REVIEW

Impact of Climate Change on Dryland Agricultural Systems: A Review of Current Status, Potentials, and Further Work Need

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Abstract

Dryland agricultural system is under threat due to climate extremes and unsustainable management. Understanding of climate change impact is important to design adaptation options for dry land agricultural systems. Thus, the present review was conducted with the objectives to identify gaps and suggest technology-based intervention that can support dry land farming under changing climate. Careful management of the available agricultural resources in the region is a current need, as it will play crucial role in the coming decades to ensure food security, reduce poverty, hunger, and malnutrition. Technology based regional collaborative interventions among Universities, Institutions, Growers, Companies etc. for water conservation, supplemental irrigation, foliar sprays, integrated nutrient management, resilient crops-based cropping systems, artificial intelligence, and precision agriculture (modeling and remote sensing) are needed to support agriculture of the region. Different process-based models have been used in different regions around the world to quantify the impacts of climate change at field, regional, and national scales to design management options for dryland cropping systems. Modeling include water and nutrient management, ideotype designing, modification in tillage practices, application of cover crops, insect, and disease management. However, diversification in the mixed and integrated crop and livestock farming system is needed to have profitable, sustainable business. The main focus in this work is to recommend different agro-adaptation measures to be part of policies for sustainable agricultural production systems in future.

Keywords Cropping systems · Climate change · Precision agriculture · Management options · Diversification

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Introduction

A farming system (FS) is an organised way of operating a piece of land to grow crops and raise livestock or both. It includes everything on farm and outside the farm related to farm operations. FS could be categorized into (i) extensive and intensive FS; (ii) subsistence and commercial FS; (iii) dry and irrigated FS; (iv) individual and multiple FS and (v) arable farming, livestock rearing and mixed farming. All of these categories might require similar development strategies and interventions to have sustainable outcomes (Byerlee & Husain, 2008). Thus, FS is an approach of developing farm strategies based on principles of productivity, profitability, stability and sustainability. Farming systems research (FSR) is an important area to be considered for the improvement of agriculture as whole. The three main elements of FSR as proposed by Simmonds, (2008) are (i) FSR sensu stricto (FS deep analysis as they exist); (ii) On farm research with farming systems perspective [OFR/FSP] and (iii) New farming systems development (NFSD) as shown in Fig. 1. However, component four needs to have new farming systems (NFS) under additional management and climate change scenarios. Systems modeling has been used in FSR, and include linear statistical modeling, mechanistic modeling, and integrated, bioeconomic or socio-ecological models (Feola et al., 2012; Rupnik et al., 2018). Since FSR is an interdisciplinary approach, its application to simulation models can be adopted to address trans-disciplinary tasks. In the past, different methods and approaches of decision support systems were used to answer why and how questions that include probabilistic and optimization models (Hindsborg & Kristensen, 2019), supervised learning models (Witten & Frank, 2002), Bayesian models (Wang et al., 2012), time series analysis (Michel & Makowski, 2013) and genetic programming (Samadianfard et al., 2022). Silva and Giller, (2021) reported about what crop models can and can't (yet) do. They explored current trends in crop modeling after reviewing research presented in the 2nd International Crop Modeling Symposium (iCropM2020). Most of the focus of the presented work was on climate change, adaptation and impact assessment, and much less on food security or policy. Similarly, more attention was on field level work with less attention on farming systems investigations. There were few contributions related to model improvement with little work about nutrient limitations, pest or disease impacts. Crops models can be used to devise hypotheses and drive new experiments to fulfill above mentioned gaps. Furthermore, outcomes of the models should be provided to policy makers so that intended purposes can be achieved. Finally they reported the importance of cross-scale and interdisciplinary efforts
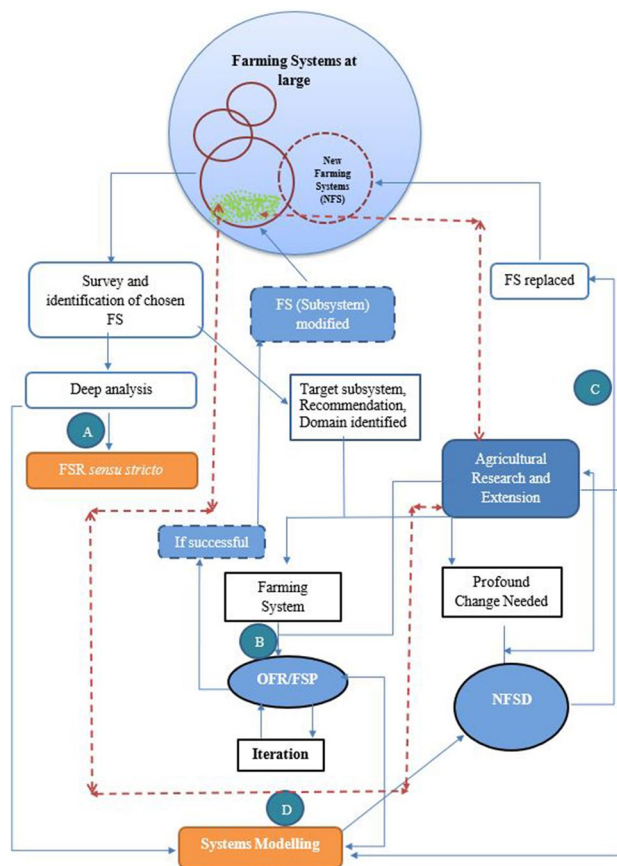

Fig. 1 The four main elements of framing systems research (FSR) (**A** FSR sensu stricto, **B** On farm farming system research, **C** New farming systems development (NFSD) and **D** Systems Modelling [Modified from Simmonds, (2008)]

with direct engagement of stakeholders to address the grand challenges faced by food and agricultural systems in the coming century.

South Asia is one of the important dry land agricultural regions in the world. It covers about 3% of the world's land area and is home to a quarter of the world's population. Climate change in the form of rise in temperature is hitting the region very hard. According to the World Bank, average annual temperature of the region will increase between 1.5 to 3 °C (hotspot) by 2050 in comparison to 1981–2010 if no action is taken to minimize C emissions (Hoegh-Guldberg et al., 2018). This could put half of the world's population in trouble this hotspot could lead to lower crop yield and declined crop productivity (Ainsworth & Ort, 2010). Thus, sustainability as a component of FSR is needed to mitigate climate change (van Zonneveld et al., 2020) through building strong, resilient system by considering different factors (Fig. 2) (van Zonneveld et al., 2020). Interactive studies of these components, with the consideration of farmers, as a basic foundation is important for designing a logical framework for FSR (Fig. 3). Hence, key characteristics of FSR

Fig. 2 Factors used to translate worldview concept into conceptualizing research and practical inquiry
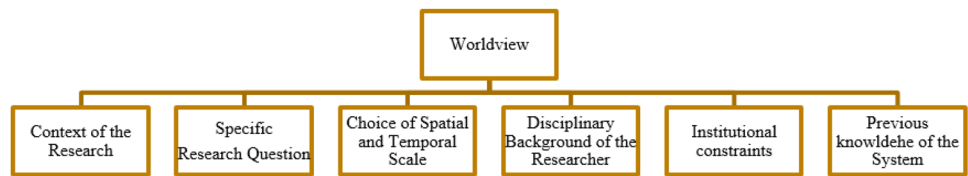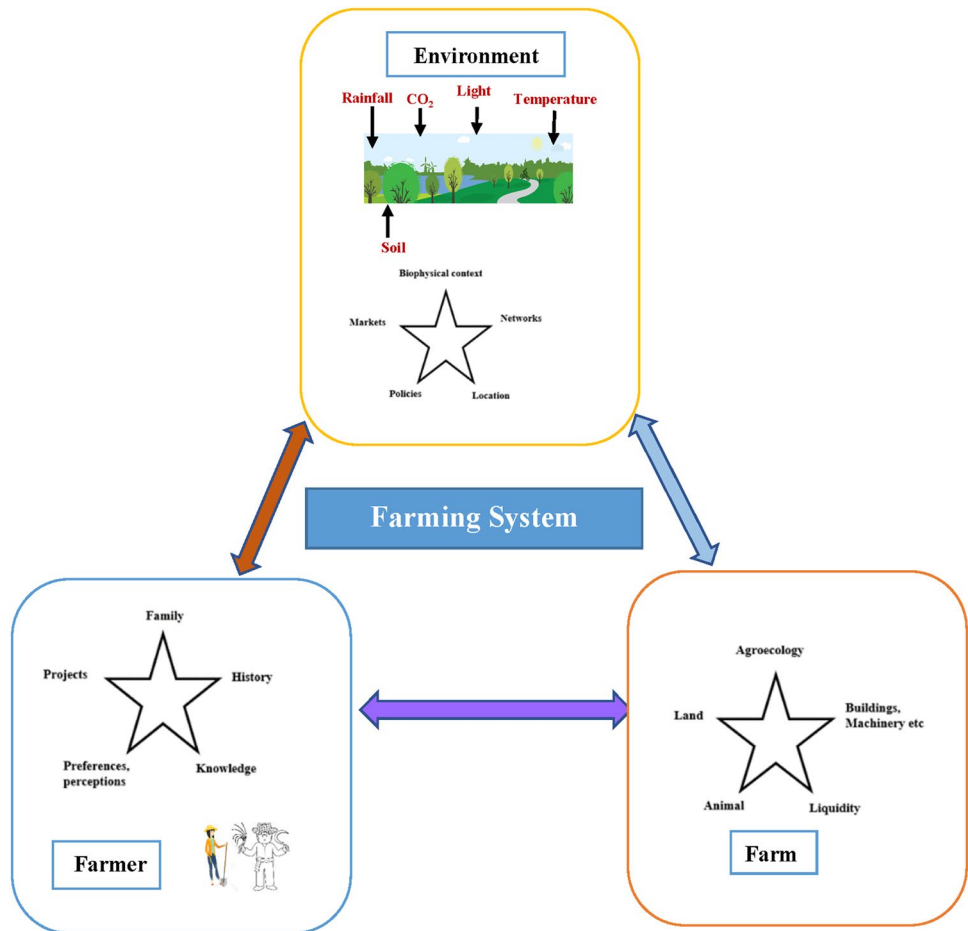

Fig. 3 Set of interacting factors (Environment, farmers and farm) for farming systems analysis

are systems thinking, and interdisciplinary and participatory approaches, and these characteristics are missing in most of the South Asian developing countries (Ogada et al., 2020).

Changes in the climatic variables (e.g. temperature and rainfall) have been observed at shorter time frames e.g. month, a season, or a year, as well as on longer time span, i.e., decadal for South Asian countries (Sivakumar & Stefanski, 2011). This variability for the shorter time span is called climate variability, however, for longer time spans it is called climate change. Both are big concerns across the globe as well as for South Asian countries (Arora, 2019). Extreme climate events at the time of wheat harvesting resulted in huge damage to the major staple crop of the region as well as to other crops (Ye et al., 2020). However, no adaptation options are currently available to give relief to the farmers. The Intergovernmental Panel on Climate Change (IPCC)

defines climate change as any change in climate over time due to human activity or natural variability. It has been proven that most of the changes in climatic parameters are mainly due to human activities on shorter time scale. As increasing concentrations of greenhouse gases (GHGs) trap extra heat in the earth's atmosphere, higher temperature results which is called global warming or enhanced greenhouse effect. This enhanced effect leads to changes in the distribution of rainfall, storm intensity, changed pattern of atmospheric circulation and higher temperature at the land/sea surfaces. Most of the earlier researchers have linked these physical and biological system changes to warming temperature (Rosenzweig et al., 2008). The IPCC in their reports predicted 1.8–4.0 °C increased temperature in 2090–2099 depending upon which scenario of future GHGs emissions was used to drive climate models (IPCC,

2007). GRID-Arendal (http://www.grida.no/about), which was established in 1989 to support environmentally sustainable development in collaboration with UN, suggested ways to control global warming.

The temperature increase impacts would be more severe for smallholder and subsistence farmers due to their lack of adaptive capacity particularly in the Indo-Gangetic Plain (Kumar et al., 2020). Since these extreme climatic events will significantly impact food production, food security in the future will become an increasingly critical issue (Shi et al., 2021). Food security is a great challenge facing humankind (Porter et al., 2014). United Nations, in their Sustainable Development Goals (SDGs) put food security first (Tamburino et al., 2020). SDGs replaced Millennium Development Goal Target 1C with an emphasis not only on hunger, but also on sustainability and nutrition (Pedercini et al., 2020; Qu et al., 2020). SDG 2 deals with zero hunger. Thus to achieve food security, improved nutrition and promote sustainable agriculture, application of a FS approach is essential (Allen et al., 2019; Eyhorn et al., 2019). This could be challenging due to rising food demand, changing climate and degraded resources (Mall et al., 2017). Godfray et al., (2010) reported a serious situation with billions of people suffering from nutritional deficiencies and malnutrition. Sustainable, climate-resilient farming systems are needed for nutritional quality and food security as mentioned in SDG (Altieri et al., 2015). This is quite a big challenge as the number of chronically undernourished people is rapidly increasing (Witten & Frank, 2002). Food security is a massive problem and it is worsened by climate change. Schmidhuber and Tubiello, (2007) concluded that the overall impact of climate change on food security will differ across regions and over time. They further reported that climate change will adversely affect food security and it will increase the dependency of developing countries on imports. Furthermore, Tesfaye, (2021) reported that climate change will threaten food security in the hottest wheat growing regions of world. Thus technological options are needed to mitigate climate change impact on food security. These options include soil and crop innovation and agricultural land reclamation (Horton et al., 2021). Similarly, recognizing the FS trajectory is necessary if future food needs are to be met. Sustainable intensification (SI) could be an option as it provides more output from the same area of land while minimizing negative impacts to the environment (Pretty et al., 2011). The main aim of SI is to increase yield without adverse environmental impacts and the cultivation of more land, or increased production from existing farmland, while minimizing environmental pressure.

South Asia, which has 20% of the world's population, faces severe challenges in agriculture mainly due to climate variability (Sivakumar & Stefanski, 2011). It had been documented earlier that extreme climate events in the form of heat and drought will create food security issues (Tesfaye, 2021). Most South Asian regions have witnessed variability in temperature and rainfall that manifested in frequent heat waves, droughts and floods leading to great damage to agriculture (Almazroui et al., 2020). Similarly, the world's largest river systems (Indus, Ganga and Brahmaputra) are in this region with maximum land usage for agriculture. Thus, people's livelihoods depend upon management of available natural resources, i.e., soil and water. However, sustainability of these resources is threatened by extreme climate events (Ali et al., 2019). Likewise, due to the high population pressure and poor management water resources are becoming stressed (Birendra et al., 2021). Since most of the land (about 60% of the cropped area) in this region is rainfed, the agriculturally based economy of these countries is heavily dependent upon summer rainfall, i.e., monsoons (Arshad et al., 2018; van Ogtrop et al., 2014). This region is a paradox as it enjoys high economic growth but suffers from food and nutritional insecurity, extreme poverty, deterioration of natural resources and climate change (Stephens et al., 2018). The management of available natural resources in dryland areas is urgent, as it will play a crucial role in the coming decades to ensure food security and reduction in poverty (Baig et al., 2013). Thus, our focus is to review gaps, and to suggest technology based collaborative intervention such as water conservation, supplemental irrigation, foliar sprays, integrated nutrient management, resilient crops and cropping systems and precision agriculture (modeling and remote sensing) that can support agriculture of the South Asian region under changing climate.

Gaps in Dryland Farming Systems

Regions where the ratio between evaporation and evapotranspiration is less than 0.65 are called dryland. Dryland farming is a special case of rainfed agriculture. Dryland farming has been practiced primarily in arid and semiarid regions where annual rainfall is about 20–35% of potential evapotranspiration. Moisture stress is the main factor limiting yield in this region.

1. Hence, successful management of dryland framing system depends upon (i) retention of precipitation on land; (ii) reduction in evaporation and (iii) utilization of drought tolerant crops. This is possible through SI which is described as raising yields without additional land conversion and without harming the environment (Cassman & Grassini, 2020). Pervez Bharucha et al., (2021) produced 100 questions through a horizon scanning method that point to the gaps in dryland farming. These were further categorized into four sections i.e. (i) natural resource inputs; (ii) crop and livestock produc-

tion; (iii) agricultural development and policy and (iv) markets and consumption. This important work identified major gaps that need to be filled to have SI in dryland framing systems. Furthermore, crops grown under dryland conditions have a larger yield gap that could be narrowed with optimal rotations (Hochman et al., 2020) and through the use of recommended management practices e.g. improved cultivars, site specific nutrient managements through use of precision agriculture and water harvesting. Therefore, in order to design appropriate research and hypotheses we need to use process-based models which can easily test what-if scenarios. Effect of climate change

Variation in climatic conditions is one of the red-hot subjects in every discipline and it can be quantified by using models as mentioned above. Climatic variability and change is affecting food production at local, regional and continental levels, therefore, influencing the lives of all human beings, plants and livestock systems (Williams et al., 2020; Ahmed 2020). Flora and fauna are particularly influenced by climate change because of life-threatening variability in maximum and minimum air temperature and precipitation patterns in all cropping systems (Challinor et al., 2014; Hutchings et al., 2020). Worldwide, the thermal trend is the greatest ecological challenge in the current century. For example it leads to enhanced mean air temperature in major cropping systems (Ali et al., 2019). The impact of high temperature (HT), drought (D), or elevated CO_2 [eCO_2] is discussed further in the following sections.

Overview of Responses to High Temperature (HT), Drought (D), or elevated CO_2 [eCO_2]

The influence of climatic variables (e.g. air temperature, precipitation and [eCO_2]) on cropping systems is complicated. These variables play a significant part in rainfed cropping systems (Williams et al., 2020). Warming stress conditions cause decreases in crop productivity (Zampieri et al., 2020). Higher air temperature stress from sowing to maturity restricts crop growth and shortens the crop cycle (Hatfield & Dold, 2018). Higher temperature than optimum hastens anthesis and induces floral aberrations (e.g., stamen hypoplasia and pistil hyperplasia), which negatively impacts proper reproductive accomplishment in cereal crops. Furthermore, very poor dehiscence of anthers, poor pollen grain formation and reduced viability of pollen are recognized as primary causes of stress-induced unproductiveness and kernel abortion in maize and wheat (He et al., 2018). During the grain filling period, higher air temperature stress negatively influences grain quality. Too little water has a greater negative influence than high-rainfall events in various cropping systems (Jalota et al., 2013). Serious water

shortage during kernel filling resulted in earlier senescence and a shorter grain filling period as well as lower green flag-leaf area perseverance in cereal crops (Asseng et al., 2019). Meanwhile, [eCO_2] has shown a positive effect on crop biomass production but higher concentrations of CO_2 lead to elevation of tissue temperature. However, interactive effects of these climatic variables on crop production might be different (Rajwade et al., 2015).

High Temperature and Drought Interaction

High air temperature and drought stress are now frequent events. In most cropping systems, drought has been intensified due to higher air temperature stress (Högy et al., 2013). Mittler, (2006) documented the effect of multiple abiotic stresses e.g. combination of HT and D stress on crops under field conditions. The combined impact of HT and D stress on crops like barley and wheat was found to be more severe as compared to a single stress (Shah & Paulsen, 2003). Rang et al., (2011) reported that HT and D interact and it has been seen in most parts of Europe where the interaction resulted in decreased productivity of wheat and maize (Ciais et al., 2005). In Asia HT and D stress was seen during the critical developmental stages of rice which resulted in major losses in the rice based cropping systems (Wassmann et al., 2009). Zhang and Huang, (2012) documented yield reduction in three major cereals i.e. rice, wheat and maize, in the northern part of China due to HT and D stress. The combined detrimental effect of HT and D on cereal, i.e., rice, sorghum, wheat, barley, and maize, was more severe as compared to individual HT or D impact (Cotter et al., 2020). Cohen et al., (2020) conducted meta-analysis of HT and D stress on crop yield and yield components. They concluded that a significant decrease in crop yield was due to the combined impact of HT and D on harvest index, life cycle, seed number, seed size and seed composition. The consequences of drought are amplified at higher temperature than lower air temperature, worldwide. The synergistic interactions of higher temperature and drought showed a decreased production more through the mutual stresses than by either stress alone, and that much of the influence was on physiological processes in crop plants in arid environments (Amarasingha et al., 2015).

Interactive Impact of High Temperature and Drought on Water Use Efficiency Water use efficiency (WUE) is the ratio of the unit crop dry matter produced per unit of water used. Blum, (2009) reported that WUE increases under D while it decreases under HT stress. Rollins et al., (2013) recorded a 45% decrease in WUE of grain yield (g grain L^{-1}) in barley due to HT × D stress while Shah and Paulsen, (2003) reported, -34 to $+24\%$ change in WUE (g grain L^{-1}) in wheat. Future climate change might increase the frequency and intensity of extreme events like drought which

will limit crop growth and yields. Increasing WUE and yield per unit of water is one of the most important challenge in dryland farming (Yulianti et al., 2016). Higher air temperature and drought stress interaction might reduce WUE, as warming trend will lead to higher evapotranspiration (ET) in the future. Furthermore, the interaction will also increase crop water demand in dry and windy situations as compared to humid and cool climatic circumstances (Porter, 2005). In South Asia, lower WUE and productivity in most of the cropping systems are mainly because of extreme climatic shocks. This will further lead to problems related to food security, as climate change induced crop productivity will negatively impact food production and prices in all south Asian countries (Thompson et al., 2017). Similarly, water stress significantly impacts physiological mechanisms of crops grown in dryland cropping systems. Their results showed that interactive stress resulted in 60–92% reduction in photosynthesis as compared to non-stressed conditions. Additionally, 28% rise in WUE was indicated under drought stress at middle/suboptimal level, however, it was reduced by 35% at high temperature (Kaur et al., 2012). Williams et al., (2020) studied crop yield, WUE, precipitation capture and soil water storage in a dryland cropping system under a given set of crop sequence treatments. WUE was calculated by using following formulae:

$$\text{WUE} = \frac{\text{CY}}{\text{HHP} + \theta_d} \qquad (1)$$

where CY = Crop yield, $HHP + \theta_d$ = Crop water use i.e. HHP = Sum of the precipitation that fell between harvests. (HHP) and θ_d = Soil water depletion in mm of soil water depleted between seeding and harvest.

Additionally, precipitation use efficiency (PUE) from seeding to harvest was calculated as:

$$\text{PUE}_{\text{STHP}} = \frac{\text{CY}}{\text{STHP}} \qquad (2)$$

where STHP = Amount of precipitation from date of sewing to harvest.

However, PUE over the year (PUE$_{\text{CYP}}$) could be calculated by using the following formula:

$$\text{PUE}_{\text{CYP}} = \frac{\text{CY}}{\text{CYP}} \qquad (3)$$

where CYP = Crop year precipitation in mm.

Soil water use efficiency (SWUE) can be calculated as used by Williams et al., (2020):

$$\text{SWUE} = \frac{CY}{\theta_{\text{depletion}}} \qquad (4)$$

where $\theta_{\text{depletion}}$ = Soil water depletion (mm) between seeding and harvest of a crop.

The work of Williams et al., (2020) suggested that in order to increase WUE, PUE, SWUE and crop productivity we should increase diversification and improve conservation of water under low rainfall dryland conditions. Furthermore, they also suggested the use of higher yielding, drought tolerant crop varieties to improve climatic and economic resilience in dryland cropping systems.

Interactive Impact of High Temperature and Drought on Nitrogen Use Efficiency Nitrogen (N) is very important for all type of farming systems but its losses in the form of volatilization and leaching are big environmental concerns (Hutchings et al., 2020). Ammonia (NH_3) emissions and nitrate (NO_3^-) pollution are big threats to the environment and to human health, and their primary source is the agricultural sector (Schullehner et al., 2018). Meanwhile, livestock production has a large environmental footprint (Leip et al., 2015). Environmental performance of crop production systems can be monitored by nitrogen use efficiency (NUE), which is a very useful indicator (Antille & Moody, 2021). Nitrogen use efficiency is negatively affected under higher temperature and drought conditions (Hutchings et al., 2020). NUE can be calculated as proposed by Rahimizadeh et al., (2010):

$$\text{NUE} = \frac{G_Y}{N_{\text{supply}}} \qquad (5)$$

where G_Y = Grain yield and N_{supply} = Soil N content at sowing + total N fertilizer applied.

Cammarano et al., (2020) concluded that negative impacts of rainfall and temperature on crop production could be offset by applying additional water and nitrogen. Nitrogen leaching and NUE strongly correlated as higher leaching results to lower NUE. Webber et al., (2015) simulated water and N-water limited yield across Europe and concluded that future N fertilization rates need to be assessed through integrated approaches. Fagodiya et al., (2017) reported the alteration of global N cycle due to global warming and climate change. They concluded that N fertilizer acts as a source of global warming (due to N_2O emission) as well as cooling [NH_3 (Reduced N compounds) and NOX (oxidized N compounds)]. Thus, they recommended that both warming and cooling effects should be studied in the future. The impact of climate change on crop duration/yields, water/N balance and NUE in a rice–wheat cropping system was studied by Jalota et al., (2013) using the CropSyst model. The results showed that around 20 and 29% of applied N goes to gaseous loss while 10 and 0% to leaching, 69 and 72% to nitrogen uptake and 0 and 2% to immobilization in rice and wheat crops, respectively. This confirms the earlier findings where they reported 17–28% gaseous loss (Reddy & Patrick, 1975), 60–77% as N uptake (Aulakh et al., 2000) and 9–36%

as leaching linked with the percolation rate of water in soil (Vlek et al., 1980).

Interactive Impact of High Temperature and Drought on Agronomic Efficiency: Yield and Yield Components Crop yield components and yield depend on air temperature during the crop growing season. An increase in air temperature can have positive or negative effects on agronomic efficiency and crop water need (Rajwade et al., 2015). It has been reported that HT can cause earlier crop maturity due to fast completion of different phenological stages (Hyles et al., 2020). Earlier maturity results in a reduction in crop yield and quality (Högy et al., 2013). Zhao et al., (2017) evaluated the impact of global temperature increase on the production of four major crops i.e. wheat, rice, maize, and soybean. They concluded that each degree-Celsius increase in global mean temperature would, on average, reduce global yields of wheat by 6.0%, rice by 3.2%, maize by 7.4%, and soybean by 3.1%. They reported this impact without adjustments for CO_2 fertilization, effective adaptation, and genetic improvement. Heat and water stress in combination have significant strong impacts on crop yield, and this combination prevails in dryland agriculture nowadays. Ostmeyer et al., (2020) reviewed the impacts of heat, drought, and their interaction with nutrients on crop physiology, grain yield and quality of crops. They concluded that drought stress impacts can be ameliorated by the use of nutrients. Knox et al., (2012) studied the projected impacts of climate change on the yield of eight major crops in Africa and South Asia. They reported that overall yield change for all crops in each region was − 8% by 2050. However, they estimated − 17%, − 5%, − 15% and − 10% mean yield change across Africa for wheat, maize, sorghum and millet respectively. The yield change in South Asia was − 16% (maize) and − 11% (sorghum). They recommended that the deleterious effect of climate change could be mitigated by adaptation options such as shifting planting dates, modifying crop rotations, development of new crop varieties and expansion of irrigation infrastructure. However, these adaptations require investments in resource poor countries.

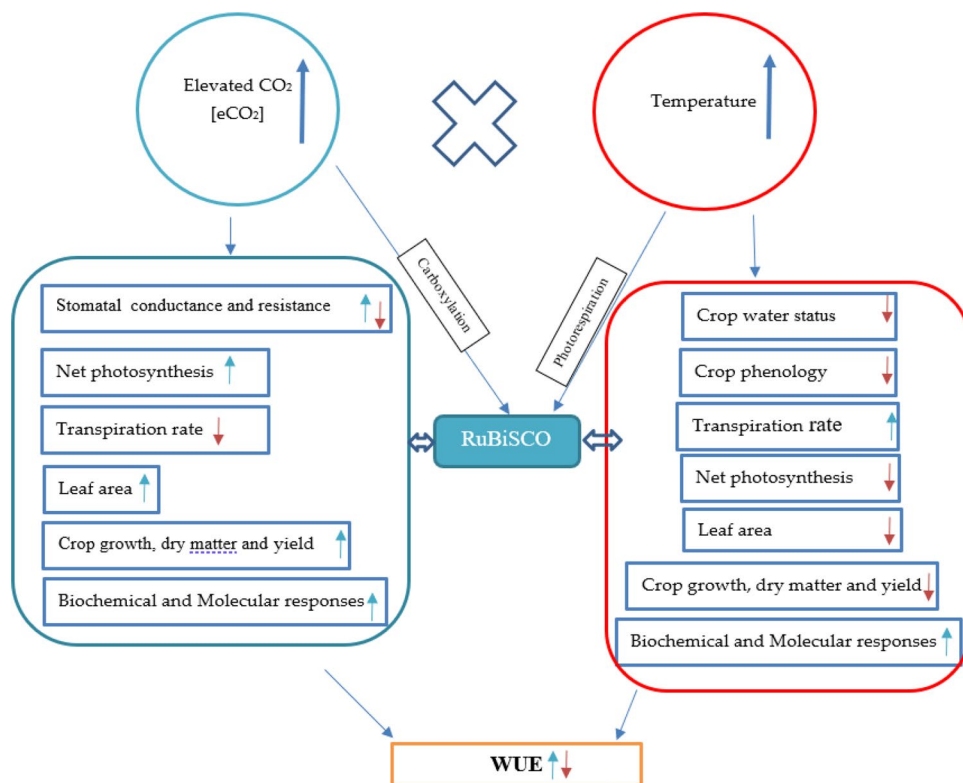**High Temperature and Elevated CO_2 Interaction**

Carbon dioxide affects crop physiological processes directly or indirectly. The direct effect include photosynthesis and stomatal physiology (Kadam et al., 2014). Allen, (1994) elaborated the direct effects of CO_2 on crops and indirect effects of CO_2 through possible climate change. Elevated CO_2 has shown a positive effect on growth and development, which was greater during earlier growth stages as compared to later growth stages. It is now well known that increased CO_2 concentrations result in greater production of carbohydrates and biomass (Thompson et al., 2017). Similarly,

enhanced yield and crop productivity have been reported due to higher photosynthesis under [eCO_2] in many crop species (Bocianowski et al., 2018). However, Mittler et al., (2012) reported negative impact on crop yield under increased temperature because of [eCO_2]. An average 3 to 5 °C rise in temperature has been documented due to the doubling of CO_2 concentration (Arora & Kumar, 2018). The interactive effect of temperature and [eCO_2] results in the partial closure of stomata which could reduce transpiration and lead to changes in leaf temperature in all cropping systems. Winslow et al., (2003) documented that [eCO_2] benefits can be offset by higher temperature since a rise in temperature can cause shortening of crop growing period. The interactive effect of high temperature and [eCO_2] on WUE, nitrogen use efficiency and agronomic efficiency has been highlighted further in this section.

Interactive Impact of High Temperature and Elevated CO_2 on Water Use Efficiency The intearctive effect of high tempearture and [eCO_2] on WUE is shown in Fig. 4. The increase or decrease in WUE will be due to direct or indirect effects of these two variables on physiological, biochemical and crop growth traits. Similarly, these two variables have linkage with RuBiSCO (Ribulose-1,5-bisphosphate carboxylase/oxygenase) either through carboxylation or photorespiration. RuBiSCO is an enzyme involved in the first major step of carbon fixation. It catalyzes the carboxylation of RuBP (Ribulose-1,5-bisphosphate). Higher tempearture results in photorespiration by promoting oxygenation reactions as compared to [eCO_2] where carboxylation increases (Ainsworth et al., 2020). Higher WUE due to [eCO_2] could be because of decreased stomatal conductance and density which will not be the case under higher tempearture (Maestre et al., 2012; Olivoto et al., 2017). Polley, (2002) reported that [eCO_2] could counteract the higher tempearture effect on evapotranspiration.

Interactive Impact of High Temperature and Elevated CO_2 on Nitrogen Use Efficiency Nitrogen use efficiency of agricultural crops at local, regional and continental levels is negatively influenced by the interactive effects of [eCO_2] and other climatic variables. The role of CO_2 is very crucial in crop physiology, by affecting photosynthesis, crop growth and yield (Wei et al., 2018). It has been documented that stomatal activity, biomass production and WUE are highly correlated. However, [eCO_2] leads to lower nutrient uptake, particularly N, because of restricted root nutrient uptake and a dilution effect (Myers et al., 2014). Li et al., (2019) reported higher photosynthetic rate and lower chlorophyll content in the flag leaf of wheat under [eCO_2] as compared to ambient CO_2. Additionally, higher N fertilization resulted in a higher grain number per spike in [eCO_2]. Thus, high temperature and [eCO_2] have negative impacts

Fig. 4 Elevated CO_2 and temperature interactive effect on WUE (Upward arrows show higher impact while downward arrows show lower impact)

on nitrogen use efficiency, which can cause poor grain quality in the future (Jobe et al., 2020).

Interactive Impact of High Temperature and Elevated CO_2 on Agronomic Efficiency: Yield and Yield Components High temperature with [eCO₂] resulted in higher yield and yield components (Challinor et al., 2014). Some positive and some negative effects of a combination of high temperature and [eCO₂] on canopy photosynthesis (μmol m^{-2} s^{-1}), leaf photosynthesis (μmol m^{-2} s^{-1}), WUE (mmol mol^{-1}) and photosynthetic WUE was reported in earlier work (Prasad & Jagadish, 2015). However, the interactive effect of high temperature and [eCO₂] have shown positive effects on wheat grain yield (+6% to+40%) as well as rice yield (+69%) (Rakshit et al., 2012). The interactive effect of high temperature and [eCO₂] on the grain weight of crops remained negative (Bocianowski et al., 2018). Roy et al., (2012) reported spikelet sterility in rice due to the interactive effect of high temperature and [eCO₂] which is the major cause of yield reduction.

Elevated CO_2 and Drought Interaction

Elevated CO_2 and drought increases WUE from leaf level to ecosystem level in C₃ as well as in C₄ plants (Kumar et al., 2019). Synergistic responses have been observed between [eCO₂] and drought for WUE among most plants (Noor et al., 2003). In C₃ plants [eCO₂] increases WUE

through fixation of carbon and decreased transpiration. However, in C₄ plants increased WUE is mainly due to the decreased transpiration rate. Conley et al., (2001) documented increased WUE in sorghum by 16 and 17% and 47% to 52% for C₃ cherry under irrigated and dry conditions respectively. This was mainly due to a decrease in evapotranspiration (Hussain et al., 2013). In sugarcane, a C₄ plant, stomatal conductance (g$_s$) and WUE under severe drought and ambient CO_2 decreased by 95% and 93% respectively in comparison with control. However, under drought stress and [eCO₂] the drop in g$_s$ and WUE was 80% and 26% of the controls values respectively (Vu & Allen, 2009). Wall et al., (2011) reported drought avoidance in barley due to [eCO₂]. It causes 34% reduction in g$_s$ and conservation of water for a longer period under water stress conditions. Another important adaptation feature is an increase in stomatal size and a decrease in stomatal density due to [eCO₂] and moderate water stress (Fig. 5).

Dryland Cropping System and Soil

Dryland agriculture accounts for 80% of the world's cultivated land and contributes to 60% of the total crop production (UNESCO, 2009). Low crop productivity in rainfed agricultural systems is mostly due to poor soil fertility. The impact of climatic variables (temperature, precipitation and [eCO₂]) on the soil of rainfed cropping system
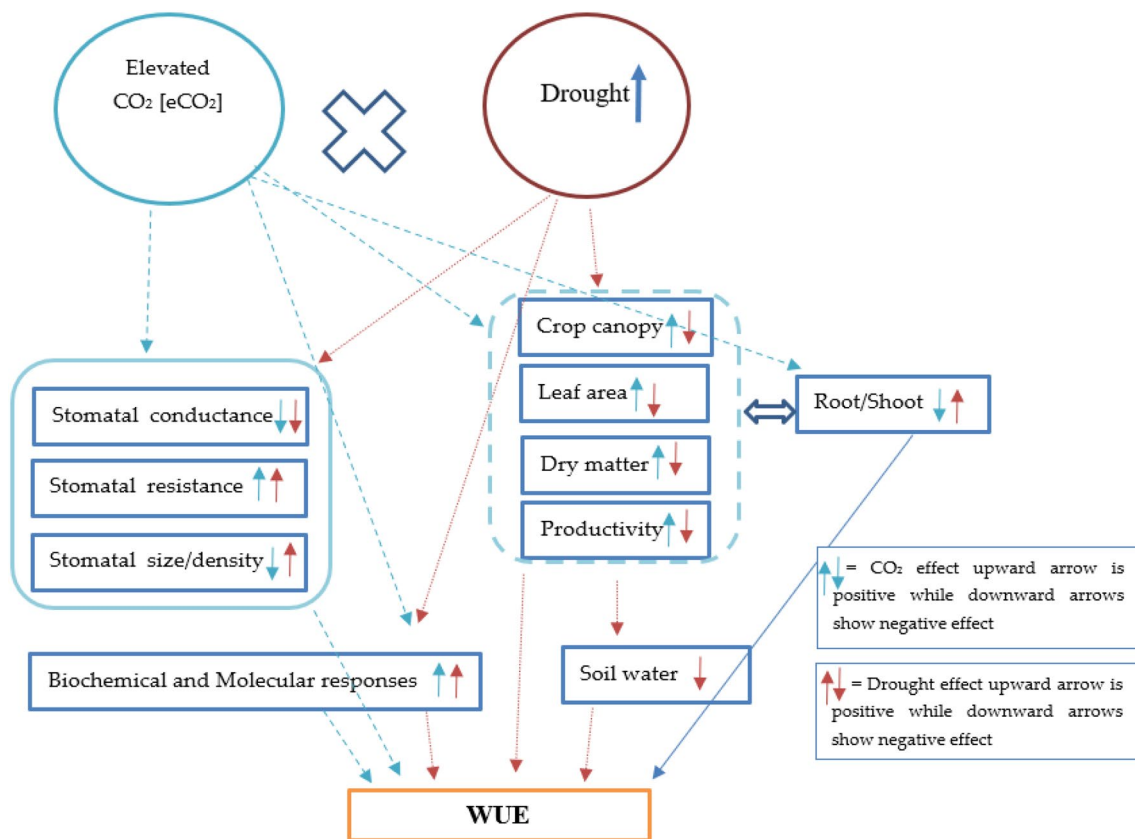
Fig. 5 Elevated CO_2 and drought interactive effect on WUE

is evident at different degrees and levels. Generally, the main question researchers look for is what the impact of global warming on the amount of carbon in the soil will be. Under current cultural practices, e.g. chisel and deep ploughing in rainfed cropping systems there is chance of increase CO_2 emissions from soils (Farina et al., 2011). Similarly, due to increased global warming and drought in the future, there is a possibility of more loss of soil organic carbon (SOC) because of higher soil respiration as shown in Fig. 6. Crowther et al., (2016) quantified global SOC losses in response to warming. They reported more soil carbon losses at higher latitude. However, they found a positive association between HT and SOC loss. Generally, higher temperature and [eCO$_2$] could promote crop productivity and SOC. However, higher temperature promotes soil organic matter decomposition and loss of SOC. A positive interaction between HT and [eCO$_2$] for crop growth, yield and SOC has been reported (Kimball, 2011). Pugnaire et al., (2019) reviewed plant soil feedback interactions under climate change. Climate change affects the plants' inputs to soil through litter and rhizodeposits. They reported that drought led to the provision of low-quality litter, low nutrient content to soil and lower decomposition rate.

Soil is home to millions of fungi, billions of bacteria and other microorganisms, and extreme climate events are showing detrimental effects to these organisms. Since these microorganisms play an important role in C and nutrient cycling, their absence or deficiency can cause poor soil fertility and productivity (Pugnaire et al., 2019). It has been well documented that long term warming causes changes in microbe communities (Cavicchioli et al., 2019). Bintanja, (2018) reported that a 5 °C increase in temperature shifted the ratio of bacteria to fungi causing alteration in the respiration rate of the soil microbial community. Temperature and respiration are strongly correlated, thus the role of elevated temperature and microbial metabolism recently attracted attention in research (Gao et al., 2018). Intensive agriculture in dry land farming systems is the main cause of loss of belowground biodiversity, leading to poor soil health. This loss will be more severe under changing climate as climate change has direct and indirect impacts on soil communities (Dubey et al., 2019). Therefore, it is important to adopt sustainable management practices so that we can promote a healthy soil microbiome in dry land cropping systems.

Carbon sequestration in rainfed cropping systems could be increased by adoption of practices like diversified cropping systems, cover crops, crop residue incorporation,
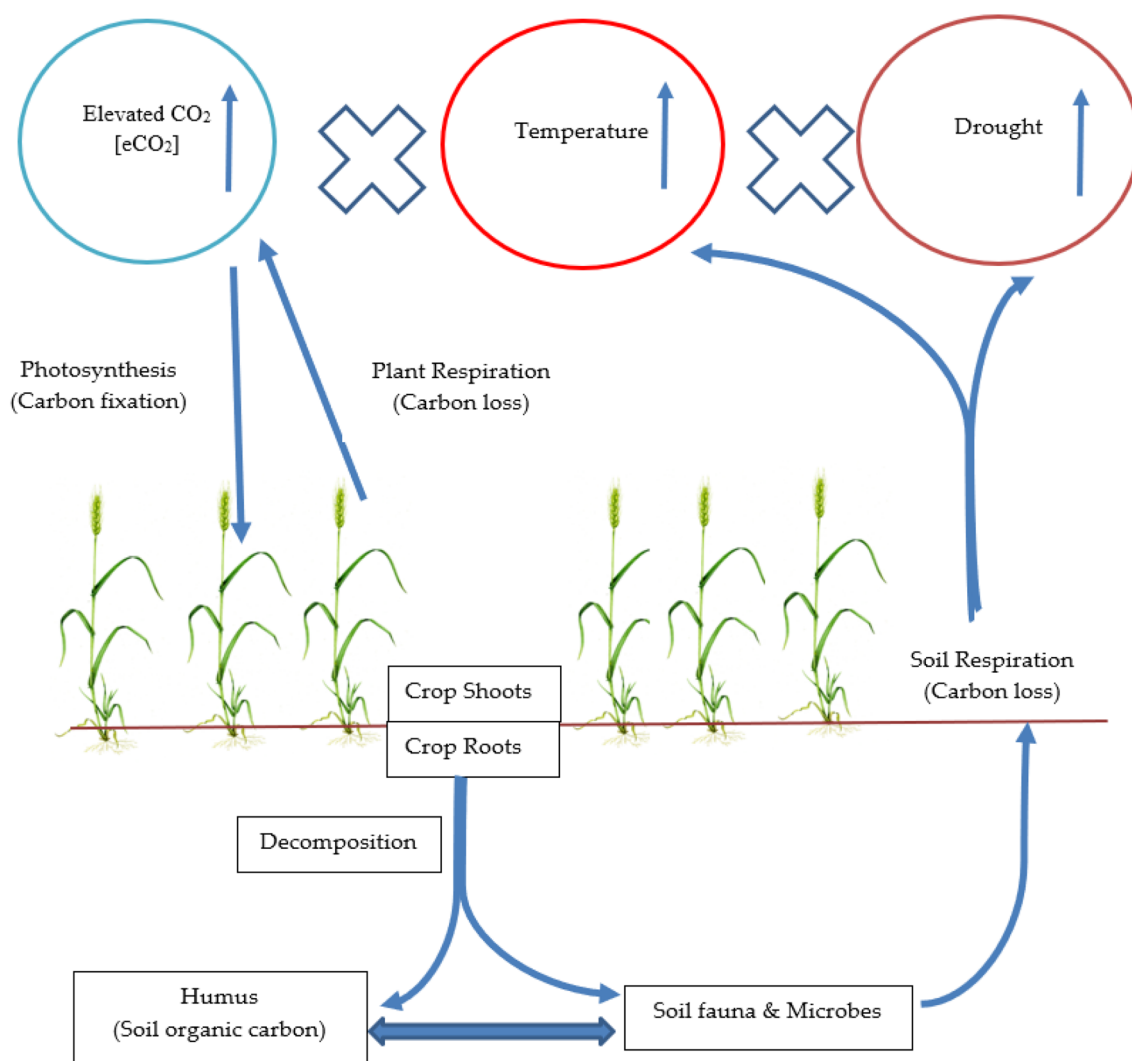
Fig. 6 Interactive effect of elevated CO_2, temperature, and drought on soil organic carbon

minimum tillage, no tillage, balanced fertilization and application of organic fertilizer (farmyard manure and green manure) (Newbold et al., 2015). Lal, (2004) further reported that with an addition of 1 ton of carbon to the soil carbon pool in degraded croplands, the yield of crop might increase by 20–40 kg ha^{-1} for wheat, 10–20 kg ha^{-1} for maize and 0.5–1 kg ha^{-1} for cowpeas. Thus, C sequestration has great potential to enhance food security and offset fossil fuel emissions (0.4–1.2 giga tons C year^{-1}).

Overview of Responses to Biotic Stresses

Human activities and natural events are accelerating changes in the global environment. The changes include increasing GHGs that result in increased global temperature and changes in water availability in coming years. These changes have also shown profound effects on biotic stresses such as disease prevalence and development, insect pest attacks and weeds abundance. Weeds are unwanted plants that compete for resources and causes huge losses to crop growth, yield and grain quality. They are also host of insect pests and pathogens. It has been reported previously that weed dynamics in different cropping systems is significantly affected by the changes in temperature, rainfall and [eCO$_2$] (Ziska & McConnell, 2015). Climate change is affecting weed-crop interactions, weed ecology and weed management. Bajwa et al., (2020) reviewed impacts of climate change elements, i.e., HT, D and [eCO$_2$], on wheat pests. They reported that climate change favors the expansion, growth and multiplication of wheat pests. Furthermore, climate change opens new geographic windows for weed infestations (Mao et al., 2021; Vilà et al., 2021), insect biodiversity (Raven & Wagner, 2021) and disease outbreaks (Chaloner et al., 2021) across

the globe. However, this will vary from place to place as drier climate might have low disease and insect occurrence in future (Dudney et al., 2021). Thus researchers suggested application of integrated pest management approaches such as frequent pest scouting, disease forecasting and predictive modeling to combat climate change induced biotic stresses.

Crops in the future will be more susceptible to biotic stresses, e.g., weed invasions, pest attacks and diseases (Chauhan et al., 2012). Weeds have shown very positive response to HT and [eCO$_2$] as reported by Mahajan et al., (2012). Ramesh et al., (2017) reported interactive effects of climate change variables on weeds. Increased temperature, D and [eCO$_2$] will result in higher weed growth with dominance of C$_4$ weeds in the cropping systems. Therefore, in the future under climate change there will be more weed pressure. Peters et al., (2014) reviewed the climate change impacts on weeds and reported that thermophile late maturing weeds are becoming more prominent, causing greater damage to crops in the cropping systems. Generally, weeds or plant species show three kinds of reactions to climate change i.e. (i) migration; (ii) acclimation and (iii) adaptation (Vilà et al., 2021). In the future, we will have to adopt sustainable weed management options to minimize the impact of weeds on cropping systems.

Climate change will increase the intensity of crop diseases in coming decades. Ziska et al., (2011) observed more prevalence of rust disease in soybean due to climate change in all growing areas of Africa and across the globe. Biotic stress will worsen the situation by indirectly affecting water, fertilizer and radiation use efficiency and ultimately yield and yield components in different cropping systems (Blois et al., 2013). During recent years, an epidemic of leaf and stem rust linked with strains of wheat is spreading in most agriculture regions across the globe due to climate variability. Increased rainfall and humid environmental conditions are favoring leaf and stem rust but on the other hand, frequent drought may limit this spread with the reduction of yield in various cropping systems. Grey leaf spot is a disease that is becoming an epidemic in various regions of world (Korres et al., 2016). During the 1st half of the twentieth century *Puccinia graminis* f. sp. *tritici* (Pgt), black stem rust of wheat, caused a serious outbreak. It results in a 19% to 28% reduction in wheat yield. However, researchers have controlled this disease by selecting wheat varieties with resistance and by removal of the alternate host in wheat growing regions. A new race of Pgt was found in Uganda in 1998 named Ug99. Ug99 has the capacity to cause disease in 90% of world wheat population as it can overcome the genes Sr31 and Sr38. The Ug99 wheat stem rust is a future challenge that could be worsened by climate change (Hernandez Nopsa et al., 2014). It causes stem rust epidemics in Africa and the Near east by controlling the widely used resistance gene Sr31. Ug99can also become a potential threat to wheat

throughout Asia (Lucas, 2017). The spread and emergence of Ug99 stimulated a coordinated international initiative to identify effective sources of resistance in wheat. This could help to develop varieties that can be deployed in regions where new races are present or are likely to emerge (see https://bgri.cornell.edu/). Plants pathogens and environment interact closely. This interaction was described as a disease triangle with environment at the central point (Pautasso et al., 2010). Changes in environmental variables, i.e., temperature, rainfall and CO$_2$, will affect this disease interaction triangle favoring occurrence of more pathogen. Fischer and Knutti, (2015) reported that weather is the key driver of disease outbreaks, so understanding disease dynamics under changing climate is necessary to have appropriate control measures.

Adaptation/Mitigation to Climate Variability and Change

Agricultural production is impaired by extreme climate events. This damage could lead to issues of crop failure, lower crop yield, poor crop quality and finally food insecurity at local, regional and global levels if proper adaptation measures are not urgently taken. Adaptations are actions taken to mitigate the damages caused by climate variability. The IPCC defines adaptation as the adjustment in systems in response to climate stimuli. Generally, if net damages are high as in case of 2–3.5 °C warming, then the adaptation cost will be higher as compared to 1.5 °C warming where less adaptive efforts will be required (National Academies of Sciences and Medicine, 2017). United Nations 17 SDGs could be considered as guidelines for the development of climate change adaptation measures (Nations, 2015). Implementation of the Sendai Framework for Disaster Reduction with a bottom up approach, and participation of different stakeholders, could also be considered to design adaptation strategies (Busayo et al., 2020). Mimura et al., (2015) recommended anticipatory adaptation or adaptation planning where measures are taken in advance to prevent adverse impacts. Examples include early warning systems (e.g. seasonal climate forecasts and disease forecasting), land use planning, crop yield forecasting and management of water resources. Travis et al., (2018) suggested that reactive adaptation has a better chance to keep pace with lower levels of warming in many production systems. Adaptation can also include disaster risk management plans or risk transfer mechanisms through which risk effects can be minimized or compensated (e.g. crop insurance and diversification). Adaptation and mitigation have strong interconnections as both can help to reduce the risks of climate change. Some

of the potential adaptation options as proposed by IPCC and other authors have been presented in Table 1 (Ahmed, 2020; IPCC 2007, 2014a, b).

Adaptation and mitigation are possible through technology change and by adding to systems options that can reduce resource inputs and emissions of GHGs. Waha et al., (2013) concluded that benefits from concomitant positive effects of climate change e.g. [eCO2] and increased rainfall is possible through adaptation strategies. These strategies include change in sowing date, appropriate choice of cropping systems and crops. Furthermore, adverse impacts of heat and drought stress could be moderated through adaptation measures. Abid et al., (2019) analyzed farmers' perceptions about climate change and explored connections between different stages of adaptation, i.e., perceptions, intention and implementation. In their work, they stated that local perceptions of climate change are important considerations for the design and implementation of adaptive measures at the farm level. Moreover, the study reported farmers' education as an important precursor to implement the adaptive measures effectively (Ghose et al., 2021). However, factors that can improve farmers' adaptive behavior to climate change include weather forecasting, market information, advisory services, and farming experience. Furthermore, large-scale farmers were able to adapt to climate change through change in planting dates and selection of new, adapted varieties. However, small land holding farmers need more attention so that they can easily access information, institutional services and resources to succeed in the face of climate change. Further detail about possible adaptation measures is discussed below:

Introduction of Legumes in the Cropping System

Introduction of legumes in the exhaustive cropping systems (e.g. fallow-wheat, cotton-wheat, rice–wheat, maize-maize, potato-wheat or maize-wheat) can be beneficial to reduce the negative impacts of climate change. Similarly, legumes can provide quality food and feed. Legumes could help to reduce the use of fertilizers and energy, and consequently lower GHG emissions. Thus, they are considered environment-friendly crops. Legumes can also minimize the use of nitrogenous fertilizers by significantly reducing the level of N_2O (e.g. 1 kg of N as N_2O is produced per 100 kg of N fertilizer) one of the active GHGs. Furthermore, legumes can also provide N effect (N provision through BNF) and break crop effect (non-legume specific benefits e.g. improvement of soil structure and organic matter contents, soil water holding capacity and availability, phosphorus mobilization and reduced biotic stress pressure) (Stagnari et al., 2017). Introduction of legumes in the cropping system could provide multiple benefits, e.g., (i) environmental (ii) socioeconomic (iii) crop diversification (iv) soil restoration (v) water conservation and (vi) reduce use of external inputs. Furthermore, legumes have high potential for conservation agriculture. Mousavi-Derazmahalleh et al., (2019) recommended legume crops as adaptive measures in response to climate change. Jensen et al., (2012) reviewed research about the growing capacity of legumes to lower GHG emissions, reduce fossil energy consumption, sequester carbon and

Table 1 Potential options for adaptation to climate change [Source: (IPCC, 2007, 2014b)]

Sector wise adaptation options	Climate extremes			
	Drought/drying	Increased rainfall/flooding	Warming/heatwaves	Wind speed/storminess
Crops	• Drought resistant varieties • Intercropping • Crop diversification • Crop residue retention • Weed management • Water harvesting • Hydroponic farming • Alternate wetting and drying	• Changes in sowing time • Promotion of alternative crops • Floating agricultural systems • Improved drainage • Improved extension services	• Heat resistant varieties • Alteration of cropping calendar and activities • Pest control • Crop surveillance • Irrigation	• Wind resistant crops • Agroforestry
Livestock	• Supplementary feeding • Change in stocking rate • Altered grazing and rotation of pasture	–	• Housing and shade provision • Change to heat-tolerant breeds	–
Water	• Water budgeting • Water conservation via mulching • Water recharge techniques • Leak reduction • Education for sustainable water use	• Flood forecasting • Early warning systems • Insurance	• Sustainable water use • Water conservation • Cover cropping	–

as source of biomass to produce biofuels. In conclusion, they recommended that due to multiple benefits of legumes they should be considered as an important component of future agroecosystems. Leguminous crops also improve soil organic matter and act as a restorative crop. Under current and future climate variability, sowing of legumes with major crops can be very useful approach (Sayari et al., 2015).

Biodiversity

Diversification is a spatio-temporal process where the objective is to have heterogenous farming systems. On-farm and off-farm diversification can build system resilience to climate shocks (Fig. 7). The issues of climate change and biodiversity are interconnected. Protection of biodiversity can help systems adapt to climate change. Biodiversity promotes healthy systems which will be more resilient to climate change. It can help us to work with, rather than against, nature. Hisano et al., (2018) reported that biodiversity can mitigate climate change as diverse systems could be more resilient to climate change. Furthermore, it can help to improve ecosystem functioning. Hufford et al., (2019) reviewed crop biodiversity as potential way to adapt agriculture to global climate change. They reported the imporatnce of crop biodivesity as it will fullfill the qualitative or quantitative demands of the agricultural production system in future.

Genetic Modifications of Crops

The development of resistant crop cultivars through different omics techniques could help to mitigate climate change.

Speed breeding is a great example developed by Dr. Hickey to expand crop diversity to feed 10 billion people and accelerate the rate of crop improvement (Watson et al., 2018). The newly developed cultivars will have higher tolerance to heat stress, severe water shortage, pests and diseases. Lopes et al., (2015) reported the importance of adaptive genotypic traits to the maintenance of grain yields in dry and warm years. Furthermore, they suggested that landraces should be used as valuable sources of genetic diversity and stress adaptation. The authors also emphasized the development of databases and the promotion of data sharing strategies among breeders, quality scientists, pathologists and physiologists so that improvements in adaptation to climate change go worldwide. Moreover, cultivars with higher water, nutrient and radiation use efficiency, and cultivars which can tolerate water logging, salinity and drought stresses, are required. Atlin et al., (2017) reviewed plant breeding and varietal replacement as critical options for adaptation to climate change. They reported that since most varieties available to smallholder farmers are obsolete, the breeding system should be strengthened in such a way that small farmers could also benefit from new cultivars.

Change in Crop Management Practices

The extreme effects of climate variability on cropping systems could be mitigated by adopting proper crop management practices. These include changes in the planting date and geometry, proper management of irrigation and fertilizer practices (rate, placement and timing), optimization of planting density and appropriate use of seed rate (Kumar et al., 2021). Asgedom and Kebreab, (2011) reviewed beneficial

Fig. 7 Levels of diversification both on-farm and off-farm (Duong et al., 2021)
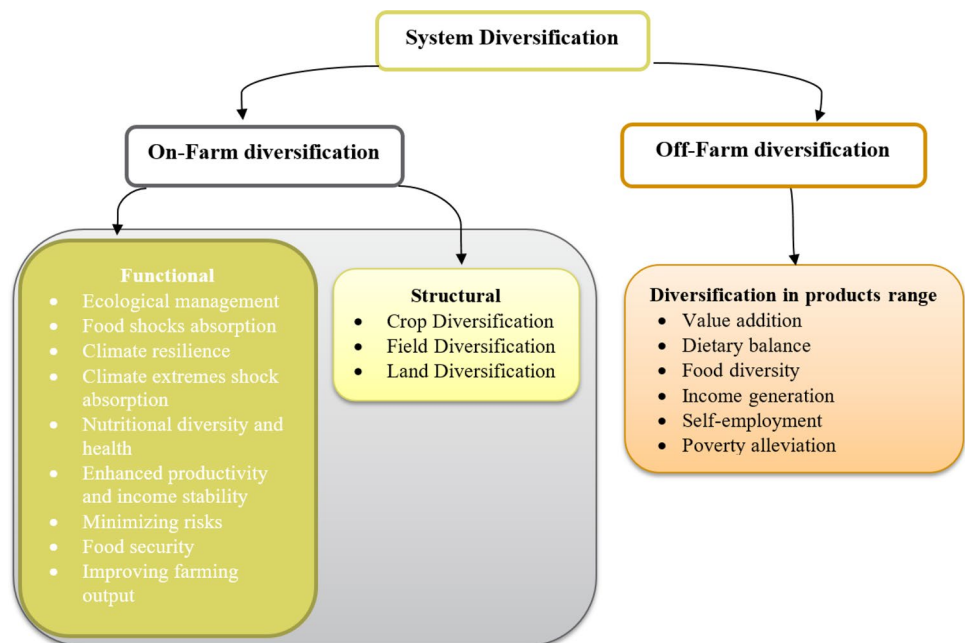
management practices and GHG mitigation options to minimize climate change impacts. Planting date shifts can help to develop stress avoidance, e.g., anthesis may be timed to avoid heat stress. In rainfed conditions, close row-to-row and plant-to-plant spacing can hasten canopy coverage of the soil surface and consequently, reduce evaporation losses (Ahmad et al., 2015). Furthermore, shifting from sole crop rotation toward the diversified and integrating farming system is a very accommodating approach (Mohammadian et al., 2020).

Conservation Agriculture for Sustainability in the Cropping System

Conservation agriculture can be a good adaptation option to mitigate climate change. Conservation agriculture can enhance cropping system performance in the long run through improvement in soil health and biogeochemical cycles (Thierfelder et al., 2016), and it helps minimize the use of artificial nutrients thus reducing GHG emissions (Smith et al., 2019). Rochecouste et al., (2015) reported about the potential of conservation agriculture practices to mitigate climate change. Similarly, Amin et al., (2020) reviewed soil C management research to improve soil physio chemical features and recommended application of social-ecological systems to offsets GHG emissions.

Carbon Sequestration

Sequestration of SOC is one of the utmost imperative opportunities for the reduction of GHGs and CO_2 production. By increasing the carbon quantity in the soil with the help of the sustainable crop management practices, we can diminish the emission of CO_2 to the atmosphere. Biochar application can be useful for carbon sequestration and enhancement of organic carbon stability in the soil under various cropping systems (Newbold et al., 2015). Olson et al., (2010) reported use of cover crops as potential sources to restore SOC and soil productivity. Growing more trees could be helpful to sequester C through atmospheric fixation of CO_2 into biomass. Therefore, it is suggested that land kept for the plantation of trees or woody plants must not be utilized or for the other purposes. The burning of cotton sticks, wheat and rice straw or stubbles must be stopped (Powlson et al., 2016) since burning of residues results in other problems such as smog, which can damage different sectors of life. Burning residues is more common in rice growing regions of India and Pakistan causing problems in both countries. Thus, immediate, coordinated action is needed on both sides of the border to prevent this problem and increase SOC. Similarly, to stop rice residue burning across the globe we should provide new technology for rice residue management. Zero-tillage drills provide a good option to sow wheat in standing rice stubble but its higher cost and accessibility to

all are impediments to the adoption of this technology on a large scale. Powlson et al., (2011) emphasized the use of crop residues or animal manure to increase SOC that could help to revegetate degraded land and minimize GHG emissions. However, they suggested use of other measures such as reforestation and improving N use efficiency instead of just giving more importance to C sequestration only in combating climate change.

Long-Term Scenario Analysis

Future impacts of climate variability on all crops and cropping systems could be studied by using crop growth models with long-term scenario analysis. Autret et al., (2020) did long term modeling of crop yield, N losses and GHG balance in organic cropping systems through the crop model STICS. The results showed that total N fertilization and total N gaseous loss as well as N surplus and N storage have significant correlations among each other. Metadata analysis can help to understand and address complex agricultural systems problems as reported by Kamilaris et al., (2017). Similarly, model scenarios help to study the impact of climate extremes and pandemic like Covid-19 on food systems that can further explore global food shocks in response to these events (Sivakumar and Stefanski, (2011). Furthermore, long term analysis can also be used to study yield stability, environmental adaptability and production risks of a specific crop in the cropping system (Macholdt et al., 2020). The initiative as reported by CGIAR, where crop modeling could be used for multiple purposes, is the best example of this approach. This give real benefits at ground scale as it involves interdisciplinary approaches to address multiple challenges (Kruseman et al., 2020; Ramirez-Villegas et al., 2020). Use of meta-analysis is a good approach to reach solid conclusions as reported in different earlier work about conservation agriculture, drought and heat stress, irrigation, intercropping, alternate wetting and drying irrigation, climate change, climate change and adaptation, [eCO$_2$] and climate warming (Cohen et al., 2020).

Artificial Intelligence (AI) and Machine Learning (ML)

Machine learning and artificial intelligence could boost farming system productivity and efficiency (Eli-Chukwu, 2019). These technologies can help farmers reduce climate extreme impacts. AI and ML techniques could help to detect extreme events such as drought and floods, disease occurrence and pest attack. AI and ML were used to advise farmers what to anticipate. It has been reported that AI brought a revolution in agriculture (Talaviya et al., 2020). AI and ML technologies have been successfully implemented in such agricultural management operations as irrigation, spraying,

crop monitoring and weeding (Partel et al., 2019) through the use of robots and drones. Thus, AI and ML could help to save water and improve productivity and quality of crops. Furthermore, future concerns of sustainable agriculture could be addressed by AI and ML (Elahi et al., 2019). AI and ML have been successfully applied in precision agriculture (Mahmud and He, 2020).

Models to Develop Tools for Improved Management of Subsistence Dryland Agricultural Systems

Process based mechanistic models can be used to support dryland agricultural systems as these models can identify yield gaps and suggest ways to minimize these gaps under alternative scenarios. Similar suggestions about usage of tools were proposed by Lobell et al., (2009) in which they reviewed the magnitude and cause of yield gaps across the globe. However, focusing on individual crop yields could not in itself bring sustainability to these systems, so a whole farm approach should be adopted to support the system. Agricultural systems modelling is needed to quantify the benefits and trade-offs from alternative practices at the farm scale. Modeling has played, and will continue to play, a significant role in improving agriculture under different scenarios to feed the billions of people across the world (Rodriguez et al., 2014). Models can help to design resilient farming systems under dryland agriculture by providing knowledge about functioning and dynamics of the systems in interactions with biotic and abiotic components, and then inform stakeholders how to manage their particular system. The Ricardian approach was used by Ochieng et al., (2016) to study the impacts of climate variability and change on agricultural revenue of small-scale farmers in Kenya. Results showed that climate variability and change have significant effects on the livelihoods of small farmers. Their findings further indicated that temperature is a much more important indicator than rainfall, and suggested implementation of policies that prevent destruction of natural resources. These policies should also include crop insurance and use of integrated adaptation measures e.g. drought tolerant crop varieties, more investment in agriculture and application of sustainable management practices (Ochieng et al., 2016; Sequeros et al., 2021). Statistical matching and econometric modeling were used to estimate how the climate smart agriculture technologies and practices impact household income and asset accumulation of small-scale dryland farmers in Kenya (Ogada et al., 2020). Results suggested use of drought tolerant crops with an investment in livestock could be good adaption strategy to mitigate the impact of climate variability and change. Furthermore, it had been suggested that crop canopy-based trait adaptation strategies (decrease the rate of canopy development in northern locations and increase the rate in southern locations)

could overcome constraints imposed by rainfall variability on water use efficiency (WUE) under dryland conditions (Sadras & Rodriguez, 2007).

Different process based dynamic crop modelling tools are now available which could be used at a larger scale. These include APSIM (Agricultural Production Systems sIMulator), AquaCrop, CropSyst, CLM (Community Land Model), DAISY, DSSAT (Decision Support Systems for Agrotechnology Transfers), ECOSYS, HERMES, INFO-CROP, LINTUL (Light INTerception and UtiLisation), STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) and RZWQM (Root Zone Water Quality Model) etc. APSIM is a well utilized model across the globe to do multiple tasks such as risk management, modelling Genotype (G) × Environment (E) × Management (M) Interactions in dryland agriculture and modelling farms and farmers. Under the sponsorship of APSIM initiative a biophysical model CLEM (Crop Livestock Enterprise Model) has been released to evaluate the impacts of management at the farm scale. Participatory modelling is necessary to answer what-if scenarios so that these tools can be practically used by farmers and extension officers to achieve field-scale objectives. Rodriguez and Sadras, (2011) tested the hypothesis that plasticity in the farming system could give options to test new opportunities. Therefore, participatory discussions and computer aided farming systems designs have proved useful for gaining insights into complex systems, generating awareness, and developing strategies to solve problems at real world scale. Further application of process-based models has been presented in Table SI. Meanwhile, success of smallholder farmers under climate shocks could be improved by the use of artificial intelligence (AI), machine learning (ML) and deep learning methods in genomic prediction models as reported by Consultative Group for International Agricultural Research (CGIAR). Massive-scale genotyping and diversity analysis of 80,000 wheat accessions was conducted by Sansaloni et al., (2020). The main objective of this work was to understand crop diversity for its use in future breeding programs. Liakos et al., (2018) reviewed ML as emerging big data science technology that can help to improve farm system productivity. Furthermore, ML can help to improve activities at farm scale by connecting ML to sensor data. Goldstein et al., (2018) applied concepts of ML on sensor data for irrigation management. They suggested ML processes could be used for irrigation planning as well as for yield and disease prediction. Furthermore, ML and AI can be used for gully erosion mapping (Tien Bui et al., 2019), groundwater mapping (Arabameri et al., 2020), drip irrigation (Klyushin & Tymoshenko, 2021), optimization of irrigation and application of pesticides and herbicides (Talaviya et al., 2020), dairy farm management (Cockburn, 2020; Shine et al., 2018), milk production forecasting (Nguyen et al., 2020), livestock farming (García

et al., 2020), selection of suitable crop traits (Shekoofa et al., 2014) and seasonal rainfall forecasting (Feng et al., 2020; van Ogtrop et al., 2014).

Future Research Focus

Future research focus needs to be changed in such a way to eliminate hunger on real term basis. It has been reported in the editorial of nature that among 570 million farms in the world, more than 475 million are smaller than 2 hectares, but most of our research has prioritized larger farms, without giving sufficient importance to small farming. Most of the past research concludes that smallholders can adapt to climate change by adopting new approaches e.g. planting climate-resilient crops through extension services, which is not the case in reality. Similarly, Ceres2030 sustainable solutions to end hunger researchers found that most past studies are not relevant to the needs of smallholder farmers (Laborde et al., 2020). They also reported that most of the reported studies did not directly involve the farmers (Stathers et al., 2020). Furthermore, in the past four decades funding priorities generally targeted big farms only. Emphasis on small farms was less desirable in universities as well as by publishers (Pardey et al., 2016). Since in most funding where the private sector is involved, rewards go to those who can procure more research funding. However, to achieve SDG, and to end hunger, we need to direct our future research more toward smallholder farms.

Conclusions

In general, all farming systems are being negatively affected by climate change and global warming, but dry land farming systems are particularly vulnerable. Resource use efficiencies, yield and yield components along with soil capabilities are on the verge of irreparable losses unless we adopt effective mitigation strategies. Thus, technology-based intervention is needed to support agriculture of dryland farming systems. This support will help to achieve sustainability development goals in the long run. The negative impacts of climate change on dry land farming systems can be minimized by the quantification of impacts on the systems, by the use of available data sets with further analysis and by the application of 'what-if' scenarios using process-based models. By these means, benefits and tradeoffs can be quantified under different sets of management practices on short term as well as on long term bases to develop tactics to reduce risk under extreme climate conditions. This could further help to design adaptation and mitigation strategies like modification in the farming system matrix, introduction of legumes (microbial-based technologies), improvement in varieties (water efficient or drought/heat tolerant),

appropriate crop management practices, intercropping, supplemental irrigation, conservation, erosion minimization and precision agriculture, carbon sequestration strategies, adoption of agroforestry and decisions for future needs.

Author Contributions MA developed the review idea and designed this work. MA, and SA prepared the original draft of the manuscript. All the authors reviewed, commented and edited the paper for submission.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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