Chapter 2
Climate Change, Agricultural Productivity, and Food Security

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Abstract Food security and agricultural-based livelihoods of smallholder farmers are under threat due to climate change and political conflicts. However, quality firm data is needed to assess the damages on food security to suggest appropriate adaptive measures. This chapter gives an overview about the climate change, agricultural productivity, and food security. It firstly provides detailed information about agricultural sector contributions to the climate change with information about water and agriculture footprint. Similarly, the reasons for the declined agricultural productivity and loss of biodiversity were discussed with possible solutions. Results depicted that without adaptations, genetic improvement, and CO_2 fertilization, every 1 °C rise in temperature could reduce yields of wheat (6.0%), rice (3.2%), maize (7.4%), and soybean (3.1%). Afterward, linkage with sustainable agriculture and food security was elaborated. Furthermore, detail about global food security was presented followed by the scenario of food security in Pakistan. The impact of climate change on food security was established through different climatic drivers, e.g., ENSO (El Niño–Southern Oscillation) and SOI (Southern Oscillation Index). These drivers are responsible for the climatic extreme events; hence, earlier prediction of these drivers could help to design appropriate adoptive measures for the agriculture sector, and they could be considered as early warning tool for the risk managements. Afterward, simulation analysis between climate change and rainfed wheat yield was presented, which confirms that climate change is affecting crop production and food security. Hence, adaptive measures, such as improved impact assessments

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M. Ahmed (ed.), *Global Agricultural Production: Resilience to Climate Change*,
https://doi.org/10.1007/978-3-031-14973-3_2

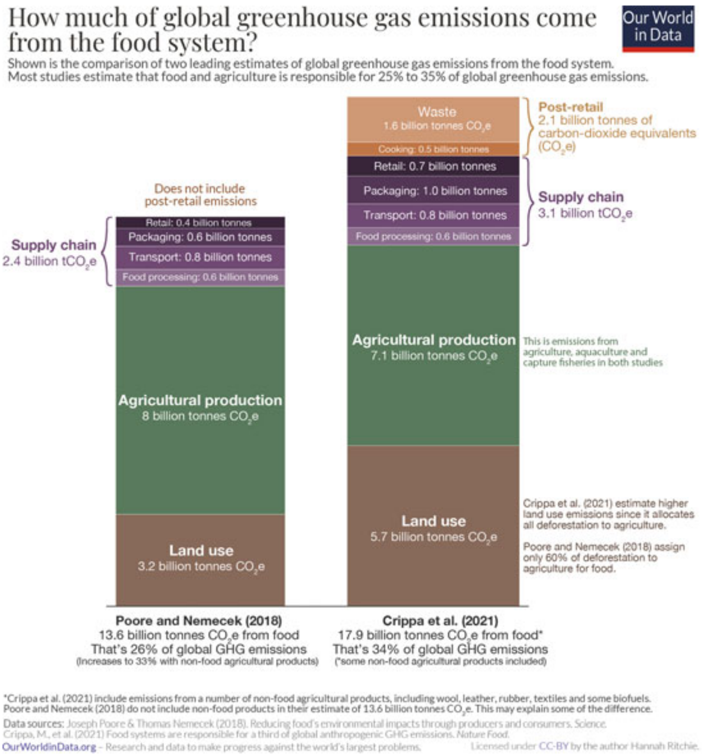
through modeling, efficient production technologies, changes in sowing windows, precision and smart farming, modernization of water supply and irrigation systems, conservation tillage, inputs and management adjustments, and improved short- and long-term climate prediction, cluster-based agriculture transformation with connections with policy makers could be good adaptation options to ensure food security.

Keywords Food security · Agricultural productivity · Climatic drivers · Adaptation options

2.1 Introduction

Climate change and variability are major causes of declined agricultural productivity across the globe. Agriculture in future will face multiple challenges that include the production of more food and fiber for billions of populations and higher production of feedstocks for bioenergy production. Generally, we think that the major threats to the environment are greenhouse gases (GHGs) coming from different anthropogenic activities, not food needed for our breakfast, lunch, and dinner. But the truth is food will be the biggest dangers to the planet Earth. Agriculture is contributing a lot to GHG emissions as compared to buses, cars, trucks, trains, and airplanes (Fig. 2.1). Methane (CH_4) mainly comes from cattle and rice farms, while oxides of nitrogen are coming from fertilized fields. Higher emissions of carbon dioxide (CO_2) are due to cutting of rain forest to clear land that can be further used to raise animal and grow crops (Crippa et al. 2021; Poore and Nemecek 2018; Lynch et al. 2021). Similarly, farming is using a lot of water, and it pollutes nearby water bodies and underground water via runoff from manure and fertilizers. Water footprint of agriculture is increasing day by day, and it is using 70% of existing freshwater as shown in Fig. 2.2. Water footprint is further divided into blue (consumption of ground and surface water), green (use of rainwater), and gray (water use in the dilution of pollutants). In future, climate change will result to the further increase in water footprint from north to south as irrigation demands will rise from 6% to 16% (Elbeltagi et al. 2020). Decrease in green water footprint was estimated due to change in precipitation (Yeşilköy and Şaylan 2021). Among crops, rice is the crop, which have a higher water footprint, and simulated outcome of study reported that blue water footprint in rice will increase as compared to green water footprint (Zheng et al. 2020). Gray and green water footprint in Amazon for soybean have been increased by 268% and 304%, respectively, in 2050, if current soybean expansion and intensification will remained as such (Miguel Ayala et al. 2016). Thus, in future, efficient water resource management (e.g., reduction of evapotranspiration and crop water use, and optimal fertilizer application) is necessary to ensure food security under changing climate.

Agriculture is also the main cause of accelerated loss of biodiversity (Dudley and Alexander 2017). In future, agriculture will pose more threat to the environment, as we must feed two billion more mouth (>9 billion) to feed by mid-century (Fig. 2.3). The countries with the highest population will need more meat, eggs, and dairy,



How much of global greenhouse gas emissions come from the food system?

Shown is the comparison of two leading estimates of global greenhouse gas emissions from the food system.
Most studies estimate that food and agriculture is responsible for 25% to 35% of global greenhouse gas emissions.

This is emissions from agriculture, aquaculture and capture fisheries in both studies

Crippa et al. (2021) estimate higher land use emissions since it allocates all deforestation to agriculture.

Poore and Nemecek (2018) assign only 60% of deforestation to agriculture for food.

Poore and Nemecek (2018)
13.6 billion tonnes CO_2e from food
That's 26% of global GHG emissions
(Increases to 33% with non-food agricultural products)

Crippa et al. (2021)
17.9 billion tonnes CO_2e from food*
That's 34% of global GHG emissions
(*some non-food agricultural products included)

*Crippa et al. (2021) include emissions from a number of non-food agricultural products, including wool, leather, rubber, textiles and some biofuels. Poore and Nemecek (2018) do not include non-food products in their estimate of 13.6 billion tonnes CO_2e. This may explain some of the difference.

Data sources: Joseph Poore & Thomas Nemecek (2018). Reducing food's environmental impacts through producers and consumers. Science.
Crippa, M., et al. (2021) Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food.
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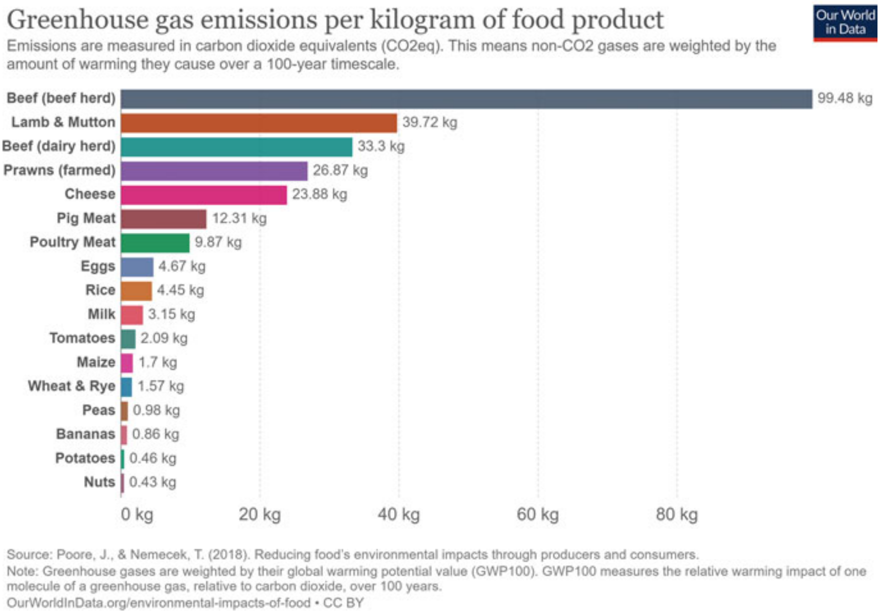

Greenhouse gas emissions per kilogram of food product

Emissions are measured in carbon dioxide equivalents (CO2eq). This means non-CO2 gases are weighted by the amount of warming they cause over a 100-year timescale.

Source: Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers.
Note: Greenhouse gases are weighted by their global warming potential value (GWP100). GWP100 measures the relative warming impact of one molecule of a greenhouse gas, relative to carbon dioxide, over 100 years.
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Fig. 2.1 Global greenhouse gas emissions from food system

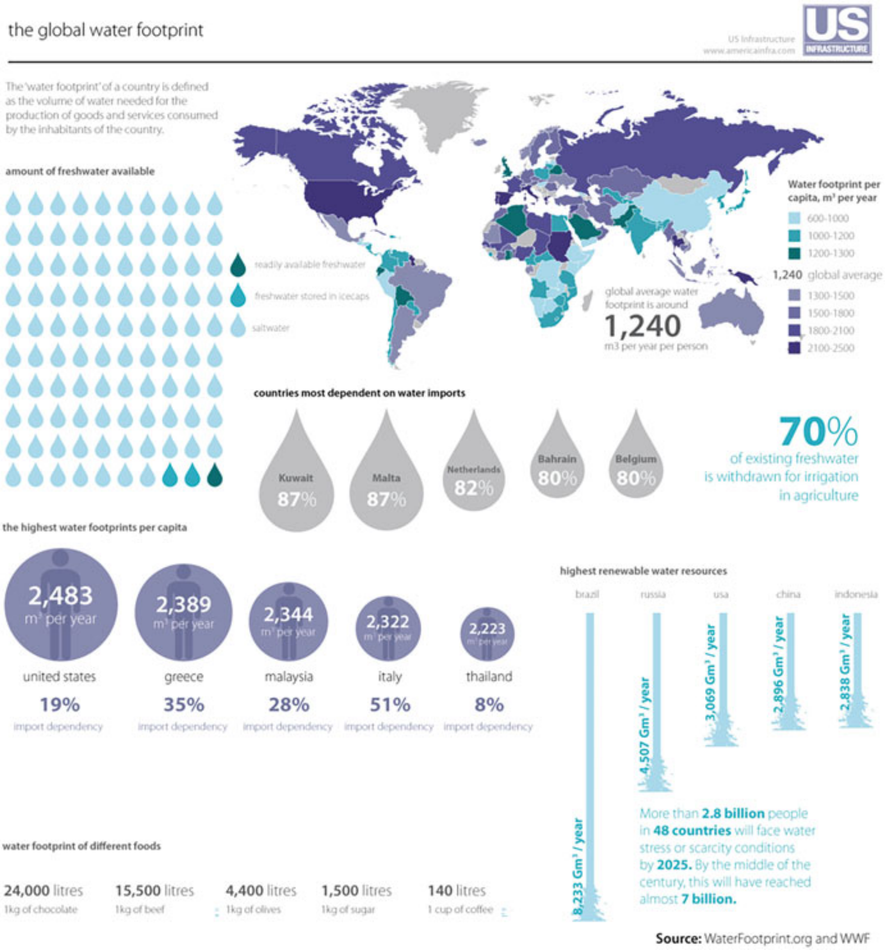


Fig. 2.2 The global water footprint

which will boost pressure to grow more crops like corn and soybean to feed animals. Hence, with this population growth and diet habits, we must double the amounts of crops production by mid-century. Furthermore, debates among conventional agriculture/global commerce and local food systems/organic farms to address the global food challenge have been polarized. Both are right in their point of views, as conventional agriculture talks more about higher food production through the applications of modern tools while organic farming produces quality food with higher benefits to the small-scale farmers and ecosystems. Jonathan Foley asked a question from team of experts, and it has been published in National Geographic magazine. The question was how world can double food availability by minimizing the environmental harm (https://www.nationalgeographic.com/foodfeatures/

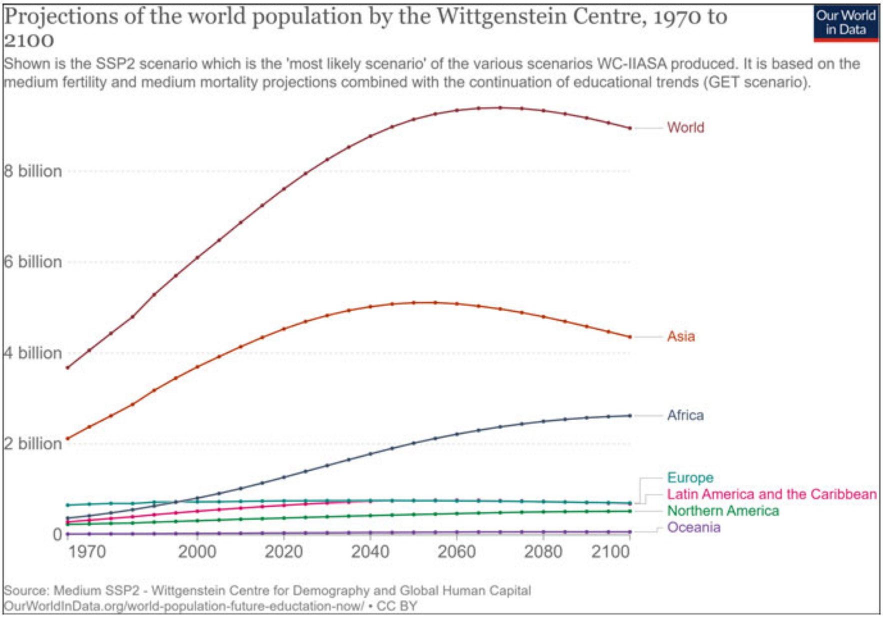


Fig. 2.3 Trend of world population

feeding-9-billion/). Jonathan Foley and team of scientist proposed a five-step mechanism to solve the world's food dilemma, which they got after analyzing a huge amount of data on agriculture and environment. It includes the following: (i) Freeze agriculture footprint (stop deforestation for crop production). (ii) Grow more on farms we have got. (iii) Use resources more efficiently. (iv) Shift diets. (v) And reduce waste. Agriculture footprint has caused the loss of whole ecosystems across the globe, e.g., prairies of North America and the Atlantic Forest of Brazil and tropical forests (Fig. 2.4) (Litskas et al. 2020). Converting tropical forest to agriculture was one of the most damaging acts to the environment by human beings, although it does not contribute a lot to global food security (Fig. 2.5). Reducing yield gaps and increasing yield on less productive areas could bring global food security and that needs to be opted by all researchers across the globe. Yield gap could be minimized by identifying yield-limiting factors, designing crop ideotypes, opting high-tech precision farming systems, as well as approaches from organic farming (Rong et al. 2021; Senapati and Semenov 2019). Similarly, using resources more efficiently through commercial and organic farming can improve soil health, conserve water, and build up nutrients. Shift in diets from livestock to crops could help to feed 9 billion population by 2050 as well as it can minimize agriculture footprint. Waste minimization is another very good option suggested by Jonathan Foley to ensure food security, as 50% of total food weights and 25% of global food calories have been lost before it should be consumed. These proposed five steps could help to double the world's food supply, cut the environmental impact of global agriculture, and ensure food security. Furthermore, the next sections in this chapter

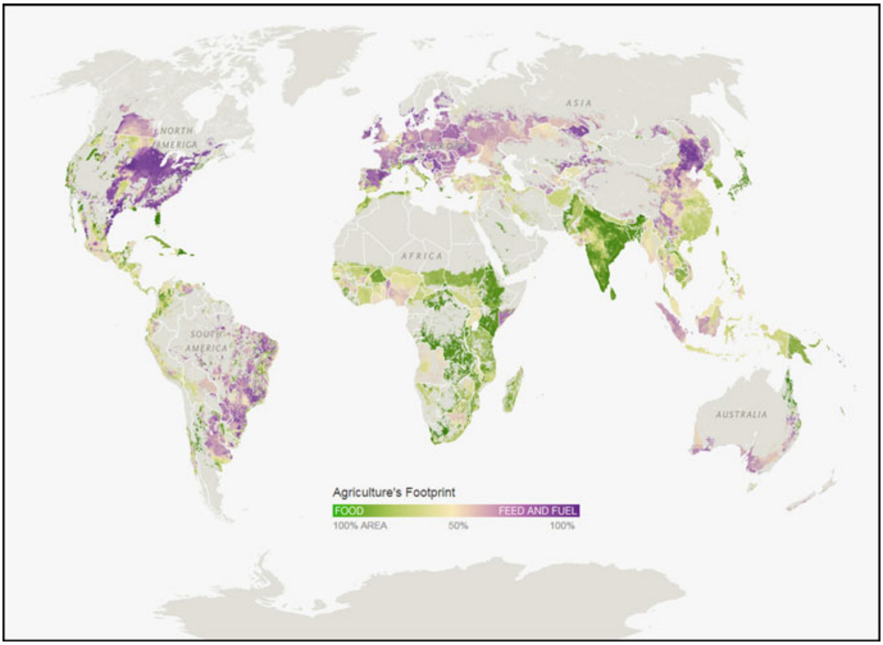


Fig. 2.4 Global agriculture footprint. (Source: Roger LeB. Hooke, University of Maine. Maps, source: Global Landscapes Initiative, Institute on the Environment, University of Minnesota)

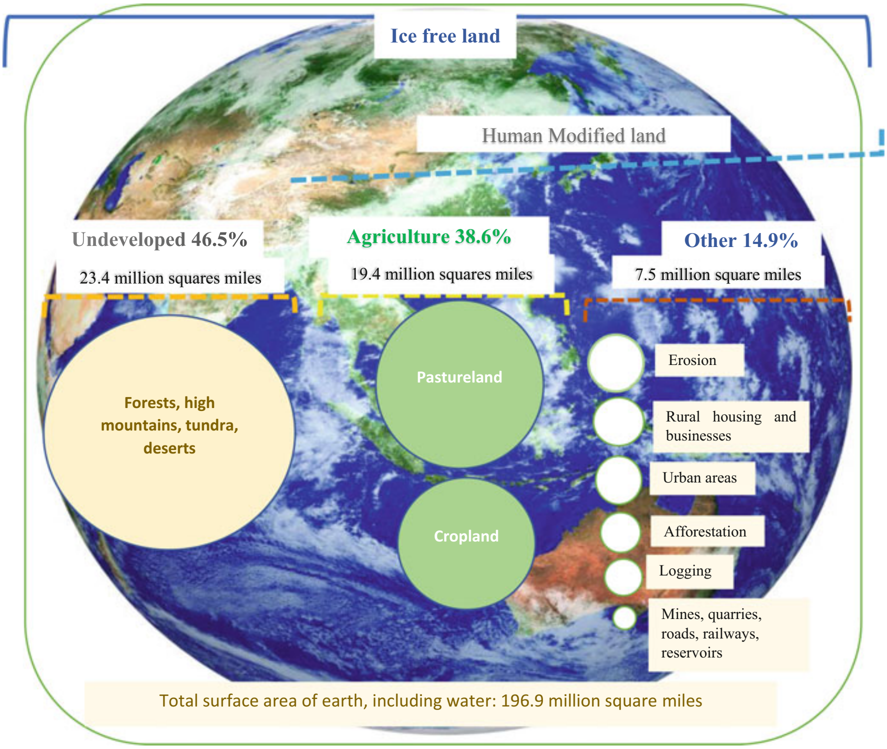


Fig. 2.5 Ratio of human modified land with total surface area of Earth

will be about agricultural productivity, food security, and its linkage with climate change.

2.2 Agricultural Productivity

Output per unit of inputs is called productivity. It is one of closely watched economic performance indicator as it contributes to a healthy economy. Agriculture is an important economic sector for most of the countries, but its output growth as compared to other sectors of economy is not same. This is because of differential response to the inputs used in agriculture sector and their interactions with climatic variables. Similarly, productivity in agriculture is also linked with investments in research and development, extension, education, and infrastructure. Dharmasiri (2012) defined agricultural productivity (AP) as the output per unit of input, and it has two measures: (i) partial measure of productivity (output per unit of a single input) and (ii) total measure of productivity (output in response to all inputs). Partial measure of productivity is generally easy to use because of the availability of data. Agricultural productivity is a good indicator to see the gap in output, e.g., yield gap. The global yield of major crops has been presented in Fig. 2.6, which shows a big gap in the crop yield among countries due to a number of different reasons. It includes land degradation (soil fertility, soil erosion, soil salinity, and waterlogging), climatic extremes (extreme temperature, drought, Flood), poor irrigation water management, agronomic, technological, socioeconomic, and institutional constraints. In Pakistan, the major factors, which contribute a lot to AP, include fertilizer consumption, seed, and credit distribution as concluded by Rehman et al. (2019). Increase in AP is a good option to solve the issue of food crisis, but it has been stalled. The growth rate of major grain crops is about 1% per year, which is lower than the population growth. Since increase in cultivated area is not a possibility to fulfill the future needs of growing population; thus, the only option is increase in AP. However, there are no silver bullet solutions, but AP could be increased by opting options like (i) water availability, (ii) education for farmers, (iii) credit availability, (iv) land reforms, (v) transport and marketing, (vi) policies, (vii) markets and agribusiness, and (viii) outreach programs to disseminate new research findings. Furthermore, new approaches to facilitate small-scale farmers in developing countries are instruments to guarantee food security. AP and yield gaps for the major crops in Pakistan have been presented in Table 2.1.

2.3 Food Security

Food security exists when “all people, at all times, have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life” (Shaw 2007). This definition gives rise to the four

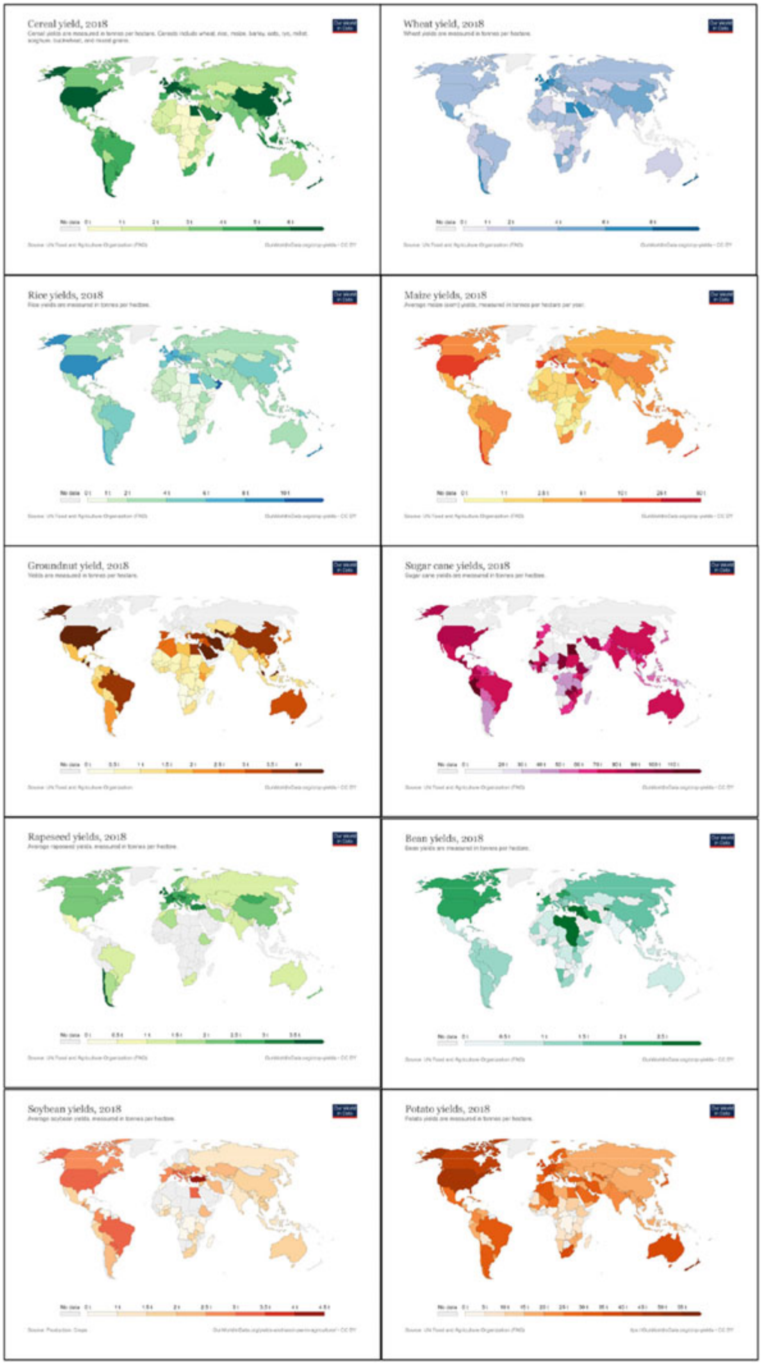


Fig. 2.6 Yield of major crops across the world

Table 2.1 Yield gap for major crops in Pakistan

Crops	World average (t ha^{-1}) (Source: FAOSTAT)	Pakistan average (t ha^{-1}) (Source: Pakistan Economic Survey, Ministry of Finance)	Yield gap
Wheat	8	2.84	5.16
Rice	6.5	2.51	3.99
Maize	10	4.75	5.25
Cotton	3	0.68	2.32
Sugarcane	112	64	48

dimensions of food security: availability of food, accessibility (economically and physically), utilization (the way it is used and assimilated by the human body), and stability of these three dimensions. According to the United Nations, food security can be defined as physical, social, and economic access to food by all people at all times to sufficient, safe, and nutritious food to meet their dietary needs according to their food preferences for an active and healthy life. Under current international scenario, food security is becoming a formidable challenge. In a developed world, most attention is given to biofuel production, and it is using huge quantities of grain, e.g., 50 million tons of maize is used to produce biofuel products (Veljković et al. 2018; Schwietzke et al. 2009). Similarly, increased used of corn grain to produce ethanol is altering the landscape and ecosystem services (Landis et al. 2008). Food security is also on stake due to climate change, increased prices of food grain, and livestock product which has been further aggravated by continuous rise in fuel prices. The cascading effects of climate change on food security have been shown in Fig. 2.7. The earlier world was striving hard to meet the Millennium Development Goals (MDGs) to reduce hunger and poverty to half by 2015 but unable to achieve the UN target. There were eight MDGs with less attention to environmental sustainability (Lomazzi et al. 2014). In Rio +20 conference, MDGs were replaced with the Sustainable Development Goals (SDGs) (Fig. 2.8) with the objectives to end poverty and protect the planet with peace and prosperity for all till 2030 (Fukuda-Parr 2016). Zero hunger (SDG2) was the top priority of the SDGs to ensure food security by 2030. SDG2 was further divided into SDG2.1 (end hunger and access to food), SDG2.2 (end malnutrition), and SDG2.3 (doubling of agricultural productivity and income of small-scale farmers) (UN 2018). Laborde et al. (2016) reported 11 billion USD per year will be required to end hunger by 2030, while Schmidhuber et al. (2011) and the FAO and UNICEF (2014) estimated 50.2 billion USD by 2025. Different interventions were recommended by previous studies to uplift agriculture and small-scale farmers to achieve SDG2 and ensure food security (Gil et al. 2019). These include investment in rural infrastructure and value chains, easy access to market, credit transfer programs, farm insurance, good governance, gender equality, and connection with research, development, and extension services (Ton et al. 2013; Atukunda et al. 2021). Furthermore, Bizikova et al. (2020) identified five different types of interventions (three single and two multiples) that can have significant impacts on food security. Single intervention was input subsidy, extension, and value chains, while multiple interventions include input subsidy-food voucher and input subsidy-extension.

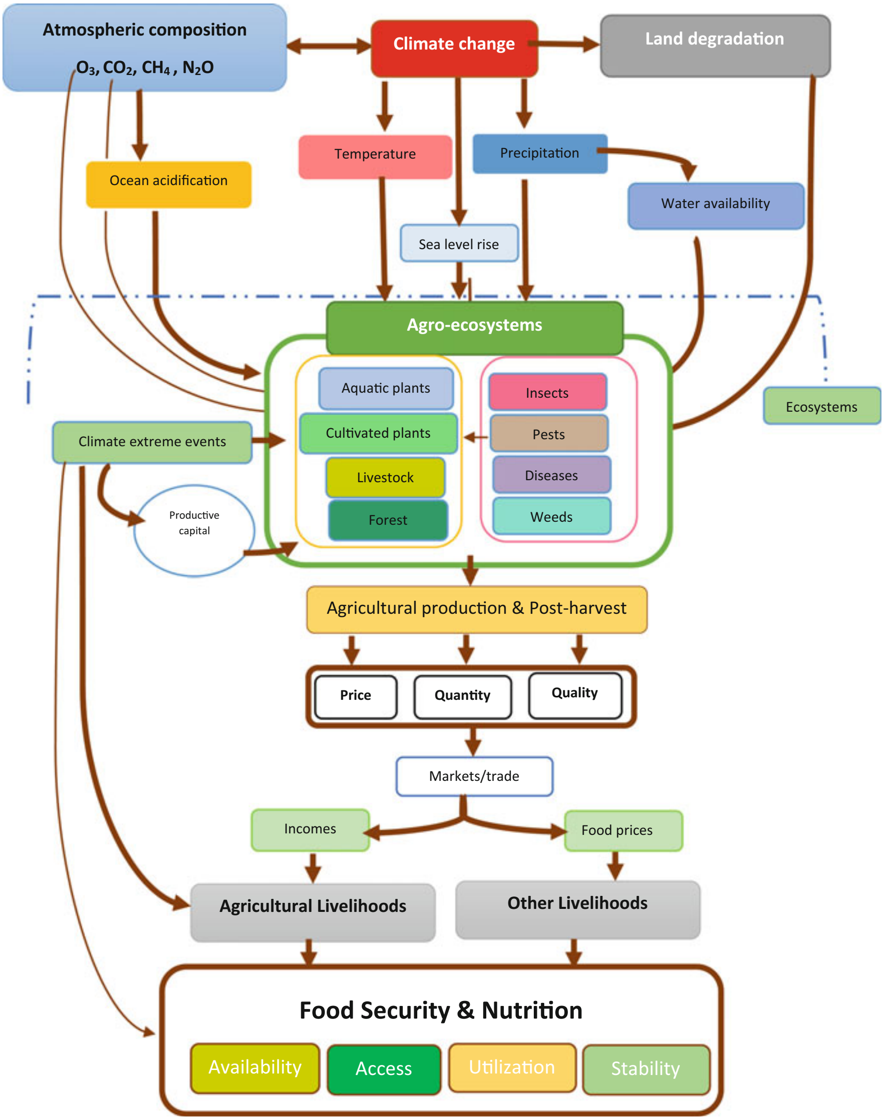


Fig. 2.7 Cascading effects of climate change on food security and nutrition. (Source: FAO)

2.3.1 *Sustainable Agriculture and Food Security*

Agriculture can be the cause and solution for the climate change, but sustainable agriculture (SA) has the potential to mitigate climate change and ensure food security. SA includes ecological and sustainable intensification, organic farming, integrated farming, climate smart and precision agriculture, vertical farming, and

Fig. 2.8 The 17 Sustainable Development Goals (SDGs). (Source: UNDP)

permaculture. Arora (2018) suggested integration of innovative biotechnology and bioengineering techniques with traditional biological methods to achieve goals of food security and sustainability. Similarly, mycorrhizal fungi and beneficial microbes could help to enhance food production by countering biotic and abiotic stresses. They also play vital roles in efficient utilization of resources, mineral solubilization, production of growth regulators, nitrogen fixation, recycling of organic matter, and restoration of degraded soil (Salwan and Sharma 2022). Spiertz (2009) reviewed about nitrogen and SA and concluded that for SA and food security, nitrogen supply should be matched with N demand in spatiotemporal scale, not only for single crops but also for all crops in rotation to have higher agronomic nitrogen use efficiency. Similarly, the role of biofertilizers in SA was discussed by Rehman et al. (2022), while Hussain et al. (2022) reported biochar a critical input and game changer for SA. Furthermore, nuclear techniques as proposed by the IAEA (International Atomic Energy Agency) and FAO could help to improve the food production from farm to fork and bring sustainability in agriculture.

2.3.2 *Global Food Security*

The world is at a critical juncture as reported in the FAO report of the State of Food Security and Nutrition in the World 2021 (FAO 2021). At present, the world is in chaos as it is committed earlier to end hunger, food insecurity, and malnutrition by 2030. This is mainly because of climate variability and extreme climate events, COVID-19 pandemic, and economic slowdown. Hence, the pathway toward SDG2 became steeper. Hunger level in the world is on rise, and it has been climbing to 9.9% in 2020 as around 720–811 million people faced hunger in 2020 (Fig. 2.9). Bold actions are needed to address the major drivers of food insecurity and

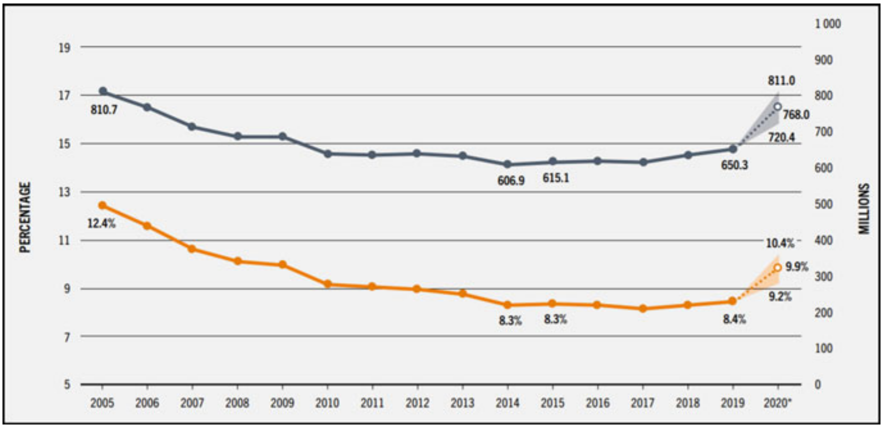


Fig. 2.9 The prevalence and number of undernourished people in the world. (Source: FAO 2021)

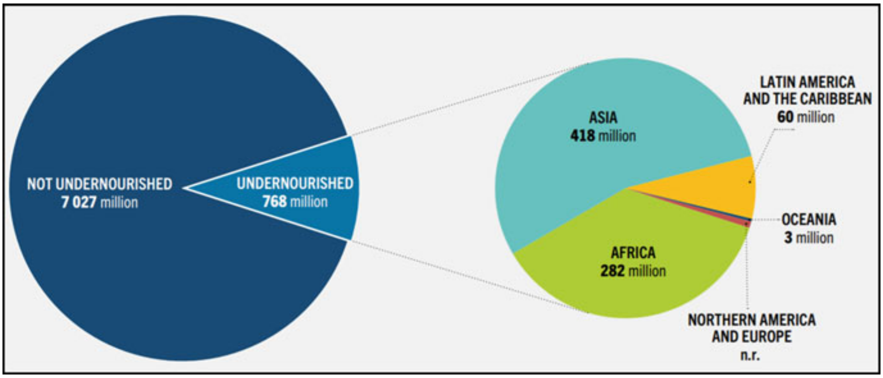


Fig. 2.10 Hunger prevalence among continents. (Source: FAO 2021)

malnutrition. More than half of the world population who are affected due to hunger lives in Asia as shown in Fig. 2.10. More than 30% of the world population has been affected due to moderate or severe food insecurity since the past 6 years (Fig. 2.11) and healthy diets are out of reach for billions of people. The COVID-19 pandemic has shown severe impact on the world economy (Afesorgbor et al. 2022). To end hunger and malnutrition, the way forward is transformation in the food system with greater resilience to major drivers, e.g., climate variability and extremes, conflicts, and economic slowdown. Six pathways were suggested for food system transformation to ensure food security and nutritive food for all. It includes (i) promotion of integrated policies (Humanitarian-Development-Peacekeeping) in affected areas, (ii) augmenting climate resilience across food systems, (iii) increasing resilience of most affected to economic hardship, (iv) lowering the cost of nutrition foods by improving food supply chains, (v) reducing poverty and inequalities, and

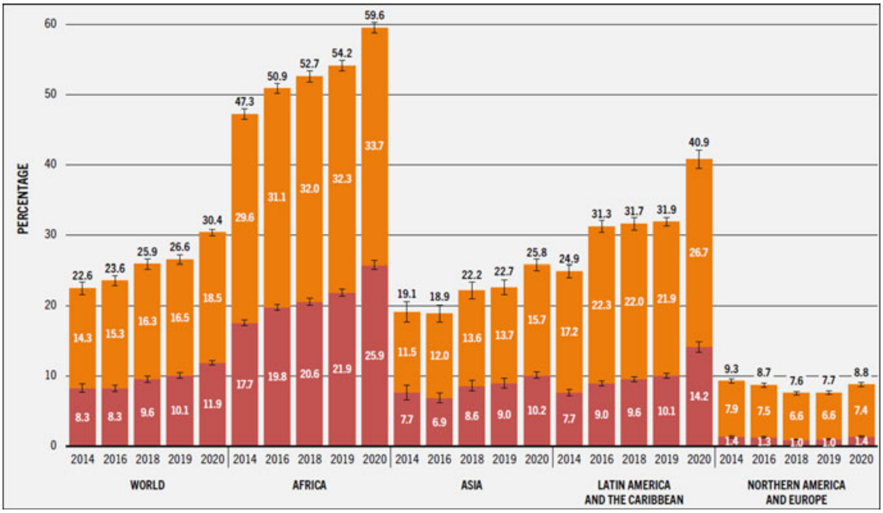


Fig. 2.11 Global food insecurity (moderate or severe) in the past 6 years. (Source: FAO 2021)

(vi) improving food environments and change in dietary habits to have more positive impacts to health and environment. Furthermore, van Dijk and Meijerink (2014) presented different drivers of food and nutrition security, which include climate change, population growth, income growth, food demand, dietary habits, and technical change. These drivers could be used to design integrated approach for the global food security (Fig. 2.12). However, these drivers may vary from country to country as elaborated in Fig. 2.13. High level of panel of experts (HLPE) on world food security have given new dimensions to ensure food security (HLPE 2019, 2020). Furthermore, relationship between different drivers, food systems, and food security have been presented in Fig. 2.14, which shows that these drivers have impacts on diet attributes (e.g., quantity, quality, diversity, safety, and adequacy) as well as on nutrition and health. The drivers, which have a major contribution to recent hunger and slowdown in progress, are given in dark blue boxes. Similarly, Fig. 2.14 elaborates circular feedback loops (e.g., increase in the consumption of unhealthy food due to economic crisis resulted toward higher emissions of GHGs) that can generate higher impacts with time. Hence, food environments have a negative relationship with food security and nutrition. Similarly, the recent COVID-19 pandemic has given a devastating blow to global food security and nutrition with multiple impacts on food systems (Fig. 2.15).

2.3.3 Food Security in Pakistan

Pakistan is committed to divert all possible efforts and resources for increasing food production and ensuring that people at large have access to food at affordable prices.

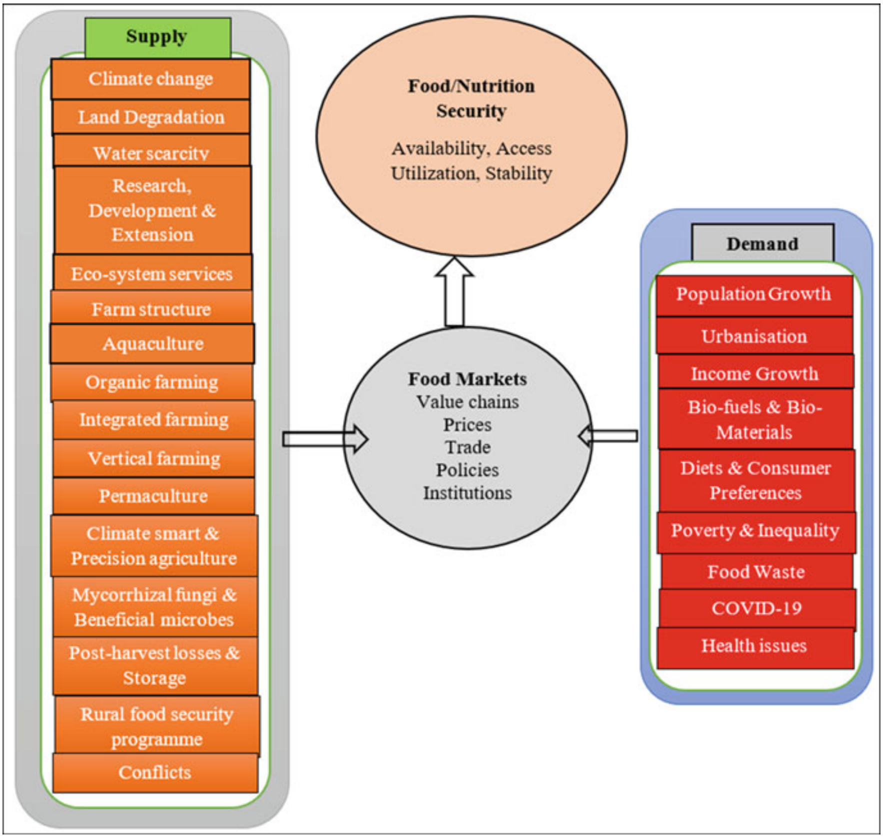


Fig. 2.12 Drivers of food/nutrition security across globe. (Modified from van Dijk and Meijerink 2014)

Pakistan agriculture sector contributes 19.2% to GDP with an employment share of 38.5%. Over 65–70% of Pakistan population depends upon agriculture sector for its livelihood. It is the engine of national economic growth and poverty reduction. However, the growth rate in this sector is on declining trend. This is mainly because of shrinkage of arable land, climate variability and climate change, water scarcity, and higher population shift from rural to urban areas. Government have implemented different agricultural policies to improve farm productivity through untapped productivity potential of crop and livestock subsectors. It includes introduction of agri-input regime and agriculture transformation plan. However, Pakistan is still a net food-importing country with high level of food insecurity that includes lack of food availability and high population growth. The other reason includes small land holdings (32% less than 1 hectare and 24% less than 2 hectare) that is not permitting to enhance farm productivity or incomes beyond a certain limit (Bashir et al. 2013; Abdullah et al. 2019). Data from different sources depicted that daily

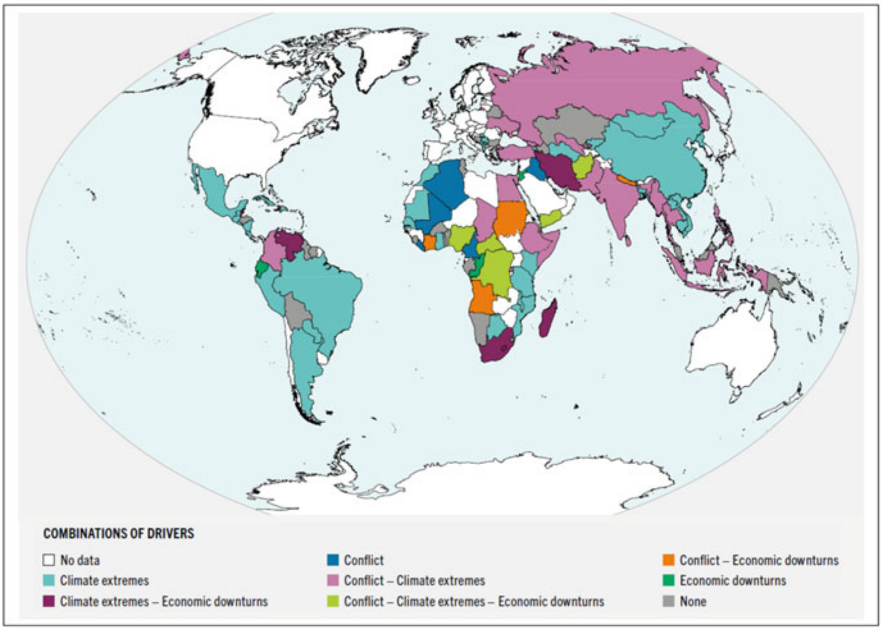


Fig. 2.13 Food security drivers across the globe

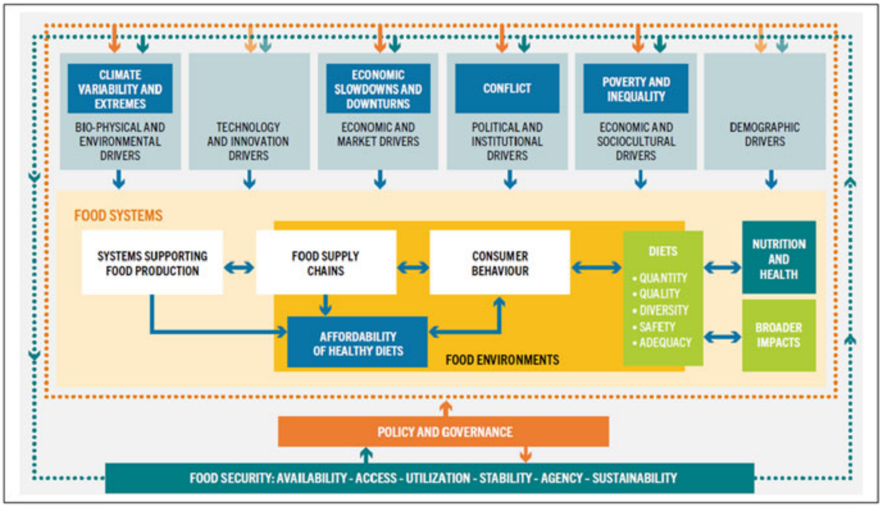


Fig. 2.14 Relationship between different drivers, food systems, and food security. (Source: FAO 2021)

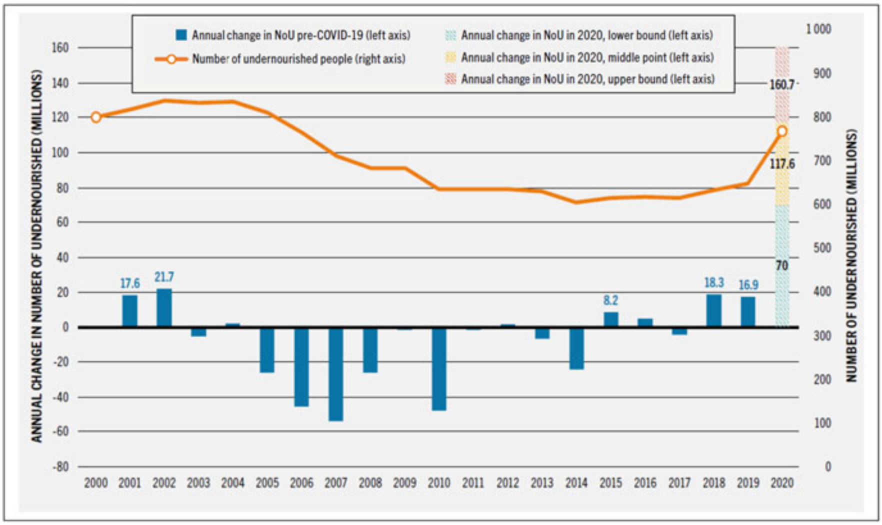


Fig. 2.15 Time series analysis of annual change in number of undernourished due to COVID

average availability of calories per person in Pakistan is lower by 10% and 26% relative to the average in developing and developed counties, respectively (Hameed et al. 2021). Pakistan has been trying to maintain the 2350 calories per person per day since the early 1990s from a level of 1754 calories per person per day in 1961. The average per capita availability of calories during 2015–2016 was 2473 kcal day^{-1}, which exceeds the minimum energy requirements (Shabnam et al. 2021). However, a higher rate of malnutrition was observed due to low nutritional intake (IFPRI 2016). In Pakistan, around half of the caloric needs are met through cereals only. Wheat and rice are the staple food crops, and shortfalls in production adversely affect both food security and national economy. Wheat production (2020–2021) was 27.3 million tons, which was 8.1% higher than the last year. However, still Pakistan has to import 3 million tons to build strategic reserves, a euphemistic indicator of local shortage. Factors which are responsible for the food insecurity in Pakistan are (i) small land holdings, (ii) technological constraints to achieve productivity potential in farming system and climate change perspective, (iii) land and soil health degradation, (iv) deteriorating irrigation and drainage system, (v) poorly regulated markets, (vi) lack of mechanization and skilled farm labor, and (vii) ineffective research-extension linkages. Per capita availability of food items in Pakistan from 2002 to 2007 have been shown in Table 2.2, while food security and related indicators for some years have also been given (Table 2.3), which shows that proper measures are needed to end hunger and malnutrition in Pakistan. Crop productivity scenario to ensure food security in Pakistan is presented in Table 2.4.

Table 2.2 Per capita availability of food items

Items	Unit	2002	2003	2004	2005	2006	2007
Wheat	Kg	114.7	112.0	116.3	115.8	123.2	127.0
Rice	Kg	13.9	17.2	16.8	17.6	10.0	16.6
Other grains	Kg	11.1	11.1	11.6	11.5	17.0	16.0
Pulses	Kg	7.02	5.8	8.00	6.8	7.9	7.2
Edible oils	Kg	11.5	11.9	11.5	11.7	12.9	13.1
Fruits and veg.	Kg	80.5	83.3	87.5	82.9	77.9	77.6
Sugar	Kg	30.3	30.8	30.5	30.7	34.8	32.2
Milk	Lit.	83.1	83.8	85.9	85.9	90.3	94.2
Meat	Kg	21.3	21.3	21.5	21.0	21.8	23.3
Eggs	Doz.	4.5	4.5	4.6	4.6	4.8	5.0

Table 2.3 Food security and related indicators

Indicators	1996	2001	2005	2008
Average per person dietary energy supply (Kcal)	2522	2706	2381	2529
Food production index	–	100	92	111
Cereal supply per person (all food grains) (Kg)	180	203	174	191
Animal protein supply per person (gram) per day	67.3	71.7	–	46.3
Value of gross investment in agriculture (mil US $)	51.5	45.1	22.8	33.3
Food price index (2000–2001 = 100)	82.9	100	111.7	169.5
Index of variability of food production (1999–2000 = 100)	–	91	95	111
Consumer price index	72.5	100	106.7	155.7

Table 2.4 Crop productivity scenario to ensure food security in Pakistan

	Average (tons/hectare)				
Scenarios	Wheat	Cotton	Rice	Maize	Sugarcane
Productivity at research stations	6.5	14.6	8.0	12.5	189.0
Productivity at progressive farmers	5.5	3.5	4.8	7.5	106.7
National average productivity	2.6	2.0	2.1	3.5	48.9
% gap between progressive farmer and national average	52.5	41.3	58.9	53.6	54.2
% gap between potential and national average	59.8	55.3	73.5	72.1	74.1

2.4 Climate Change and Food Security: Impacts

Food security is the topmost challenge of the twenty-first century, but it has been threatened by the climate change. However, ensuring food security is an important task to feed billions in future by sustaining stressed environmental resources (Lal 2005). Magadza (2000) reported more severe impacts of climate change on food security, water, and human health for African countries. Kang et al. (2009) reviewed that uncertainty in food production has been increased due to climate change. Climate change is increasing the intensity and frequency of extreme events across

Table 2.5 Crop productivity variation and climate change

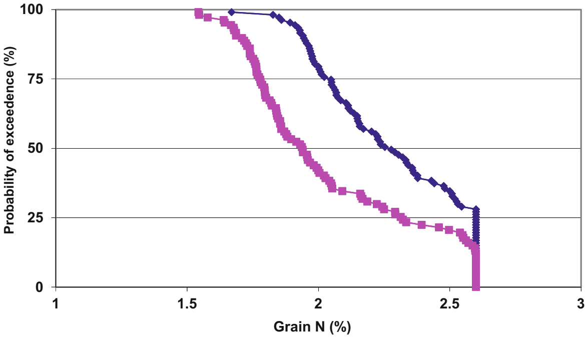
Variation	Causes
Variation from field to field on the same farm under the same management	Soil and microenvironment
Variation from farm to farm even on similar soil and area	Agro-management
Variation from year to year on the same site, soil, and similar management	Weather and climate variability

the globe, which resulted to the disasters in livestock, crops, and food production and supply sectors (Hallegatte et al. 2007; Dastagir 2015). Climate change and variability resulted to the depletion in water resources and declined agricultural productivity (Fatima et al. 2022; Arunrat et al. 2022; Yeşilköy and Şaylan 2021). Similarly, it has been well-documented that global temperature at the end of the twenty-first century may increase by 1.4–5.8 °C, which will reduce freshwater and agricultural crop yield and ultimately leads toward the issue of food security (Misra 2014). Furthermore, variation in crop productivity due to climate change have been listed in Table 2.5. Climate change impacts are now visible in the form of growing deserts, more occurrence of floods, heat waves and droughts. These climate extremes cause reduction in crop yields, food shortages, and increase in food inflation. Hence, to protect different crops and production systems from the damaging effect of climate change, most of the recent studies are focused on the climate impacts and adaptation strategies (Naz et al. 2022; Ahmad et al. 2019; Hoogenboom et al. 2017; Li et al. 2015; Asseng et al. 2015; Araya et al. 2015; White et al. 2011). Crop growth models have been significantly used to study the impacts of climate change and furthermore in the designing of adaptation strategies (Tui et al. 2021; Kapur et al. 2019; Dubey and Sharma 2018; Hussain et al. 2018; Mohanty et al. 2012; Akponikpè et al. 2010; Pearson et al. 2008). Simulation models are good tools to study climate impacts and addressed them in a risk management context (both food security and climate change). Similarly, assessing both impacts and adaptations through modeling will help to increase our understanding of climate processes and food production. Thus, understanding the link between food requirements and climate variability is important to design appropriate future sustainable food production options.

2.4.1 *Climate Factors Affecting Food Security*

Different direct and indirect climate factors are affecting food security. Direct factor changes crop biodynamism, and it includes carbon dioxide (CO_2), temperature, rainfall, solar radiation, frost, fog, and smog. Elevated CO_2 has shown positive effect (fertilization effect) on crop production and water use efficiency but affected negatively the produce quality (Varga et al. 2015; Sulieman et al. 2015; Fitzgerald et al. 2016; O'Leary et al. 2015; Erbs et al. 2015; Manderscheid et al. 2015). The nutritional quality of produce is at stake under elevated CO_2, as in C3 plants higher CO_2 concentrations resulted to the production of more carbohydrates and less

Fig. 2.16 Grain nitrogen in response to elevated CO_2



minerals (zinc and iron) (Ebi and Loladze 2019). Higher CO_2 is directly affecting crops' nutritional quality by decreasing protein and mineral concentration by 5–15% and B vitamins by 30% (Loladze 2014; Myers et al. 2014; Zhu et al. 2018). Reduction in grain nitrogen due to elevated CO_2 is shown in Fig. 2.16. Loladze (2002) reported declined essential element to carbon ratio, which could intensify the problem of micronutrient malnutrition in future. Furthermore, micronutrient deficiencies will cause higher disease burden than food insecurity. However, legume plants have shown more positive response to elevated CO_2 due to increased nitrogen fixation (Hikosaka et al. 2011). C4 crops, although get less benefits from elevated CO_2 as carbon uptake in these plants, is saturated at ambient CO_2 levels, so no carbon dilution occurs with no effect on protein and micronutrients levels (von Caemmerer and Furbank 2003). Hence, C4 crops have great potential to fulfill nutritional needs of human beings under changing climate as they have good adaptability to warm and dry climates. But to have full potential of C4 crops under future changing climate, complete understanding and linkage between mineral nutrition and C4 photosynthesis is needed (Jobe et al. 2020). Rise in temperature is another important limiting factor, which is affecting food security at global scale. Recent temperature anomalies generated by the NASA (the National Aeronautics and Space Administration) have clearly shown that global surface temperature have increased by +1 °C in almost every month (Fig. 2.17). The climate spiral (designed by climate scientist Ed Hawkins from NASA) has been widely distributed during Rio de Janeiro Olympics to show clearly how important it is to address the issue of climate change (https://svs.gsfc.nasa.gov/4975). Increased temperature is the major reason of reduced crop yield and poor quality, as higher temperature decreases water use efficiency, crop growth period, photosynthesis, and yield (Ahmad et al. 2019; Urban et al. 2018; Mäkinen et al. 2018; Lizaso et al. 2018; Prasad and Jagadish 2015). Zhao et al. (2017) investigated the impacts of temperature on yields of four crops, i.e., wheat, rice, maize, and soybean, using published work, where they have used different analytical techniques (e.g., field warming experiments, regression, and global grid-based and local point-based models). Results depicted that without adaptations, genetic improvement, and CO_2 fertilization, every 1 °C rise in temperature could reduce yields of wheat (6.0%), rice (3.2%), maize (7.4%), and soybean (3.1%). Iizumi et al. (2017) studied the responses of crop yield growth to

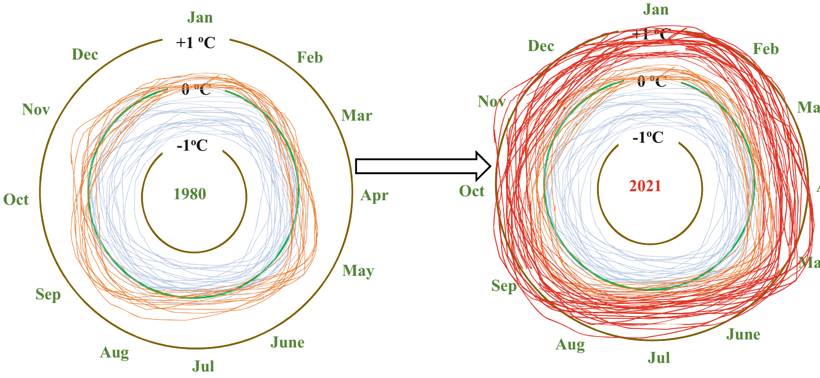


Fig. 2.17 Monthly global surface temperatures from 1980 to 2021. (Modified from NASA)

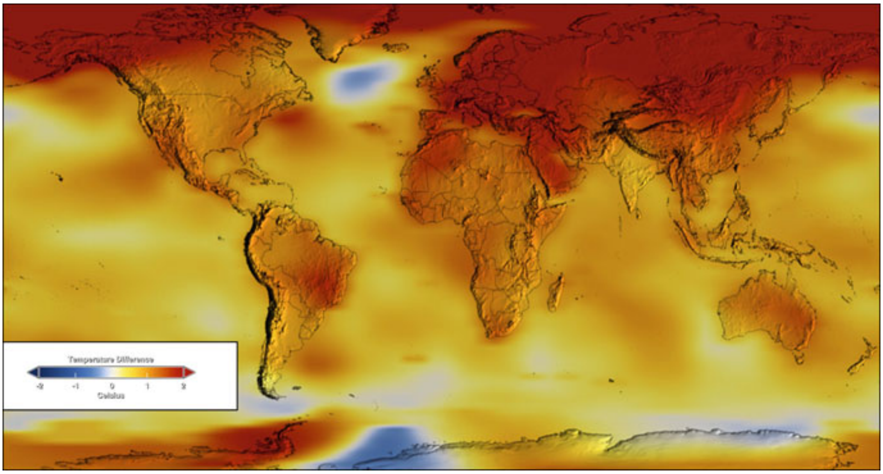


Fig. 2.18 Global temperature anomalies (°C) from 1880 to 2020 (higher than normal temperature = red and lower than normal temperature = blue and normal temperature = average over thirty years baseline period 1951–1980). (Source: NASA's Scientific Visualization Studio)

temperature and concluded that intensive mitigation is needed in low-income countries to improve food security and prevents damage to major crops. The map of global temperature changes for the year 2020 in comparison to baseline period (1951–1980) showed that across the globe there is significant increase in temperature (Fig. 2.18). The dramatic increase is more in far northern latitudes. CO_2 concentration, temperature, rainfall, and solar radiation changes will interactively effect crop productivity and ultimately food security. However, indirect factors of climate change which affect crop existence and food security include water resources, floods, soil degradation, drought spells, pest, and diseases.

2.4.2 Climate Change Extreme Events

Climate change is visible in the form of different extreme events happening across the globe in recent decades. Intensification of weather extremes is important facets of climate change (Jentsch et al. 2007). It includes extreme heat wave (>49.6 °C temperature in Canada on June 29), Hurricane Ida, European summer flood, and flooding in China, July 2021: Earth's warmest month in recorded history and melting of glaciers. These extreme events are causing disasters in vulnerable communities and ecosystems (Mal et al. 2017, 2018). Changes in global precipitation is one of the clear indicators because of global warming. Some parts of the world (mainly northern latitudes) are experiencing increased precipitation, whereas other regions will experience decreased precipitation (Fig. 2.19). Hence, understanding of climate extremes is important to design disaster risk reduction mechanism.

2.4.3 Understanding Climate Change Extreme Events to Ensure Food Security

Understating of climate change is important to ensure food security. Climate change has already threatened agriculture, food production, and food security. Hence, understanding of climate extreme is the first step to design adaptation strategies. Different climatic drivers could be used to understand the future climatic changes. ENSO (El Niño–Southern Oscillation) is the topmost driver which has been used to predict future climatic changes before time (Lee et al. 2021; Thirumalai et al. 2017; Tack and Ubilava 2015; Woli et al. 2015). ENSO changes the global atmospheric

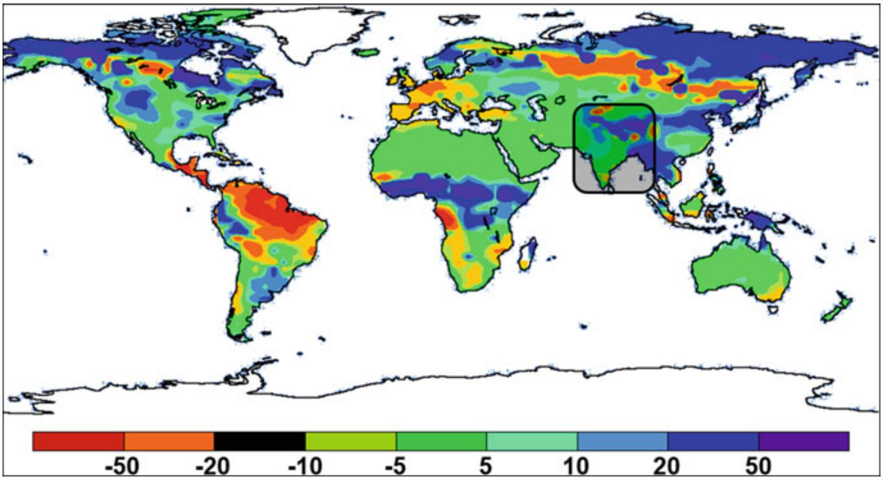


Fig. 2.19 Potential worldwide precipitation changes

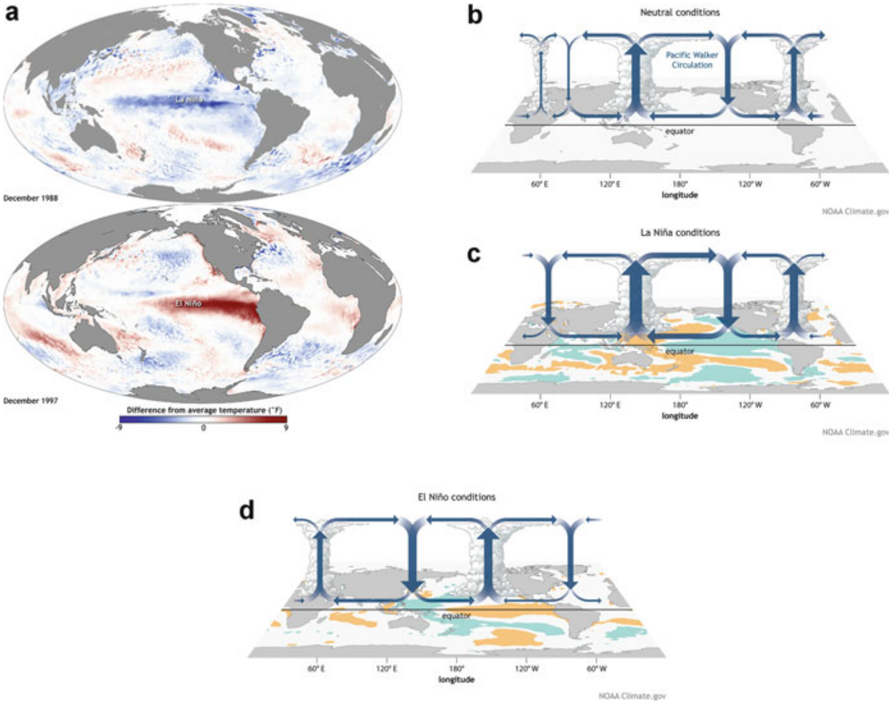


Fig. 2.20 Neutral, La Niña, and El Niño three phases of ENSO (El Niño–Southern Oscillation). (Source: NOAA)

circulation, which results to the change in precipitation and temperature across the globe. Prediction of ENSO arrival in advance is helpful to understand future weather and climate. ENSO has three states or phases, i.e., (i) El Niño (warming of ocean surface or above-average sea-surface temperatures (SST)), (ii) La Niña (cooling of ocean surface or below average SST), and (iii) neutral (neither El Niño or La Niña) (Fig. 2.20). Hence, process-based seasonal forecasting using ENSO could be the most practical way of designing risk management options for dealing with both climate variability and climate change (Davey et al. 2014; Singh et al. 2022). Similarly, prediction of regional heat waves over the South Asian region, particularly over Pakistan, could help to design adaptation options for agriculture sector (Rashid et al. 2022). Wangchen and Dorji (2022) examined the potential impact of agrometeorology initiative for climate change adaptation and food security in Bhutan. Study reported that food security challenges will be further aggravated due to the changing climate. Hence, adaptation is necessary to enhance food security. They suggested the use of agromet decision support system to generate and disseminate information to the stakeholders so that they can plan accordingly. Similarly, information can also be used to manage smart irrigation system and development of pest forecasting system. Thus, the overall enhancement of food security is possible through the establishment of early warning system using climatological information.

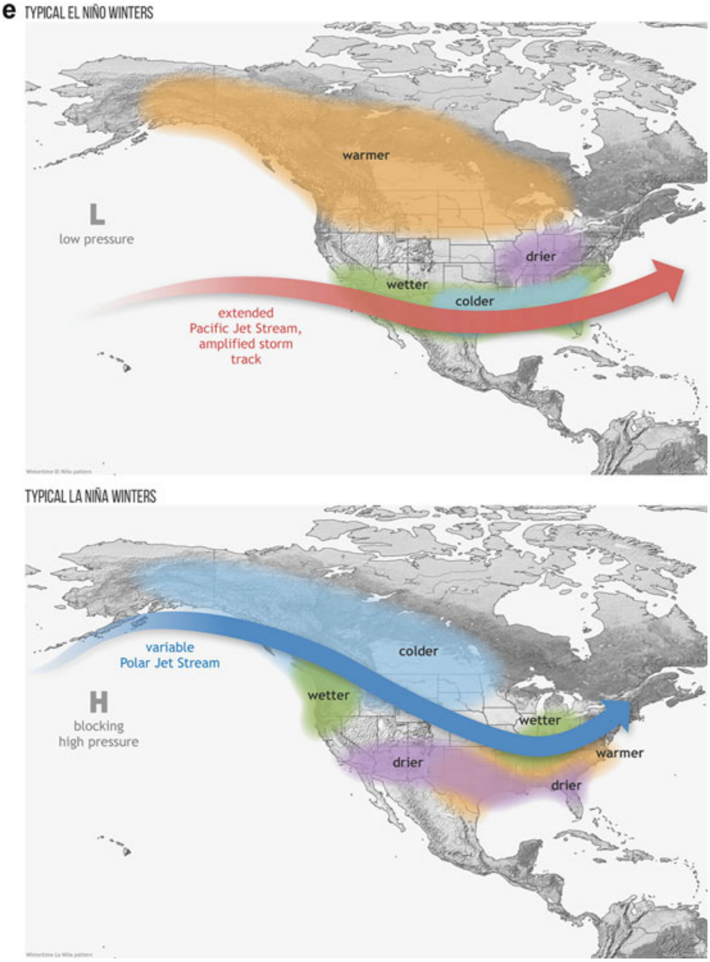


Fig. 2.20 (continued)

van Ogtrop et al. (2014) developed a time-lagged relationship between SSTs and rainfall periods and provided forecast system for the rainfed agriculture. The impact of climate change events (El Niño and La Niña) on rainfed wheat production has been presented in Table 2.6. Variability in yield data during different cropping year was due to variability in rainfall, which has strong connections with ENSO and SOI phases. Therefore, ENSO can be used as an early warning tool for the risk managements in different sectors of life (e.g., agriculture sector) as reported in previously published work (Ludescher et al. 2014; Rashid et al. 2022; Lee et al. 2021; Thirumalai et al. 2017; Tack and Ubilava 2015; Woli et al. 2015). Similarly, rainwater dynamics for rainfed agriculture could be accurately modeled by making teleconnections with climatic drivers like SST and pressure (Ahmed et al. 2014). Long-term rainfall data for rainfed area of Pakistan, i.e., Islamabad, shows a slight

Table 2.6 Effects of climate events on rainfed wheat production

Cropping Year	Yield (Kg/ha)	% change	Climate events	SOI Phase (July)
1999-00	1319	-25	Drought Year (Weak La Niña)	4
2000-01	534	-70	Drought +Terminal heat stress (Non El Niño drought)	5
2001-02	717	-59	Drought +Terminal heat stress (Non El Niño drought)	5
2002-03	1310	-25	Drought Year (Moderate El Niño)	5
2003-04	1321	-25	Terminal heat stress (Non El Niño drought)	4
2004-05	1730	-1	(Weak El Niño)	1
2005-06	1354	-23	Terminal heat stress (Non El Niño drought)	5
2006-07	1755	=	Bumper Year as Benchmark (Moderate El Niño)	5
2007-08	1205	-31	Frost +Terminal heat stress (Moderate La Niña)	3
2008-09	1290	-31	Drought Year (Weak La Niña)	5
2009-10	1276	-26	Drought & Moderate El Niño	4
2010-11	1375	-27	Strong La Niña	4
2011-12	1357	-22	Moderate La Niña	4
2012-13	1398	-23	Heat stress without El Niño	2
2013-14	1412	-20	-	5
2014-15	1363	-20	Weak El Niño	1
2015-16	1376	-22	Very Strong El Niño	5
2016-17	1486	-22	Weak Lanina	4
2017-18	1425	-15	Weak Lanina	4
2018-19	1403	-19	Weak El Niño	1
2019-20	1433	-20	-	4
2020-21	1487	-18	Moderate La Niña	4

decreasing trend in winter rainfall while increasing trends in the occurrence of summer rainfall (Fig. 2.21). Similarly, rainfall intensity in the month of July has increased overtime (Fig. 2.22), which shows the importance of monsoon rainfall. Hence, simulation models provide the way to focus on risks and responses of food system in relation to climate.

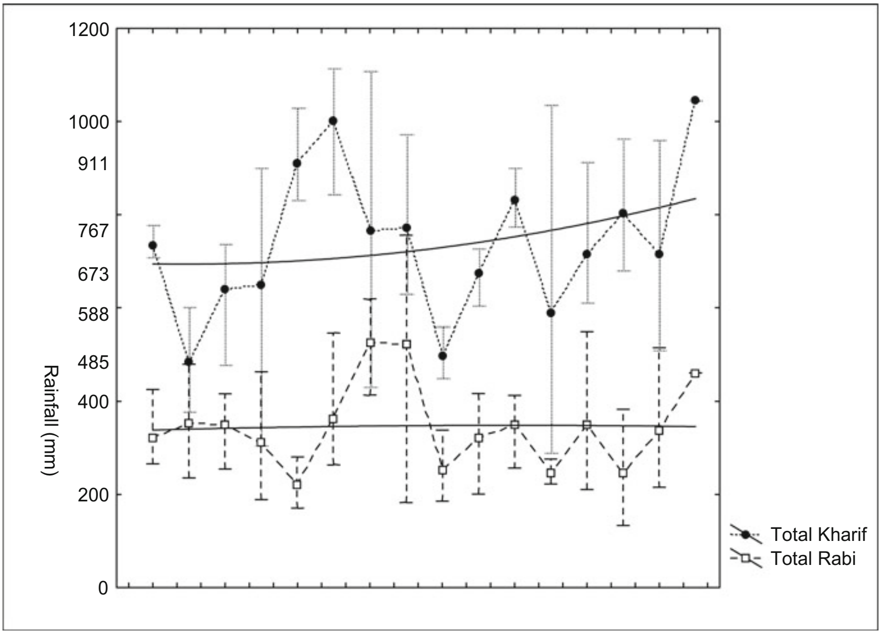


Fig. 2.21 Long-term rainfall pattern in Islamabad during summer (*kharif*) and winter (*rabi*) seasons

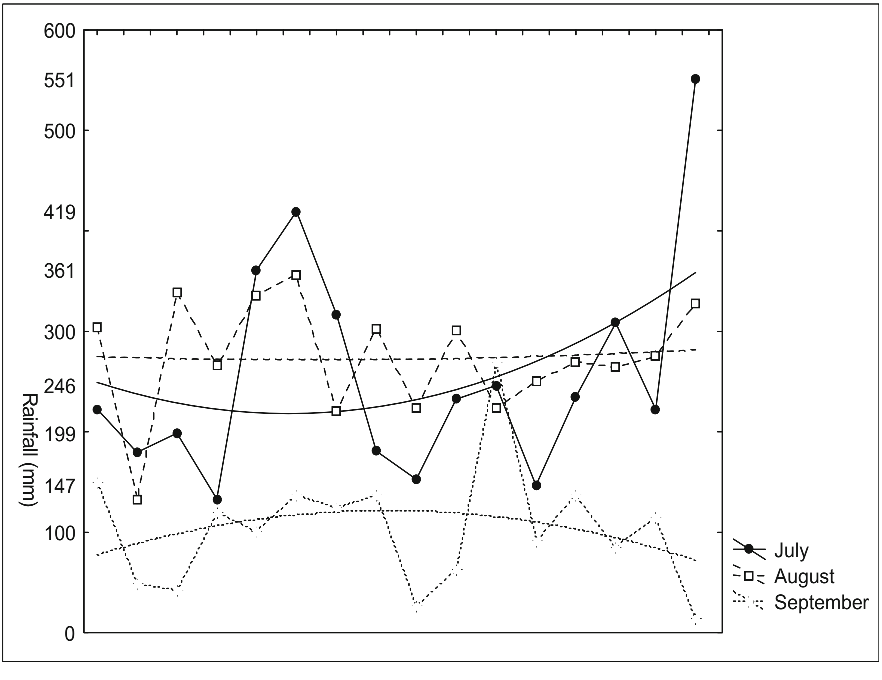


Fig. 2.22 Rainfall intensity in the month of July, August, and September

The strength of El Niño and La Niña events can be further gauged by using the Southern Oscillation Index (SOI), which is the measure of the strength of the Walker circulation (ENSO's atmospheric buddy) (Fig. 2.23). The SOI measures the difference in air pressure between Tahiti and Darwin. The phases of the SOI were defined by Stone et al. (1996), who used cluster analysis to group 2-month pairs of the SOI from 1882 to 1991 into five clusters as phases. The phases are as follows: Phase 1, consistently negative; Phase 2, consistently positive; Phase 3, falling; Phase

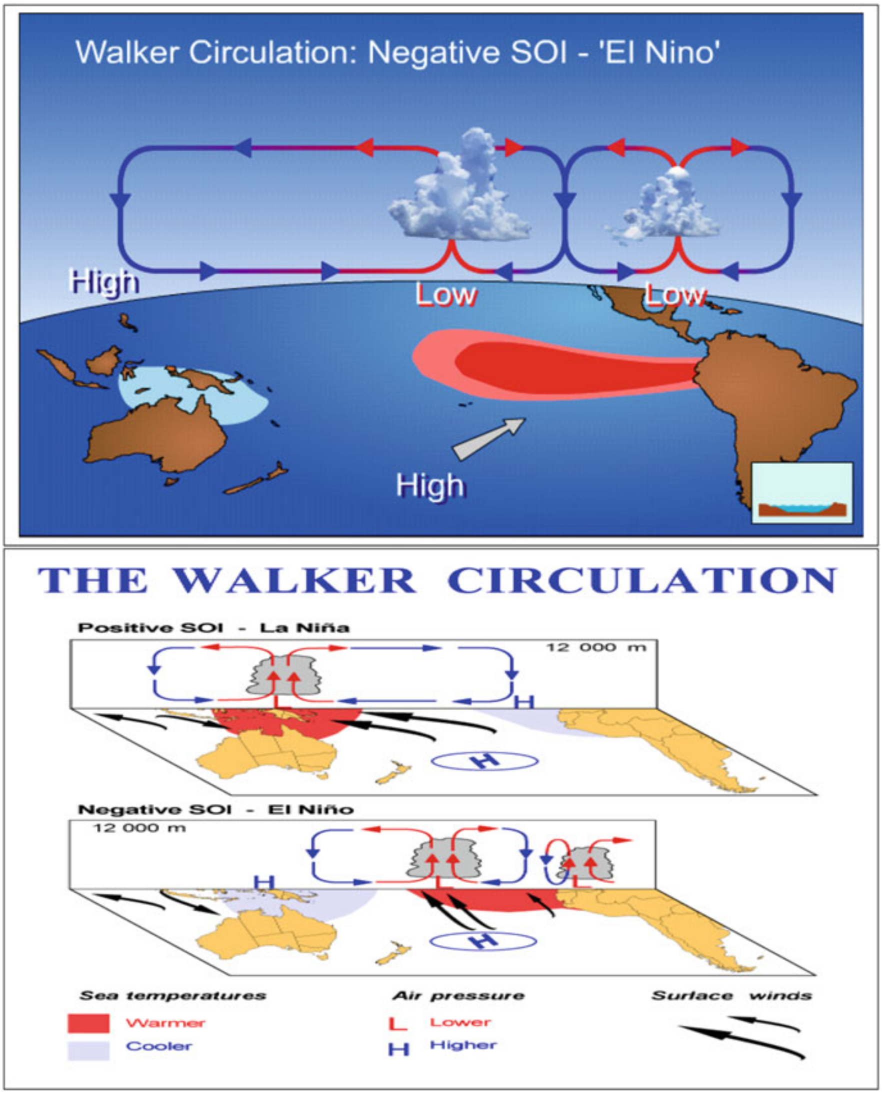


Fig. 2.23 The Walker circulation showing negative and positive SOI. (Source: NOAA)

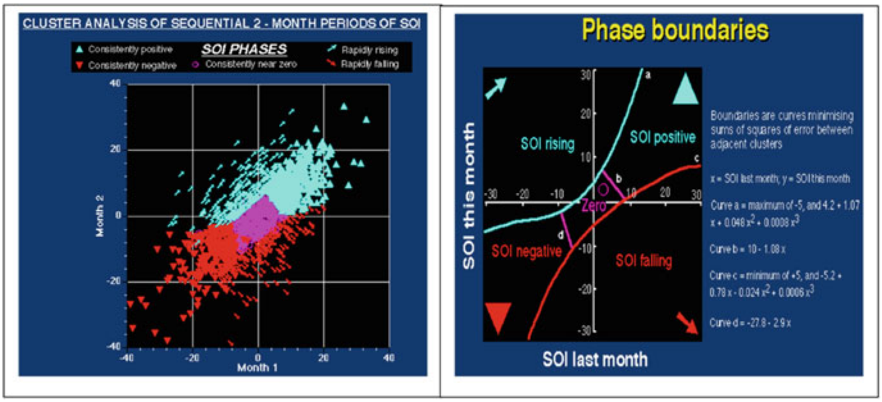


Fig. 2.24 Five clusters of SOI. (Source: Stone et al. 1996)

4, rising; and Phase 5, consistently near zero (Fig. 2.24). Stone et al. (1996) reported that accurate prediction of ENSO is helpful to accurately predict the global rainfall variations, which can be further used to manage agricultural production, reduce risks, and maximize profits. Furthermore, the SOI provides a good basis for rainfall forecasting with accuracy of 2 months which is helpful for key management decisions (Cobon and Toombs 2013).

2.4.4 Climate Change and Rainfed Wheat Production: Simulation Study

The Agricultural Production Systems Simulator (APSIM) was calibrated and evaluated for wheat genotypes in rainfed region of Pakistan (Table 2.7), which shows close association with the field observed yield data. Furthermore, simulation study was conducted to study the impact of rise in temperature and elevated CO_2 on rainfed wheat. Results showed that rise in temperature resulted to the reduction in the days to maturity, but this effect was compensated by the elevated CO_2, which resulted to the higher grain yield (Table 2.8). Guoju et al. (2005) studied the interactive effect of rise in temperature and elevated CO_2 on wheat yield and reported similar outcome. However, when temperature increase was 1.8 °C, then wheat yield was reduced. They suggested supplemental irrigation as an adaptation strategy to minimize the loss of yield. Similarly, variability in temperature during wheat growing season is shown in Fig. 2.25, which confirms that climate is changing, and adaptation options are need of time. Growing degree day or heat unit is the best indicator to monitor temperature response on crop phenology. Temperature requirement of wheat (thermal times/degree days) under normal conditions have been given in Table 2.9. However, with the rise in temperature, availability of heat unit during different phenological stages will be changed (Fatima et al. 2020; Ahmad

Table 2.7 Simulation of different wheat genotypes yield (kg ha^{-1})

Genotypes	Measured		Simulated		Bias	*t*	Regression equation	r^2
	Mean	SD	Mean	SD				
Wafaq-2001	3245	485	3177	444	−68	−0.36	S = 0.88M + 324.3	0.92
Chakwal-97	3056	542	3017	464	−39	−0.19	S = 0.83M + 473.5	0.94
NR-55	2729	466	2729	483	0.2	0.001	S = 1.02M − 61.73	0.98
NR-232	3062	524	3067	462	5	0.02	S = 0.83M + 528.5	0.88
R-234	3184	485	3180	417	−3	−0.02	S = 0.60M + 1273	0.49
Margalla-99	2938	559	3067	455	129	0.54	S = 0.69M + 1028	0.73

Table 2.8 Simulation of impact of climate change on wheat crop parameters

Variables	Baseline	2020	2050
	1990	0.9 °C	1.8 °C
CO_2 concentration	360 ppm		
Maturity days	183	180	175
Grain yield (Kg ha^{-1})	4090	4425	4397
Grain (number/spike)	28	30	30
Grain weight (mg)	34	37	39
CO_2 concentration	500 ppm		
Maturity days	183	180	175
Grain yield (Kg ha^{-1})	4090	4781	4781
Grain (number/spike)	28	30	29
Grain weight (mg)	34	38	30

et al. 2019). Relationship between wheat critical growth stages and degree days utilized and rainfall received has been elaborated in Fig. 2.26. Kapur et al. (2019) reviewed the impact of climate change and CO_2 on wheat yield. They reported around 25% increase in wheat yield with a twofold increase in CO_2 concentration. However, this increase due to elevated CO_2 was offset by the temperature rise of 3 °C. Hence, they suggested application of proper irrigation management techniques to coup the future water stress. Hernandez-Ochoa et al. (2018) quantified the impact of future climate change on wheat production and reported reduction in yield.

2.4.5 Changing Planting Window: Adaptation Option for Enhancing Food Security

Change in planting window can be a good option to adapt to climate change for enhanced crop productivity and improved food security. Different crops and varieties can give variable yield for different combinations with ENSO phenomenon of climate. The response of wheat crop under different plating windows has been shown in Fig. 2.27. It is clearly visible that delayed sowing resulted to the earlier anthesis and maturity with reduction in grain yield (Fig. 2.28). Furthermore, the

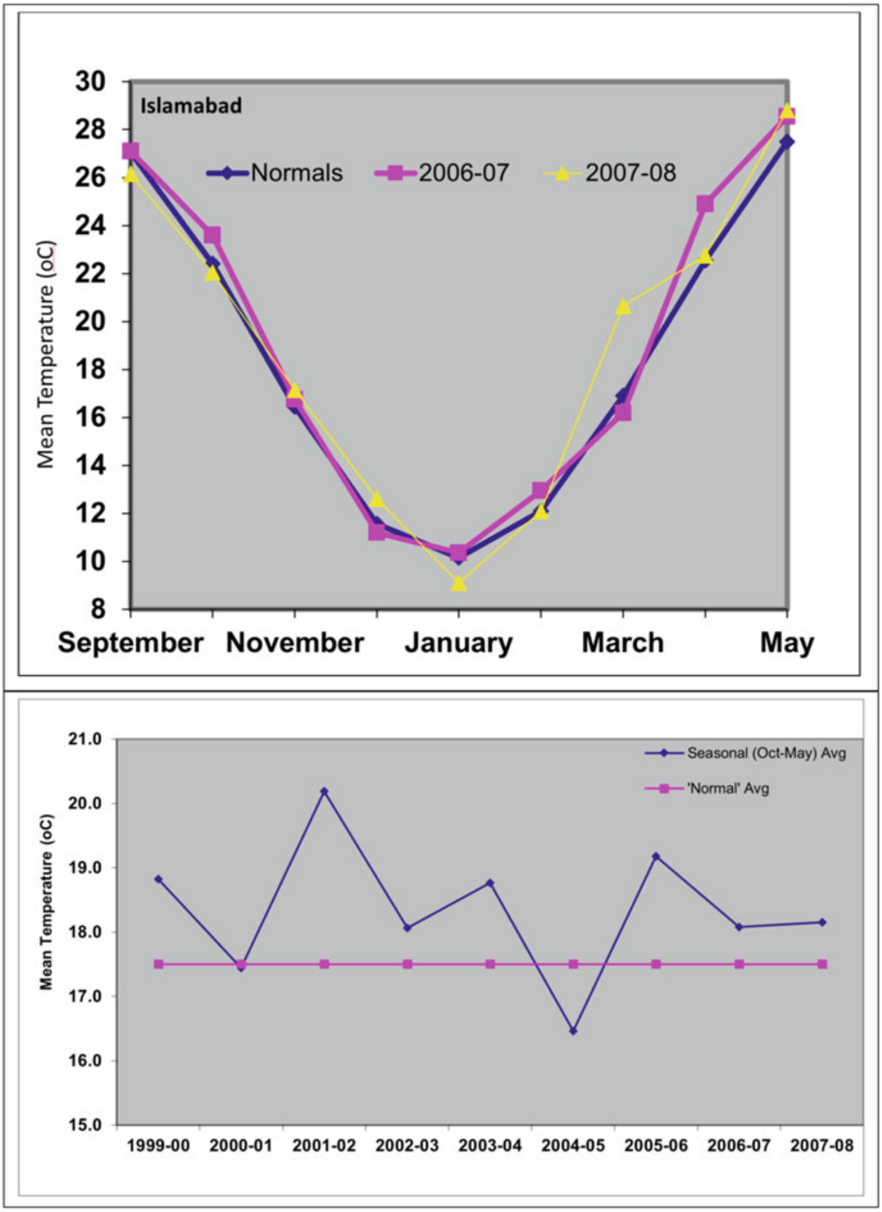


Fig. 2.25 Temperature variability during wheat growing season

impact of SOI phases on wheat yield was simulated, which showed that planting after mid-November (PW3 and PW4) was vulnerable to climatic fluctuation governed by SOI phase in July (Figs. 2.29 and 2.30). Moreover, different wheat

Table 2.9 Temperature requirement of wheat (thermal times/degree days)

At normal seeding depth, thermal time required for germination 65 °Cd
After emergence, the crop takes up to 450 °Cd to reach anthesis
The duration of grain filling is cultivar specific and varies between 500 and 800 °Cd
From sowing to maturity, wheat crop generally requires thermal time between 1350 and 1450 °Cd

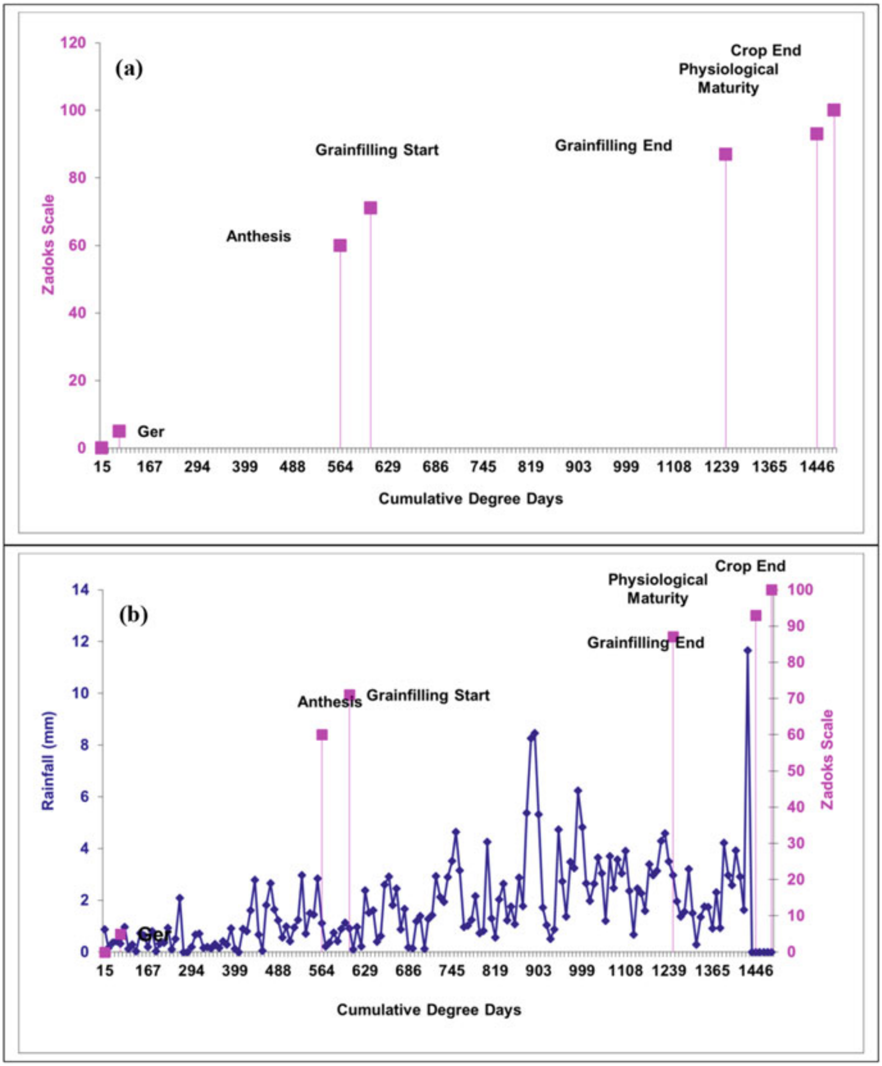
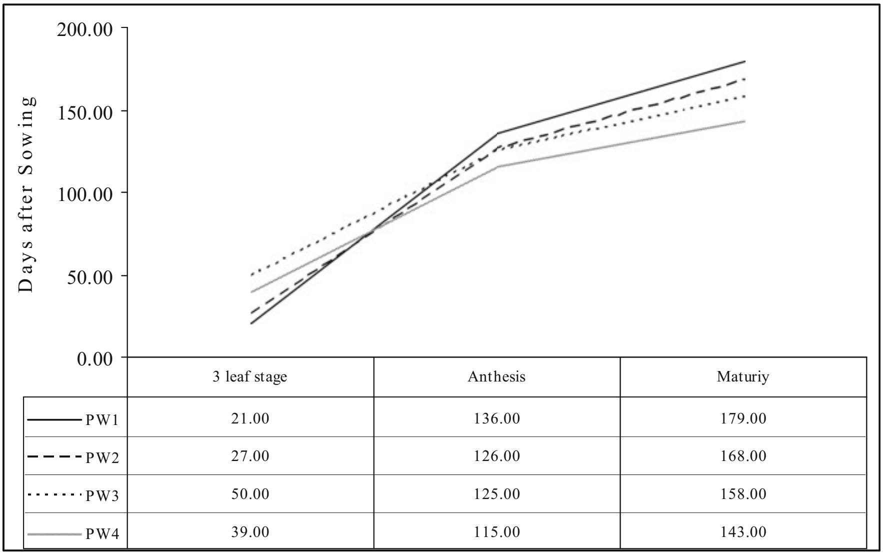


Fig. 2.26 Wheat critical growth stages and degree days utilized (a) and rainfall received (b)

varieties responded differently to SOI phase (Fig. 2.31). Similar to our recommendations, Ali et al. (2022) suggested change in planting date as suitable adaptation



	3 leaf stage	Anthesis	Maturiy
PW1	21.00	136.00	179.00
PW2	27.00	126.00	168.00
PW3	50.00	125.00	158.00
PW4	39.00	115.00	143.00

Fig. 2.27 Planting windows (PW) and duration of wheat phenological stages (PW1 = sowing between 15 and 25 October, PW2 = sowing between 10 and 17 November, PW3 = sowing between 27 November and 02 December, PW4 = Sowing between 10 and 24 December)

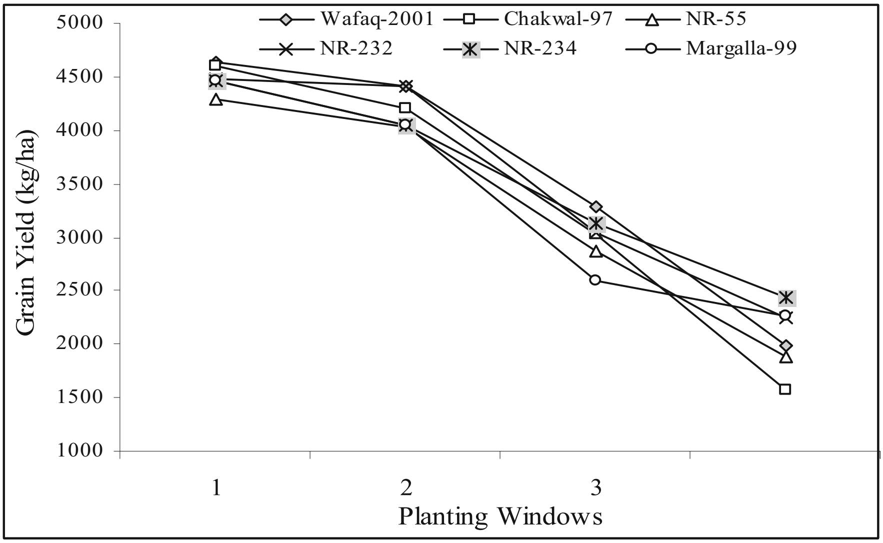


Fig. 2.28 Planting windows and wheat yield (PW1 = sowing between 15 and 25 October, PW2 = sowing between 10 and 17 November, PW3 = sowing between 27 November and 02 December, PW4 = sowing between 10 and 24 December)

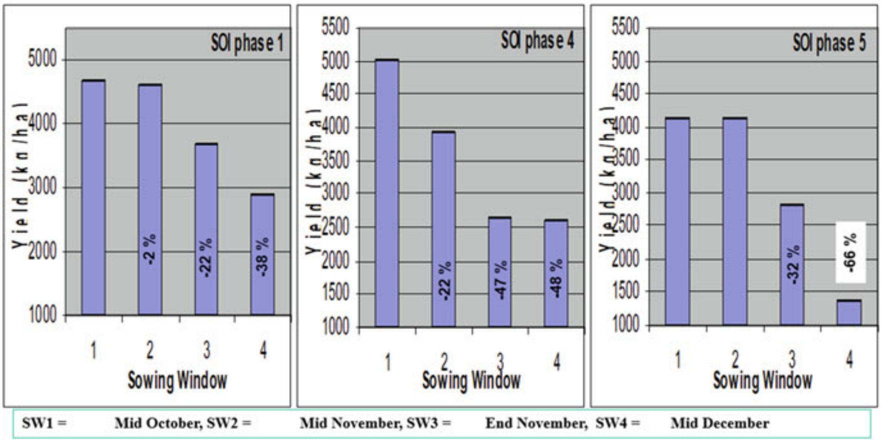


Fig. 2.29 Simulated yield variations in relation to sowing time partitioned against the prevailing SOI phase in July

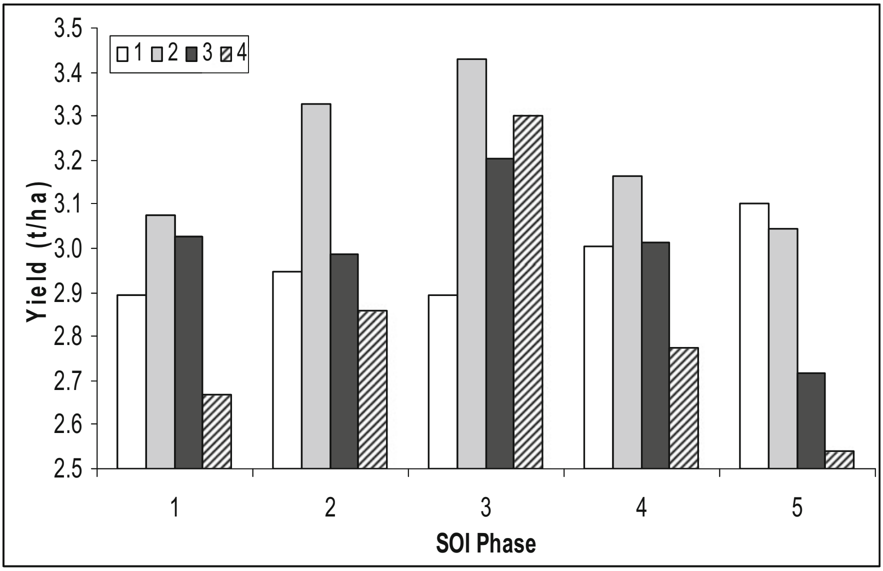


Fig. 2.30 The impact of SOI phases on wheat yield

option to minimize the potential impact of climate change. Similarly, the productivity of rainfed crops could be improved by opting an optimal timing for sowing (Tsegay et al. 2015). Sadras et al. (2015) reported sowing date trials as an effective, practical, inexpensive, and reliable screening method for crop adaptation to high temperature stress. Additionally, He et al. (2015) indicated that later sowing dates and new cultivars with longer thermal time could be helpful to have sustainable crop

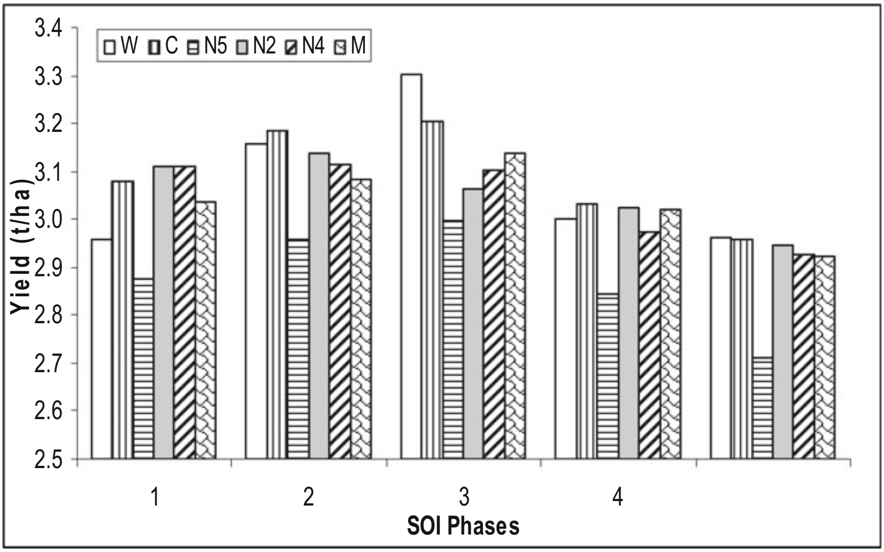


Fig. 2.31 Simulated wheat yield partitioned against July SOI phases (*W* Wafaq-2001, *C* Chakwal-97, *N5* NR-55, *N2* NR-232, *N4* NR-234, *M* Margalla-99)

yield under future rise in temperature. Sowing date as an adaptation to climate warming was studied by different researchers, and they reported sowing date as an important management tool to ensure food security by minimizing yield losses (Naz et al. 2022; Ding et al. 2015; Ahmad et al. 2019; Fletcher et al. 2019; Matthews et al. 1997).

2.5 Potential Options to Manage Food Security and Climate Change

Different measures can be used to manage the issue of food security and climate change. It includes bringing new areas under crops, using improved crop variety or species, and adoption of improved production technologies (e.g., changes in sowing windows, precision and smart farming, modernization of water supply and irrigation systems, inputs and management adjustments, and tillage). Similarly, improved short- and long-term climate prediction can help to identify vulnerabilities of present agricultural systems to climate extremes, which can be used to minimize risk. Furthermore, robustness of new farming strategies to meet the challenges of food security and climate change could be modeled for policy makers. Hence, advanced strategies to ensure food security could be tested accurately through models. Moreover, networking among different research groups and stations is very crucial to design national adaptation plan to mitigate climate change. Similarly, interactive communication can bring research results to different stakeholders (e.g., policy makers and farmers) that could solve the issue of food insecurity. Furthermore, the yield gap in the agricultural commodities could be minimized by cluster development initiative started by the planning commission of Pakistan with the name Cluster Development-Based Agriculture Transformation (CDBAT)-Vision 2025. Different food security programs already going on in Pakistan are listed below:

- Agriculture transformation plan, which includes first- and second-generation interventions. The focus of first-generation interventions is bridging the yield.
- Crop Maximization Programme (costing Rs 8 billions) covering 1,020 villages in four provinces, AJK and FATA/NA, with the objectives to (i) enhance crop productivity of small farmers; (ii) support them to start income-generating activities of livestock, fisheries, on sustainable basis; and (iii) create required systems for value addition of crop and livestock produce coupled with improved market linkages.
- The National Oilseed Development and Commercial Production Program to increase the production of oilseeds in the country to reduce the import bill.
- Two projects of 3.0 billion rupees for livestock farming to enhance community-driven milk and dairy production and increase red meat production.
- The Prime Minister’s special initiatives to enhance productivity of livestock through the provision of extension services at farmers’ doorsteps.
- For the promotion of commercialization in the livestock sector, two private sector-led companies, namely, “Livestock and Dairy Development Board (LDDB)” and “Pakistan Dairy Company (PDC)” have been established.
- To boost the overall production of crops and improve water use efficiency a mega On-Farm Water Management program has been started, with a cost of Rs. 66.0 billion to renovate 87,000 watercourses.
- Program for the promotion of high efficiency irrigation system, including drip and sprinkler.
- High-value crop production especially horticulture sector.
- The Wheat Maximization Program being launched at a cost of Rs.1.5 billion to increase the production of wheat.
- The Prime Minister’s Special Initiative for White Revolution is being launched with an allocation of Rs. 500.0 million for increasing the milk production in the country.
- In line with the Prime Minister’s 100-day program National Commercial Seed Production Program.
- Social safety nets are being strengthened, and the government has launched a new Bachat Card Scheme and Income Support Program for the poorest.

2.6 Conclusion

Ensuring food security is very important to feed billions in future, and it is only possible by understanding the impacts of different drivers on food system through different innovative techniques. After impact assessments, different adaptation options, e.g., early warning systems, water management, changes in sowing dates, choice of cultivar, and diversification of agricultural systems could be opted to minimize the devastating effects of climate change. However, the implementation of these adaptive measures in third world countries is a big concern, which is mainly due to lack of coordination between researchers, policy makers, and farmers. Hence, policy and institutional reforms are necessary to implement appropriate adaptive measures. Similarly, policy makers should understand the complex war of hunger, which has been increased due to climate change shocks. Thus, it should be handled carefully so that solution to the food insecurity could be implemented on a ground scale with true pace. Integration of climate predictions with policies could help to adapt food systems to climate change impacts, thus minimizing vulnerability and food insecurity.

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