conservation, improvement in irrigation methods for efficient use of irrigation water, wastewater treatment, alternative land uses, reclamation of marginal lands, agroforestry on degraded lands, residue- and nutrient management (Battaglia *et al.*, 2022; Seleiman *et al.*, 2022). will not only improve the agricultural production but also help in combating climate change impacts (Venkateswarlu *et al.*, 2012; Jat, 2016; Arora, 2019).

Minimum soil disturbance and permanent organic soil cover reduces the soil erosion, evapotranspiration losses, weeds problem and increases soil infiltration rate (Jat, 2016; Wang *et al.*, 2021). Studies revealed that by adopting conservation practices, soil carbon sequestration can be achieved at 0.2–1.0 tones ha⁻¹ year⁻¹ depending on agroecological conditions (Corsi *et al.*, 2012) that would help to decrease greenhouse gas emission, further environmental damage improve and improve soil productivity (Jat, 2016). The conservation agricultural (CA) practices are being adopted in 125 million hectares located in different countries, and are further rapidly increasing in subtropical, tropical and temperate areas of the world (Friedrich *et al.*, 2012). Maximum area under CA is in South America (49.6 million hectares) followed by North America (40 million hectares), New Zealand and Australia and (12.2 million hectares) while Africa (0.50 million hectares) has minimum area under CA (Kassam *et al.*, 2009). Many studies have indicated that CA increased the crops yields and improved soil health compared to conventional practices (Sharma *et al.*, 2008; Govaerts, 2010; Jat *et al.*, 2011; Jat *et al.*, 2016). Furthermore, conservation practices increased soil infiltration rate, water holding capacity, reduced water runoff, soil erosion, the also decreased the incidence of pests and diseases (Chhokar *et al.*, 2007; Hobbs and Govaerts, 2010; Jat *et al.*, 2016). Sowing of crops on permanent raised-bed with residue management, decreased soil sodicity by 1.80 to 2.64 times in upper layer of soil compared to conventional beds (Govaerts *et al.*, 2007). In semi-arid regions, soil evaporation declined by 34–50% by covering the soil surface with crop residues or plastic mulch (Gan *et al.*, 2013).

Application of hormones and osmoprotectants

External application of osmoprotectants and plant growth regulators (PGRs) has the potential to improve water stress, salt and heat stress tolerance in plants. Proline, glycine betaine (GB), polyols, sorbitol, mannitol, abscisic acid (ABA) and salicylic acid (SA) etc. have been used in different plant species to ameliorate the adverse effects of heat, temperature and water stress by improving osmotic adjustment (OA) and antioxidant system (Ma *et al.*, 2006; Travaglia *et al.*, 2007; Farooq *et al.*, 2014; Farooq *et al.*, 2015; Farooq *et al.*, 2017). For instance, foliar spray of SA, ascorbic acid and proline reduced the adverse effect of salt stress in Sunflower (*Helianthus annuus* L.) and increased, chlorophyll a, b molecules and total biomass of sunflower by 80% (Noreen *et al.*, 2019). Likewise, El-Taher *et al.* (2021) applied foliar spray of SA to cowpeas (*Vigna*

unguiculata) planted under salt stress. The authors reported that foliar spray of SA reduced negative effects of salinity stress and significantly enhanced the plant height, leaves, fresh weights, photosynthetic pigments, uptake of N, P, K, and final cowpea yield when compared with control. In another study conducted by Khan *et al.* (2010) was revealed that application of 0.5 mM SA enhanced the enzymatic activity of antioxidants and uptake of N, P, K, and Ca in mungbean under salt stress. Yang *et al.* (2003) reported an increase in chlorophyll content in flag leaf of wheat after foliar spray of cytokine. Likewise, Wang *et al.* (2011) applied sodium nitroprusside in wheat at grain filling stage to ameliorate adverse effect of drought stress. Naqve *et al.* (2021) applied external application of alpha-tocopherol (100, 200, and 300 mg L⁻¹) to okra (*Abelmoschus esculentus* L. Moench) grown under salt stress (100 mM NaCl). They reported that alpha-tocopherol significantly increased in okra yield by enhancing the antioxidants activity, total free proline and accumulation of GB in fruit tissues under saline conditions.

Thus, external osmoprotectants improved plant growth and yield by decreasing adverse impacts of stresses by modulating the antioxidant defense system.

Nutrients management

Judicious use of nutrients can enhance the plant vigor and resilient to biotic and abiotic stresses. Plants needs macronutrients (N, P, K, Ca etc.) and micronutrients (B, Zn, Fe, Cu, Si etc.) contribute to different physiological and metabolic functions of plants, and enable the plants to withstand against various stresses such as biotic stress (pests and diseases) abiotic stresses (heat, temperature, water and salinity stress) by increasing antioxidant system of plants (Gautam *et al.*, 2016; Ma *et al.*, 2016). Lv *et al.* (2021) reported that foliar N fertilizer at later growth stages of bread wheat is an effective method of mitigating drought stress impacts and enhancing grain filling. Balance dose of N fertilizer increased plant stem reserve remobilization and improved grain-filling rate, which can reimburse the losses of declined photosynthesis rate and grain-filling duration under drought stress conditions (Yang and Zhang, 2006). The foliar sprays of amino acids and K considerably increased grain yield by improving physiological and biochemical traits of wheat planted under well water and drought stress conditions (Ahmad *et al.*, 2019). Likewise, wheat grown under drought stress conditions showed an increase in grain by 15 and 19% after foliar spray of Zn and B, respectively as compared to untreated plants (Karim *et al.*, 2012). In another trial of wheat grown under water stressed conditions, foliar application of Zn and Mn enhanced the grain yield 13 and 10%, respectively by increasing plant growth (Karim *et al.*, 2012). Supplemental foliar fertilization of NPK significantly increased the gas exchange characteristics of wheat, water relations and nutrient contents in wheat planted under water deficit or well water conditions (Shabbir *et al.*, 2015). Alike, Ca applied exogenously enhanced drought resistance in plants by improving endogenous polyamines content (Ma *et al.*, 2005). Si application in agricultural crops has the potential to relieve the damages caused by stresses. For example, 1.0 mM of Si increased the shoot length and leaf chlorophyll content to some extent in wheat crop under water deficit conditions (Pei *et al.*, 2010). Similarly, beneficial effects of Se have been reported for different crop plants under drought stress conditions (Farooq *et al.*, 2015; Farooq *et al.*, 2017). Kabir *et al.* (2004) reported that high dose of K to mungbean planted in mild salinity stress conditions enhanced the growth and productivity as compared to plants of control treatments. Similarly, K and Ca application mitigated the adverse impacts of salt stress on lentil (*Lens culinaris*) and improved dry matter yield (Kafi *et al.*, 2012).

Water management

Irrigation water demand will increase by 8–9% by the mid-21st century while rainfall will decrease (11–18%) (Woznicki *et al.*, 2015). Thus, development of innovative water management practices might help to alleviate the negative impacts of climate change. To avoid over- or under-watering of crops, growers monitor the weather forecast. Farmers use irrigation water judiciously to crops at their critical growth stages. For

example, in case of wheat, if farmers have two irrigation options, then apply at crown root initiation and booting stage of crop, while if they have three irrigation options, then apply at crown root initiation, booting and grain filling stages of wheat. Farmers provide irrigation to crops during cooler periods of the day (at night or early morning), further decreasing water loss. Use of the most efficient irrigation method, for example, drip irrigation method delivers water directly to roots of plant, decreasing the loss of water through evaporation. Moreover, planting the crops that are suitable to region's climate is another way to get more crops per drop. Plant variety that is native to semi-arid and arid areas is obviously drought and heat-tolerant than those selected from irrigated areas. For example, sorghum, pearl millet (*Pennisetum glaucum*), foxtail millet (*Setaria italica* L.), sweet potato (*Ipomoea batatas*), cassava (*Manihot esculenta*), sesame (*Sesamum indicum*) and cowpea (*Vigna unguiculata*) are relatively drought-tolerant crops (Vetriventhan *et al.*, 2016; Lieberman-Lazarovich *et al.*, 2021) and can be grown in drought prone areas. Growing of cover crops to protect soil erosion, enhance organic matter and soil fertility, and reduce weeds. This will allow the irrigation or rain water to more infiltrate in the soil and increase soil water-holding capacity (WHC). Likewise, use of farm yard manure and decomposed organic matter not only increase the yield of crops but also increases the soil physical and chemical properties, soil organic matter, WHC of soil, microbial activity of soil and reduces soil compaction (Li *et al.*, 2021). Farmers adopt conservation tillage practices or partially plough the soil and leave at least 30% crops residues on soil surface to reduce decrease erosion, evaporation, and compaction of soil. Flooded rice fields create the suitable conditions for bacteria that produce the methane gas (greenhouse gas). So flooded rice cultivation should be discouraged and follow direct seeded rice or alternate wetting and drying method to decrease the methane gas emission and improve water use efficiency (Rehman *et al.*, 2011). Planting of crops (vegetables, wheat, maize, cotton, etc.) on permanent raised beds is a good soil and water management choice to increase water use efficiency, nutrient use efficiency, soil structure and finally crop yield in drought stress or waterlogged conditions (Hussain *et al.*, 2018). In addition, sowing on beds also decreases pesticides application due to less attack of pests and diseases because of improved aeration, reduced humidity, more interception of radiation on the crop canopy (Alwang *et al.*, 2018).

Cultivation of climate resilient crops

Crops that resilient to climate change have been suggested to growers to cope with or adapt to climate change. Superior genotypes with better resilience to biotic and abiotic (water, heat, and salinity etc.) stresses will perform a significant role in adaptation to climate changes. Adoption of climate-resilient crops, such as short stature and early-maturing varieties in cereals, heat, drought and salinity tolerant cultivars, rice varieties with submergence tolerance, and drought tolerant tuber or legumes crops can help the growers to cope with climate change (Acevedo *et al.*, 2020). Stress tolerant crop varieties have high potential to resist against stresses and less economic yield losses. Thus, better understanding of relevant stress related parameters and their relationship to particular environment is crucial to variety development. Sorghum, foxtail millet, pearl millet, sweet potato, cassava, sesame and cowpea are comparatively drought and temperature resistant crops (Vetriventhan *et al.*, 2016; Lieberman-Lazarovich *et al.*, 2021) compared to cotton, maize, rice, wheat, etc. In salt prone areas, sowing of salt tolerant crops can yield (Table 8) as compared to salt sensitive crops. Thus, the development of crop varieties demanding less water input to yield along with better site-specific production technology is very important to sustain crop production in drought prone regions. Similarly, advancement in the field of biotechnology and genomics seem viable to increase the crops performance under various stresses (Farooq *et al.*, 2015; Jat *et al.*, 2016; Farooq *et al.*, 2017).

Climate-smart agriculture

Climate-smart agriculture (CSA) is being adopted in the world to cope with the negative impacts of climate change on crops. Climate-smart agriculture is technique or agricultural system, which transforms and reorients the agriculture sector under new realities of climate change (Lipper *et al.*, 2014). Climate-smart agriculture enhances the productivity, increases resilience, reduces greenhouse gas emission where possible, and enhances food security and development goals (Lipper *et al.*, 2014; Rosenstock *et al.*, 2016; Taylor, 2018).

Table 8. High salt tolerance range of some agricultural crops (Qadir *et al.*, 2000; Machado and Serralheiro, 2017)

Salt level (dSm ⁻¹)	Crop name
8.0	Barley (<i>Hordeum vulgare</i> L.)
7.7	Cotton (<i>Gossypium hirsutum</i> L.)
6.8	Sorghum [(<i>Sorghum bicolor</i> (L.) Moench)]
5.0	Soybean [(<i>Glycine max</i> (L.) Merrill)]
7.0	Sugar beet (<i>Beta vulgaris</i> L.)
3.0	Rice (<i>Oryza sativa</i> L.)
6.0	Wheat
4.1	Asparagus (<i>Asparagus officinalis</i> L.)
4.9	Cowpea [<i>Vigna unguiculate</i> (L.) Walc]
3.4	Pea (<i>Pisum sativum</i> L.)
5.6	Rye grass (<i>Lolium perenne</i> L.)
6.9	Bermuda grass [(<i>Cynodon dactylon</i> (L.) Pers)]

The aim of CSA is to increase sustainability in agriculture and productivity or incomes from agricultural sector without imposing adverse effects on environment (Figure 5). In CSA, sustainable farm-based agricultural practices such as highly efficient water management practices, conservation tillage, residue management and agroforestry (Pye-Smith, 2011; World Bank, 2011). In CSA, the focus is given on the implementation of these farm and field practices, and the ways that can further improve these practices with respect to changing climate. These farm-based practices deliver two or three climate-smart-benefits. For instance, agroforestry system in some regions of Kenya provide timbers for income generation, fire-woods for domestic use and sequester carbon (4.07 Mg C/ha) (Reppin *et al.*, 2019). Likewise, different cropping practices in Zimbabwe and Tanzania considerably enhanced crop yield, income, and food security (Makate *et al.*, 2016; Kimaro *et al.*, 2019). Moreover, diversified cropping system increases resilience against stresses, enhances yields and quality, soil fertility, and reduces the pests and diseases (Truscott *et al.*, 2009; Lin, 2011). According to Kimaro *et al.* (2019), in Tanzania, agroforestry and conservation agriculture not only increased the maize yield and but also improved resilience and mitigation benefits. In north-west Ethiopia, farmers who followed CSA practices between 2015 and 2017, had higher farms productivity by 22% over non-adopters (Asrat and Simane, 2017).

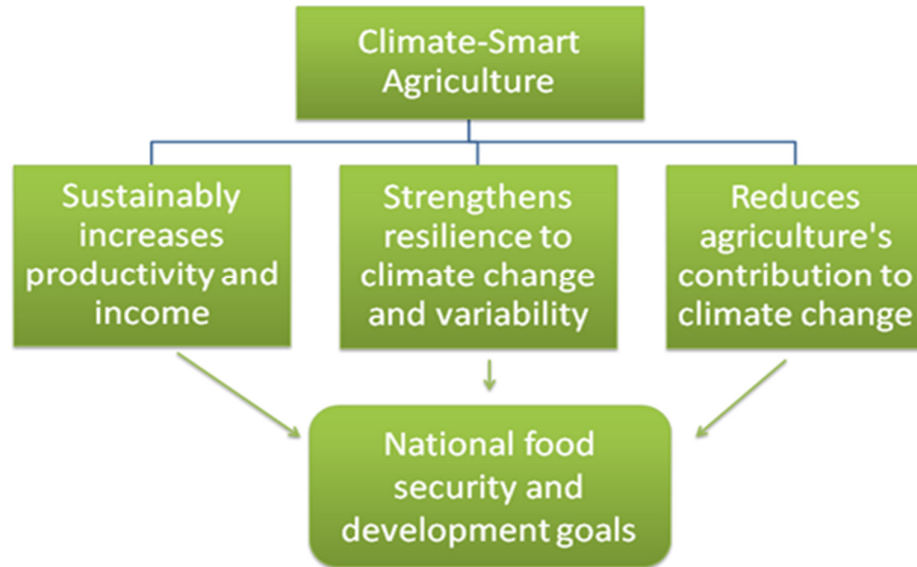


Figure 5. Benefits of climate-smart agriculture

Use of nanotechnology

Nanotechnology has the potential to transform and modernize the agriculture system by providing innovative tools for the management of water, plant nutrients, pests and diseases of crops in changing climate (Khan *et al.*, 2016; Elshayb *et al.*, 2022b; Al-Selwey *et al.*, 2023). Thus, it can increase growth, yields and quality of crops, and also plants tolerance or resistance to biotic and abiotic stresses (Tarafdar *et al.*, 2013). Use of engineered smart nanotools in high-tech agricultural system could be brilliant approach to make revolutions in agricultural practices to increase yields and quality, and thus decrease and/or eradicate the negative impact of current agriculture on climate (Sekhon, 2014; Liu and Lal, 2015; Elshayb *et al.*, 2022a; Al-Selwey *et al.*, 2023). Recent studies showed that application chitosan nanoparticles in tomato and maize, silver nanoparticles in wheat and multi-walled carbon nanotubes in broccoli significantly alleviated negative effects of salinity stress (Bruna *et al.*, 2016; Martinez-Ballesta *et al.*, 2016; Mohamed *et al.*, 2017; HernandezHernandez *et al.*, 2018; Abou-Zeid and Ismail, 2018). Similarly, zinc oxide nanoparticles increased seed germination in soybean under drought stress. Foliar spray of fullereneol and TiO₂ nanoparticles increased the final yield of sugar beet (*Beta vulgaris*) and linseed (*Linum usitatissimum*), respectively by alleviating the adverse impact of drought stress (Aghdam *et al.*, 2016; Borisev *et al.*, 2016). Alike, Iqbal *et al.* (2017) applied silver nanoparticles in wheat under heat stress conditions, and anthers reported an increase in growth and yield. Application of organic fertilizers and foliar spray of SiO₂ suspension at early growth and capitulum emergence stage of safflower increased the final yield (Janmohammadi *et al.*, 2016). In rice crop, application of nano-potassium fertilizer enhanced the growth, productive tillers and final grain yield (Lemraski *et al.*, 2017). Thus, nanofertilizers are quite effective, which reduces the nutrient deficiencies in the soil and increases the plants growth, development and final economic yields. Likewise, nanoencapsulated pesticides are also effective against pests and diseases, and have led to decrease the dosage of pesticides and increased crops yields (Bhattacharyya *et al.*, 2016; Nuruzzaman *et al.*, 2016).

Farmers training

Recently, some experimental reports showed the various strategies and practices used by farmers to tackle the climatic variations, are very helpful to increase resilience and yield (Table 9 and 10).

Table 9. Climate change adaptations for agronomic crops

Adaptations	Crop	Region or country	Reference
Plantation of heat and drought resilient varieties, variation in sowing dates and plant population	Wheat	Pakistan	Pimentel <i>et al.</i> , 2015; Ahmad <i>et al.</i> , 2018
Selection of heat tolerant crops/varieties, change in sowing date, more plant population	Wheat	Brazil	Pimentel <i>et al.</i> , 2015; Ahmad <i>et al.</i> , 2018
Direct sowing of rice instead of nursery transplanting, system of rice intensification (SRI), alternate wetting and draying for saving of water	Rice	Bangladesh	Latif <i>et al.</i> , 2005; Weerakoon <i>et al.</i> , 2011
SRI, direct sowing of seeds in filed instead of transplanting and puddling, alternate wetting and draying	Rice	Sri Lanka	Latif <i>et al.</i> , 2005; Weerakoon <i>et al.</i> , 2011
Direct plating, alternate wetting and drying	Rice	Pakistan	Rehman <i>et al.</i> , 2011
Sowing on raised beds. Selection of early maturing varieties. Valance use fertilizers	Maize	Nepal	CIAT, 2017
Plantation of early maturing varieties. Bed sowing, balance does of nutrients	Maize	Asia	CIAT, 2017; Ahmed <i>et al.</i> , 2019
Selection of drought and heat resistant varieties and 18% increase in plant population	Cotton	Pakistan	Rahman <i>et al.</i> , 2018
Management of ratoon crop. Sowing of sugarcane through pit planting method	S. cane	Swaziland	Knox <i>et al.</i> , 2010; Singh <i>et al.</i> , 2011
Pit plantation. Ratoon crop management		India	Knox <i>et al.</i> , 2010; Singh <i>et al.</i> , 2011
Agro-forestry (Wind barrier), integrated weed management, sowing of early maturing varieties	Grams	India	Ratnam <i>et al.</i> , 2011; Ahmed <i>et al.</i> , 2019

Table 10. Options for adaptation to climate change at farm level (FAO, 2015, 2020)

Risk response	Farmer strategies or practices
Change in climatic conditions and seasonality	Participation in monitoring schemes. Variation in planting date, sowing of food and feed crops. Plantation of many varieties, or cultivars of crops at farm. Selection of short duration and early maturing varieties. Sowing of climate resilient crops. Sowing of currently abandoned species or rare crops should be included. Early plantation and dry sowing techniques. Steps to word diversified cropping. Intercropping. Green manuring, crop rotation, Integrated system where livestock and/or aquaculture should be included to increase resilience. Modification in post-harvest practices
Change in rainfall and water availability	Modification in irrigation practices. Adopt improved water catchment and saving practices. Use wastewater and marginal water resources. Conservation of rainwater. Modification in agronomic practices. Follow reduced tillage, use of mulch material, and sowing of cover crops to decrease evaporation, integrated use of nutrients, use of farm yard manure and compost. Green manuring to increase soil organic matter that would increase soil fertility and water holding capacity
Increased frequencies of droughts, storms, floods, wildfire events, sea level rise	Participate in monitoring schemes with available. Follow water saving practices. Sowing of varieties tolerant to flooding, drought and saline conditions. Improved drainage practices, green manuring to enhance soil organic matter. Modern farm design to decrease waste of soil and gullyng. Take insurance policy to cover losses due to extreme events
Pest, weed and diseases, disruption of pollinator ecosystem services	Participation in risk monitoring and preventing programs. Follow integrated approach to control pests and disease. Conservation of natural ecosystem

Changes or adjusting sowing and harvesting time, selection of crops or varieties with short life cycles, rotation of crops, green manuring, water-saving techniques, and diversified cropping scheme are helpful for crops adaptability under changing climate (Table 3). For example, in Brazil and Pakistan, farmers have made adjustments in sowing time and plant population to adapt the climate change variability (Ahmad *et al.*, 2018; Ahmed *et al.*, 2019). Adjustment of sowing time is imperative to explore the full potential of the crop. High temperature during anthesis and grain filling stage of crops such as wheat and maize significantly decreases the grains development and yield. In arid regions, adjusting the sowing date with onset of rains would increase the crops growth and reduce yield losses. Plant population plays a key role for final economic yield in crops. For example, in wheat crop, if the number of tillers dies or remains unfertile due to terminal drought or heat stress significant yield losses would occur (Ahmed *et al.*, 2019). Thus, the appropriate plant population reimburses the yield loss. In sugarcane, ratoon crop requires less tillage practices and is more adaptive to climate vulnerabilities, fuel consumption is less that leads to decline greenhouse gas emission. Pit planting is another new method of sowing in sugarcane that reduces weed infestation, increases irrigation water use efficiency, a greater number of millable canes and better quality of cane juice (Yadav, 2004).

Conclusions

Climate change can disturb the environment and pose threats to the agricultural system and food security. The increase in the earth's temperature resulted in variations in the precipitation, increased heat waves, and droughts in arid and semi-arid areas of the world. The variability in global climate change has both positive and negative consequences but the negative impacts are more thought-provoking. The climatic changes have increased the growth of weeds, insect pests and diseases in many geographic areas, and increased problems for sustainable agriculture. Therefore, how to ameliorate or eliminate impact of changing climate on agricultural system and what strategies we should follow to minimize yield losses is very thoughtful. Hence, there is a need to focus on technologies, strategies and agricultural practices that optimize the plant growth, reduces the adverse impacts of biotic and abiotic stresses. Application of novel cultural methods, diversified cropping schemes, pattern, and various conventional and non-conventional recent techniques or approaches such as functional genomics and transgenic approaches, biotechnology and nanotechnology to develop climate resilient varieties to sustain agriculture with respect to climate change. Similarly, agronomic approaches such as adjusting sowing dates, nutrient management, water management, use of plant hormones and osmoprotectants have been significantly applied to mitigate the adverse effect of climatic parameters. Knowledge of nanotechnology and climate-smart agriculture can be used to battle against climate change.

Authors' Contributions

The author read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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