Mukhtar Ahmed *Editor*

Global Agricultural Production: Resilience to Climate Change

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Contents

Chapter 1
Climate Change: An Overview

Mukhtar Ahmed, Shakeel Ahmad, and Ahmed M. S. Kheir

Abstract Climate variability and change is the main concern for scientific communities since the past decades. This chapter gives an overview about the basics of climate change. It firstly provides detail information about climate change and its responsible factors. Techniques that have been used to quantify climate change were discussed. It includes the application of general circulation or global climate models (GCMs) and use of borehole temperature, cores from deep accumulations of ice, flora and fauna records, sea records and sediment layer analysis. Furthermore, a historical milestone in the science of climate change was given. The Coupled Model Intercomparison Project (CMIP) and its application were discussed in detail. Similarly, the relationship between radiative forcing (RF) and climate change showed that the earth's radiative balance is changed. This was mainly because of the climate change drivers that resulted to the change in air temperature. True picture about climate change was further confirmed by using different climate change drivers coming from different sources. Data showed that climate change is a real phenomenon causing real threat to the human race on planet earth. Meanwhile, the applications of strategic management tools that include RCP (representative concentration pathway), SSP (shared socio-economic pathways) and SPA (shared climate policy assumptions) were presented as they give clear directions in the field of climate change research. Furthermore, they give directions to do climate impact assessments and design climate and socio-economic adaptation and mitigation options. Finally,

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the responses of the different systems to climatic variables were given as indicators of climate change.

Keywords Climate change · Radiative forcing · Scenario analysis · Climate change drivers · Indicators

1.1 What Is Climate Change?

Climate variability and change is the centre of work in most of the research activities across the globe in the recent decade. Climate variability is the fluctuations in the climatic parameters from its long-term mean. Climate change is the significant variation in weather conditions for the longer period. It is the change in the climatic variables on decadal timescale, i.e. conditions becoming wetter, drier or warmer over several decades. It is different from the natural weather variability as it deals with only shorter time or seasonal climate variability. Climate change is affecting every living being, and it is displaying itself in myriad ways. It can be seen across the globe in the form of extreme events of raging storms, record floods and deadly heat. Different natural and anthropogenic factors are responsible for climate variability and change.

Several techniques have been used to collect data that can be applied to understand the past and future climate. These include borehole temperature, cores from deep accumulations of ice, records of flora and fauna, sediment layer analysis and sea records. GCMs are used extensively to confirm past data and make future projections. GCMs are mathematical models that can model the response of global climate to the increasing greenhouse gas (GHG) emission (IPCC 2013). These models can represent the earth in a few latitudinal bands and can be divided into atmospheric GCMs (AGCMs), the ocean GCMs (OGCMs) and both atmospheric and ocean GCMs (AOGCMs). The basic structure of GCM is shown in Fig. 1.1. The history of these models is closely connected with computing power. Thus, these models are in continuous state of development and evolution so that they can give accurate prediction. Details of the commonly used GCMs have been given in Table 1.1, which are in the process of improvement since their origin as they have shortcomings in computing power due to incompetence to solve crucial climate mechanisms. Similarly, low-resolution models are not capable to portray phenomena at local and smaller scales while its downscaling to higher-resolution propagate error (Lupo et al. 2013). One example of application of GCM has been shown in Fig. 1.2. It shows simulation of global average annual surface temperature changes (°C) from 1860 to 2005 by the geophysical fluid dynamics laboratory coupled model (GFDL-CM3) under four 'representative concentration pathway' (RCP) scenarios. Another category of models includes earth system model (ESM). It can predict CO_2 in atmosphere by using carbon cycle approach. It also has also biological and chemical models that can simulate aerosols, trace gases and cloud condensation nuclei (Hartmann 2016). In most of the earlier GCM simulations, atmosphere and ocean data was generated by fixing different climate drivers. These drivers include

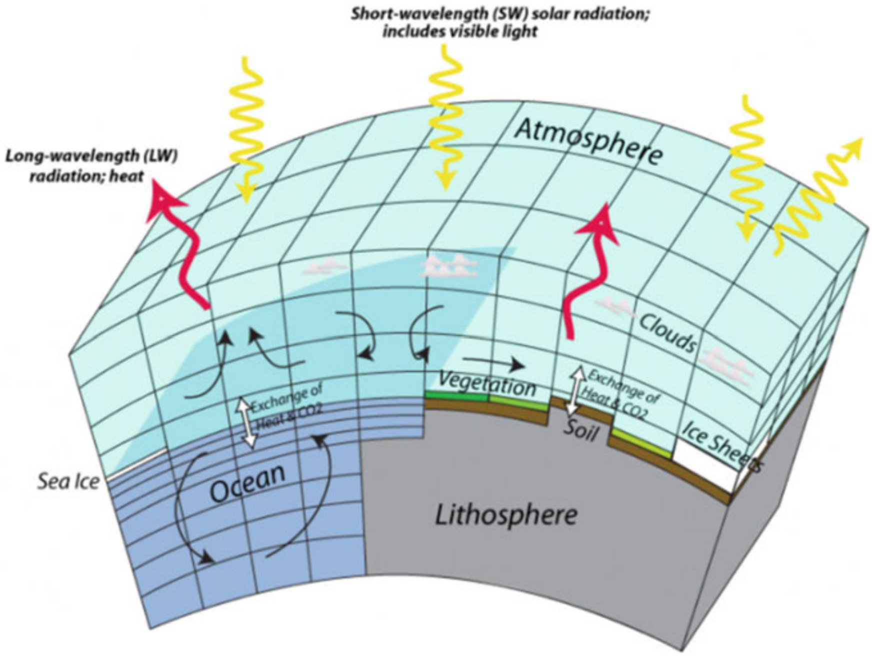


Fig. 1.1 Schematic representation of general circulation model (GCM). (Source: Penn State University)

wind stress, air temperature, sea surface temperature (SST), precipitation and radiative forcing. They all determined the fluxes of heat, exchange of moisture and momentum between the ocean and the atmosphere. However, coupled atmosphere-ocean climate models have shown deficiencies that could be solved by including ESM that consider land surface processes. The components of ESM are shown in Fig. 1.3. It includes physical climate system, biosphere and human influences. ESM can predict vegetation changes, atmospheric composition, biogeochemical cycling, elevated CO_2 effect on leaf stomata, transpiration losses, soil moisture and temperature. Diagrammatic representation of the physical components of GCM has been shown in Fig. 1.4. It has three physical components of the climate system (atmosphere, ocean and land). The frozen places of planet earth are called cryosphere, and it has a significant impact on climate as it has high albedo/reflectivity, acts as insulator, requires latent heat of fusion and absorbs GHG (e.g. permafrost contains 1400–1600 billion tonnes of carbon). Under 1.5 °C–2.0 °C climate warming scenario, it has been reported that the melting of permafrost will produce 150–200 and 220–300 Gt CO_2-eq emissions, respectively (Pörtner et al. 2019). The atmosphere component of GCMs mainly involved weather forecasting through numerical weather prediction systems that can forecast weather in advance for short intervals. However, for longer forecasts, different climatology-based models have been used. In numerical modelling the components of systems (atmosphere or ocean) are

Table 1.1 List of the commonly used GCMs with resolution

S. No.	GCMs	Resolution	
		Latitude	Longitude
1.	ACCESS-CM (Australian Community Climate and Earth System Simulator Coupled Model) (ACCESS1.0 & 1.3)	1.25	1.875
2.	BCC_CSM1.1 (Beijing Climate Centre Climate System Model)	2.7906	2.8125
3.	BNU-ESM (Beijing Normal University Earth System Model)	2.7906	2.8125
4.	CCSM (Community Climate System Model)	0.9424	1.25
5.	CESM (Community Earth System Model)	0.9424	1.25
6.	CESM1(BGC) (Community Earth System Model (CESM1) carbon cycle)	0.9424	1.25
7.	CESM1(CAM5) (Community Earth System Model version 1 (Community Atmospheric Model; CAM))	0.9424	1.25
8.	CESM1(FASTCHEM) (Community Earth System Model version 1 (CAM and Chemistry Model))	0.9424	1.25
9.	CESM1(WACCM) (NCAR Community Earth System Model (Whole Atmosphere Community Climate Model))	1.8848	2.5
10.	CFSv2–2011(National Centers for Environmental Prediction (NCEP) Climate Forecast System Version 2)	1	1
11.	CMCC-CESM (Centro Euro-Mediterraneo per I Cambiamenti Climatici-Earth System Model)	3.4431	3.75
12.	CMCC-CM (Centro Euro-Mediterraneo per I Cambiamenti Climatici-Climate Model)	0.7484	0.75
13.	CMCC-CMS (Centro Euro-Mediterraneo per I Cambiamenti Climatici-Climate Model with a resolved stratosphere)	3.7111	3.75
14.	CNRM-CM5 (Centre National de Recherches Météorologiques-Coupled Model Intercomparison Project)	1.4008	1.40625
15.	CSIRO-Mk3.6.0 (Centre of Excellence and Commonwealth Scientific and Industrial Research Organization)	1.8653	1.875
16.	CSIRO Mk3L (a computationally efficient coupled atmosphere-sea ice-ocean general circulation model)	3.1857	5.625
17.	CanAM4 (Canadian Fourth Generation Atmospheric Global Climate Model)	2.7906	2.8125
18.	CanCM4 (Canadian Fourth Generation Coupled Global Climate Model)	2.7906	2.8125
19.	CanESM2 (Canadian Second Generation Earth System Model)	2.7906	2.8125
20.	EC-EARTH (European Earth System Model)	1.1215	1.125
21.	FGOALS-g2 (Flexible Global Ocean-Atmosphere-Land System Model: Grid-point Version 2)	2.7906	2.8125
22.	FGOALS-gl (Flexible Global Ocean-Atmosphere-Land-Sea-ice)	4.1026	5
23.	GFDL-CM3 (Geophysical Fluid Dynamics Laboratory-Coupled Model 3)	2	2.5
24.	GISS-E2_R (Goddard Institute for Space Studies, USA)	2	2.5
25.	HadGEM2 (Hadley Centre Global Environment Model version 2/UK)	1.25	1.875
26.	MIROC5 (Model for Interdisciplinary Research On Climate/Japan)	2.7906	2.8125
27.	MPI-ESM-MR (The Max Planck Institute for Meteorology-Earth System Model)	1.8653	1.875
28.	MRI-CGCM3 (Meteorological Research Institute Coupled Global Climate Model Version Three, Japan)	1.12148	1.125

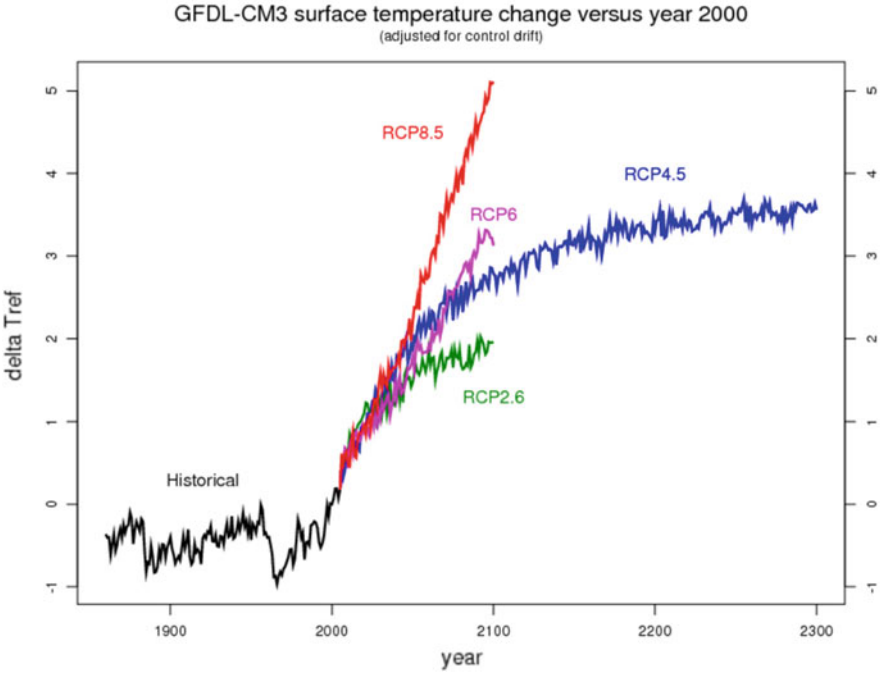


Fig. 1.2 Simulation of changes in surface temperature by GFDL-CM3

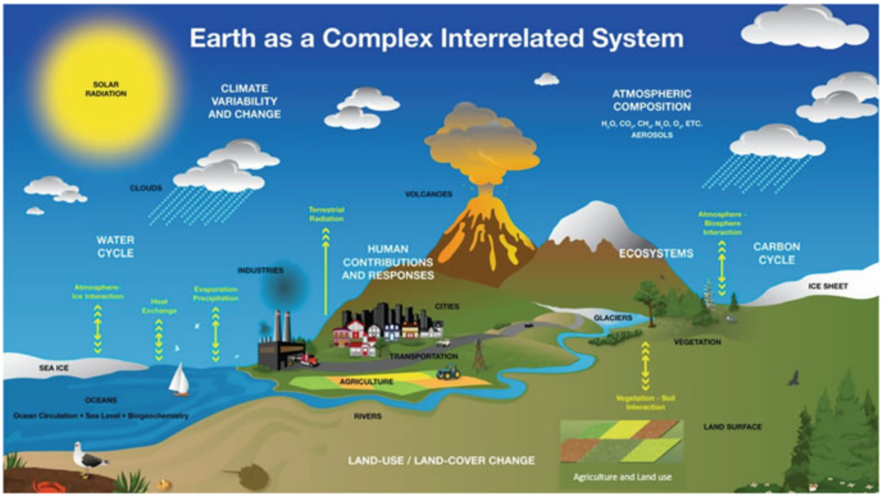


Fig. 1.3 Earth as a complex interrelated system. (Source: NASA)

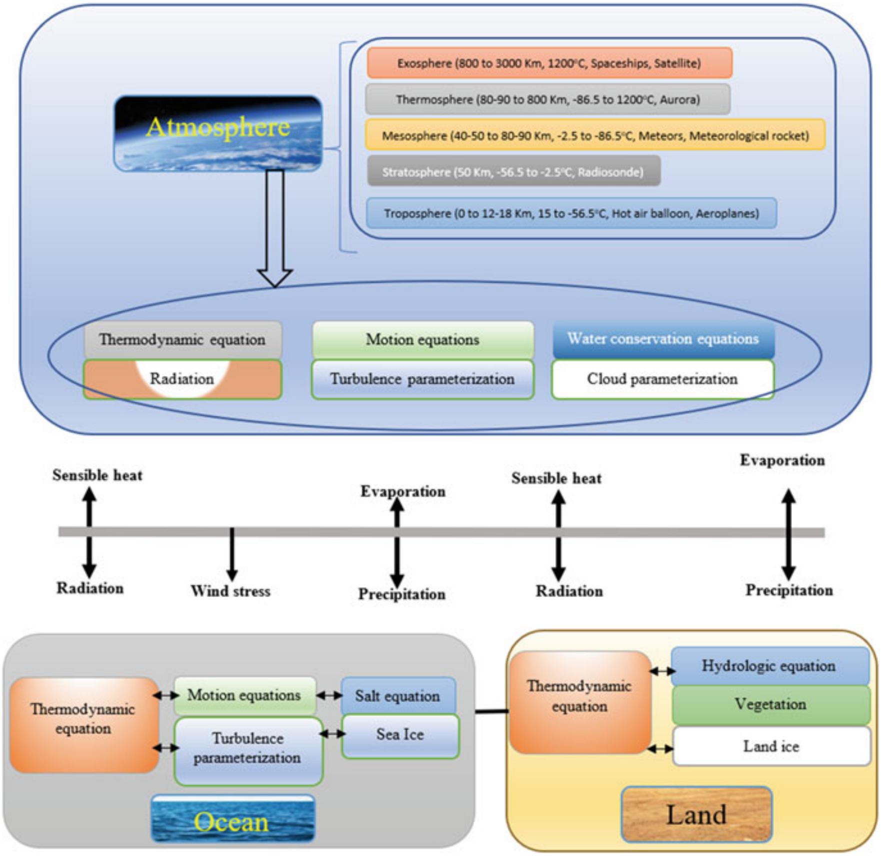


Fig. 1.4 Physical components (atmosphere, ocean and land) of global climate model

divided into spatial grid work with further application of physics equations. The land component of GCM considers surface heat balance and moisture equation as well as model for snow cover. In the case of the ocean component of GCM, the motion equations explaining the general circulation of the ocean were considered. Recent accelerated work in climate change science resulted to the improvement of GCMs. This includes incorporation of physical processes in GCMs that can accurately simulate different phenomena at ocean-atmosphere and land scale (Fig. 1.5). Hence, GCMs could be used to accurately detect climate change causes, future predictions and matching of past climate data (Bhattacharya 2019). Different causes or drivers of climate are called climate forcings. These include alterations in solar radiation, changes in the earth's orbits and albedo/reflectivity of the continents and changes in GHG concentrations.

The Intergovernmental Panel on Climate Change (IPCC) published its first assessment report (FAR) in 1990, and nobody accepted at that time that climate change will be a real issue in the future. The IPCC is the leading body that provides

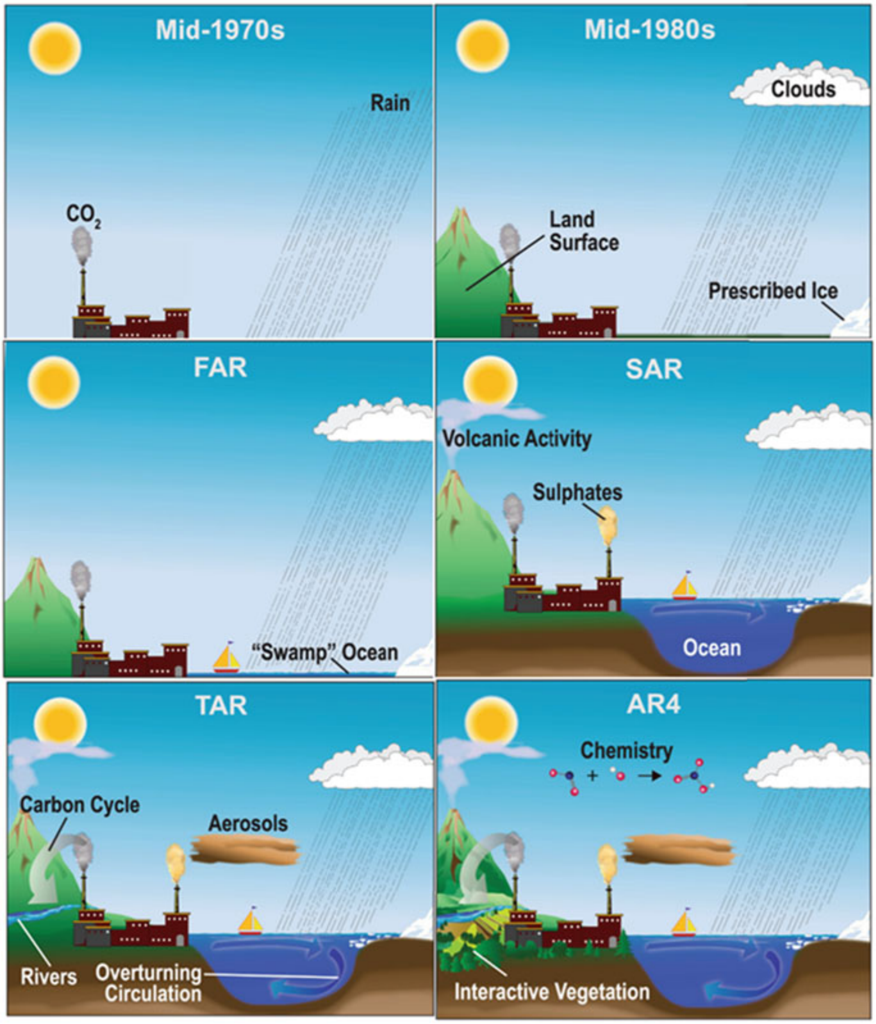


Fig. 1.5 Pictorial description in the climate model complexity over the last few decades. (Source: Le Treut 2007)

true scientific picture about climate change. It also illustrates the potential socio-economic and environmental consequences across the globe. In the 2007 IPCC report, it has been elaborated that significant climate changes are going to happen, which will be mainly due to higher GHGs (Solomon 2007). Higher build-up of GHGs in the environment leads to global warming. Thus, climate change is a broader term that could be due to global warming resulting to the changes in rainfall and ocean acidification. The different important terms that the reader should know to understand the phenomenon of climate change include the following: abatement (decreased greenhouse gas emission); adaptation (adjustment/shifting); adaptability (adjustment ability); adaptive capacity (system ability to adjust to climate change); aerosols; afforestation; agriculture, forestry and other land use (AFOLU); albedo; black carbon; biogeochemical cycle; CO_2 equivalent (scale to compare the emissions from GHGs based upon their GWP (global warming potential)); CO_2 fertilization; carbon footprint; carbon sequestration; Conference of the Parties (COP); chlorofluorocarbons; El Niño-Southern Oscillation (ENSO); enteric fermentation; greenhouse gases; global warming; GWP (total energy a GHG can absorb per 100 years); greenhouse effect; nitrogen oxides (NOX); mitigation; parameterization; risk; risk assessment; uncertainty; validation; and vulnerability.

Climate change importance was already pointed by the Swedish scientist Svante Arrhenius in 1896. He has given the relationship between fossil fuels and increased amount of CO_2 in the air. Detailed historical milestones in the field of climate science had been given in Table 1.2.

Table 1.2 History of milestones in the field of climate change

Years	Milestones
1820	Fourier description about atmosphere contribution to planetary temperature
1850	Foote observed heat-trapping variability in H_2O and CO_2
1859	Tyndall described CO_2 blocking of infrared and elaborated radiative properties of gases
1896	Warming due to doubling of CO_2 by Arrhenius (father of climate change science)
1928	Rate of lunar heat loss was measured
1932	Calculation of 4 °C warming due to doubling of CO_2 by Hulburt
1938	Callendar confirms that warming is occurring
1950–60	CO_2 sources were identified, and models described the earth systems, carbon cycle and climate
1960	Charles keeling started Mauna Loa observatory
1965	Water vapour feedback was described
1965	Warnings by climate scientist to policymakers
1967	Syukuro Manabe and Richard Wetherald (CO_2 and temperature rise have perfect relationship)
1967–68	The first climate models by Syukuro Manabe and Richard Wetherald showing that global temperatures would increase by 2.0 °C (3.6 °F) if the CO_2 content of the atmosphere doubled
1979	Charney report (carbon dioxide and climate: A scientific assessment) doubling of CO_2 leads to 3 °C change in temperature with probable error of 1.5 °C
1988	Hansen predictions about warming
1988	Birth of the IPCC
1992	Establishment of the United Nations framework convention on climate change (UNFCCC) with the aim to combat climate change
1995	Conference of the parties 1 (COP1): The first conference of the parties to the UNFCCC (COP-1) met in Berlin
1996	COP2 in Geneva
1997	COP3, Kyoto protocol; GHG reduction treaty
1998	COP4-Buenos Aires-Argentina

(continued)

Table 1.2 (continued)

Years	Milestones
1999	COP5-Bonn-Germany
2000	COP6-The Hague-Netherlands
2001	COP7-Marrakech-Morocco
2002	COP8-New Delhi-India-Technology transfer
2003	COP9-Milan-Italy-Adaptation Fund
2004	COP10, Buenos Aires, Argentina, climate change mitigation and adaptation
2005	COP11-Montreal-Canada (biggest intergovernmental conferences on climate change)
2006	COP12-Nairobi-Kenya
2007	COP13-Bali-Indonesia
2008	COP14-Poznań-Poland-Funding to poorest nations
2009	COP15-Copenhagen-Denmark (the Copenhagen accord)
2010	COP16-Cancún-Mexico (Green climate fund and climate technology centre/network)
2011	COP17-Durban-South Africa (Green Climate Fund (GCF))
2012	COP18, Doha, Qatar, the Doha climate gateway
2013	COP19-Warsaw-Poland
2014	COP20-Lima-Peru
2015	COP21-Paris-France (Paris agreement)
2016	COP22-Marrakech-Morocco (water-related sustainability, reduction in GHG emissions and utilization of low-carbon energy sources)
2017	COP23-Bonn-Germany
2018	COP24-Katowice-Poland
2020	COP25-Madrid-Spain
2021	COP26-Glasgow-Scotland (Glasgow climate pact to keep 1.5oC alive and finalize the outstanding elements of the Paris agreement)

1.2 Climate Change and Coupled Model Intercomparison Project (CMIP)

The CMIP (Coupled Model Intercomparison Project) was started by the Working Group on Coupled Modelling (WGCM) of the World Climate Research Programme (WCRP) in 1995 to better recognize the past, present and future climate changes that arise from different natural, unforced variability or due to changes in the radiative forcing. This includes historical assessments of model performance and quantifications of the causes of the spread in future climate projections. The results from CMIP have been used in the IPCC assessment reports. CMIP is the foundational element of climate science, and it includes coupled models of the earth's climate (Fig. 1.6). The CMIP's first two phases were simple. In CMIP1, 18 GCMs were involved in data collection. In CMIP2, simulation was conducted with assumptions of no inter-annual changes in radiative forcing (RF) and doubling of CO_2 concentration at a rate of 1% per year (Stouffer et al. 2017). CMIP3 resulted to the paradigm shift in the field of climate science. It has given the state-of-the-art climate change simulations that have

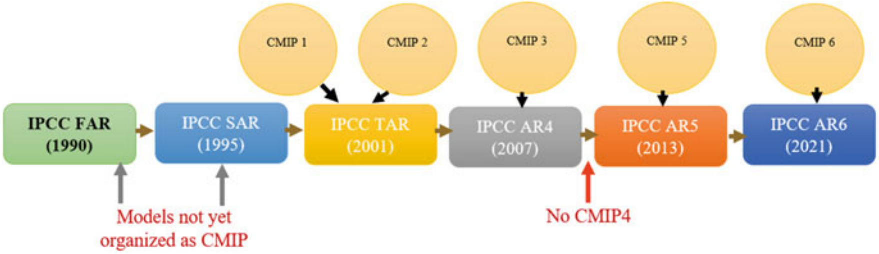


Fig. 1.6 Historical description of Coupled Model Intercomparison Projects (CMIPs) and their contributions to IPCC assessment reports (ARS)

been used on larger scale (Meehl et al. 2007). However, there was no CMIP4, so CMIP5 was developed upon CMIP3. CMIP5 can help to understand the climate system accurately. It generated 2 petabits (PB) of output from different experiments completed through climate models. The salient features of CMIP5 include climate responses to perturbed atmospheric CO_2, impact of atmospheric chemistry on climate, carbon-climate interactions, troposphere-stratosphere interactions, feed-backs and idealized model configurations. The idea of near- and long-term time horizons was implemented in CMIP5. Furthermore, to address the range of advanced scientific questions that come from different scientific communities, CMIP6 was implemented. It has three major components: (i) the DECK (Diagnostic, Evaluation and Characterization of Klima) and CMIP historical simulations (1850–near present); (ii) characterization of the model ensemble and dissemination of model outputs through common standards, coordination, infrastructure and documentation (SCID); and (iii) filling of scientific gaps through the ensemble of CMIP-Endorsed Model Intercomparison Projects (MIPs) that will build on the DECK and CMIP historical simulations. The following three broad questions will be addressed in CMIP6: (i) how does the earth system respond to forcing?; (ii) what are the origins/consequences of model biases?; and (iii) how can future climate change be assessed under the scenarios of uncertainties, predictability and internal climate variability? (Eyring et al. 2016). Further description about CMIP6 has been shown in Fig. 1.7.

1.2.1 Application of CMIP

CMIP/CMIP6 have been widely used in different studies across the globe to quantify the effect of climate change. This includes the climate change effect on soil organic carbon (Wang et al. 2022a); agronomic managements to boost crop yield (Ali et al. 2022); simulation of air-sea CO_2 fluxes (FCO_2) (Jing et al. 2022); anthropogenic aerosol emission inventory (Wang et al. 2022b); heatwave simulation (Hirsch et al. 2021); prediction of future precipitation and hydrological hazard (Nashwan and Shahid 2022); drought prediction (Mondal et al. 2021; Supharatid and Nafung

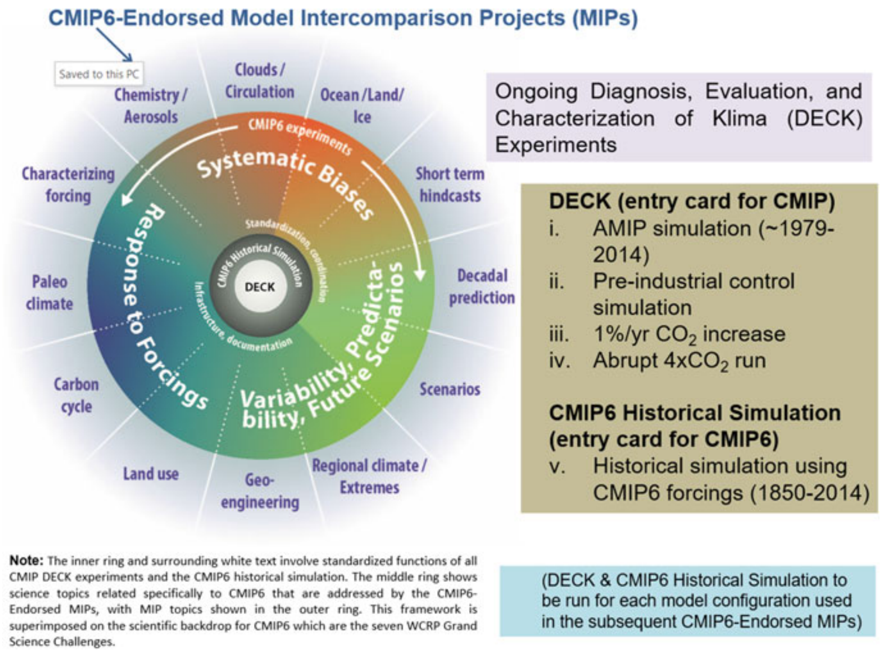


Fig. 1.7 Schematic representation of CMIP6 experiment design. (Source with permission: Eyring et al. 2016)

2021); evaluation of spatio-temporal variability in drought/rainfall in Bangladesh (Kamal et al. 2021); global assessment of meteorological, hydrological and agricultural drought (Zeng et al. 2021); prediction of crop yield and water footprint (Arunrat et al. 2022); temperature simulations over Thailand (Kamworapan et al. 2021); climate projections for Canada (Sobie et al. 2021); ENSO evaluation (Lee et al. 2021); and simulation of ENSO phase-locking (Chen and Jin 2021).

1.3 Radiative Forcing (RF) and Climate Change

Total (downward minus upward) radiative flux (expressed in W m^{-2}) at the top of the atmosphere due to changes in the external drivers of climate change (mainly GHGs) is called radiative forcing (RF). Mathematically, it can be expressed as follows:

$$\begin{aligned} Radiative\ forcing &= Incoming\ energy\ (short\ wavelength) \\ &\quad - Outgoing\ energy(both\ short\&long\ wavelength) \end{aligned}$$

Radiative forcing determines the energy budget of the earth (Fig. 1.8). It can be positive or negative. If radiative forcing is positive, it means the earth is getting higher energy from the sun than it is returning to space. This net gain causes warming. However, if the earth loses more energy to space, then what it gets from the sun it produces cooling. Hence, the temperature of the earth is determined by the RF. Around one-third (29.4%) of radiation that comes from the sun is reflected, while the rest is absorbed by the earth system. Calculation about the earth's energy budget has been presented in Table 1.3. Factors that determine the sunlight reflection back into space include land surfaces and the reflectivity (albedo) of clouds, oceans and particles in the atmosphere. However, the strong determinants are cloud albedo, snow and ice cover as they have much higher albedos. Furthermore, important factors that regulate the earth's temperature are incoming sunlight, absorbed/ reflected sunlight, emitted infrared radiation and absorbed and re-emitted infrared radiation (mainly by GHGs). The earth's radiative balance has been changed due to changes in these factors, which resulted to the change in air temperature. Anthropogenic activities have changed radiative balance of the earth (Table 1.4), which resulted to the changes in the rainfall pattern, temperature extremes and other climatic variables through a complicated set of coupled physical processes. Radiative forcing caused by human activities since 1750 has been shown in Fig. 1.9.

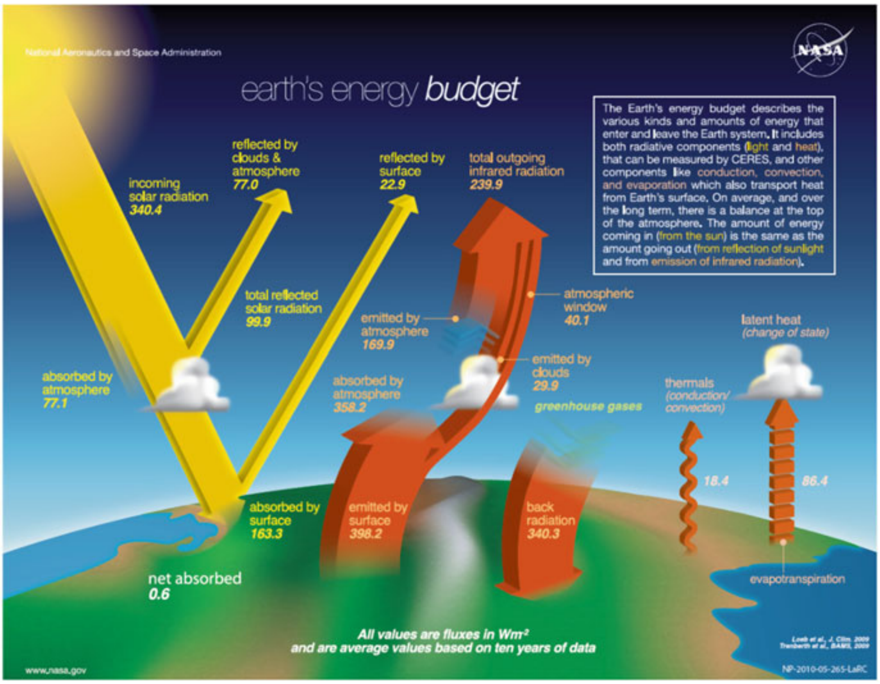


Fig. 1.8 Earth's energy budget. (Source: NASA)

Table 1.3 Calculation about the earth's energy budget

Incoming solar radiation at the top of the atmosphere (TOA)	Outgoing radiation at TOA	Downwelling (back radiation at the surface from GHGs in the atmosphere)	Solar radiation reflected into space
= 340.4 Wm^{-2}. (1/4th of 1361.6 Wm^{-2} solar constant, i.e. total solar irradiance at the top of the atmosphere) Solar constant average varies from 1360 to 1370 Wm^{-2}	= 239.9 Wm^{-2} IR + 77.0 + 22.9 = 339.8 W/m^2, which is 0.6 W/m^2 less than the incoming solar radiation	= 340.3 Wm^{-2} (same as the solar irradiance at TOA)	= 22.6% (77 W/m^2)

Source: Kramer et al. (2021)

Table 1.4 The earth's radiative forcing relative to 1750

Year	Radiative forcing relative to 1750 (Wm^{-2})
1750	0.0
1950	0.57
1980	11.25
2011	2.29

Source: IPCC AR5 WG1

1.4 Drivers of Climate Change

Most of the climate change drivers are mainly associated with anthropogenic activity and, to a lesser extent, with natural origin. Well-known natural climate drivers are solar irradiance, volcanic eruptions and ENSO. Drivers of climate change can be categorized into two types: (i) natural and (ii) man induced. Natural climate drivers consist of radiative forcing, variations in the earth's orbital cycle, ocean cycles and volcanic and geologic activity. Human-induced drivers of climate change are burning fossil fuels, cutting down forests and farming livestock. These human activities resulted to global warming due to increased accumulation of GHGs and changes in the reflectivity or absorption of the sun's energy. Details about the drivers of climate change have been further elaborated below.

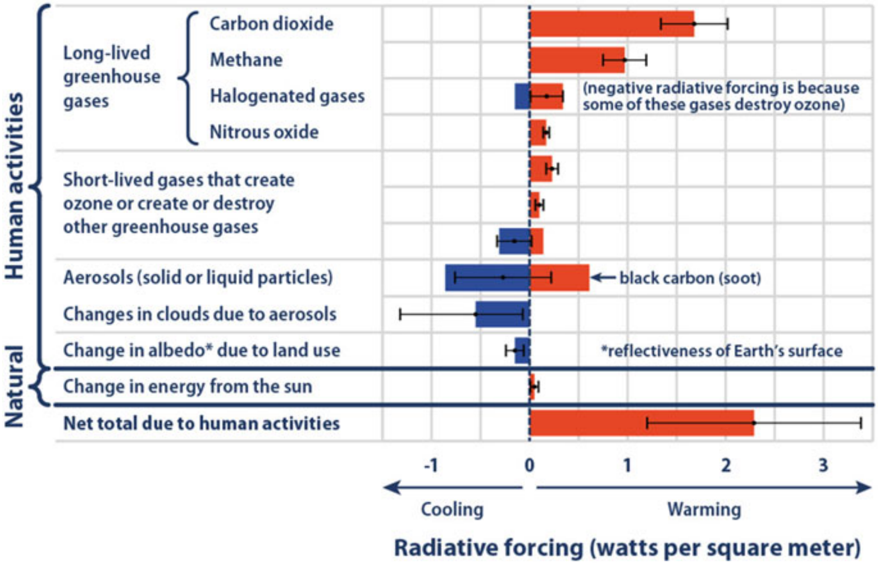


Fig. 1.9 Radiative forcing caused by human activities since 1750. (Source: IPCC 2013)

1.4.1 Anthropogenic Drivers

1.4.1.1 Greenhouse Gases

Greenhouse gases (GHGs) are the main drivers of global climate change. The principal GHGs are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Concentrations of these GHGs have increased significantly since from the industrial revolution, which resulted to the increased greenhouse effect. On annual scale over 30 billion tonnes of CO_2 have been released into atmosphere due to human activities. The levels of CO_2 have been increased by more than 40% since pre-industrial times. It has been increased from 280 ppm to 417 ppm in 2022. The trend of CO_2 based on C. David Keeling (Keeling Curve) has been shown in Fig. 1.10. CO_2 has global sources and sinks. The major sources of the rise in the concentration of CO_2 are fossil fuel burning, cement industry and changes in land use (e.g. housing sector and deforestation). Sink of CO_2 includes absorption by the oceans, carbonation of finished cement products and its use by the plants in the process of photosynthesis. The data depicted that CO_2 atmospheric growth rate has been increased exponentially, and it has shown the largest RF as compared to other GHGs (Fig. 1.11). Global distribution of GHGs in percentage with their emissions from different economic sector and countries has been shown in Fig. 1.12. CO_2 has been used as reference to define the global warming potential (GWP) of other GHGs. The GWP of CO_2 is 1 as it is used as reference, while for CH_4 (methane)

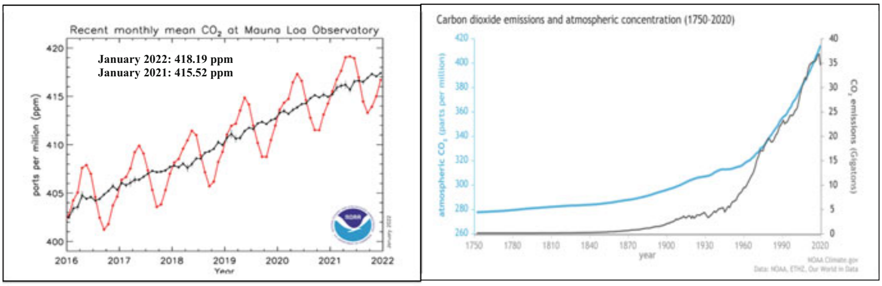
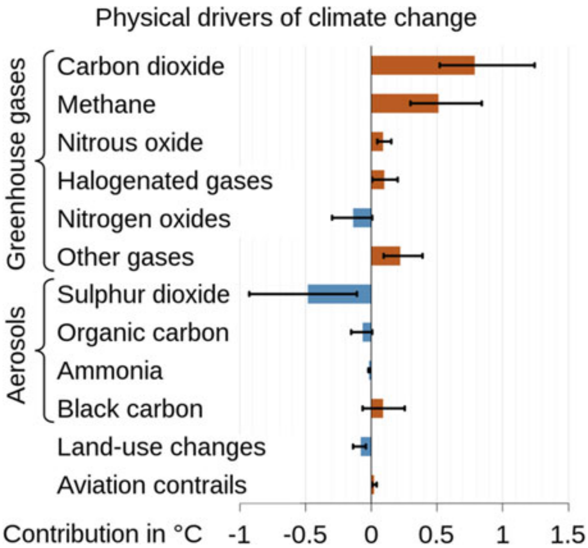


Fig. 1.10 Trend of CO_2 measured at Mauna Loa Observatory, Hawaii. (Source: NOAA)

Fig. 1.11 Radiative forcing of physical drivers of climate change. (IPCC 2013)



it is 28–36 per 100 year and N_2O has a GWP of 265–298 times that of CO_2 for a 100-year timescale. Halogen's derivatives (CFCs (chlorofluorocarbons), HFCs (hydrofluorocarbons), HCFCs (hydrochlorofluorocarbons), PFCs (perfluorocarbons)) and SF_6 (sulphur hexafluoride) are called high-ranking GWP gases as they can trap more heat than CO_2 (Fig. 1.13) (Vallero 2019). Most of our daily activities are responsible for GHG emissions, and it can be calculated by using apps like carbon footprint calculator and greenhouse gas equivalencies calculator. The methane concentration and RF have also been increased since the industrial era. Unlike CO_2, CH_4 is increasing at faster rate (Saunois et al. 2016). The major sources of CH_4 include decaying of organic material, seepage from underground deposits, digestion of food by cattle, rice farming and waste management (IPCC 2013; Liu et al. 2021; Matthews and Wassmann 2003). N_2O has a variety of natural and human-caused sources that include use of artificial nitrogenous fertilizers, animal waste, biological N_2 fixation, crop residue, animal husbandry, burning of waste,

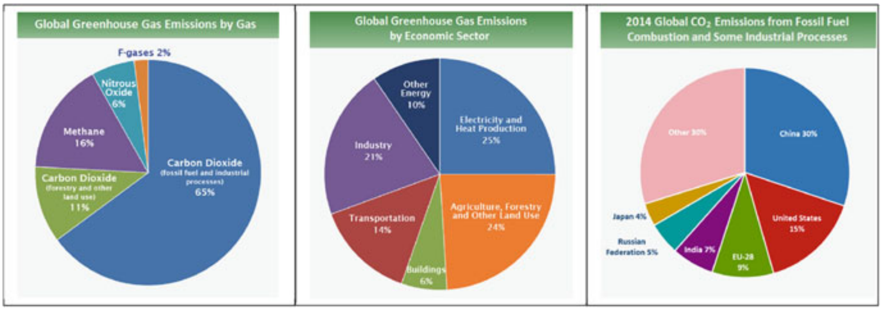


Fig. 1.12 Percentage distribution of GHG emissions by gas, economic sector and CO_2 emissions from fossil fuels. (Source: NOAA)

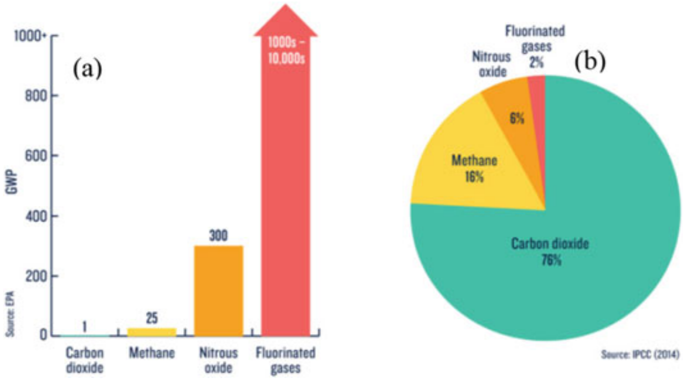


Fig. 1.13 The global warming potential (GWP) of human-generated GHGs (**a**) and per person share to GHG emissions (**b**). (Source: USA, Environment Protection Agency (EPA); IPCC 2014)

combustion of fuel in automobiles and wastewater treatment. Another issue related to N_2O is its destruction in the stratosphere due to photochemical reactions, which form nitrogen oxides (NOX) that destroy ozone (O_3) (Skiba and Rees 2014). Projection of future climate using different climate change scenarios has been well elaborated by the IPCC and presented in Fig. 1.14.

1.4.1.2 Water Vapours

Water vapours account for 60% of the earth's greenhouse warming effect. Water vapours are the most abundant GHG. Researchers from the NASA using novel data from AIRS (Atmospheric Infrared Sounder) on NASA's Aqua satellite have estimated that water also has heat-trapping effect in the air. Furthermore, powerful heat-amplifying effect of water has been confirmed, which can double the climate warming effect caused by higher concentrations of CO_2 (Matthews 2018). The

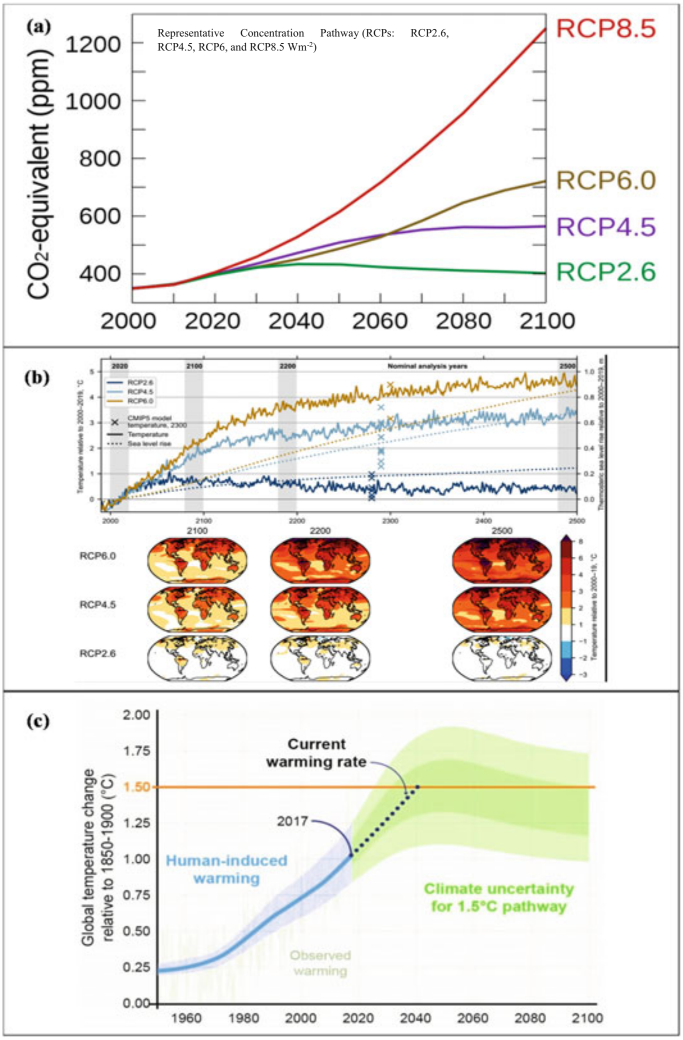


Fig. 1.14 Diagrammatic representation of future climate using (**a**) RCPs, (**b**) global temperature and (**c**) global temperature trend if the current emissions continue. (Source: IPCC 2014)

strength of water vapour feedback has been estimated by climate models and experts that have found that if the earth warms by 1.8 °F, then the increase in water vapour will trap an extra 2 watts m^{-2}. The energy-trapping potential of water vapour at different latitudes has been shown in Fig. 1.15. Water vapours are significantly increasing the earth's temperature. Abundance of water vapours in the troposphere is controlled by two factors: (i) transport from troposphere (the lower atmosphere layer) and (ii) oxidation of CH_4. Since the level of CH_4 is increasing because of anthropogenic activities, it will, hence, increase stratosphere water vapour that will

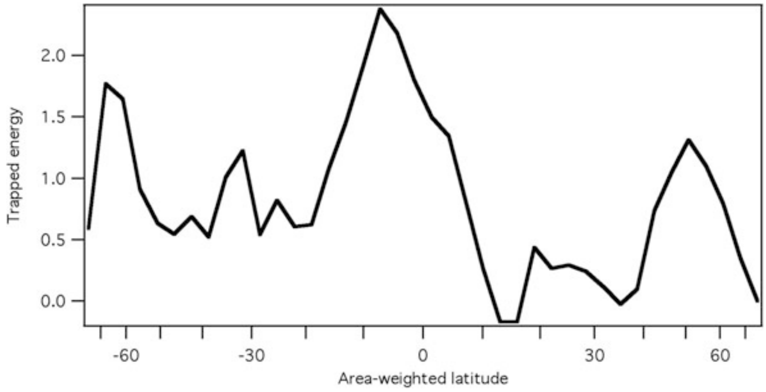


Fig. 1.15 Water vapour trapped energy (southern to northern latitudes). (Source: NASA, Credit: Andrew Dessler)

lead to positive RF (Solomon et al. 2010; Hegglin et al. 2014). Other less important sources of water vapours include hydrogen oxidation, volcanic eruptions and aircraft exhaust. The relationship between increased stratospheric water vapour and ozone and climate change has been reported in earlier work (Shindell 2001). However, water vapour in the troposphere is controlled by temperature. Circulation in the atmosphere limits the build-up of water vapours. Direct changes in water vapours are negligible as compared to indirect changes due to temperature variability that comes from RF. Hence, water vapours are considered as feedback in the climate system as increase in GHG concentration warms the atmosphere that leads to increase in water vapour concentrations, thus amplifying the warming effect.

1.4.1.3 Ozone

Ozone (O_3) is a naturally occurring GHG. It is mainly present in the stratosphere (ozone layer), but a small amount, which is harmful, also generates in the troposphere. O_3 is produced and destroyed due to anthropogenic and natural emissions. CH_4, NOX, carbon monoxide and volatile organic compounds (VOC) are producing O_3 photochemically. This increase in O_3 production results to positive RF (Dentener et al. 2005). However, in polar regions, O_3 has been destroyed due to halocarbons, which leads to negative RF. O_3 is harmful for plants, animals and humans. In plants higher concentration of O_3 causes closure of stomata, decrease in photosynthesis and reduced plant growth. Similarly, O_3 could cause oxidative damage to the plant cells (McAdam et al. 2017; Vainonen and Kangasjärvi 2015; Li et al. 2021; Jimenez-Montenegro et al. 2021).

1.4.1.4 Aerosols

Aerosols are suspended particles from the surface of planet earth to the edge of space. Aerosols are dispersion of solid/liquid particles in a gas (Hidy 2003). Smoke, particulate air pollutants, dust, soot and sea salt are primary aerosols that come from the anthropogenic activities. Open burning is a major cause of aerosols in the atmosphere (Kumar et al. 2022). Natural aerosols are forest exudates, geyser steam, dust and fog/mist. Aerosols have a significant impact on climate as higher concentrations of aerosols lead to the rise in the temperature. Aerosols have shown an impact on climate change through its two-way interactions: (i) aerosol-radiation interactions (direct effect) and (ii) aerosol-cloud interactions/cloud albedo (indirect effect). The RF for both of this interaction is negative; however, it changes with the types of aerosols. The aerosol, such as black carbon, absorbs light, so they produces positive RF and warms the atmosphere (Flanner et al. 2009).

1.4.1.5 Land Use Change (LUC)

Changes and variability in land use resulted to the alterations in surface features, and it is a major driver of climate change but given less preference (Vose et al. 2004). LUC leads to higher aerosols, CH_4 and CO_2 in the atmosphere. Similarly, it modifies the surface albedo, which alters the climate variables (e.g. temperature, precipitation, etc.). Spatio-temporal variability in the pattern of thunderstorms and ENSO are well-known examples of LUC (Pielke 2005). LUC influences the mass-energy fluxes, which alter the climate of the surroundings. LUC resulted to the change in the albedo, particularly due to deforestation and afforestation. This leads to alteration in RF and carbon and hydrologic cycles.

1.4.1.6 Contrails

Clouds that are line (linear) shaped are produced by the aircraft engine exhaust in the mid to upper troposphere under elevated ambient humidity. Contrail's production resulted to the change in the earth's radiative balance by absorbing outgoing long-wave radiation. Contrails have intensified the effect of global warming, and it can account for more than half of the entire climate impact of aviation. It can interact with solar and thermal radiation, thus producing global net positive RF. Tweaking flight altitude could minimize the impact of contrails (Caldeira and McKay 2021).

1.4.2 Natural Drivers

1.4.2.1 Solar Irradiance

Solar irradiance is the number of solar radiation that reaches the surface of the earth without being absorbed or dispersed. It is a promising source of energy. It also affects different processes such as evaporation, hydrological cycle, ice melting, photosynthesis and carbon uptake and diurnal and seasonal changes in the surface temperatures (Wild 2012). The relationship between climate, solar cycles and trends in solar irradiance has been discussed earlier (Lean 2010). The connection between solar irradiance and climate indicators (global temperature, sea level, sea ice content and precipitation) has been reported in the work of Bhargawa and Singh (2019).

1.4.2.2 Volcanoes

Volcanic eruptions are minor events that lead to significant change in the climate. Active volcanoes inject significant amount of sulphur dioxide (SO_2) in the air. On oxidation SO_2 changes to sulphuric acid (H_2SO_4), which resulted to increase in the earth albedo and negative RF. Furthermore, volcanic eruptions also result to O_3 depletion and changes in the heating and circulation. It also emits CO_2 and water vapour, which then change the climate of surrounding. Volcanic activity has triggered El Niño events due to volcanic radiative forcing. Similarly, decrease in global temperature of 0.5 °C was recorded due to Mount Pinatubo eruption (Cole-Dai 2010).

1.5 Scenario Analysis (RCP, SSP and SPA)

A scenario analysis that includes RCP (representative concentration pathway), shared socio-economic pathways (SSP) and shared climate policy assumptions (SPA) is a strategic management tool that has been used to explore future changes across the globe. They can also be used to design adaptation options under the changing climate (Kebede et al. 2018). Furthermore, they can investigate the consequences of long-term climatic-environmental-anthropogenic futures to design robust policies (Harrison et al. 2015). In initial scenarios most of the focus was on climate change (Hulme et al. 1999) that was addressed by the IPCC through SRES (Special Report on Emission Scenarios), which includes both socio-economic and climate change (Arnell et al. 2004). In the IPCC AR5 three-dimensional aspects (climate/socio-economic/policy dimensions of change) were presented using RCP-SSP-SPA scenarios (van Vuuren et al. 2011; O'Neill et al. 2014; Kriegler et al. 2014). These three dimensional frameworks provide basis for the climate change impact assessment, adaptation and mitigation under a wide range of climate and socio-economic scenarios (Fig. 1.16).

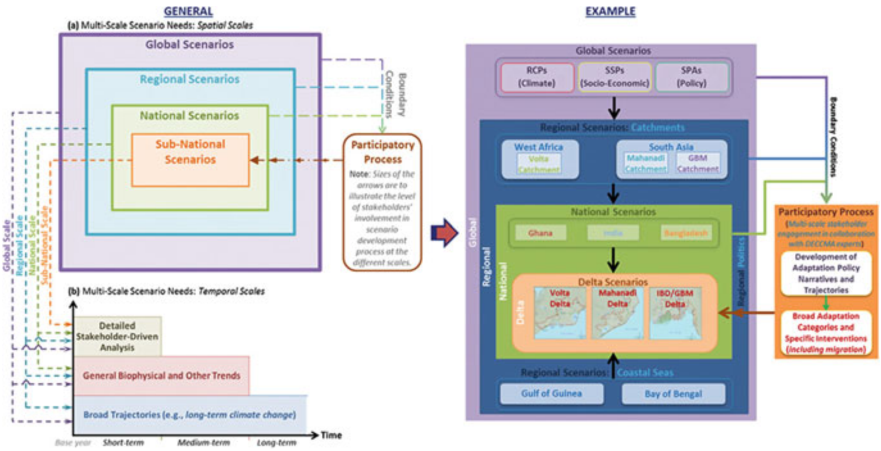


Fig. 1.16 Application of integrated scenario frameworks. (Source: Kebede et al. 2018)

Table 1.5 Temperature and mean sea level change under different RCPs in the mid- and late-twenty-first century

	2046–2065	2081–2100	2046–2065	2081–2100
RCP Scenarios	Temperature mean (range)	Temperature mean (range)	Mean sea level (m) increase (range)	Mean sea level (m) increase (range)
RCP2.6	1.0 (0.4 to 1.6)	1.0 (0.3 to 1.7)	0.24 (0.17 to 0.32)	0.40 (0.26 to 0.55)
RCP4.5	1.4 (0.9 to 2.0)	1.8 (1.1 to 2.6)	0.26 (0.19 to 0.33)	0.47 (0.32 to 0.63)
RCP6	1.3 (0.8 to 1.8)	2.2 (1.4 to 3.1)	0.25 (0.18 to 0.32)	0.48 (0.33 to 0.63)
RCP8.5	2.0 (1.4 to 2.6)	3.7 (2.6 to 4.8)	0.30 (0.22 to 0.38)	0.63 (0.45 to 0.82)

Source: IPCC (2013)

A representative concentration pathway (RCP) is a GHG trajectory provided by the IPCC. It has been used in climate modelling and impact assessments for the IPCC AR5 and includes four pathways (RCP2.6 (2.6 Wm^{-2} RF), RCP4.5 (4.5 Wm^{-2} RF), RCP6 (6.0 Wm^{-2} RF) and RCP8.5 (8.5 Wm^{-2} RF)). RCP can be further divided into RCP1.9 (limit global warming <1.5 °C as per the Paris Agreement), RCP2.6, RCP3.4, RCP4.5, RCP6, RCP7 and RCP8.5. RCP2.6 is a very strict pathway, and it requires that CO_2 emissions should be declined by 2020 and should go to zero by 2100. Similarly, CH_4 should be dropped to half by 2020, and SO_2 emissions need to be declined by 10%. RCP2.6 requires that global temperature should be kept below 2 °C through absorption of CO_2. The most possible pathway is RCP3.4, which forces to keep temperature between 2.0 and 2.4 °C till 2100. RCP4.5 is an intermediate scenario that suggests dropping CO_2 and other GHGs by 2045. However, most of the plant and animal species will not be able to adapt because of RCP4.5. Further details about RCP scenarios are given in Table 1.5. The scenarios that are used to project socio-economic changes across the globe are called SSPs. It deals with socio-economic development by working on the aspects of impact assessments of climate change, adaptation and mitigation. Further detail about SSP is given in Fig. 1.17.

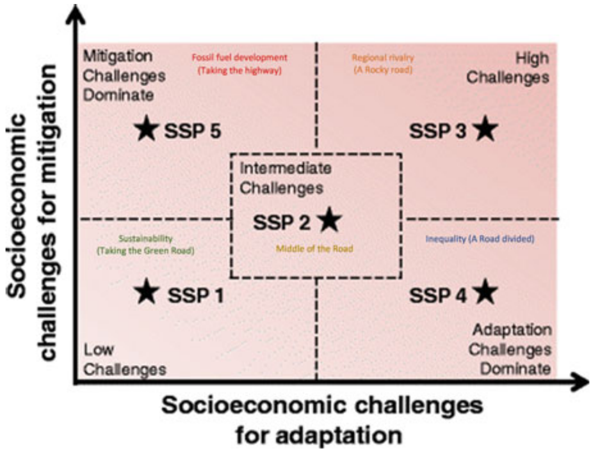


Fig. 1.17 Concept of SSP (shared socio-economic pathways). (Source: O'Neill et al. 2014)

1.6 Indicators of Climate Change

Different indicators could be utilized as early warning signals to identify the impact of climate change. The gathered information can help to design adaptation and mitigation option to the climate change. The major indicators of climate change have been shown in Fig. 1.18. Temperature is the topmost indicator that showed that climate change is a real phenomenon affecting global environment. The average temperature of planet earth has been risen to 1.18 °C since the nineteenth century. Higher concentration of CO_2 and human activities are the main drivers of this rise in temperature. However, this temperature rise is not uniform across the globe (Fig. 1.19). The higher temperature will be more on the land particularly in the tropics as compared to the sea. At 1.5 °C rise in temperature, extreme heatwaves will be more common and widespread across the globe. Deadly heatwave due to 2 °C warming was seen in 2015 in India and Pakistan. Cold extremes will be visible in the Arctic land regions. Temperature extremes will lead to drought in some part of the world while extreme precipitation on the other part. The connection between ENSO (El Niño/Southern Oscillation) phenomenon and extreme temperature in Southeast Asia have been seen in April 2016. Results indicated that 49% of the 2016 anomaly was caused by El Niño while 29% due to warming (Thirumalai et al. 2017). Intensification of hydrological cycle (extreme precipitation and flood) due to global warming has been reported over all climatic regions (Tabari 2020). Furthermore, the intensity of drought under the changing climate was studied using different indices (Bouabdelli et al. 2022). The indices include (i) precipitation only and (ii) overall climate (precipitation plus temperature). Results showed that drought events in plains will be more and long-lasting in hot season that will threaten the agricultural production as well as food security under RCP4.5. Temperature extremes will modify crop life cycle and productivity. Since crop vegetative development requires higher optimum temperature than reproductive phase, rise in temperature will,

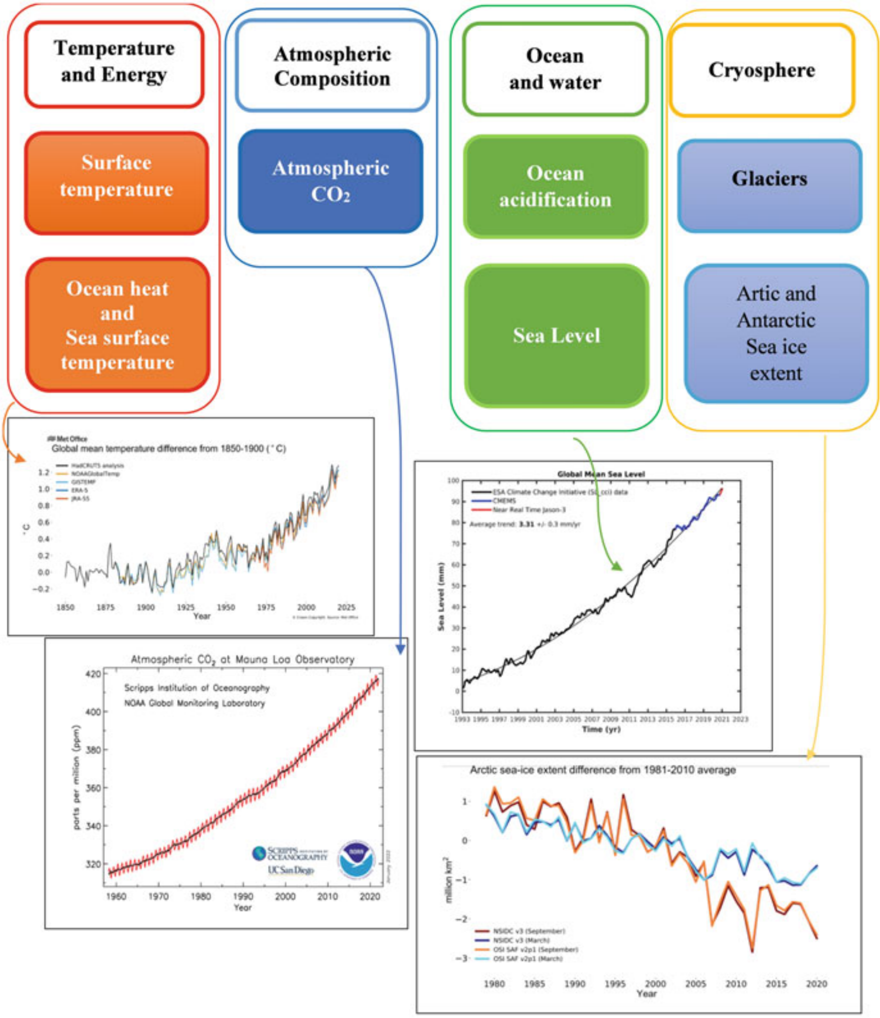


Fig. 1.18 Major indicators of climate change

hence, severely affect pollen viability, grain development and grain weight. The impact is visible on photoperiod sensitive crops (e.g. soybean). Meanwhile, in crops, pollen viability will be decreased due to its exposure to temperature greater than 35 °C. Similarly, in rice, pollen capability and production decreases when daytime temperature goes above 33 °C and stops when it exceeds 40 °C (Hatfield et al. 2011, 2020; Hatfield and Prueger 2015). Other indirect indicators of climate change include plant pathogens (Hatfield et al. 2020; Garrett et al. 2016), crops and livestock systems (Hatfield et al. 2020), biodiversity (Mashwani 2020; Habibullah et al. 2022), loss of species and extinction (Caro et al. 2022), shift in herbicide paradigm (Ziska 2020) and human health (Carlson 2022). Further details about the responses of different systems to different climatic variables have been given in Table 1.6.

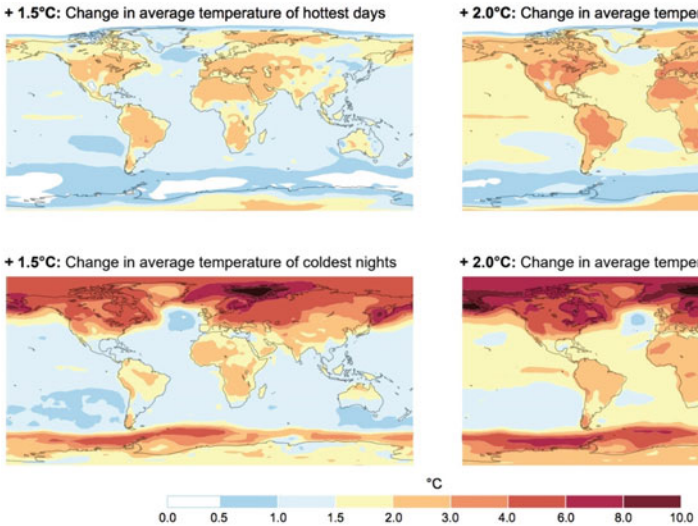


Fig. 1.19 Projection of global warming of 1.5 and 2 °C with hottest and cold days. (Source: NASA)

1.7 Humidity as a Driver of Climate Change

A recent study published in the Proceedings of the National Academy of Sciences (PNAS) by climate scientists reported that temperature is not the only best way to measure climate change (Song et al. 2022). Instead, humidity should also be used as an indicator to measure global warming. They showed that surface equivalent potential temperature (temperature and humidity) is a comprehensive metric to monitor global warming. Similarly, this also has an impact on climate and weather extremes.

1.8 Solar Dimming

The earth is dimming due to climate change as shown in Fig. 1.20. The light reflected from the earth, called the earth's reflectance or albedo, is decreasing. It is now ½ a watt less light per m^2 than what was received 20 years ago, which is equal to 0.5% reduction in the earth's reflectance. About 30% of the sunlight is reflected by the earth, since the earth's albedo has been dropped due to air pollution, which will reduce the intensity of photosynthetically active radiation (PAR) and agricultural production (Yadav et al. 2022). However, on the other hand, researchers are planning to spray sunlight-reflecting particles (the sun dimmers) into the stratosphere to lower the planet temperature (Tollefson 2018).

Table 1.6 Responses of different systems to climatic variables

Systems	Climatic variables	Impact on system	Indicators
Plants	Temperature	Plant phenology	Phenological changes
		Chilling hours	Flowering timing
		Growing degree days	Crop zoning
	Elevated CO_2	Stimulate photosynthesis, plant productivity, fertilization effect, modified water and nutrient cycles	Crop quality
	Elevated CO_2 and soil nutrients	Nutrient's availability	Beneficial to legumes, N-dilution
	Temperature, precipitation and elevated CO_2	Plant productivity, water use efficiency (WUE), N-deposition, yield, biomass	Variable response in plant productivity, more beneficial for C3
Soil	Extreme rainfall	Nutrient run-off/soil erosion/loss of topsoil	Rainfall intensity
	GHG exchange and carbon sequestration	Soil health	Changes in organic carbon
	Precipitation	Soil nutrients, soil water content and infiltration	Water availability for plant production
	Temperature	Soil health	Loss in organic carbon and microbial biomass
Weeds	Temperature	Plant phenology	Changes in onset of phenological development, e.g. bud break, first flower
		Good biomass and establishment	Higher stand
			Crop zoning
	Elevated CO_2	Stimulate photosynthesis, modified water, nutrient cycles	Higher weed abundance
	Temperature, precipitation and CO_2	Plant productivity, yield, biomass	Variable response in plant productivity
Livestock	Extreme events (hot and cold)	Animal productivity	Temperature humidity index, climate index
Pests	CO_2-temperature interactions	Plant productivity	More attacks
	Temperature/humidity	Insect or disease pressures	Pressures of insects/diseases
	Temperature/precipitation	Weed pressures	More weed distribution
Disease	Climate extremes	System productivity	Promote plantdisease and pest outbreaks
Economics	Extreme events	Declined productivity	Insurance

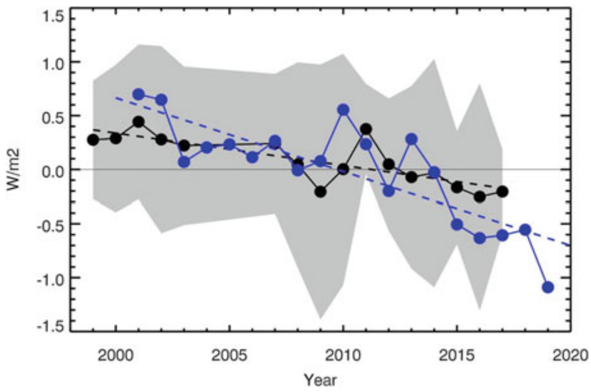


Fig. 1.20 Earth dimming due to climate change. (Source: Goode et al. 2021)

1.9 Conclusion

Climate change is a major environmental concern for the people in all fields of life starting from researchers to policymakers. It is a real phenomenon happening, and its rising impacts cannot be denied. Natural (solar variability, volcanic activity and plate tectonics) and anthropogenic drivers (greenhouse gas emissions, water vapours, ozone, aerosols, land use change and contrails) are the major reasons of accelerated climate change. Another factor includes urbanization, which is the main cause of urban climate change. Since IPCC in AR5 reported that global average surface temperature has increased by 0.85 °C (1880–2012), 0.3–0.7 °C (2016–2036 in comparison with 1986–2005) and 0.3–4.8 °C (end of century in comparison with 1986–2005). Thus, it is essential to use climate change information and adopt measures to control the drivers responsible for this increased climate change. If swift measures will not be taken, these climatic drivers will be responsible for higher possibilities of extreme events, issues of food security, increased weed pressures and occurrence of pest and disease attacks. Climate models are good tools that can give accurate prediction to design adaptation and mitigation strategies for different systems. For example, consider agriculture systems which provides food fuel and fibre to human being is strongly affected by climate change could be managed by using different climate models. The data obtained from these models could be used to understand the relationship between agriculture and climate. The information generated could be used afterwards to improve agricultural systems by adopting different adaptation measures, which can reduce GHG emissions, enhance soil organic carbon and bring sustainability in the system.

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Chapter 2
Climate Change, Agricultural Productivity, and Food Security

Mukhtar Ahmed, Muhammad Asim, Shakeel Ahmad, and Muhammad Aslam

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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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,

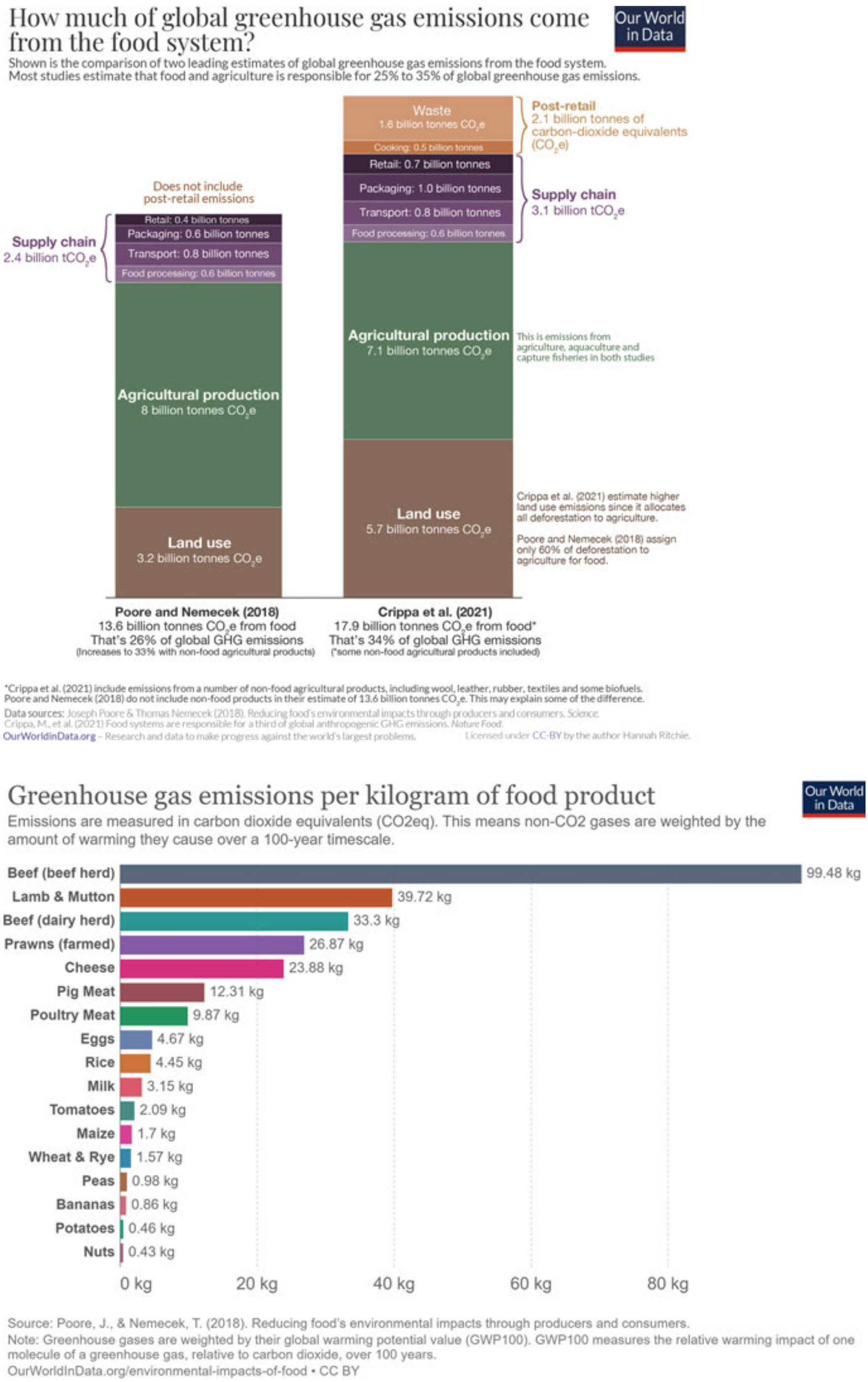

Fig. 2.1 Global greenhouse gas emissions from food system

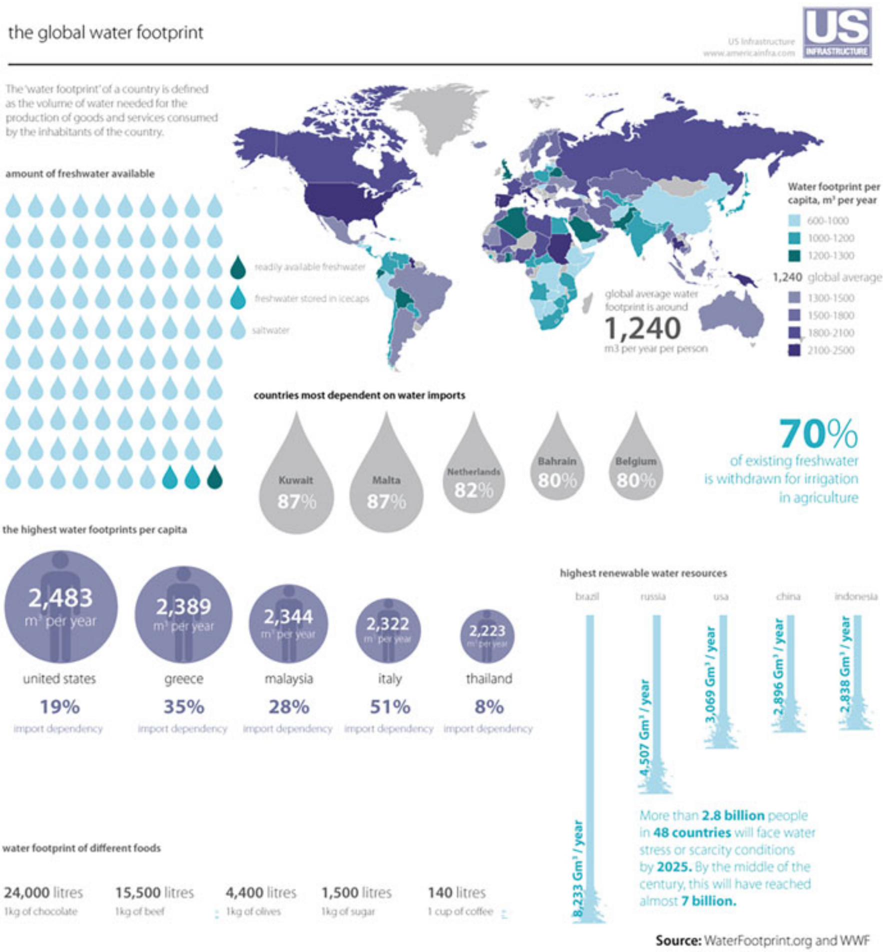

Fig. 2.2 The global water footprint

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/

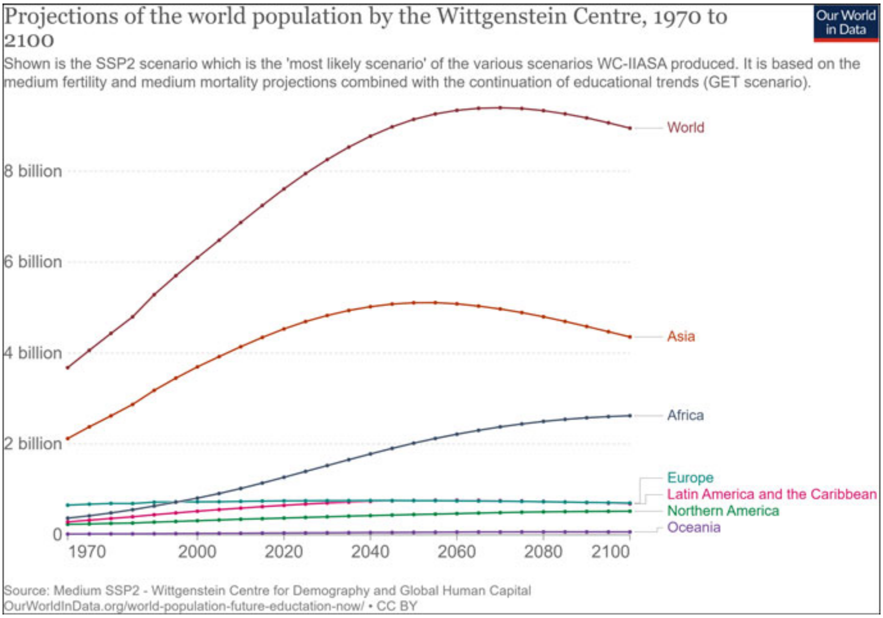

Fig. 2.3 Trend of world population

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

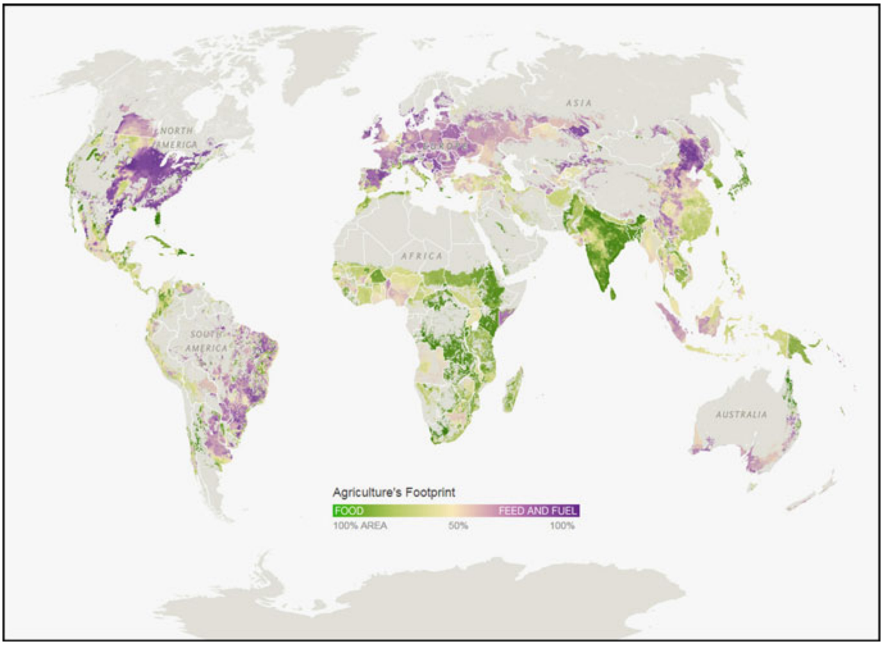

Fig. 2.4 Global agriculture footprint. (Source: Roger LeB. Hooke, University of Maine. Maps, source: Global Landscapes Initiative, Institute on the Environment, University of Minnesota)

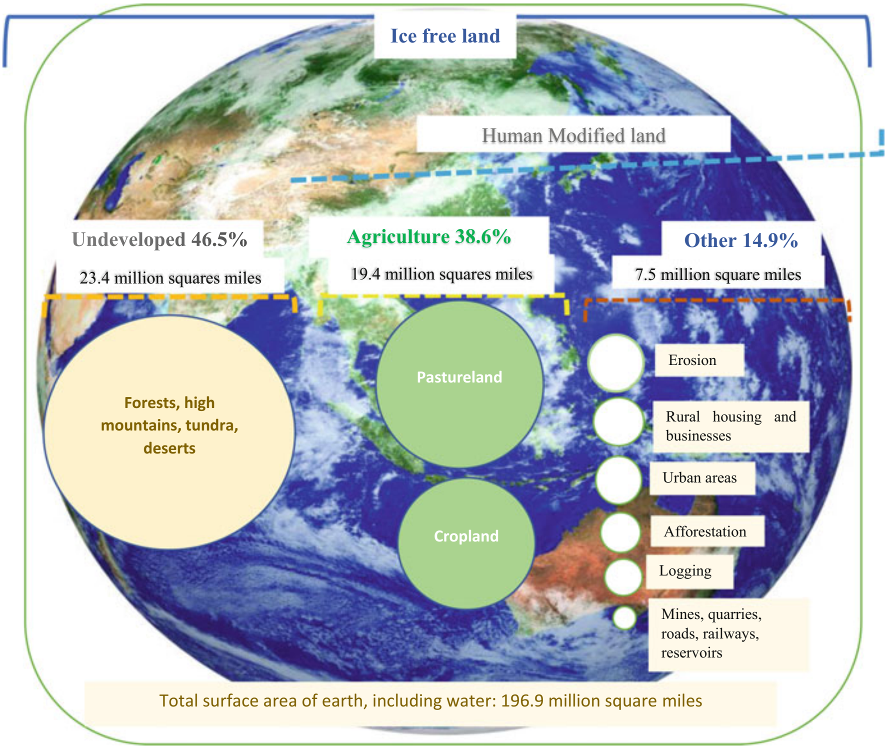

Fig. 2.5 Ratio of human modified land with total surface area of Earth

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

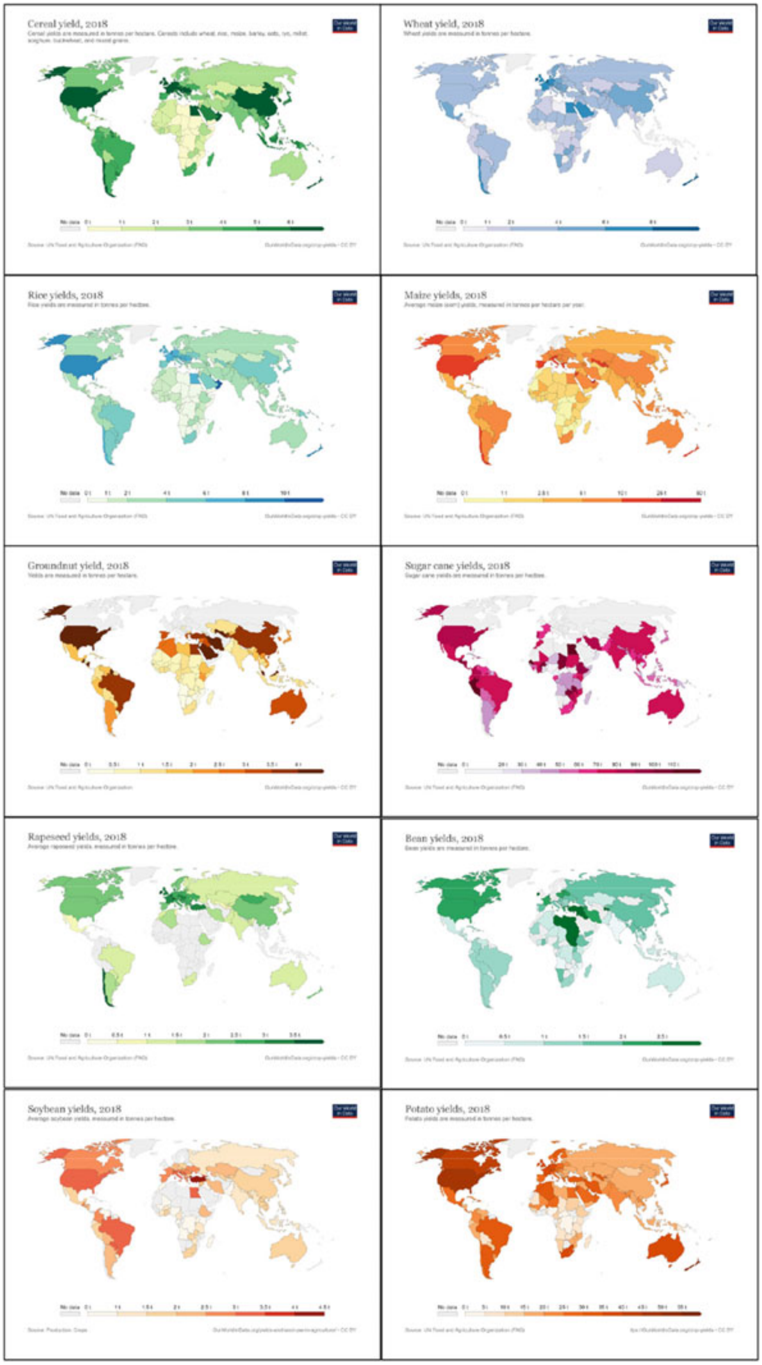

Fig. 2.6 Yield of major crops across the world

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.

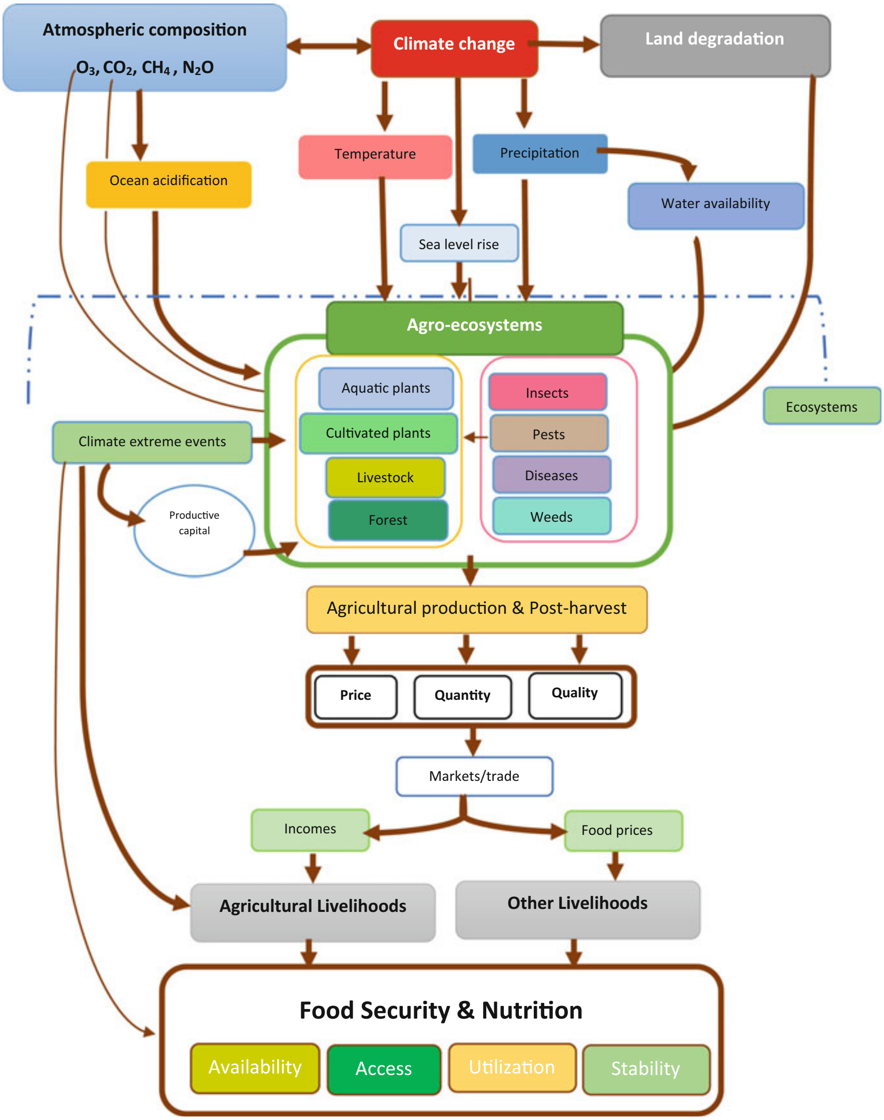

Fig. 2.7 Cascading effects of climate change on food security and nutrition. (Source: FAO)

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

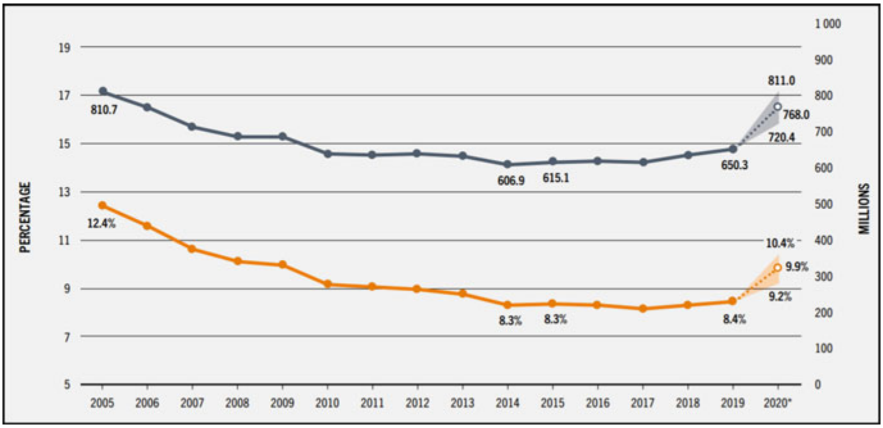

Fig. 2.9 The prevalence and number of undernourished people in the world. (Source: FAO 2021)

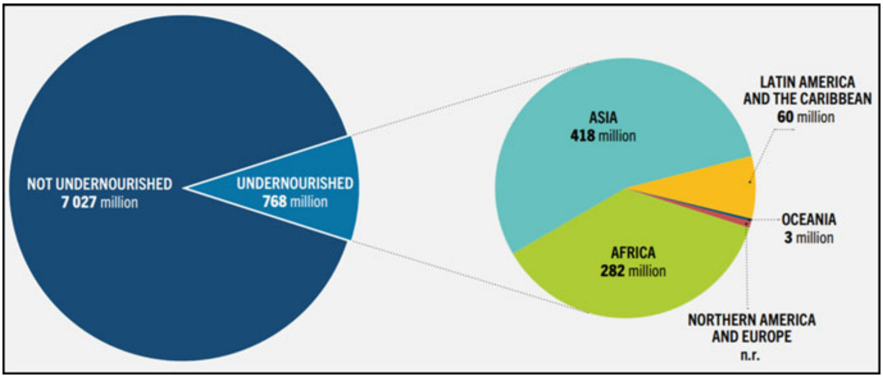

Fig. 2.10 Hunger prevalence among continents. (Source: FAO 2021)

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

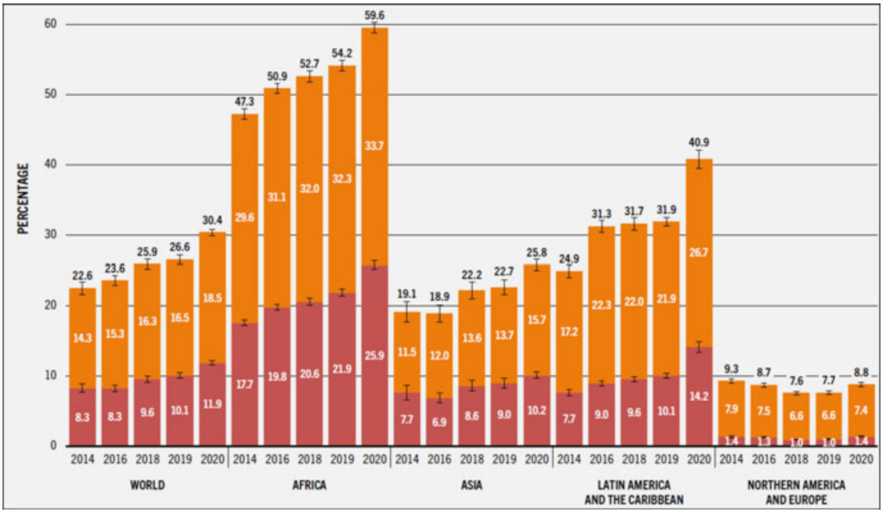

Fig. 2.11 Global food insecurity (moderate or severe) in the past 6 years. (Source: FAO 2021)

(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.

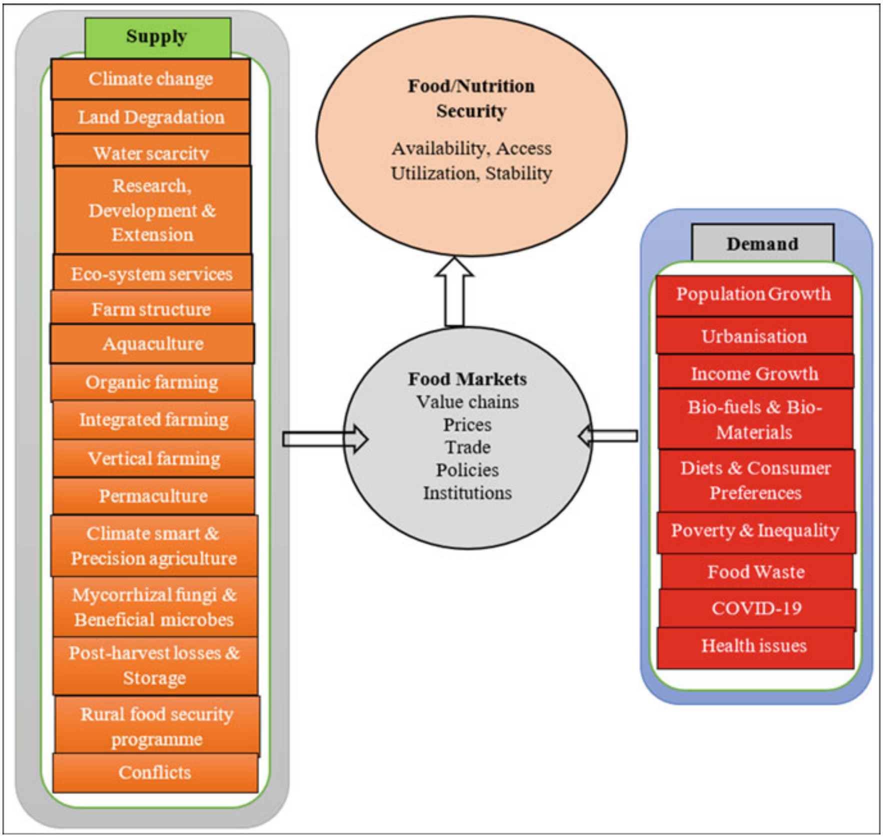

Fig. 2.12 Drivers of food/nutrition security across globe. (Modified from van Dijk and Meijerink 2014)

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

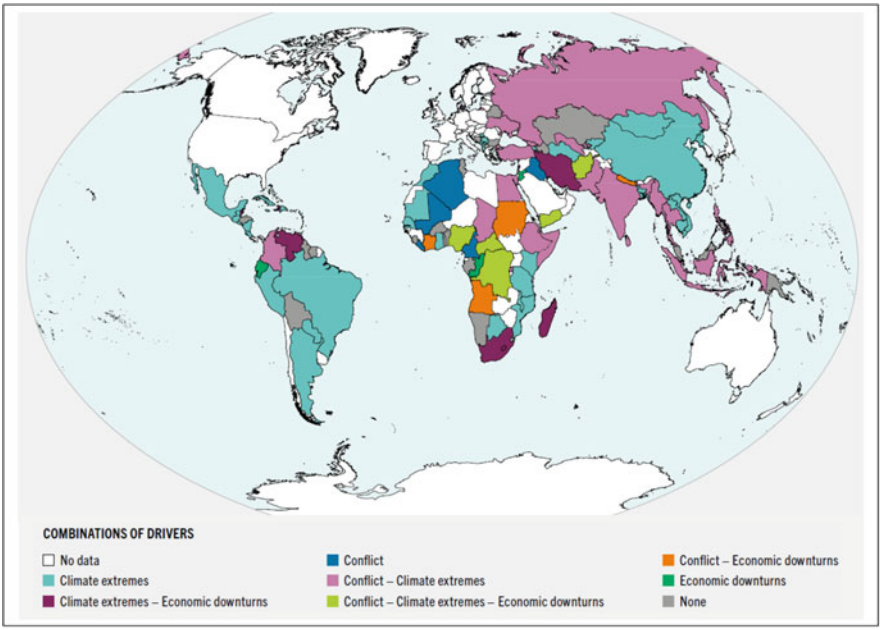

Fig. 2.13 Food security drivers across the globe

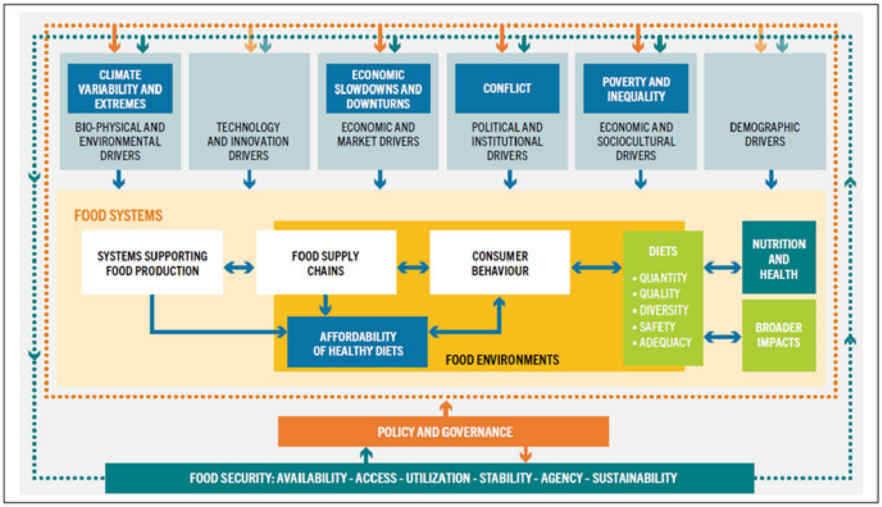

Fig. 2.14 Relationship between different drivers, food systems, and food security. (Source: FAO 2021)

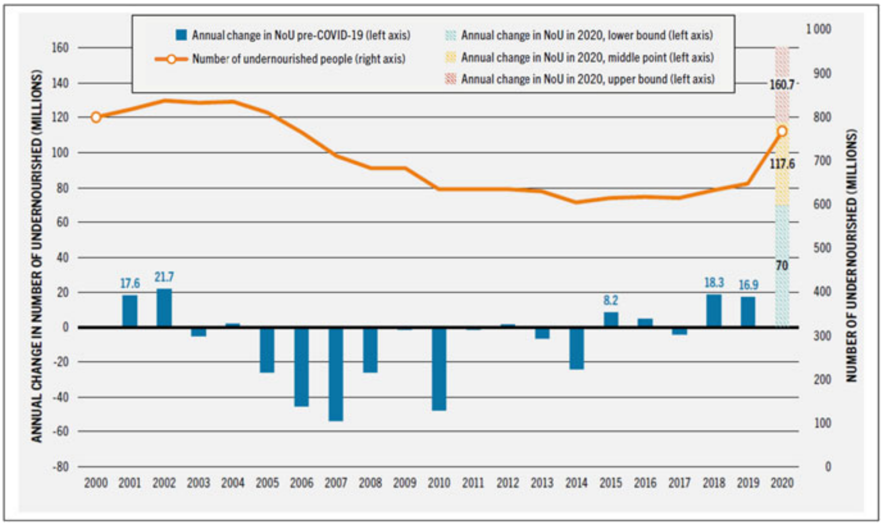

Fig. 2.15 Time series analysis of annual change in number of undernourished due to COVID

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

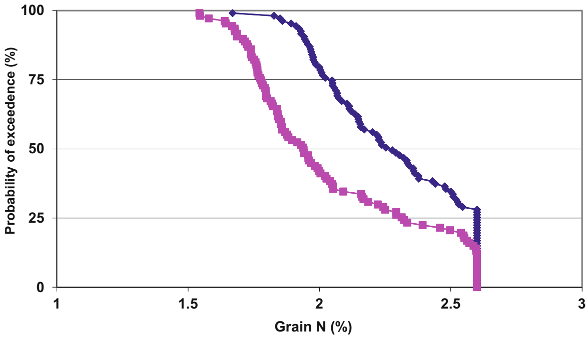

Fig. 2.16 Grain nitrogen in response to elevated CO_2

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

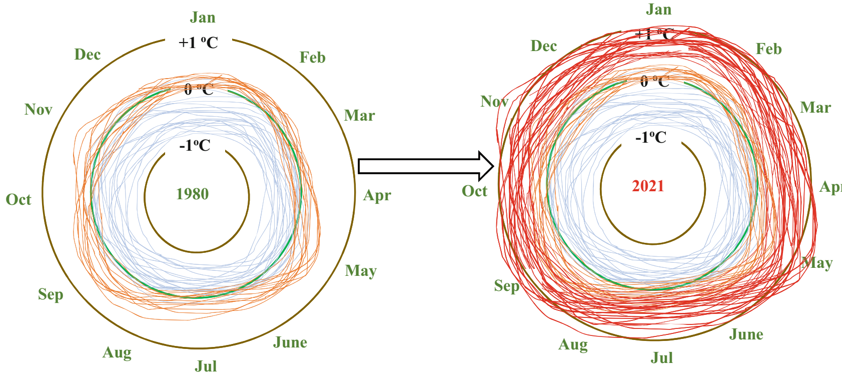

Fig. 2.17 Monthly global surface temperatures from 1980 to 2021. (Modified from NASA)

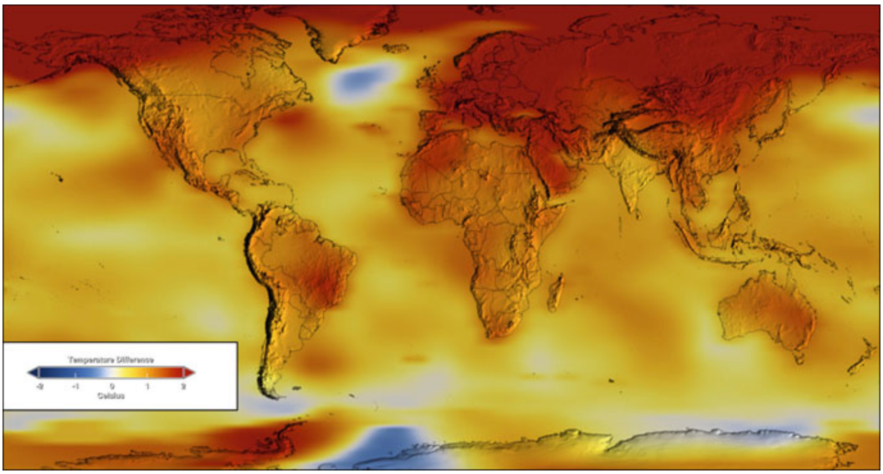

Fig. 2.18 Global temperature anomalies (°C) from 1880 to 2020 (higher than normal temperature = red and lower than normal temperature = blue and normal temperature = average over thirty years baseline period 1951–1980). (Source: NASA's Scientific Visualization Studio)

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

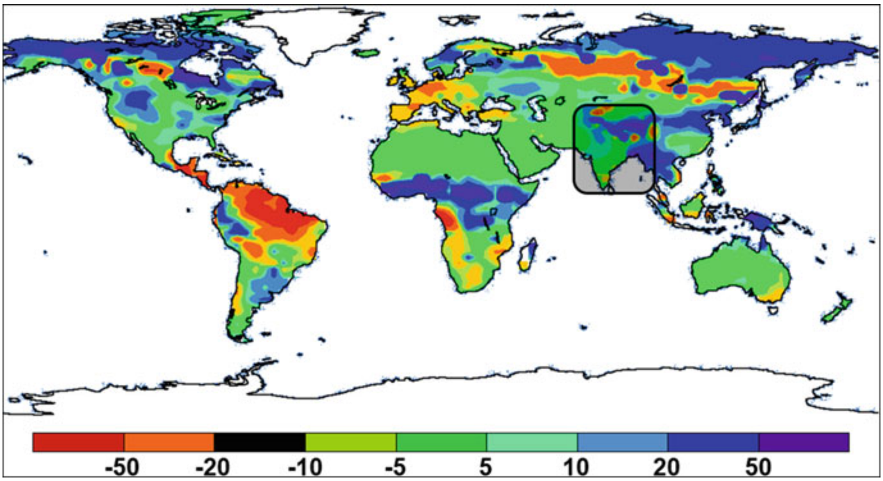

Fig. 2.19 Potential worldwide precipitation changes

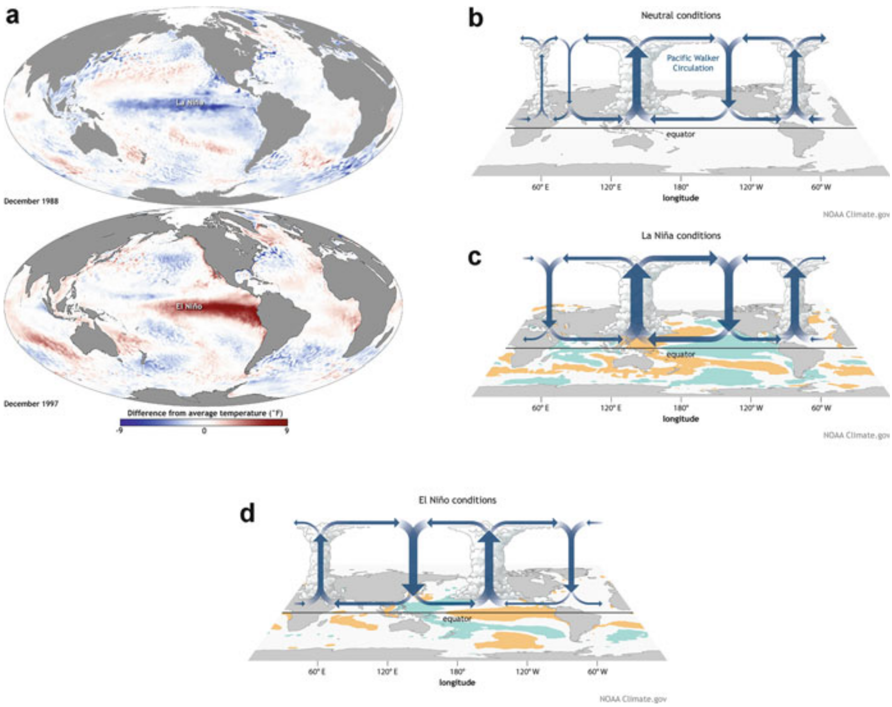

Fig. 2.20 Neutral, La Niña, and El Niño three phases of ENSO (El Niño–Southern Oscillation). (Source: NOAA)

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.

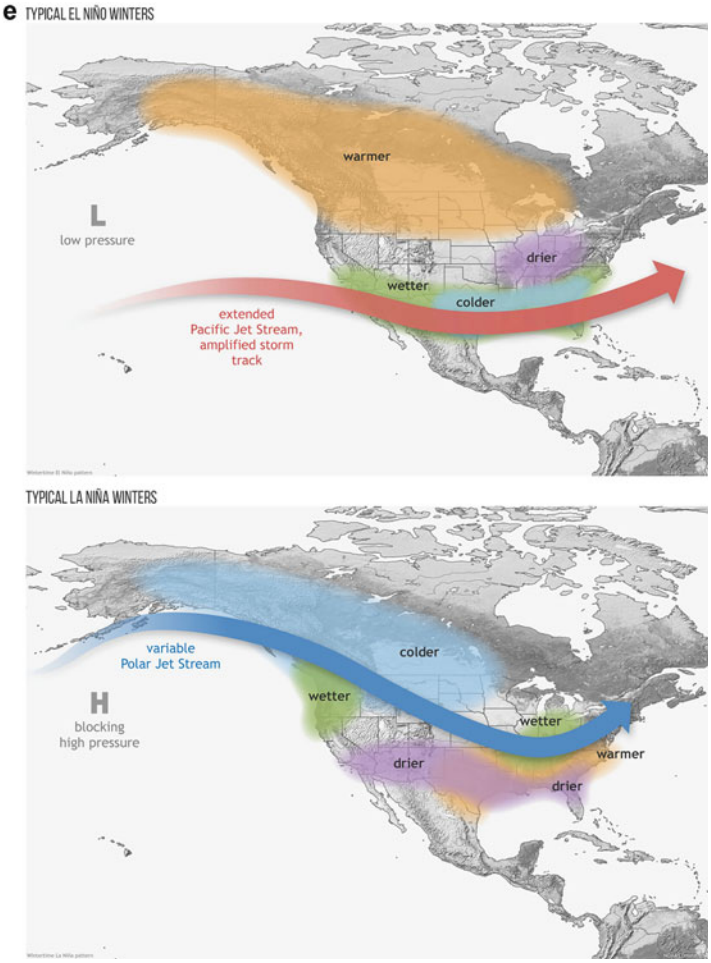

Fig. 2.20 (continued)

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.

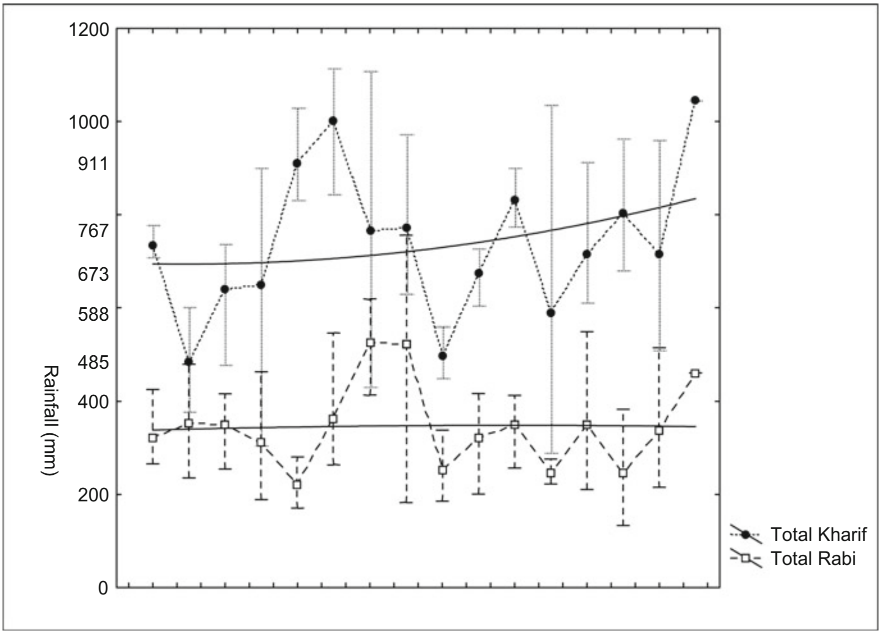

Fig. 2.21 Long-term rainfall pattern in Islamabad during summer (*kharif*) and winter (*rabi*) seasons

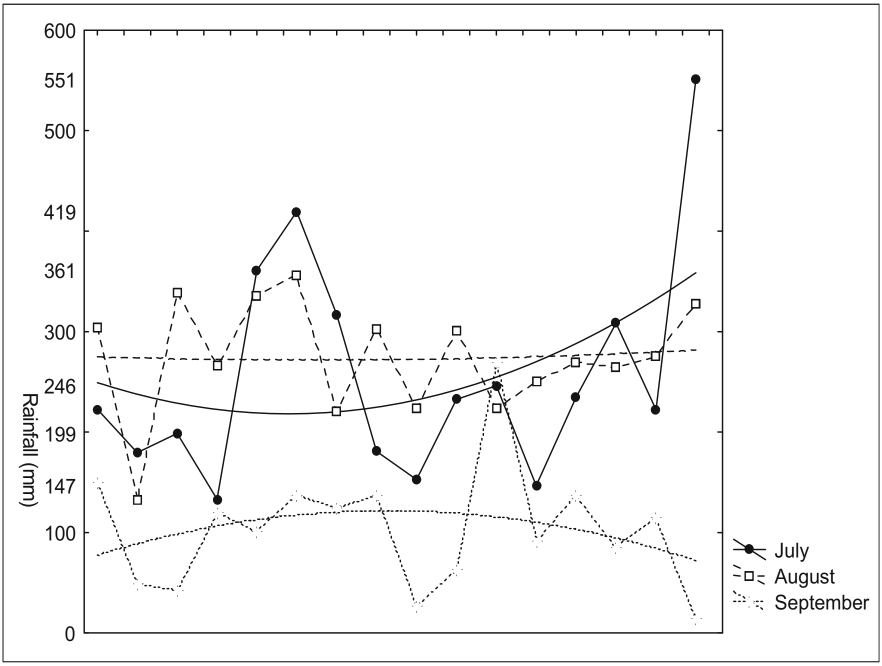

Fig. 2.22 Rainfall intensity in the month of July, August, and September

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

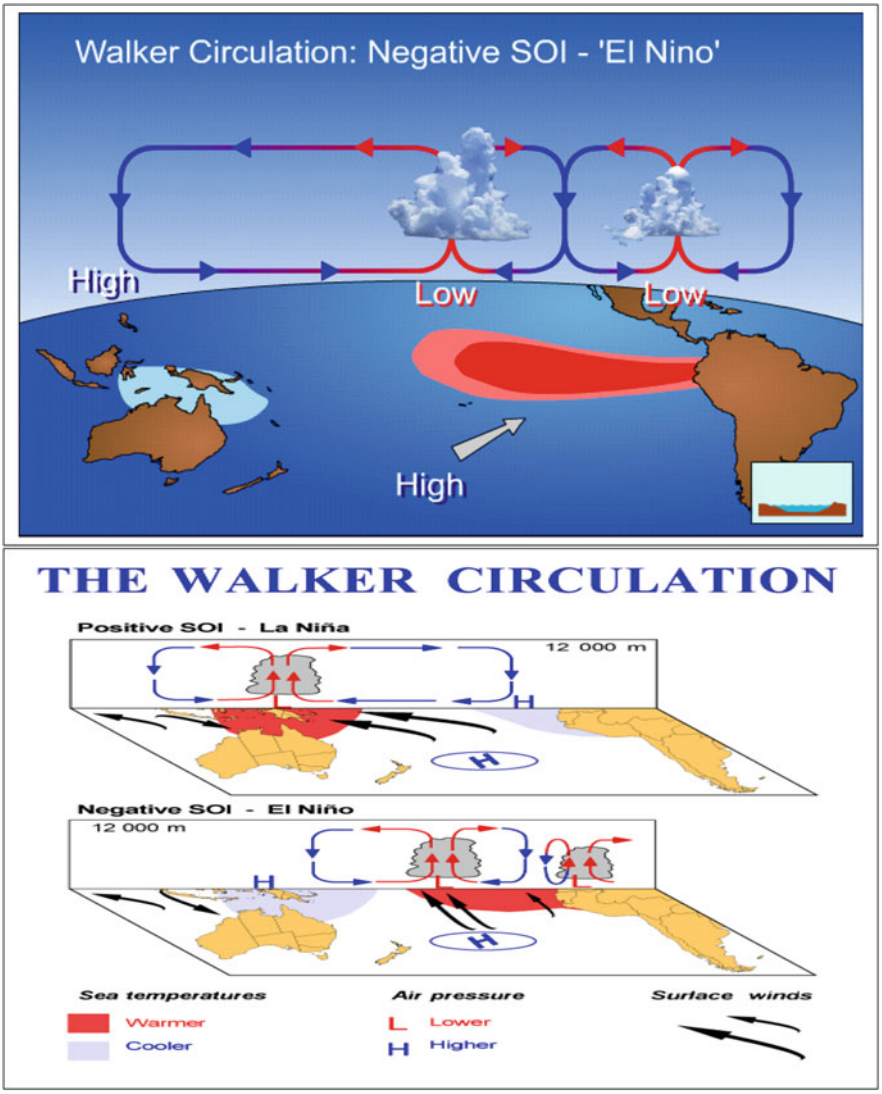

Fig. 2.23 The Walker circulation showing negative and positive SOI. (Source: NOAA)

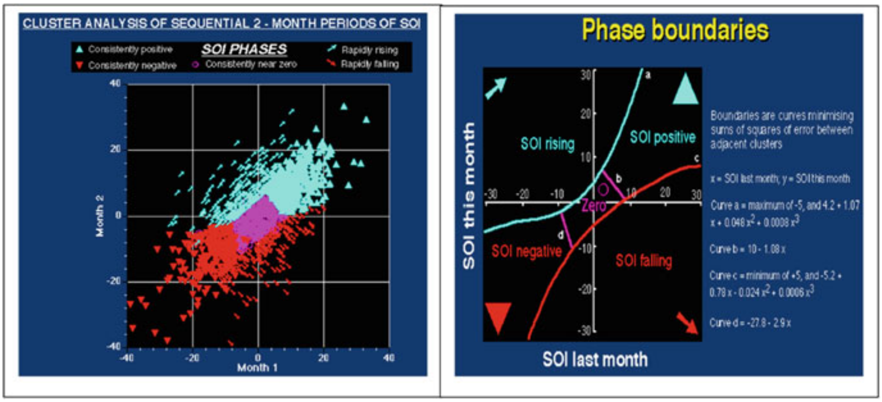

Fig. 2.24 Five clusters of SOI. (Source: Stone et al. 1996)

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

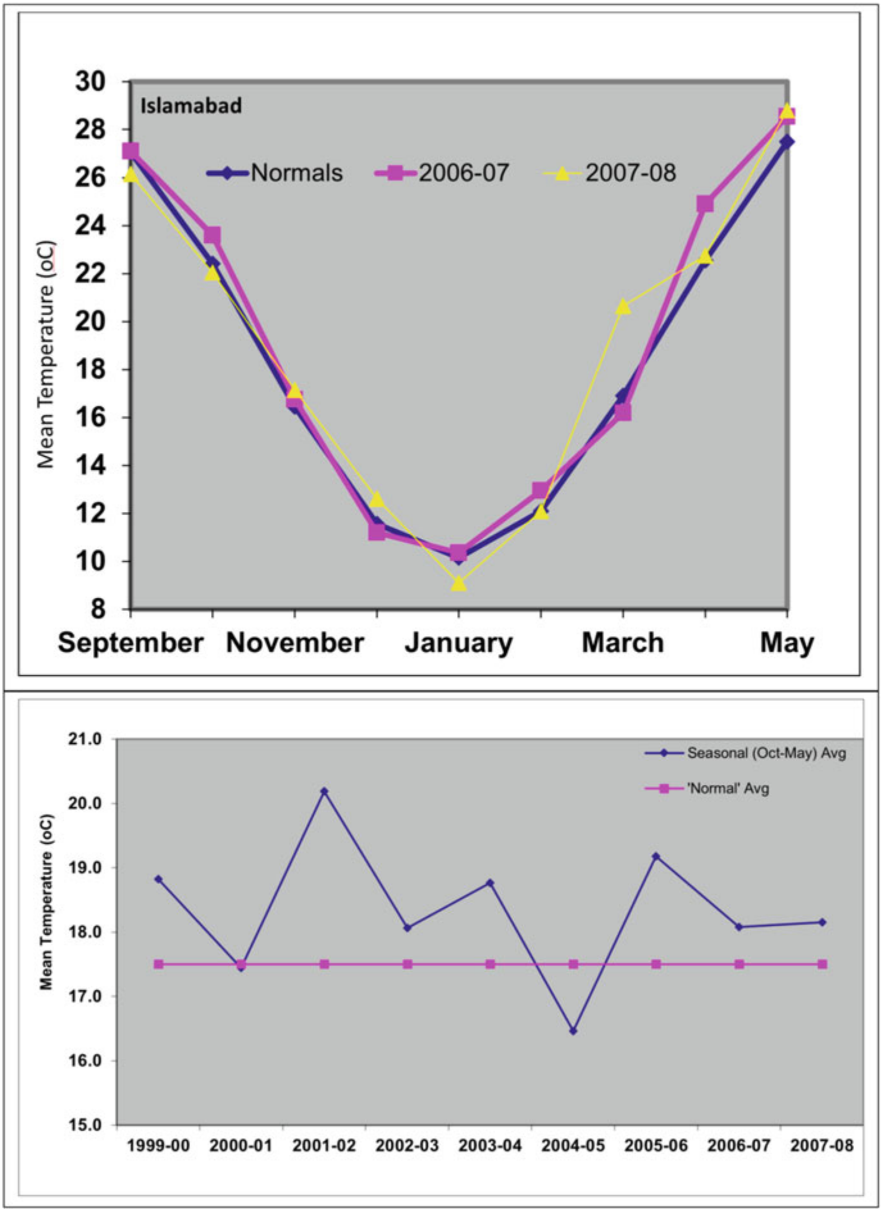

Fig. 2.25 Temperature variability during wheat growing season

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

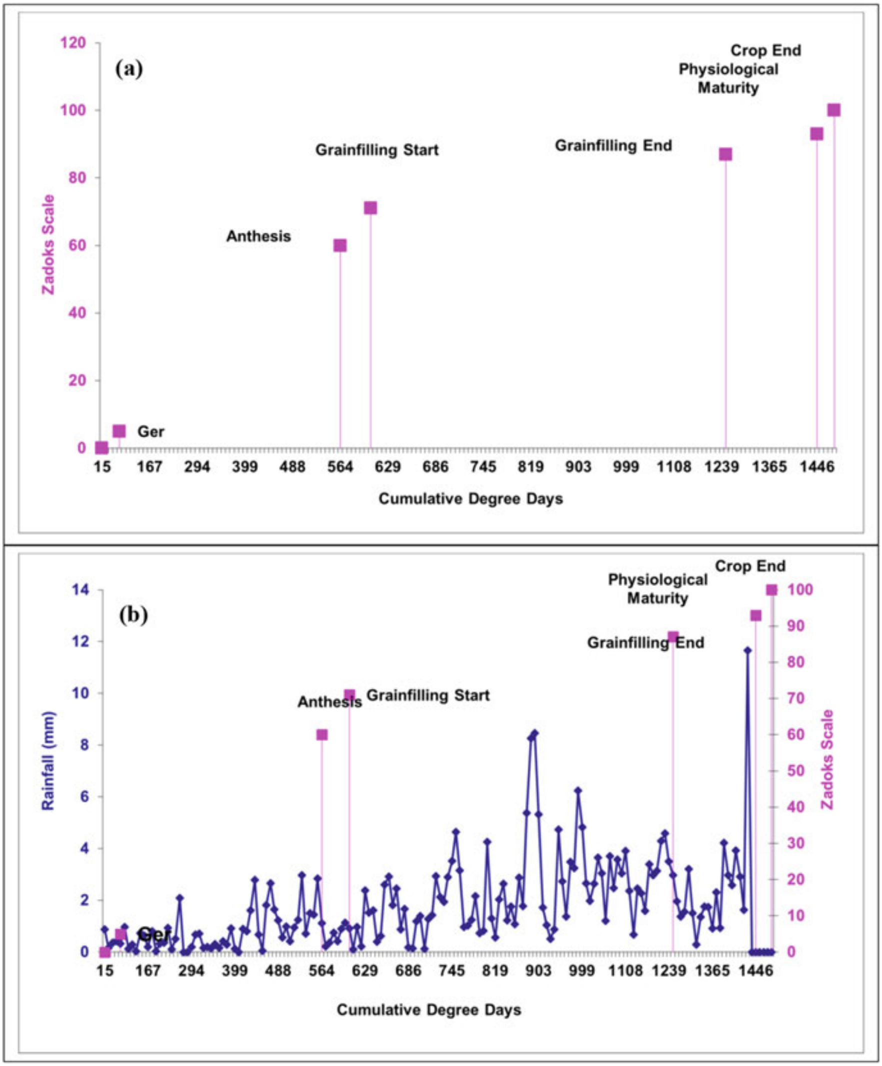

Fig. 2.26 Wheat critical growth stages and degree days utilized (a) and rainfall received (b)

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

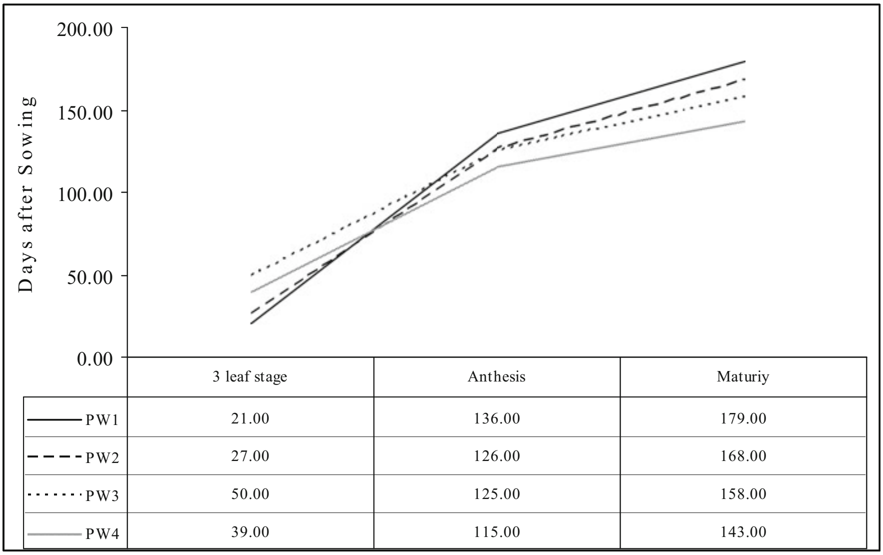

Fig. 2.27 Planting windows (PW) and duration of wheat phenological stages (PW1 = sowing between 15 and 25 October, PW2 = sowing between 10 and 17 November, PW3 = sowing between 27 November and 02 December, PW4 = Sowing between 10 and 24 December)

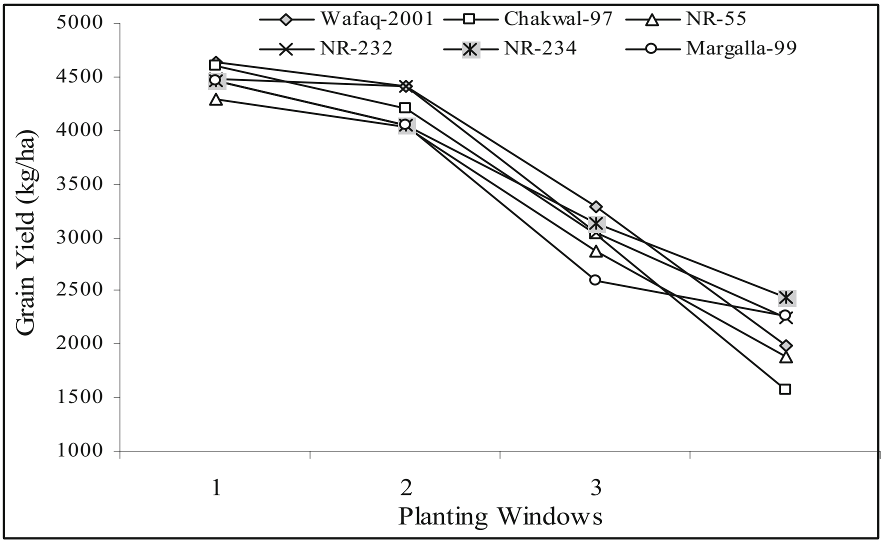

Fig. 2.28 Planting windows and wheat yield (PW1 = sowing between 15 and 25 October, PW2 = sowing between 10 and 17 November, PW3 = sowing between 27 November and 02 December, PW4 = sowing between 10 and 24 December)

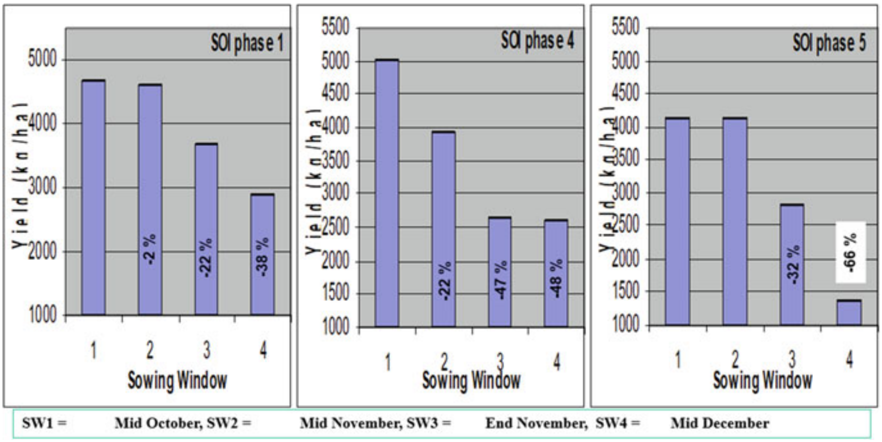

Fig. 2.29 Simulated yield variations in relation to sowing time partitioned against the prevailing SOI phase in July

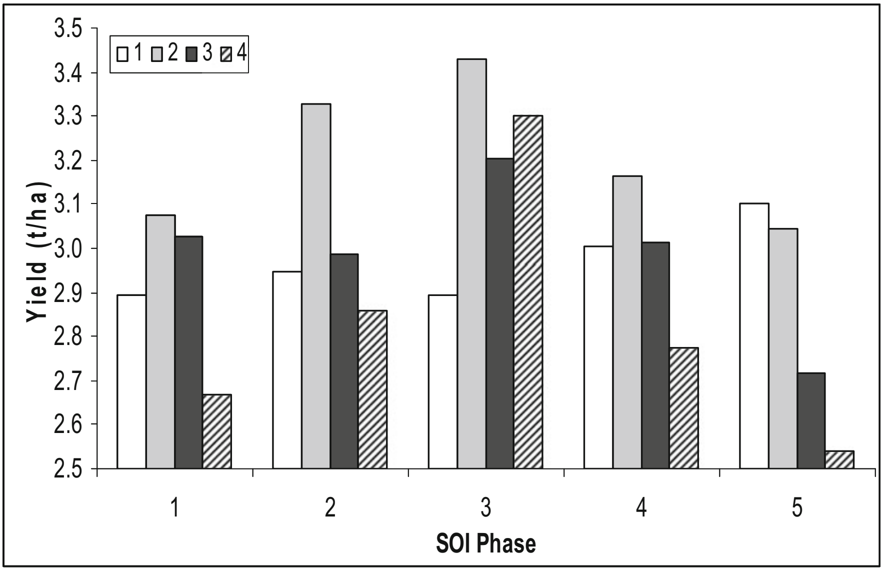

Fig. 2.30 The impact of SOI phases on wheat yield

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

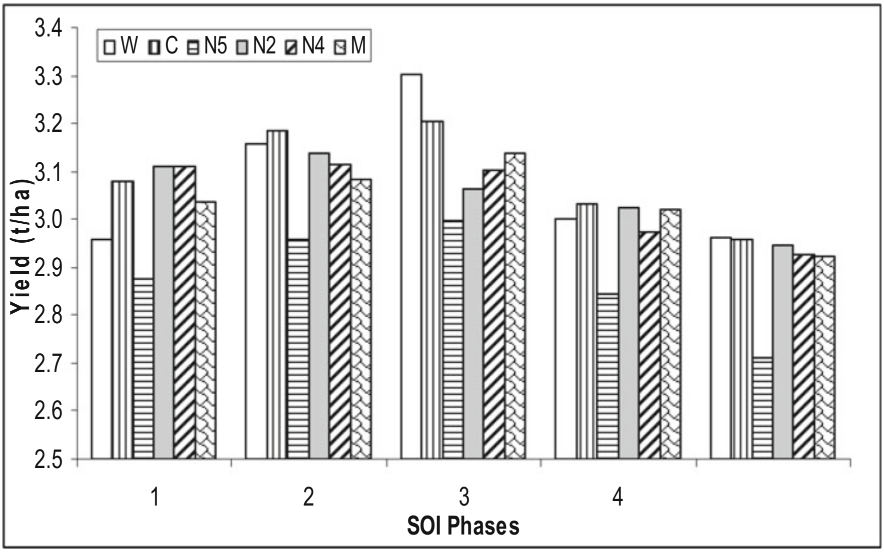

Fig. 2.31 Simulated wheat yield partitioned against July SOI phases (*W* Wafaq-2001, *C* Chakwal-97, *N5* NR-55, *N2* NR-232, *N4* NR-234, *M* Margalla-99)

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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Chapter 3
Climate Change and Process-Based Soil Modeling

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Abstract Soil is under pressure due to climate change. Higher temperature is increasing decomposition and mineralization of the soil organic matter (SOM), thus reducing soil organic carbon, which is the blood of the soil. Furthermore, rise in temperature is causing changes in soil moisture. In addition, elevated concentration of carbon dioxide (CO_2) could cause higher activity of soil microbes, thus breaking SOM at a faster rate and releasing more CO_2. Similarly, the production of methane (CH_4) will be more in future if current traditional agricultural practices would be carried out at the same pace. Thus, it is clear that warming is a responsible factor of higher greenhouse gas (GHGs) emissions from soil. Hence, in this chapter, we are proposing different techniques, which could be used to keep the carbon underground, thus making soil as sink, not the source. Carbon (C) sequestration is low-hanging fruit nowadays, being used to improve SOM. However, understanding or quantification of soil health is important to design adaptation and mitigation strategies to climate change. Modern day tools, such as remote sensing and modeling, can be used to quantify the health status of soil, as mentioned in this chapter. Similarly, knowledge of soil physical processes (e.g., hydrologic dynamics, energy dynamics, and overwinter dynamics) is utmost important to get good returns from the soil. Thus, the Green-Ampt approach, Darcy law, and moving multifront (MMF)

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were discussed in this chapter. Similarly, the approaches used by the different process-based models in their soil modules were elaborated. At the end of this chapter, the practical application of remote sensing and modeling was given at different spatiotemporal scale. Finally, it can be concluded that multiple adaptation and mitigation strategies should be used to improve SOM, which can further help to achieve sustainable development goals (SDGs), the blueprint to achieve a sustainable future for all.

Keywords SoilClimate change · Soil organic matter · Greenhouse gasses · Adaptation and mitigation · Remote sensing · Modeling

3.1 Soils and Climate Change

Soil is the loose surface material that covers the land, and it is the basic resource needed for the survival of living organisms. It contains organic and inorganic material. It is a living treasurer under our feet. Soil is a mixture of mineral matter, water, air, and organic matter as shown in Fig. 3.1. It is the natural medium which nourishes and supports plants. Soil is the end product of decomposition of the parent material. This weathering of the parent material is dependent upon climate, topography, and organisms like flora, fauna, and human. Hence, soil differs in texture, structure, color, physical, chemical, and biological properties. Soil is an important component of land and ecosystems, and it also determines the social and economic conditions of the region. Soil is the second largest store or sink of carbon after ocean, and to mitigate climate change, it is essential to improve soil organic matter (SOM) through different land management's techniques. The relationship between soil and climate change has been well described by the European Environmental Agency (Fig. 3.2). Similarly, soil management can play an important role in climate change adaptation and mitigation (Fig. 3.3). Improving carbon (C) in soil will help to protect

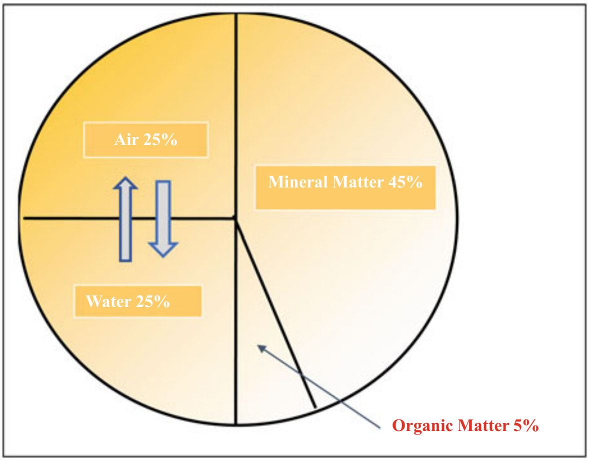

Fig. 3.1 Composition by volume of soil

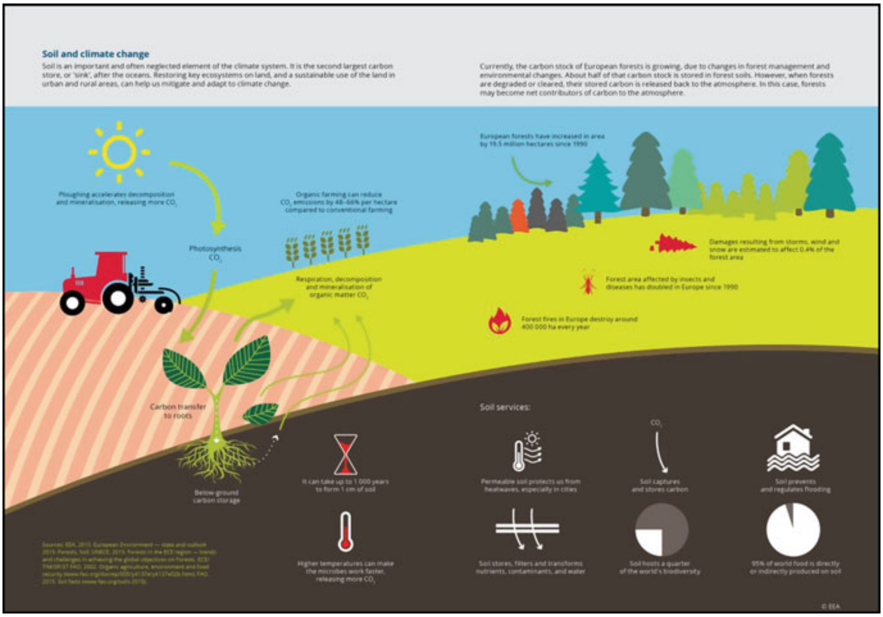

Fig. 3.2 Soil and climate change. (Source: European Environmental Agency (EEA))

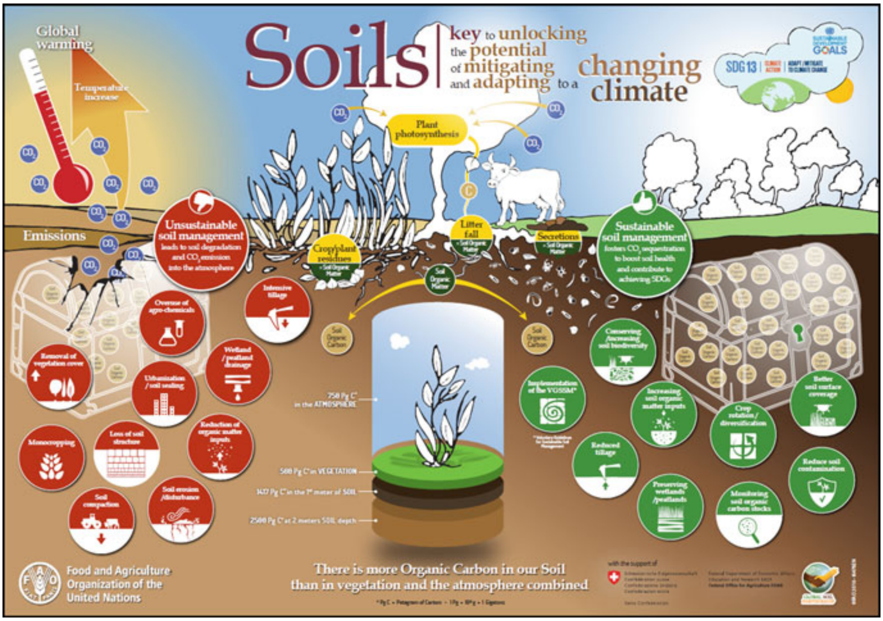

Fig. 3.3 Unlocking potentials of soil to mitigate and adapt to climate change. (Source: FAO)

soil from degradation, increases water holding capacity (WHC) of the soil, promotes microbial growth, and ensures food security. C-sequestration is the transfer of atmospheric CO_2 into different global pools (e.g., oceanic/pedologic/biotic and geological strata) to reduce the increase of CO_2 in the atmosphere. It is a very important technique which can help to maintain the concentration of carbon dioxide (CO_2) in the atmosphere, as concentration of CO_2 is increasing at a rapid pace. It has been increased from 280 ppm (1850) to 417 ppm (2022). This higher CO_2 concentration resulted to the increased surface temperature (1.5–5.8 °C) (IPCC 2001, 2014). C-sequestration have two basic methods, i.e., (i) direct (immediate binding at the source) and (ii) indirect (fixation of CO_2 by photosynthesis or its binding in a soil environment). Agriculture can play a significant role in C-sequestration. It is possible through agroforestry, soil mulching, residue incorporation, application of biochar, proper fertilization, intercropping, crop rotation, and growing of cover crops, which can further improve soil health by preventing soil degradation. Mattila et al. (2022) conducted a farmer participatory research to explore how farmers consider carbon (C) sequestration (low-hanging fruit). Farmers were given training about the basics of C-farming and C-farming plans to improve C-stocks in the field. The study suggested the use of remote sensing, modeling, and soil sampling as an integrated approach to verify the C storage in the field (Diaz-Gonzalez et al. 2022). C-sequestration is an important climate change mitigation approach. Therefore, C-farming was promoted to reduce climate change impact (Paustian et al. 2019). Lal (2008) suggested that reduction in atmospheric CO_2 loading is possible through biological, chemical, and technological options. Biological pumping, a C-sequestration technique in which CO_2 is injected below the ground surface to form carbonates, has so many benefits, which can enhance ecosystem services (e.g., improving soil quality and health, enhancing biodiversity, improving ground water quality, and increasing use efficiency of agronomic inputs), and ensures food security. Furthermore, C-sequestration reduces greenhouse effect (Kowalska et al. 2020; Lal 2005, 2008). Amundson and Biardeau (2018) reported that annual increase in atmospheric CO_2 can be halted if soil carbon could be increased by 0.4% on a yearly basis. Hence, soil C- sequestration is an important mitigation tool. Paustian et al. (2019) reported C-sequestration as an effective CO_2 removal strategy. Different management practices as elaborated in Table 3.1 could be opted to minimize the impact of climate change from soil.

3.2 Understanding Soil

Understanding of soil is very important to design adaptation and mitigation strategies to climate change as mentioned above. Knowledge of soil physical processes is utmost important to get good returns from soil. Soil physical processes include (i) hydrologic dynamics (infiltration, runoff, macropore flow, chemical transport, water table and tile flow, redistribution), (ii) energy dynamics (potential evapotranspiration, soil heat transport and temperatures, energy balance), and (iii) overwinter

Table 3.1 Management practices to increase soil C-sequestration and CO_2 removals

S. No	Management practices	Benefits	References
1.	Crop rotations and cover cropping	Higher C-sequester and economic returns Mitigating climate change Improvement in the soil quality Decrease CO_2 emission Improvement in soil temperature, moisture, and total aboveground biomass Reduces erosion and nitrogen leaching, fix atmospheric nitrogen and improves soil health Mitigation of CO_2 emissions	Chahal et al. (2020), Smith et al. (2008), Abdollahi and Munkholm (2014), Nguyen and Kravchenko (2021), Kaye and Quemada (2017) and Rigon and Calonego (2020)
2.	Composting	Reduces emissions of greenhouse gases (GHGs)	Favoino and Hogg (2008)
3.	Manuring	Reduction in GHGs emissions	Dalgaard et al. (2011)
4.	No tillage, zero tillage	Mitigate GHG emissions Viable greenhouse gas mitigation strategy Lower GHGs fluxes Application of DAYCENT model in the estimation of GHGs Minimizing emissions of GHGs Preservation of soil organic carbon	Ogle et al. (2019), Krauss et al. (2017), Forte et al. (2017), Rafique et al. (2014), Mangalassery et al. (2014) and Haddaway et al. (2017)
5.	Cultivation of perennial grasses and legumes	Higher soil C storage Reduced N_2O emissions Suppress weed invasion Reduced use of inorganic fertilizer Lowering of C-footprint	Yang et al. (2019), Liu et al. (2016) and Gan et al. (2014)
6.	Plantation of deep-rooted crops	Improved soil carbon budget Reduced emissions of CO_2 Improves soil structure Improves water and nutrient retention	Jansson et al. (2021) and Kell (2011)
7.	Rewetting organic soils	Lowering CO_2 and N_2O emissions	Wilson et al. (2016) and Paustian et al. (2016)
8.	Grazing land management	Lowers atmospheric CO_2 emissions and surface temperature Improvement of soil carbon stocks	Mayer et al. (2018) and Conant et al. (2017)
9.	Biochar application	Reduced N_2O emissions Improved soil water holding capacity Suppression of soil CO_2 emissions Variable response in CO_2 production Soil greenhouse gas (GHG) fluxes remained variable in response to different biochar application	Martin et al. (2015), Conant et al. (2017), Spokas and Reicosky (2009) and He et al. (2017)
10.	Plant-soil interactions	Restoration of degraded soil	Maiti and Ghosh (2020)

dynamics (simplistic snow accumulation and melt process). Infiltration of water into a layered soil could be monitored by the Green-Ampt approach, which requires saturated hydraulic conductivity K_S and wetting-front suction S_{WF} of each soil layer (Green and Ampt 1911). It is a mechanistic model for infiltration under ponded conditions with well-defined wetting front. The following equation elaborates parameters in the Green-Ampt infiltration model:

$$V = \overline{K}_S \frac{(S_{\mathrm{wf}} + H_O + Z_{\mathrm{WF}})}{Z_{\mathrm{WF}}}$$

where S_{WF} = integral of relative unsaturated hydraulic conductivity $K(h)/K_s$, known or derived from soil-water retention curve, $\theta(h)$ and θ = volumetric soil water content, and h = soil-water pressure head (−ive soil-water suction). Due to air entrapment, field-saturated θ_s is about 0.90 and effective K_s is approximately $K_s/2$. Further description about Green-Ampt infiltration model has been shown in Fig. 3.4.

Water penetration from the ground into the soil is governed by the soil surface condition, vegetation cover, soil properties, hydraulic conductivity, and antecedent

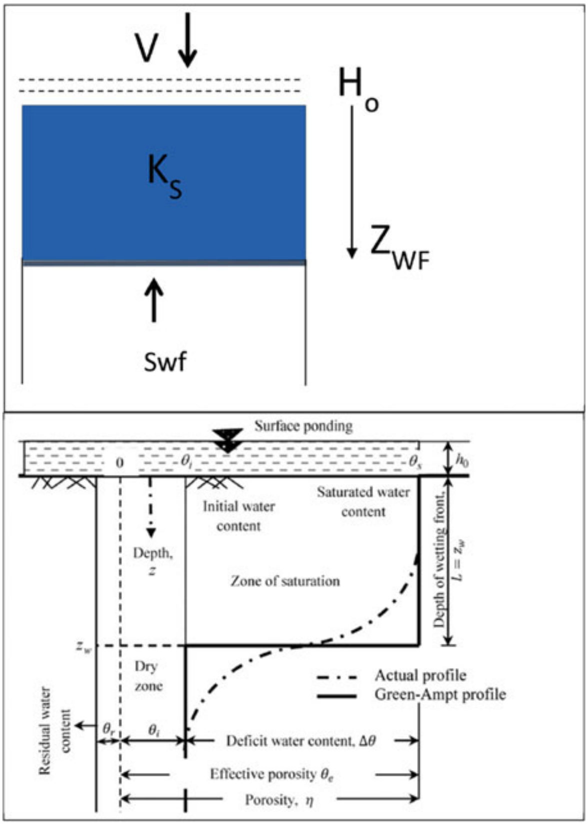

Fig. 3.4 Green-Ampt infiltration model. (Source: Kale and Sahoo 2011)

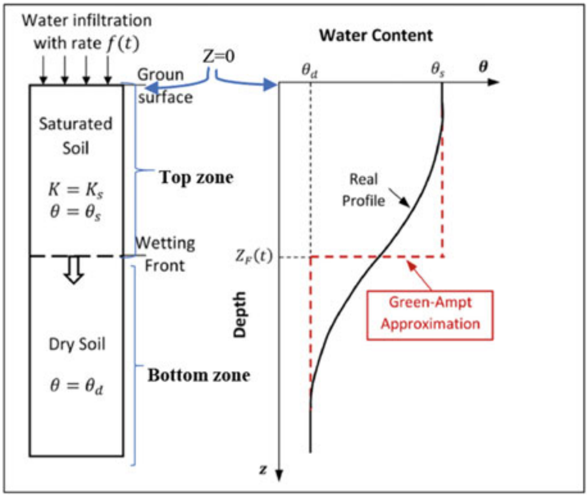

Fig. 3.5 Green-Ampt piston flow. (Source with permission via Rightslink: Alastal and Ababou 2019)

soil moisture. Generally, it has four zones (i) saturated, (ii) transmission, (iii) wetting, and (iv) wetting front. The rate at which water enters the soil is called infiltration rate, represented as f(t), while cumulative infiltration ($F(t)$) is the accumulated depth of water infiltrating during given time period. The Green-Ampt infiltration model (GAIM) assumes saturated piston-type flow into the dry soil (flow is modeled as the displacement of a single sharp wetting front into a dry soil). The front sharply separates in two regions, i.e., (i) fully saturated region (above) and (ii) very dry region (Below). The wetting front move downward due to gravity and capillary suction (Fig. 3.5). The GAIM is a single front model as it is based on the movement of a single front (Zf(t)) as shown in Fig. 3.5. The GAIM divides the soil into two zones as shown in Fig. 3.5.

Darcy law could be used to describes water flux (q). For example, in case of two-layered soil as shown in Fig. 3.6, water flux for the first layer (q_1) and second layer could be monitored by the following equations:

$$\text{Water flux for the 1st layer}(q_1)\ (\text{Volume per unit area per unit time})$$

$$= \text{Hydraulic conductivity of 1st layer } (K_1) \times \frac{\text{Hydraulic gradient}(\Delta H_1)}{L_1\ (\text{Thickness of 1st layer})}$$

$$= K_1 \frac{H_A - H_B}{L_1}$$

$$\therefore \frac{q_1 L_1}{K_1} - H_A = -H_B$$

$$\therefore -\frac{q_1 L_1}{K_1} + H_A = H_B$$

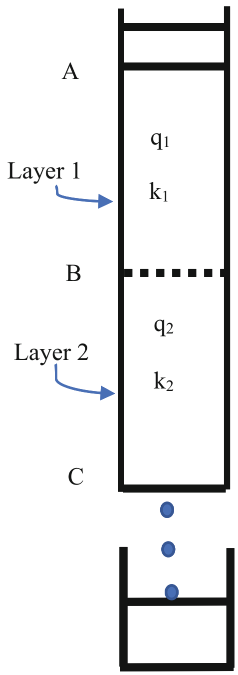

Fig. 3.6 Darcy law for layered soils

$$H_B = H_A - \frac{q_1 L_1}{K_1}$$

Water flux for the 2nd layer(q_2) (Volume per unit area per unit time)

$$= \text{Hydraulic conductivity of 1st layer } (K_2) \times \frac{\text{Hydraulic gradient}(\Delta H_2)}{L_2 \text{ (Thickness of 2nd layer)}}$$

$$= K_2 \frac{H_B - H_C}{L_2}$$

$$\therefore q_2 = \frac{K_2}{L_2}\,(H_B - H_c)$$

Putting the value of H_B from the first layer into second-layered equation generates the following equation:

$$q_2 = \frac{K_2}{L_2}\left(H_A - \frac{q_1 L_1}{K_1} - H_c\right)$$

For a steady state system, flux will be:

$$q_1 = q_2 = q$$

Hence,

$$q = \frac{K_2}{L_2}\left(H_A - \frac{qL_1}{K_1} - H_c\right)$$

After rearrangement, equation will be:

$$\frac{qL_2}{K_2} + \frac{qL_1}{K_1} = H_A - H_C$$

$$q\left(\frac{L_2}{K_2} + \frac{L_1}{K_1}\right) = H_A - H_C$$

Hence, Dracy's law for layered soil will be:

$$q = \frac{H_A - H_C}{\frac{L_2}{K_2} + \frac{L_1}{K_1}}$$

Let $\frac{L \text{ (lenght of the given soil layer)}}{K \text{ (Hysraulic conductivity of the soil layer)}} = \text{Hydraulic resistanc}e = R_h$
Then

$$q = \frac{H_A - H_C}{R_{h_1} + R_{h_2}} = \frac{\Delta H}{R_{h_1} + R_{h_2}} =$$

Alastal and Ababou (2019) developed and tested moving multifront (MMF) to solve the Richards equation (Fig. 3.7). The root uptake part of the sink term $W(z,t)$ could be evaluated by using the approach of Nimah and Hanks (1973). Evapotranspiration is generally monitored by using the Penman-Montieth or Shuttleworth and Wallace methods.

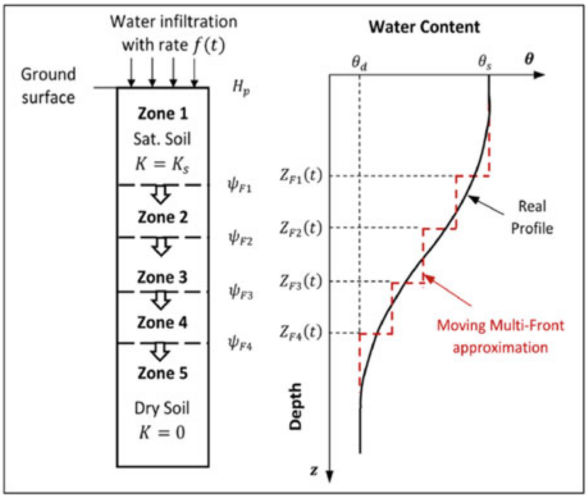

Fig. 3.7 Moving multifront (MMF) model. (Source with permission via Rightslink: Alastal and Ababou 2019)

3.3 Soil Modules in Different Models

3.3.1 AquaCrop

AquaCrop is a FAO model, and it uses soil water balance, soil water movement, and soil profile characteristic modules. The functioning of soil water module in AquaCrop is elaborated in Fig. 3.8. AquaCrop derives soil texture, organic matter, soil compaction, and stoniness by using hydraulic properties calculator developed by the USDA and Washington State University (https://hrsl.ba.ars.usda.gov/soilwater/Index.htm).

3.3.2 Agricultural Production Systems sIMulator (APSIM)_Soil Module

The APSIM is an internationally well-known model (https://www.apsim.info/). The APSIM soil module has multiple components, i.e., (i) erosion, (ii) fertilizer, (iii)

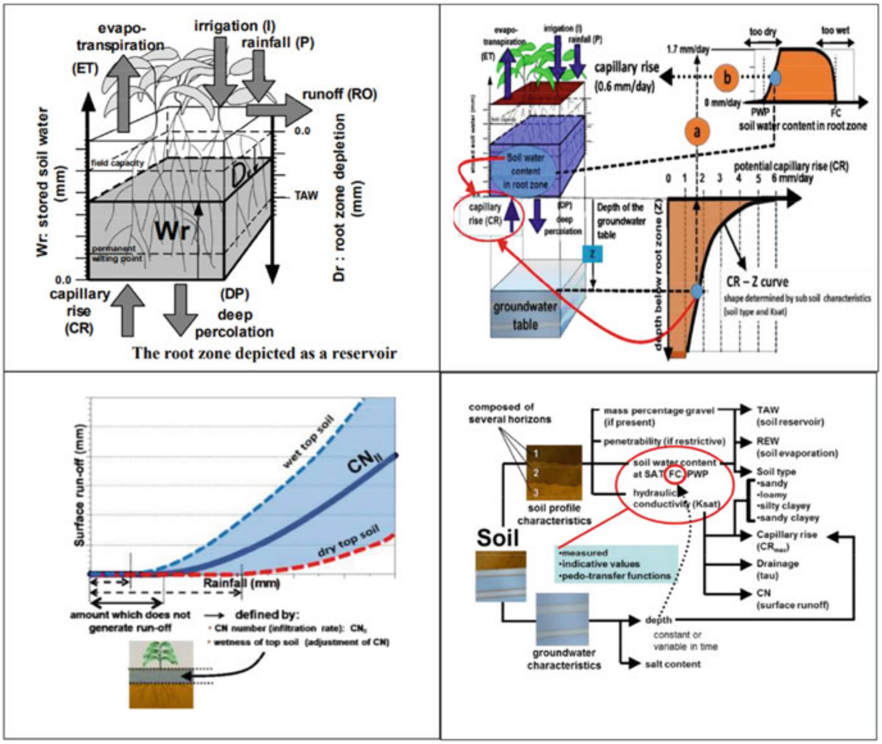

Fig. 3.8 Description of soil module in AquaCrop

irrigation, (iv) map, (v) SoilN, (vi) SoilP, (vii), SoilTemp, (viii), SoilWat (ix), solute, (x) surface, (xi) SurfaceOM, (xii) SWIM, (xiii) SWIM3, and (xiv) WaterSuppl. The APSIM soil module is diagrammatically presented in Fig. 3.9. Both C and N dynamics has been described by SoilN module as elaborated in Fig. 3.10, where

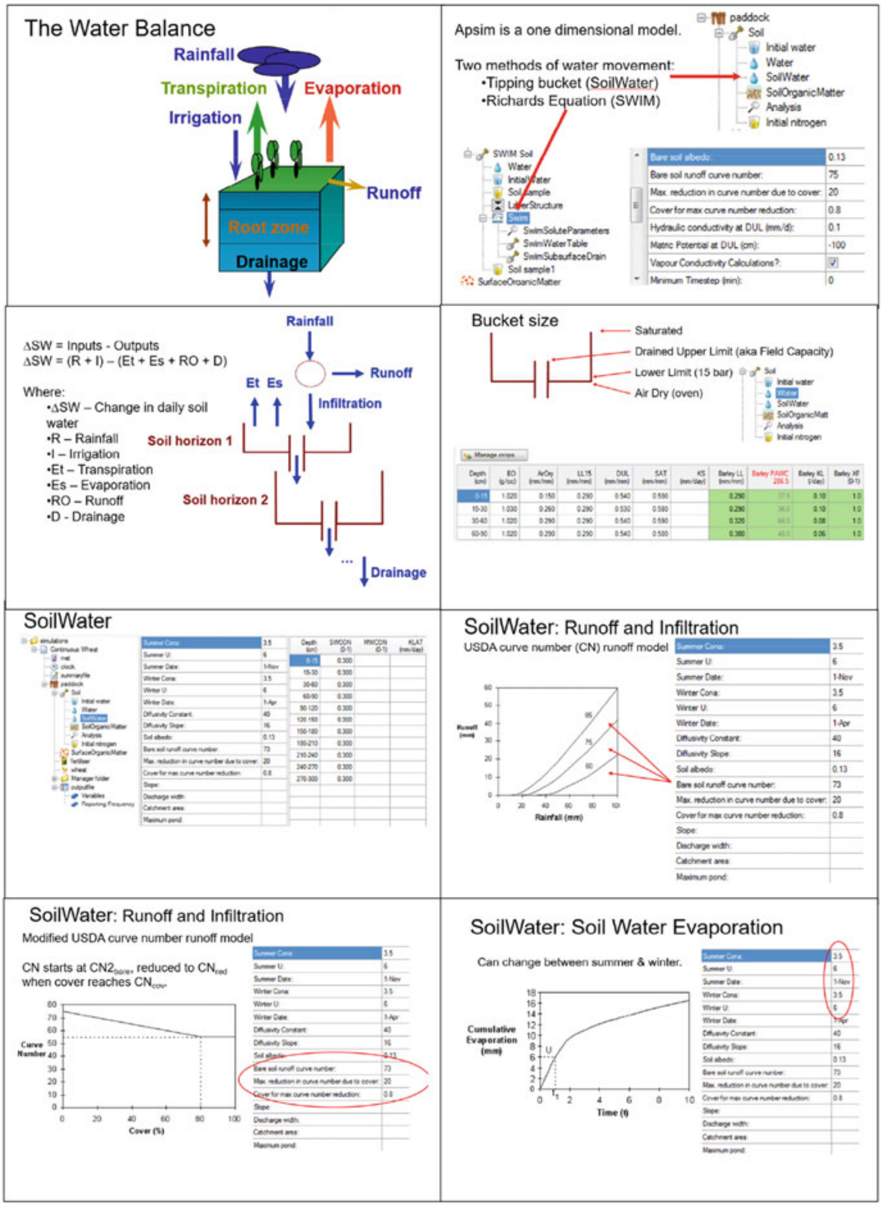

Fig. 3.9 Diagrammatic representation of the APSIM soil module. (Source: APSIM)

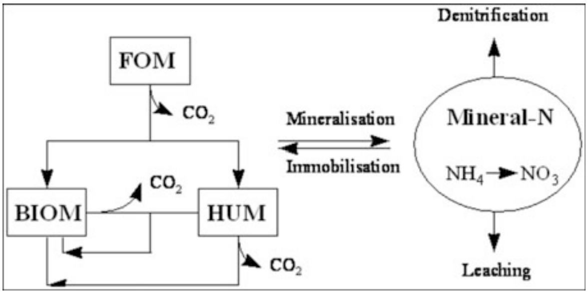

Fig. 3.10 Transformation in the APSIM_soilN module. (Source: APSIM)

SOM is divided into two pools (Hum and Biom). Labile, soil microbial biomass, and microbial products are represented by "biom" pool, while the rest of the SOM comprises "hum." The flow between different pools is quantified in terms of C, while N flows depend upon C:N ratio of receiving pool. The "ini file" is used to specified C:N for "biom," while for "hum" it comes from the soil as an input. Decomposition in these two pools were calculated as first-order processes with a rate constant being modified by soil moisture and temperature in the layer. The CERES_Maize approach was used to represent fresh organic matter pool (fom), while C:N factor determines "fom" rate of decomposition (Jones 1986). Mineral N is determined though balance between decomposition and immobilization. At initialization, "hum" and "biom" C amount is calculated using soil inputs. The following equations will represent total, organic C, inert C, biom_C, and hum_C at initialization:

$$\text{Total C} = \text{Fresh organic matter (FOM) C} + \text{Orgnaic carbon (OC)}$$

$$\text{Organic Carbon}\left(\text{Kg ha}^{-1}\right) = \text{biom\_C} + \text{hum\_C}$$

$$\text{inert \_ C} = F_{\text{inert}} \times \text{OC}(\text{Kg ha}^{-1})$$

$$\text{biom\_C} = F_{\text{biom}} \times (\text{hum\_C} - \text{inert\_C})$$

since

$$\text{hum\_C} = \text{OC} - \text{biom\_C}$$

Thus, biom_C equation will be:

$$\text{biom\_C} = \frac{(F_{\text{biom}} \times (\text{OC} - \text{inert\_C}))}{(1 - F_{\text{biom}})}$$

$$\text{hum\_C} = \text{OC} - \text{biom\_C}$$

Soil temperature in the APSIM_Soil module is calculated using the Williams (1984) approach as applied in the EPIC (erosion-productivity impact calculator) model. The following equations were used in the EPIC model:

$$T(Z,t) = \overline{T} + \frac{\mathrm{AM}}{2}\exp\left(\frac{-Z}{\mathrm{DD}}\right)\cos\left(\frac{2\pi}{365}(t-200) - \frac{Z}{\mathrm{DD}}\right)$$

where Z = depth from the soil surface (mm), t = time (days), T = average annual air temperature (°C), AM = annual amplitude in daily average temperature (°C), and DD = damping depth for the soil (mm). However, this equation provides the same value for soil temperature as is for air temperature. Hence, to use air temperature as a driver for the soil temperature, the new equation developed was:

$$\mathrm{TG}_{\mathrm{IDA}} = (1-\mathrm{AB})\left(\frac{T_{\max} + T_{\min}}{2}\right)\left(1 - \frac{\mathrm{RA}}{800}\right) + T_{\max}\frac{\mathrm{RA}}{800} + (\mathrm{AB}) \times (\mathrm{TG}_{\mathrm{IDA}-1})\ldots\ldots\ldots$$

where TG = soil surface temperature (oC), AB = surface albedo, $T_{\max}$ = maximum daily air temperature, $T_{\min}$ = minimum daily air temperature, and RA = daily solar radiation.

The final equation for calculating soil temperature at any depth is:

$$T(Z,t) = \overline{T} + \left(\frac{\mathrm{AM}}{2}\cos\left(\frac{2\pi}{365}(t-200) + \mathrm{TG} - T(O,\ \ t)\right)\right)e^{-Z/\mathrm{DD}}$$

Decomposition of SOM pools in the APSIM_Soil module was calculated using the following equations:

$$\begin{aligned}\text{fom decomposition} = {} & F_{\mathrm{pool}}(\text{Carbohydate, cellulose or lignin fraction}) \\ & \times \text{decay rate (rd)for a give fraction}\left(\mathrm{rd}_{\mathrm{carb}}, \mathrm{rd}_{\mathrm{cell}}, \mathrm{rd}_{\mathrm{lign}}\right) \\ & \times \text{Soil water factor} \times \text{Soil tempearture factor} \times \text{C} \\ & : \text{N factor}\end{aligned}$$

$$\text{biom decomposition} = \text{biom} \times \mathrm{rd}_{\mathrm{biom}} \times \text{Soil water factor} \times \text{Soil temperature factor}$$

$$\text{hum decomposition} = (\text{hum} - \text{inert\_C}) \times \mathrm{rd}_{\mathrm{hum}} \times \text{Soil water factor} \times \text{Soil temperature factor}$$

The factors affecting individual decay rates are shown in Fig. 3.11. Nitrification is an APSIM_Soil module which is calculated using the Michaelis-Menton kinetics. The following equations have been used to determine the nitrification rate:

$$\text{Potential rate} = \frac{\text{Nitrification}_{\text{pot}}(\text{mg N/kg soil/day}) \times \text{NH}_{4(\text{ppm})}}{\left(\text{NH}_{4(\text{ppm})} + \text{NH}_{4\ \text{at half pot (ppm)}}\right)}$$

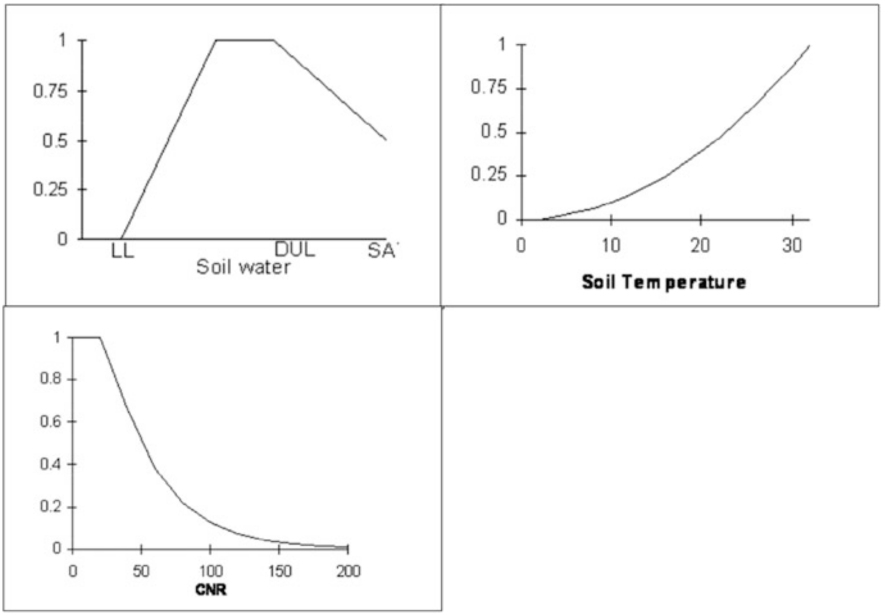

Fig. 3.11 Factors affecting SOM decay rates. (Source: APSIM)

$$\text{Nitrification rate} = \text{Potential rate} \times \min\left(\text{water factor, temperature factor, pH factor}\right)$$

Factors, i.e., soil water, temperature, and pH, affecting the nitrification rate of ammonium, are shown in Fig. 3.12. Nitrous oxide (N_2O) emission from nitrification is calculated using the following equation:

$$N_2O = K2 \times R_{nit}$$

where Rnit = rate of nitrification ((kg N ha^{-1} day^{-1}) and range of values as were used for $K2$ (Li 2000). Denitrification in APSIM_Soil module was taken from CERES-Maize V1, which uses the following equations:

$$\text{Denitrification rate} = 0.0006 \times NO_3 \times \text{Active } C_{ppm} \times \text{water factor} \times \text{temperature factor}$$

where

$$\text{Active } C_{ppm} = 0.0031 \times \left(\text{hum\_}C_{ppm} + \text{FOM\_}C_{ppm}\right) + 24.5$$

Factors affecting denitrification of nitrate is shown in Fig. 3.13. Further details of all other components in APSIM_Soil module are available on https://www.apsim.info/documentation/model-documentation/soil-modules-documentation/

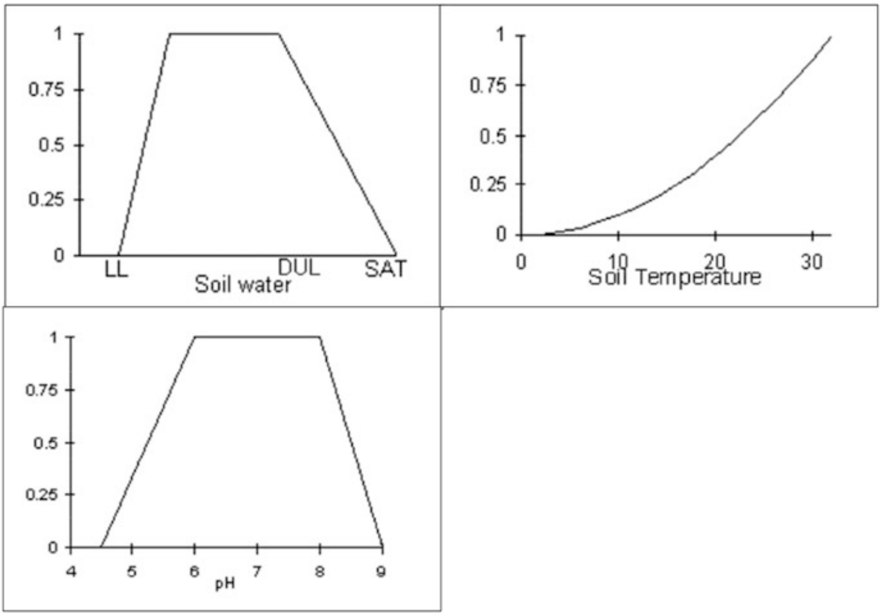

Fig. 3.12 Factors affecting *nitrification rate of ammonium.* (Source: APSIM)

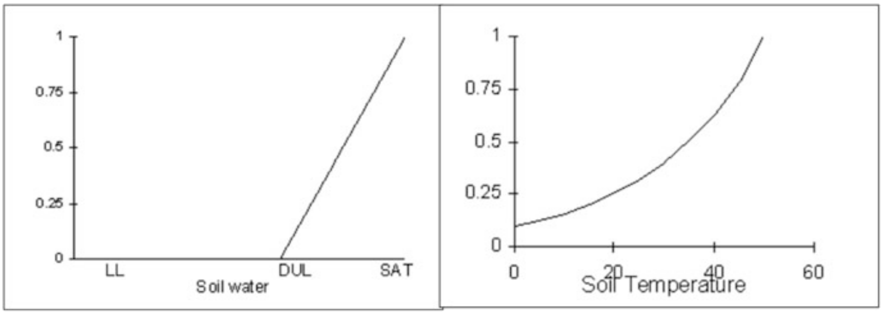

Fig. 3.13 Factors affecting *denitrification.* (Source: APSIM)

3.3.3 Decision Support System for Agrotechnology Transfer (DSSAT)_Soil Module

The simulation of the dynamics of soil in DSSAT is possible through different soil modules. These include soil water, inorganic soil N, soil P, and soil K modules. DSSAT also has soil organic matter modules with two options: (i) CERES-Godwin soil organic matter module and (ii) CENTURY (Parton) soil organic matter module. Furthermore, DSSAT has GHG emission modules, i.e., CERES denitrification, DayCent denitrification, N-gas emissions, and methane emissions. The DSSAT_soil module can also simulate dynamic soil properties as well as flood N dynamics. Further detail is available at https://dssat.net/models-overview/components/soil-module/

3.3.4 CropSyst_Soil

CropSyst simulates soil water budgets (precipitation, irrigation, runoff, interception, water infiltration, water redistribution in the soil profile), nutrients budgets (N and P), and C cycling on daily as well as hourly time step. Soil water fluxes in CropSyst is determined by a simple cascading approach or by a finite difference approach. Evapotranspiration in CropSyst can be calculated by three approaches, i.e., (i) Penman-Monteith model (ii) Priestley-Taylor model, and (iii) simpler implementation of the Priestley-Taylor, which considers only air temperature (Stöckle et al. 2003).

3.3.4.1 CropSyst Carbon/Nitrogen Model

This portion of the carbon/nitrogen model only includes the description of decay and mineralization of organic residues (crop, manure, etc.) incorporated into soil layers and dead roots. Surface residues are treated in a separate module using a slightly different approach. The pools included in the model are given in Table 3.2, all of them with units of kg m^{-2} ground area and with specified carbon/nitrogen ratios, except for residues whose ratio depends on their specific nitrogen content. The separate set of pools are defined for each soil layer. Figure 3.1 depicts the relations and exchanges of carbon (and nitrogen indirectly) among pools. Decomposition of organic residues and organic matter follows first-order kinetics with the following decomposition constants (day^{-1}).

A significant fraction of the carbon resulting from the decomposition of the different pools is lost as CO_2, and the rest is transferred to other pools (Fig. 3.14) according to the following carbon distribution fractions, where $F_{X\text{->}Y}$ represents the fraction of carbon transferred from pool X to pool Y (Badini et al. 2007).

$$F_{R\rightarrow \mathrm{CO_2}} = 0.55$$

$$F_{R\rightarrow \mathrm{MB}} = 1 - F_{R\rightarrow \mathrm{CO_2}}$$

$$F_{\mathrm{MB}\rightarrow \mathrm{CO_2}} = \mathrm{Minimum}\left[(0.55),\left(0.85 - 0.68\left(F_{\mathrm{Silt}} + F_{clay}\right)\right)\right]$$

where F_{Silt} and F_{Clay} are the soil silt and clay fractions, respectively.

$$F_{\mathrm{MB}\rightarrow P} = 0.003 + 0.032\, F_{\mathrm{Clay}}$$

Table 3.2 Description of different pools in the CropSyst carbon/nitrogen model

Acronym	**Description**	**Carbon/nitrogen ratio**
R	Organic residue	Variable
MB	Microbial biomass	10
LA	Labile active soil organic matter	10
MA	Metastable active soil organic matter	10
P	Passive soil organic matter	10
Pool	**Notation**	**Value**
R	K_R	0.02
MB	K_{MB}	0.02 [1–0.75(F_{Silt}+F_{Clay})]
LA	K_{LA}	0.01
MA	K_{MA}	0.00055
P	K_P	0.000019

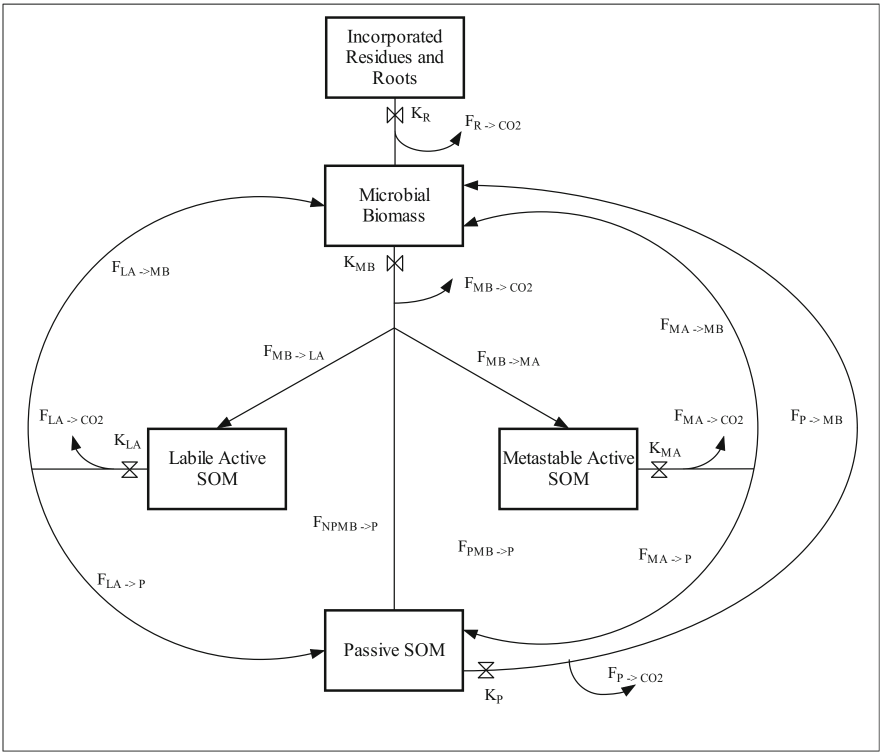

Fig. 3.14 CropSyst conceptual carbon flow model. (Source with permission: Badini et al. 2007)

$$F_{MB \to LA} = (1 - F_{MB \to CO_2} - F_{MB \to P})\text{FNPSV}$$

$$F_{MB \to MA} = (1 - F_{MB \to CO_2} - F_{MB \to P})(1 - \text{FNPSV})$$

where FNPSV is the fraction of non-protected soil volume, which is zero or low for consolidated and undisturbed soil layers and higher for layers recently disturbed by tillage.

$$F_{LA\rightarrow CO_2} = F_{MA\rightarrow CO_2} = F_{P\rightarrow CO_2} = 0.55$$

$$F_{LA\rightarrow P} = F_{MA\rightarrow P} = \text{Maximum}\left[(0.0), \left(0.003 - 0.009F_{Clay}\right)\right]$$

$$F_{LA\rightarrow MB} = 1 - F_{LA\rightarrow CO_2} - F_{LA\rightarrow P}$$

$$F_{MA\rightarrow MB} = 1 - F_{MA\rightarrow CO_2} - F_{MA\rightarrow P}$$

$$F_{P\rightarrow MB} = \left(1 - F_{P\rightarrow CO_2}\right)$$

The carbon transferred among pools also determines the nitrogen transfer, which is equal to the amount of nitrogen required to preserve the carbon/nitrogen ratio of the receiving pools. In this process, if the amount of nitrogen released by the decomposing pool is greater than the amount of nitrogen required by the receiving pools, mineral nitrogen in the form of ammonium is released to the soil layer (mineralization). If the opposite is true, ammonium (first source) and nitrate (secondary source) from the soil layer is taken up for microbial consumption (immobilization). If no sufficient mineral nitrogen is available in the soil to supply the microbial demand, the decomposition is reduced in all pools requiring immobilization proportionally to the fraction of immobilization demand not satisfied. The initial amount of carbon allocated to each soil organic matter (SOM) pool in Fig. 3.14 depends on the organic matter content of the soil layer, expressed in kg carbon per square meter ground area. The total amount of carbon initially present in the soil layer is apportioned to each pool as mentioned in Table 3.3.

3.3.5 STTCS (Simulateur mulTIdisciplinaire Pour les Cultures Standard)

STICS is a model developed by INRA (France), now called as INRAE (Brisson et al. 2003). Soil surface can modify the water and heat balances in STICS, and it is linked

Table 3.3 Total amount of carbon in different pools

Pool	Fraction
Microbial biomass	0.02
Labile active SOM	(1 – Microbial biomass fraction – passive SOM fraction) physically non-protected soil volume
Metastable active SOM	(1 – Microbial biomass fraction – passive SOM fraction) physically protected soil volume
Passive SOM	Minimum (0.5, 0.3 + 0.4 F_{Clay}) for grasslands Minimum (0.5, 0.4 + 0.2 F_{Clay}) for croplands

Source: Badini et al. (2007)

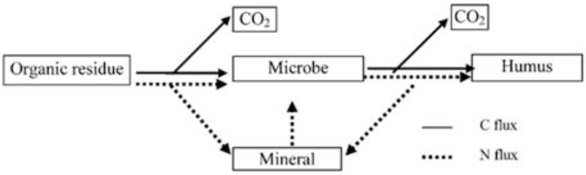

Fig. 3.15 C and N fluxes in STICS. (Source with permission: Brisson et al. 2003)

with the albedo of soil in dry state. Runoff coefficients determines the runoff proportion above a threshold in the presence of plants or mulch. Water balance in STICS is computed by using precipitation, irrigation, and reference evapotranspiration. Bulk density, field capacity, and wilting point was assumed constant in each soil horizon. The whole soil profile in STICS was characterized by five horizons of different depth. Beer's law is applied to calculate potential evaporation. N balance in STICS is calculated through N mineralization that originates from the three pools of organic matter (OM), i.e., (i) humified OM, (ii) microbial biomass (BIOM), and (iii) crop residues (RES) (Fig. 3.15). Denitrification (the gaseous loss) was calculated by using the NEMIS model (Hénault and Germon 2000). Nitrogen absorption is linked to crop requirements and supply from soil root system. Crop requirements was connected with the upper envelop of N dilution curves as reported by Lemaire and Gastal (1997). Soil N supply is equal to two fluxes, i.e. (i) transport flux (NO_3^{-1} transport via convection and diffusion from soil to closet root) and (ii) sink flux (active absorption by the root). In case of legumes, symbiotic fixation option is available that maintains N nutrition at the critical N level, and it depends on nodule activity, NO_3^{-1} presence, water stress, anoxia, and temperature. Soil temperature in STICS is calculated by using the model of McCann et al. (1991), which considers daily crop temperature and its amplitude (Brisson et al. 1998, 2003).

3.3.6 Erosion Productivity Impact Calculator (EPIC)

The EPIC model was developed by Williams (1984) to quantify the relationship between erosion and productivity. It is one of the comprehensive cropping system models developed initially (Williams et al. 1989; Williams 1990, 1995; Rosenberg et al. 1992; Stockle et al. 1992). The extended version of EPIC is APEX (Agricultural Policy/Environmental eXtender) developed by Texas A&M University (Jones et al. 2021; Gassman et al. 2009). Izaurralde et al. (2012) elaborated the development and application of EPIC in C-cycle, GHG mitigation. The EPIC model can simulate more than 100 crops, and it uses the Seligman and Keulen (1980) approach to calculate N transformations and dynamics. Afterward, soil organic carbon was calculated using a fixed fraction of soil organic N and C:N ratio of 10. This gives realistic picture of soil C dynamics and fluxes of C. However, EPIC performance to simulate long-term C dynamics was not up to mark as compared to other models, i.e., CENTURY, DNDC (DeNitrification DeComposition), ecosys, RothC, SOCRATES (Soil Organic Carbon Reserves And Transformations in agro-EcoSystems) used in

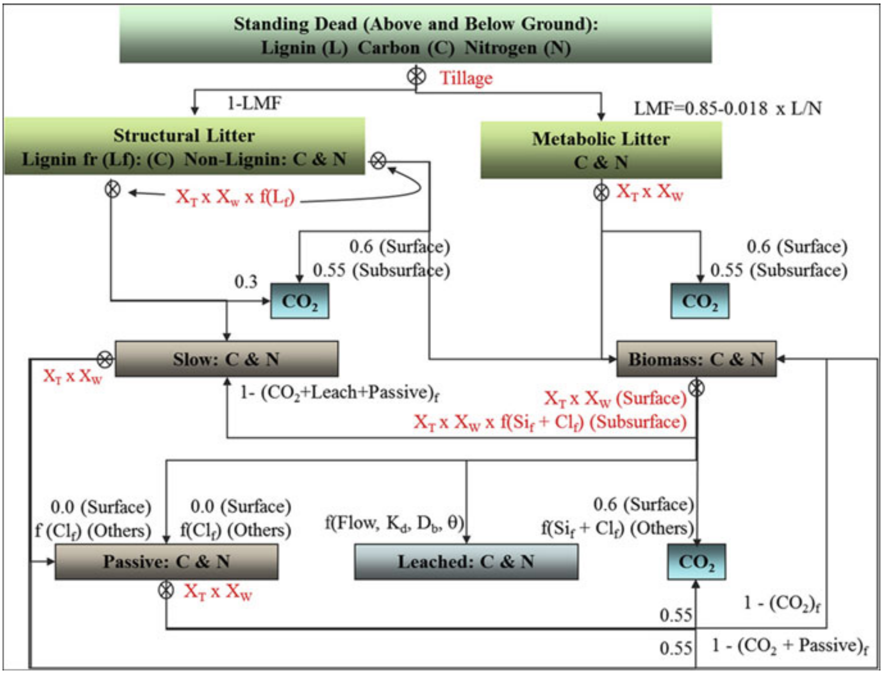

Fig. 3.16 EPIC soil C and N pools with their flows. (Source with permission: Jones et al. 2021)

the study conducted in Canada (Izaurralde et al. 2001). Hence, for improvement in EPIC, C-dynamics was needed, as elaborated by Jones et al. (2021). The C and N in SOM are distributed among the three pools as shown in Fig. 3.16 Furthermore, C balance in ecosystem prospective is given in Fig. 3.17, as EPIC generally gives C only in plant material, but with this modification, EPIC can describe C cycling at an ecosystem scale (Jones et al. 2021).

3.3.7 WOrld FOod Studies Crop Simulation Model (WOFOST)

WOFOST is a mechanistic, dynamic simulation model, which can simulate the production of annual crops (van Diepen et al. 1989; de Wit et al. 2019) in response to different managements and climate change. The WOFOST_Soil module includes soil water balance using tipping bucket and SWAP (soil-water-atmosphere-plant) approach. SWAP uses the Richards equation to simulate the flow of water and solutes among different layers (Kroes et al. 2009). WOFOST has also been connected through the BioMA framework to simulate soil water balance (Donatelli et al. 2010). WOFOST has the potential to be used in precision agriculture and smart farming.

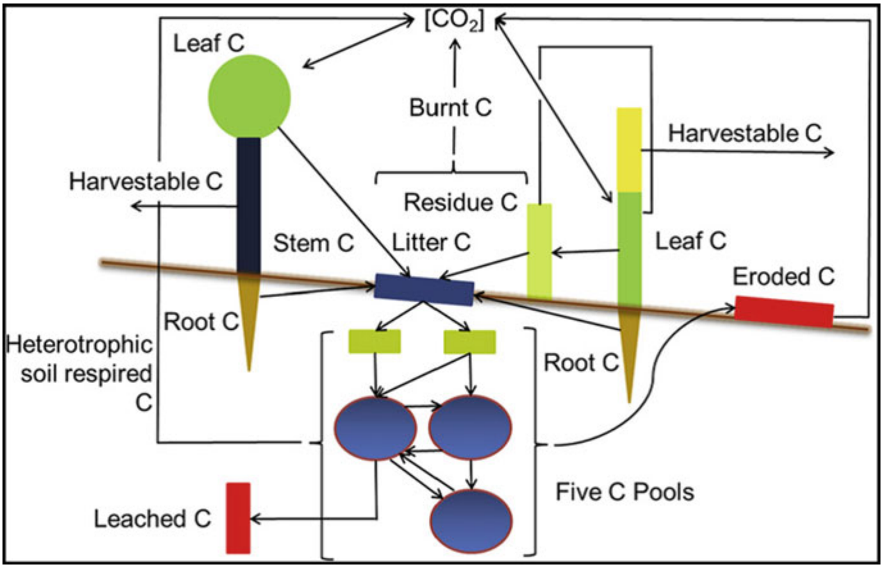

Fig. 3.17 EPIC ecosystem C balance. (Source with permission: Jones et al. 2021)

3.3.8 DNDC (DeNitrification DeComposition)

DNDC is a mathematical model that has been used in the study of management and climate change impacts on agriculture. DNDC has the potential to simulate dynamics (production, consumption, and transport) of nitrous oxide from different sources in agricultural systems (Gilhespy et al. 2014). Initially, DNDC (1–7) has three submodels, i.e., (i) denitrification (ii), decomposition (three soil organic carbon pools), and (iii) Soil_Climate_thermal hydraulic flux (Li et al. 1992). However, in DNDC_7.1, an additional empirical plant growth submodel was added; thus, it has four submodels. DNDC has so many further versions (e.g., PnET-N-DNDC, DNDC v. 8.0, Crop-DNDC, DNDC v. 8.2, Wetland-DNDC, UK-DNDC, DNDC v. 8.5, Forest-DNDC, NZ-DNDC, Forest-DNDC-Tropica, EFEM-DNDC, BE-DNDC, DNDC v. 9.0, DNDC-Europe, DNDC-Rice, and Mobile-DNDC), which was built to answer multiple questions of different scenarios. Smith et al. (2010) suggested improvement in the DNDCv9.3. estimation of soil evaporation. Manure-DNDC can quantify the manure life cycle on farms, and DNDCv.9.5 is the latest updated version, which can quantify hydrological features and GHGs estimation (Zhang and Niu 2016). Fluxes of GHGs among soil, plant, and atmosphere that elaborate DNDC mechanisms are shown in Fig. 3.18. Li et al. (2019) conducted a study to suggest improvement in the DNDC simulation of ammonia (NH_3) volatilization. They suggested major modifications in the source code. These include pedo-transfer functions in soil hydraulic parameters to simulate soil moisture, temperature effect on ammonium bicarbonate decomposition, and soil texture effect on NH_3 volatilization (Fig. 3.19).

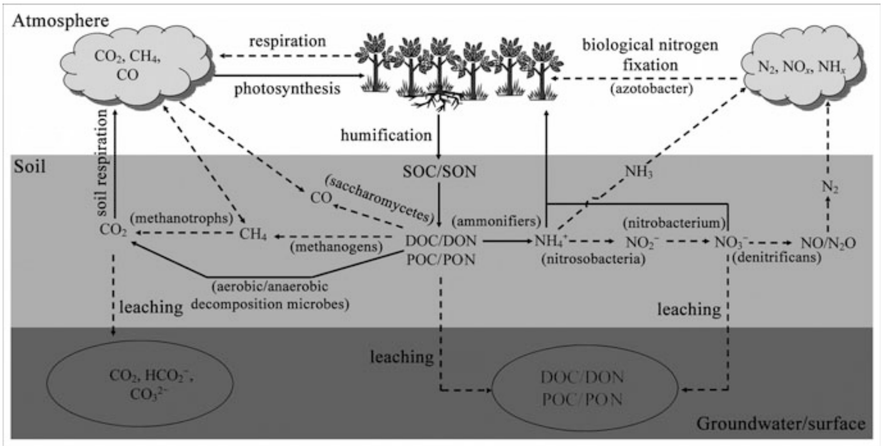

Fig. 3.18 Diagrammatic representation of DNDC showing carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) fluxes in forest/arable soil. (Source with permission: Zhang and Niu 2016)

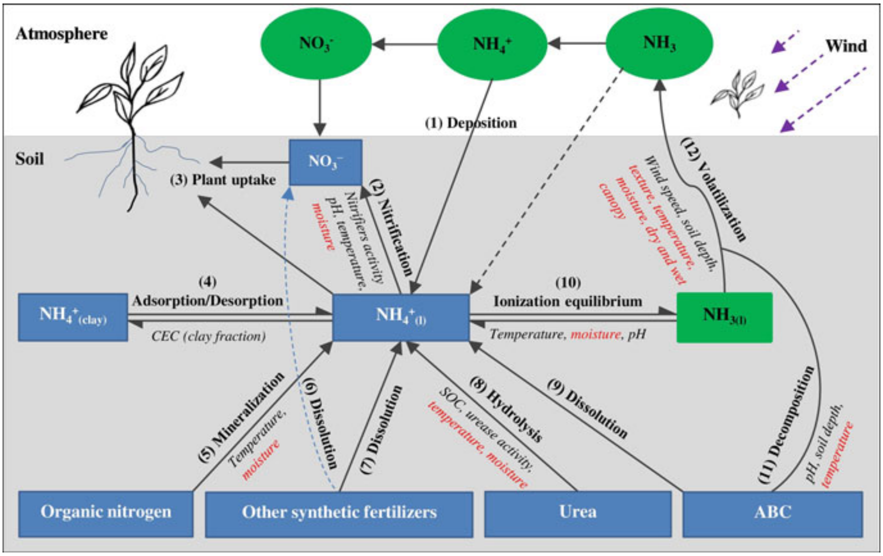

Fig. 3.19 Ammonia (NH_3) volatilization in DNDC. (Source with permission: Li et al. 2019)

3.4 Monitoring Soil Through Remote Sensing

Soil quality has been deteriorated due to intensive agriculture, and it poses big challenge to ensure food security. Traditional and modern soil quality assessment tools for data collection and processing can offer good opportunities to improve soil

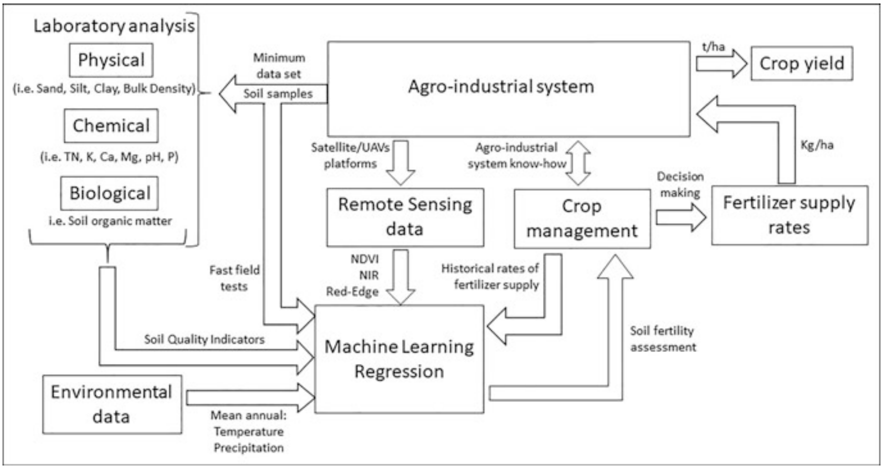

Fig. 3.20 Application of remote sensing and machine learning in soil quality assessments. (Source with permission: Diaz-Gonzalez et al. 2022)

health through different managements (Jung et al. 2021; Ge et al. 2011; Campbell et al. 2022; Bretreger et al. 2022; Angelopoulou et al. 2019). Artificial intelligence techniques provide useful information to farmers to decide treatments as per need. Generally, soil is assessed before the sowing of crop to select accurate management practices. But soil quality cannot be determined directly, and it can only be estimated by a wide range of quality indicators/indices. Traditional indicators to assess soil quality are (i) physical, (ii) chemical, and (iii) biological. Remote sensing is a powerful tool, which can be used to build different types of soil quality indicators based on soil nutrients and SOC contents (Fig. 3.20). However, to process data from remote sensing systems, different machine learning techniques are used. It includes supervised learning methods, i.e., random forest, support vector regression, artificial neural network, bagging decision tree, Bayesian models, boosted regression trees, cubist model, regression tree, regression kriging, random forest regression, partial least squares, k-nearest neighbor, generalized linear model, and deep learning (Diaz-Gonzalez et al. 2022; Harrington 2012; Loureiro et al. 2019; Bhatnagar and Gohain 2020).

3.5 Models Applications

Climate change is negatively affecting the crop productivity and food security due to its direct or indirect effect on different soil processes. Thus, adaptation options are needed to address the issue of climate change. The AquaCrop model was used by Alvar-Beltrán et al. (2021) to study the impact of climate change on the major crops (What and Sugarcane) of Pakistan, which is fifth in number due to the occurrence of extreme weather events. The study suggested that policy makers should act swiftly with solid adaptation options to cope with the changing environmental conditions in Pakistan. Bird et al. (2016) studied the relationship of future yield (2040–2070) variability with soil texture and climate models using AquaCrop to develop possible adaptation strategies. Results showed that yield was reduced by 64% on clay loams while it was increased by 8% on sandy loams and 26% on sandy clay loams soils. They suggested change in plant date and mulching as sustainable adaptation options to reduce crop losses. AquaCrop and DRAINMOD-S were used in a paddy field to simulate salt concentration. Both models were able to simulate soil salinity with good accuracy; thus, they can be used to manage salinity at field scale (Pourgholam-Amiji et al. 2021). Water and fertilizer management is important to get good crop yield and higher nitrogen use efficiency. Hence, Wu et al. (2022) developed a framework to simulate evapotranspiration under water and N stress in modified version of AquaCrop. The accurate performance of AquaCrop has shown that it can be used as a robust tool to develop precise managements for arid areas. Optimization of irrigation scheduling requires knowledge of crop and soil, which is possible through a decision support system. The AquaCrop and MOPECO models were used by Martínez-Romero et al. (2021) to optimize irrigation for barley crop. The results showed that both models were complementary to simulate gross irrigation water depths to attain the potential crop yield (e.g., 310 mm is required by barley to give potential yield). Rahimikhoob et al. (2021) applied AquaCrop a semiquantitative approach to simulate crop response to N stress using the critical N-concentration idea. Results depicted that direct simulation by using crop N status is a good option to improve soil fertility management. Biochar is a climate-friendly practice that can ensure food security by preventing water stress and fertilizer overuse. The AquaCrop model was used by Huang et al. (2022) to optimize the integrated strategies that involves irrigation, N, and biochar regimes. Results showed that AquaCrop simulated treatments impacts on crop yield with good accuracy. Hence, it can be used as a reliable tool for the optimization of field management, e.g., addition of fertilizer, biochar, and irrigation. Adeboye et al. (2019) evaluated AquaCrop to simulate soil water storage and water productivity of soybean. The model has shown low performance in simulating evapotranspiration and water productivity that needs to be fixed for dryland agriculture. AquaCrop-OSPy was proposed as an open source to be used to bridge the gap between research and practice (Kelly and Foster 2021). Groundnut is crop of dryland regions; hence, its simulation is tricky. Chibarabada et al. (2020) tested AquaCrop to simulate evapotranspiration, crop canopy cover, biomass, and yield under water stress conditions. Overall, the model shown good performance under water stress conditions, but it should be further tested under different soils and climates. Han et al. (2020) suggested that performance of crop models could be improved by upscaling the approach through remote sensing, as it can generate spatial distribution of crop parameters.

Soil organic carbon (SOC) is an important C pool, which can minimize atmospheric CO_2 concentration if managed properly. Wan et al. (2011) used the RothC model to study the impact of climate change on SOC stock. Results depicted that

SOC will decrease at higher rate in future if adaptation options, such as adding organic matter in soil through residues management and manure applications, will not be opted quickly. Furthermore, SOC could be increased by applying conservation agriculture practices, intercropping, cover cropping, and mixed farming. Lychuk et al. (2021) used the EPIC model to assess the losses of NO_3-N and labile P under changing climate, three levels of agricultural inputs (organic, reduced, and high), and three levels of cropping diversity (low, diversified annual crops, mixture of annual and perennial crops). Results showed that climate change resulted to the increase losses of NO_3-N, which can be mitigated by increasing cropping diversity as suggested in this work. LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator) was used by Ma et al. (2022) to assess the impacts of agricultural managements on soil C stocks, nitrogen loss, and crop production. Conservation agriculture practices, i.e., no tillage, cover crop, residue, and manure application, have shown positive effect on SOC, while loss of N was also minimum under these practices. A hydro-biogeochemical model (SWAT-DayCent) was used to investigate the effect of climate warming and root zone soil water contents on SOC. Three Representative Concentration Pathways (RCP2.6, 4.5, and 8.5) and five global climate models were used in this study. The results showed that SOC will decrease in future due to higher warming but higher soil water content could depress SOC losses (Zhao et al. 2021).

Climate change will negatively affect SOM dynamics, soil organisms, and soil properties, but warmer conditions could lead to the higher availability of soil N due to higher mineralization rate. Hence, soil management particularly N application will be governed by future climate change (Jat et al. 2018). SOC dynamics is the core of interlinked environmental problems. However, its management is a mystery due to its complex relationship with N availability, moisture, and temperature. Srivastava et al. (2017) reviewed soil C dynamics under changing climate and suggested that soil may act as a potential C sink if managed properly (e.g., management of soil inorganic N pools and its proper linkage with microbial processes). Climate change mitigation is the implementation of efforts to halt or reverse climate change through behavior, technological, and management strategies (Fig. 3.21). With practical on ground mitigation practices, soil can play a role to reduce CO_2 emissions. It can be a carbon sink instead of the source (Lal 2004; Paustian et al. 2016). On the other hand, the adaptation is to achieve higher resilience toward extreme climatic events. It is possible through different managements as shown in Figure 3.21, which can improve SOC. This higher SOC will help to retain more water and could produce crops even under drought. Sustainable development goals (SDGs), which are the blueprint to achieve a sustainable future for all, could be achieved through improving SOC. The benefit of improvement of SOC to achieve SDGs is elaborated in Fig. 3.22. Mitigation and adaptation both offer solutions to climate change, and they are directly and indirectly related to SDGs. However, they are not always complementary as sometimes they can be independent from each other. Balanced fertilization is the key adaptation strategy, which can sustain SOC on long term basis. Mohanty et al. (2020) simulated C-sequestration potential of balanced fertilization (N and farmyard manure) in soybean-wheat cropping system using the

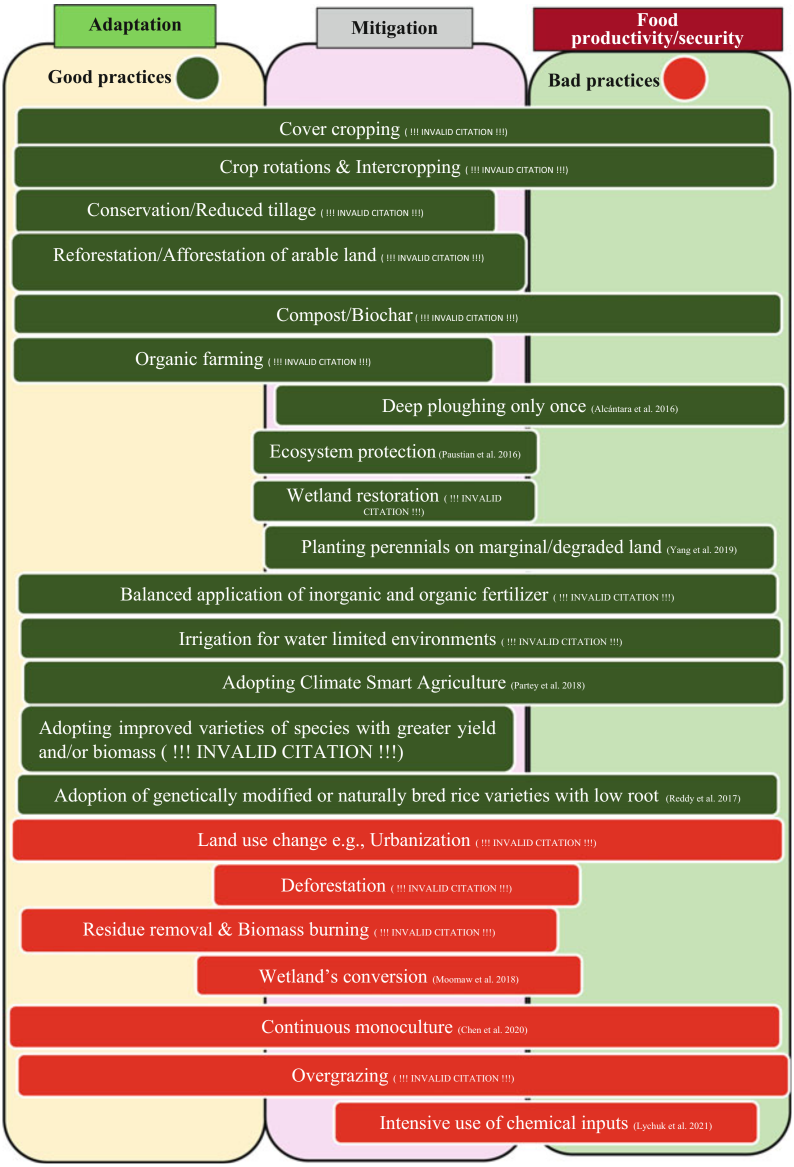

Fig. 3.21 Management strategies (Suggested and dissuaded) for the improvement of soil health and their impacts on climate change adaptation, mitigation, and food productivity/security

43-year long-term experimental dataset. The APSIM results showed that improved N and FYM management had the potential to increase SOC. Chaki et al. (2022) evaluated the APSIM potential to simulate conservation and conventional tillage practices in rice-wheat system. Results showed that the model was able to capture the

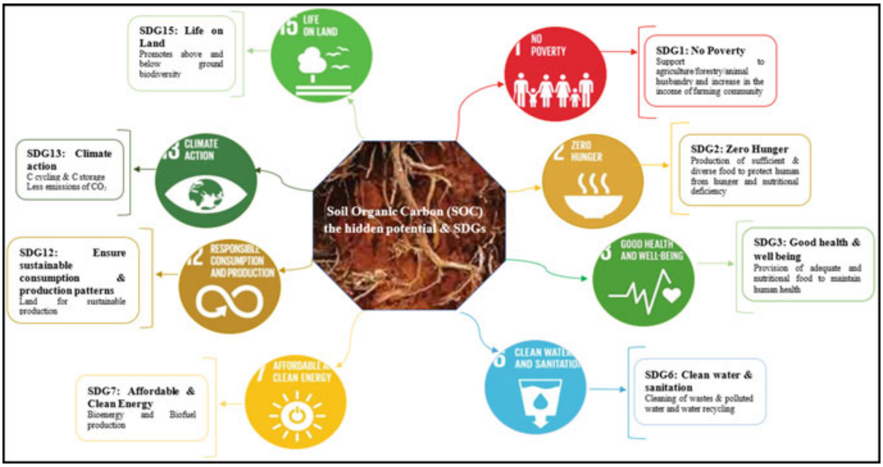

Fig. 3.22 Relationship between SOC and SDGs

effect of tillage, residue, N application, and cropping system; thus, it can be a good tool for designing the adaptation and mitigation options to climate change. Furthermore, the APSIM model was used evaluate the potential of conservation agriculture to mitigate climate change in water-scarce region Tunisia. Results depicted that mulching (residue retention) is more effective than conservation tillage under semi-arid and subhumid conditions. It can increase crop yield, WUE, and SOC as well as would help in the prevention of erosion (Bahri et al. 2019). Singh et al. (2022) compared the simulated potential of DRAINMOD-DSSAT and RZWQM2 to simulate the effects of management practices (N application rates and timings) on NO_3-N losses and crop yield. Results showed that both models provided the same conclusion for the N management strategy. Similarly, DSSAT was used as a valuable tool to suggest conservation agriculture as a potential way to adapt to climate change (Ngwira et al. 2014). Since process-based models are a good tool to design adaptation practices to climate change and, hence, to use them in real sense and to have true field picture, these models should be properly calibrated using different upscaling strategies (Chen et al. 2021).

3.6 Conclusion

Climate change is posing a major threat to food security through soil degradation. Since soil is the largest source of C, then it is necessary to conserve and improve SOM through its judicious use and management. Soil heath improvement will help to combat soil degradation, address food security, and mitigate climate change. Understanding and quantification of soil health through modern tools (e.g., remote sensing and modeling) are utmost important to design adaptation and mitigation strategies. Different adaptation and mitigation strategies are already available, which should be used to improve SOM. These includes reforestation, use of conservation tillage, intercropping, residue management, cover cropping, application of compost and biochar, balanced use of inorganic and organic fertilizer, and adoption of climate smart agriculture. However, these interventions need to be implemented properly through their dissemination to the real stakeholders, i.e., policy makers and farmers.

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Chapter 4
Soil Microbes and Climate-Smart Agriculture

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Abstract Climate-smart agriculture (CSA) includes approaches that help in reducing climatic extremities and agricultural greenhouse gas (GHG) responsible to global warming. CSA also focuses to balanced and reasonable transformations for agricultural practices. Soil is very diversified due to variations in physical and chemical properties, depending upon the quality and quantity of organic matter, redox potential, and pH status of soil, which also significantly impact the population, growth, and activity of microbes. The microorganism as an arbitrate ensures the sustainable farming by designing effective nutrient cycling strategies and pest control process and minimizing the negative impact of abiotic stress. Therefore, proper managing and development of beneficial microbes can help to achieve sustainable goals and reduce negative effects on the environment. The microbial biofertilizers, biopesticides, and plant growth-promoting rhizosphere bacteria (PGPR) will replace or at least supplement agrochemicals. Soil microbes also provide carbon sinks and help sequester carbon through various processes like the formation of recalcitrant vegetative tissues, bio-products, and different metabolic and biochemical mechanisms that capture CO_2 from the atmosphere; capacity of carbonate sedimentation; and formation of stable soil aggregates, which holds up carbon. Microbes contribute to carbon sequestration by the interactions between the amount of microbial biomass, microbial by-products, its community structure, and soil properties, like clay mineralogy, texture, pore-size distribution, and aggregate dynamics. Soil microbes play a role in climate change through decomposition of organic matter in soil. The diversity and population of soil microorganisms are indirectly influenced by changes in microclimate due to its effects on growth of plant and alignment of vegetation. Soil microbes endorse the sustainability of agriculture and effective operation of agroecosystem through precision agriculture under climate-smart agriculture.

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4.1 Introduction

Agriculture is the backbone of Pakistan economy like many other nations around globe. The world population is expecting to be more than 9 billion in 2050, and to feed this growing population, agricultural production system needs to be transformed based on sustainable land management technologies. The basic objective of this transformation would be to increase food production without depleting soil and water resources under changing climate scenarios (Branca et al. 2011). Sustainable agricultural practices lead to reduce gaseous emission and increased carbon sequestration necessary for mitigating climate change. Continuous vulnerabilities in climate, especially changes in temperature, wind, and precipitation pattern, is the cause of uncertainty, risk, and real threat to food security. The modern approach like climate-smart agriculture (CSA) can help to improve the sustainability in the production system by increasing resilience and resource use efficiency (Lipper et al. 2014). Soils are integral to the function of all terrestrial ecosystems and to food and fiber production. Soil microbes are main drivers of different ecosystem processes, and their population and functions determine the sustainable soil productivity, water resources, and gaseous emissions (Wagg et al. 2014). The change in climate, such as elevated atmospheric CO_2 concentration (eCO_2), temperature, and drought, adversely affects the soil microbial activities. The removal of nutrient-rich topsoil through dusty winds also threatens food security. Soil microbes are farmers' allies and can help in dealing the climate challenges faced by agriculture. Soil microbes play a role in fighting against this climate change challenge very effectively and can restore depleted or degraded soil. Soil microbes improve soil health, crop growth, water holding capacity, and carbon sequestration and allow for increased agricultural productivity on existing land. Soil microbes can help crops to tolerate elevated temperature and svere moisture shortage. Crops inoculated with soil microbes have a deeper root system helping to withstand drought and, consequently, accept more water effectively from drying soil. Soil microbes also minimize insect pest deleterious crop diseases and improve the overall crop growth and yield. Soil holds three times more carbon as exists in the atmosphere, and more carbon storage in the soils minimizes greenhouse gas concentrations between 50% and 80% (Paustian et al. 2016).

The terminology climate-smart agriculture (CSA) has established to portray an array of approaches that could facilitate these obstacles by enhancing toughness to climatic extremities, acclimatizing to varying climate, and reducing agricultural greenhouse gas (GHG) that causes global warming. CSA also focuses to augment balanced and reasonable transformations for agricultural practices and employments across balances, varying from small-hold owners to transnational alliances, making an essential fragment of the wider green development plan for agriculture (Braimoh 2013; Palombi and Sessa 2013). Soil is very diversified in the world due to variations in physical and chemical properties (Quesada et al. 2010). The chemical and physical properties of soil depend upon the quality and quantity of organic matter, redox potential, and pH status of soil, which also significantly impact the population, growth, and activity of microbes along with soil productivity (Lombard et al. 2011). Production of food, feed, fiber, and shelter depends upon the agricultural land (Toor and Adnan 2020). In many developing countries, agriculture offers self-employment and is vital for their economic development (Gindling and Newhouse 2014). To meet the need of food, feed, fiber, fuel, and raw material, burden on agricultural soils is increased in recent years due to the heavy increment in the human population. Although the synthetic fertilizers and pesticides are applied to increase the crop growth, they worsen the soil and environment and deteriorate soil organisms (Jacobsen and Hjelmsø 2014). Climate-smart agriculture (CSA) is an approach and addressed to mitigate the issues endeavoring to elevate agriculture production, increase adaptation, and facilitate GHG discharge drops. CSA focuses on emerging agricultural approaches not just to safeguard food security in varying climatic conditions but also to diminish GHG liberations and to ameliorate soil C sequestration (Lipper et al. 2014). Biochar (the C abundant solid produced via biomass pyrolysis) improvement in agriculture lands has been recommended as a tactic to subside climate modification by sequestering C and lessening GHG (specifically N_2O) whereas concurrently enhancing the crop productivity (Woolf et al. 2010; Jiang et al. 2020).

4.2 Soil Microbes and Sustainable Agriculture

Sustainable farming is known as a part of agriculture, which aims on the production of lasting crops and domestic animal despite causing the minimum effect on the environment. In the environment, this type of farming creates a suitable balance between food production demand and protection of ecosystem. The main standard, which ensures the sustainable farming, is the property of soil, in which the role of microorganism is very vital. The key achievements for maintaining sustainability are designing effective nutrient cycling strategies and pest control process and minimizing the negative impact of abiotic stress. Microbial services are acting as an arbitrate in such type of activities; therefore, proper managing and development of beneficial microbes can help to achieve sustainable goals and reduce negative effects on the environment. On the sustainable agriculture, the main impact of agriculture microbiology will be the replacement and addition of the fertilizers and pesticides (agrochemicals) with the microbial preparation. Some of the most common explanations for the use of microorganisms in sustainable farming are biofertilizers, biopesticides, and plant growth-promoting rhizosphere bacteria (PGPR) (Mohanty and Swain 2018).

Biofertilizers are the best tools for sustainable agriculture and considered as a gift from the latest agriculture. Moreover, biofertilizers, being used in agricultural sector, are more efficient and the best substitute to organic fertilizers and manures. Organic fertilizers consist of household wastes, compost, farmyard manure, and green manure, which can help to uphold the quality and sustainability of soil for longer period but not able to cover the instant requirements of crop. Meanwhile, manufactured chemical fertilizers influence the environment like burning of fossil fuels and emission of greenhouse gases (GHGs), which lead to the pollution of soil, air, and water. Furthermore, the constant use of chemical fertilizer for a longer period leads to nutrient imbalance in soil, which also impacts its sustainability. Microbes are also present in biofertilizers, which endorse the adequate availability of primary and secondary nutrients to their host plants and make sure to improve their physiological regulation and structural growth efficiently. In the production of biofertilizers, living microorganisms with specific functions are used to improve plant growth and reproduction. Biofertilizers are an essential element of organic agriculture and perform a key role to maintain the fertility and resilience of plants for long term. Specific microbes are identified and reproduced in vitro that have the ability to absorb nitrogen (N2) directly through the atmosphere, which can be applied in the rhizosphere to make nitrogen available to plants. Such plants or microorganisms containing such materials are knowns as biofertilizers. *Rhizobium*, *Azolla*, *Azospirillum*, *Azotobacter*, and blue-green algae are the frequently used biofertilizers in organic farming (Mohanty and Swain 2018).

Biological pesticides are made of organic components, like bacteria and plants, comprising of minerals that are commonly utilized to fight against disease-causing insects and pathogens. They are classified into microbial pesticides, crop protection agents, and biochemical pesticides. Biopesticides are made up of natural substances that fight with pests through harmless mechanisms. Microbial insecticides, such as *Bacillus thuringiensis*, release toxin A, which paralyzes the insect's midgut and prevents further food intake. Similarly, the spores of *Metarhizium anisopliae* and *Beauveria bassiana* enter the skin/cuticle of the host and releases lethal metabolites, known as destruxin and bovericin, respectively, that lead to insect death. Hence, biological pesticides are intrinsically low in toxicity, only target the relevant host pest, can easily be biodegraded, and have low exposure, because they are effective in lesser amounts. Moreover, they can solve the problem of environmental pollution (Mohanty and Swain 2018). Plant growth-promoting rhizosphere bacteria (PGPR) are found naturally in soil, which improve the productivity and immunity of plant; but these PGPRs are present in the rhizosphere, that is, a soil influenced by the roots of plant and their secretions and exudates. Because of their plant collaboration and interaction, these beneficial rhizobacteria are divided into mutually symbiotic rhizobacteria (living inside the host plant and directly exchanging nutrients and metabolites) and nonsymbiotic bacteria that live freely outside the plant roots (Gray and Smith 2005). In addition, some genera of symbiotic bacteria can physiologically incorporate with plants to make specific root structures. Depending on their working principle, beneficial bacteria are categorized as a biofertilizer, biopesticide, and plant stimulant, and certain bacteria have an overlapping application such as the adhesion of the ACC (1-aminocyclopropane 1-carboxylate) deaminase gene and the availability of phytohormones such as IAA (indoleacetic acid), siderophores on the side, intertorkinin, gibberellin, etc. In this way, they can improve the yield and growth of the plant as well as the availability and uptake of nutrients from the several types of crop plants in diverse agroecosystems. Due to multiple uses of growth-promoting bacteria, they become a pivotal part for managing sustainable agricultural systems (Mohanty and Swain 2018).

4.3 Soil Microbes and Carbon Sequestration

In broad terms, carbon sequestration is defined as the elimination, removal, or sequestration carbon dioxide from the atmosphere to moderate or reverse atmospheric CO_2 contamination and to mitigate or reverse climate change. Carbon dioxide (CO_2) is naturally captured from the atmosphere through physical, chemical, and biological processes. While in the agriculture sector, carbon sequestration is defined as the capability of forests and agriculture lands to minimize CO_2 concentration from atmosphere. The removal of CO_2 from the environment is done by its absorbance by means of photosynthesis by crops, plants, and trees and deposition of carbon in foliage, branches, roots, tree trunks, and soil (Schahczenski and Hill 2009).

In general, there are a number of technologies for sequestering carbon from the atmosphere. The main three categories are (i) ocean sequestration, (ii) geologic sequestration, and (iii) terrestrial sequestration. The world's oceans are the primary long-term sink for CO_2 emissions by the anthropogenic activities. Naturally, oceans absorb 2 giga tons of carbon annually through the chemical reactions between seawater and CO_2 in the atmosphere. As a result of these reactions, oceans become more acidic. Numerous marine bodies and ecosystems depend on the formation of sediments and carbonate skeletons, which are vulnerable to dissolution in acidic H_2O. Near the surface, most of the carbon is fixed by photosynthesis of phytoplankton, which are then eaten by sea animals (Sundquist et al. 2008). In geological sequestration, CO_2 is captured from the exhaust of fossil fuel power plants and other major sources, and then, it is supplied through pipes from 1–4 km beneath the Earth's crust layer and incorporated into the formations of porous rock. This type of sequestration is currently utilized for stocking a very lesser amounts of C per year. Many sequestrations are visualized to take advantage of the durability and capacity of geologic storage. Terrestrial sequestration/bio-sequestration is conducted by means of conserving techniques to sequester C in soil and forest that also intensify and enhance its storage (like establishing and restoring forests, wetlands, and grasslands) or reduce CO_2 emissions (like suppressing wildfires and reducing agricultural tillage). These practices are used to meet a variety of land management objectives. Carbon is released in the form of carbon dioxide into the atmosphere by different anthropogenic activities, like the burning of fossil fuels that releases carbon from its long-term geologic storage (such as coal, petroleum, and natural gas). Naturally, CO_2 is emitted through the respiration of living organisms and decomposition of plants and animals. Since the beginning of the industrial era, the amount of carbon dioxide in the atmosphere has increased due to the extensive burning of fossil fuels. CO_2, being a high potential greenhouse gas (GHG), has led to increase the normal temperature of Earth's atmosphere (Klafehn 2019). Carbon sinks are the reservoirs that store carbon and keep it from entering the Earth's atmosphere. For example, afforestation helps in sequestration and capturing of carbon from the atmosphere while C is released into atmosphere through deforestation. Naturally, carbon dioxide present in the atmosphere is sequestered through photosynthesis to the carbon sinks on Earth like plant biomass above soil or inside soils. Other than the plant's natural growth, some terrestrial mechanisms, like cropland management practices, also take part in the atmospheric carbon sequestration. It should be kept in mind that, depending upon the land use, the sequestered carbon in the above-ground vegetation and in soils can be emitted again into the atmosphere.

Microbes also provide carbon sinks and help sequester carbon through various processes like formation of recalcitrant vegetative tissues and bio-products, different metabolic and biochemical mechanisms that capture CO_2 from the atmosphere, capacity of carbonates sedimentation, and formation of stable soil aggregates, which holds up carbon. Microbes contribute to carbon sequestration by the interactions between the amount of microbial biomass, microbial by-products, its community structure, and soil properties, like clay mineralogy, texture, pore-size distribution, and aggregate dynamics. Accumulation of derived organic matter by microbes depends on the balance between decomposition and production of microbial products in the soil. Microbial growth efficiency (the efficiency with which substrates are incorporated into microbial biomass and by-products) is dependent on the (i) degree of protection of microbial biomass in soil structure and (ii) rate of decomposition of by-products by other microorganisms (Six et al. 2006). Microbes adopted different strategies for carbon sequestration like fungal and bacterial dominance (Strickland and Rousk 2010), mycorrhizal association for carbon sequestration (Wright and Upadhyaya 1998), microalgae for CO_2 capture (Buragohain 2019), etc. The bacterial and fungal soils are linked with carbon sequestration potential. If there is a greater number of fungi, then there is a greater C storage (Strickland and Rousk 2010). In the soil, where the microbial community is composed of fungi, the production of microbial biomass and by-products will be larger, because they have higher growth efficiency rates than other microbes like bacteria. Therefore, these communities will retain more carbon in biomass per unit substrate consumed and release less as carbon dioxide. Degradation of microbial-derived organic matter is slower in soils having greater proportion of fungi, as fungal products are chemically resistant to decompose, because of their interactions with clay minerals and soil aggregates (Simpson et al. 2004). The total carbon assimilation increases significantly by mycorrhizal-plant symbiosis. In this association, arbuscular mycorrhiza fungi capture carbon in soil and translocate photosynthetic metabolites present inside the associative plants to the intra-radical of arbuscular mycorrhiza fungi and succeeding extra-radical hyphae, which are then released to the soil medium (Leake et al. 2004). This mycorrhizal association could drain 4–20% of C present in the symbiotic plant to their hyphae and indirectly impact soil carbon sequestration (Graham 2000). The increasing growth and development of fungal extra-radical hyphae within the rhizospheric soil directly enhances the soil carbon sequestration. Soil carbon sequestration by arbuscular mycorrhiza relies upon the turnover time of accumulated biomass of fungal hyphae, the volume of hyphal biomass produced, and the role of fungi to stabilize the formation of soil aggregates (Zhu and Miller 2003). Hyphae produce glomalin protein, which increases the stability of aggregates; this increase in stability leads to larger amounts of protected organic carbon and thereby larger carbon sequestration (Wright and Upadhyaya 1998). Carbon dioxide fixation through microalgae is a favorable and potential technique to sequester CO_2 (Zhao and Su 2014). Microalgae fix and store carbon dioxide through photosynthesis in carbon dioxide and water are transformed into organic assimilates without consuming additional energy having no secondary pollutants. Comparing with the other C capturing and storing methods, fixation of carbon dioxide through microalgae has many benefits, like a rapid growth rate, a high photosynthesis rate (Suali and Sarbatly 2012), efficient adaptability to the environment, and less operational cost. The rate of carbon dioxide fixation through biomass and microalgae production is dependent upon the species of microalgae, soil environment (e.g., pH, light, temperature, and availability and amount of nutrients), and concentration of CO_2. In short, microbes contribute to ecosystem carbon budgets through their roles as pathogens, plant symbionts, or detritivores, thereby influencing the C turnover and modifying the nutrient availability and retention in soil. On decomposition of biomass, carbon losses from the soil due to microbial respiration, while a small proportion of the carbon is retained in the soil by the formation of stable organic matter. Carbon sequestration occurs when SOC levels increase over time as carbon inputs from photosynthesis exceed C losses through soil respiration. Terrestrial ecosystems can be manipulated through land management practices and land use for the development of distinct microbial communities that enhance C sequestration.

4.4 Agricultural Practices and Carbon Sequestration

Vegetative and root systems of grass species and forest trees can store a huge amount of carbon for an extended period; therefore, they are known as sinks for carbon. Agricultural lands can also hold an accountable amount of sequestered carbon; however, their ability to store or sequester carbon depends on climatic conditions, soil and crop or vegetation types, as well as management systems of the cropping land. The total carbon stored in the soil is also affected by the addition of dead plant and animal materials, respiration, and decomposition losses of carbon. However, the carbon losses could be reserved through farming practices through minimal soil disturbance and encouraging carbon sequestration. Overall, there are two distinct trends of the effect of nitrogen fertilization on soil organic carbon fertilizer. On the one hand, nitrogen fertilizer stimulates primary production, resulting in increased above- and below-ground biomass, which can enrich SOC reserves (Chaudhary et al. 2017). Nitrogen fertilization, on the other hand, can promote litter and soil organic matter's biodegradation (Recous et al. 1995). This results in the reduction of SOC stocks (Ladha et al. 2011). Thus, a sufficient supply may be critical for soil carbon sequestration (Van Groenigen et al. 2017). By affecting arbuscular mycorrhizal fungi, phosphorus fertilizers can influence soil carbon sequestration. In contrast to simple nitrogen fertilizers, NPK application inhibits arbuscular mycorrhizal fungi colonization, therefore limiting fungal-mediated nutrient plant absorption, which has a detrimental impact on soil carbon sequestration (Joner 2000; Liu et al. 2020).

Organic additives have numerous effects on SOC pool. Organic fertilization stimulates net primary production, allowing atmospheric carbon to be fixed through photosynthesis (Jacobs et al. 2020; Mathew et al. 2020; Sykes et al. 2020). Source of SOC provide an additional organic alterations for the prevailing pool (Maillard and Angers 2014), and organic fertilization may stimulate SOC biodegradation in the same way that mineral fertilization does (Chenu et al. 2019). When organic fertilizers are used, the outcome is predominantly translation with higher organic carbon intensities at certain sites and lower concentrations at contributing sites (Wiesmeier et al. 2020). Overall, the alternative uses of organic materials are critical, and net appropriation will happen when manures and organic fertilizers are made for a specific farmland field and when C in contemporary fertilizer will then be distributed into the atmosphere (Sykes et al. 2020). Integrating crop wastes into agronomic soils modifies soil structure, decreases bulk density, shrinks erosion, diminishes evaporation, and magnifies the infiltration ratio in soils and in supplement to cumulative SOC stocks (Bronick and Lal 2005; Lehtinen et al. 2014; Spiegel et al. 2018; Trajanov et al. 2019). Straw and hay are exploited for animal suckling or the production of thermal energy in agricultural organization systems. SOC stocks were amended by using deposits (Lehtinen et al. 2014). The carbon impounding influences a fresh equipoise, that is a constant soil organic carbon (SOC) reservoirs in top layer of soil a span after straw is unified (Wang et al. 2018). Numerous crop species and crop alternation are an important module of the natural C cycle, since plants absorb over 10% of atmospheric C production's complete photosynthesis (Raich and Potter 1995). Carbon is consumed via plants, which may be united as biomass, satisfied like root exudes or exhaled back into the atmosphere as CO_2 (Ostle et al. 2003). Maize integrates the atmospheric C more competently than C3 crops like barley, due to its C4 photosynthetic pathway and higher leaf area (Wang et al. 2012). SOC storing is prejudiced by the vegetative cover of agricultural soils and how it is accomplished. Plant biomass delivers the mainstream of organic matter contribution in the topsoil, which reductions as soil depth upsurges (Kaiser and Kalbitz 2012). Varied agricultural spins with several primary crops, cover crops, perennial crops, and forages provide suggestively greater soil organic stocks (SOC) than single cropping systems of monoculture with cereals or maize (Jarecki and Lal 2003; Poeplau and Don 2015). Crop rotational assortment, organic fertilizer/alteration use, and/or perennial farming patterns, all of these can be possible to accrue higher soil organic carbon (SOC) than traditional mono-cropping systems (Don et al. 2018; Minasny et al. 2017).

Root exudations (e.g., organic acids, amino acids, and sugars) from deep delving species and cultivars of crop can transport C into the soil subsurface, where there is a high carbon impounding potential (Sokol et al. 2019), particularly if organic compounds are endangered in organo-mineral aggregates (Paustian et al. 2016). Sunflower (*Helianthus annuus*), alfalfa (*Medicago sativa*), or perennial crops like grass clover, grass, legume, and alfalfa grass amalgamations have deep rooting systems. After the primary crops (e.g., cereals) have been harvested, catch crops are grown or they are undersown in/with the main crops. This consequences in a perpetual vegetative cover on arable land as well as a supplementary period of carbon fascination (Chahal et al. 2020). Traditional tillage practices like plowing eliminate soil aggregates from topsoil, revealing previously endangered SOM to microbial deprivation (Dignac et al. 2017). It also stimulates soil erosion and in lowering SOC stages (De Clercq et al. 2015; Six et al. 2000; Veloso et al. 2019). SOC satisfied in the topsoil (0–10 cm) was originated to be higher in fields refined with no- or reduced-tillage performs than in fields refined with conservative tillage, such as moldboard plowing (Beniston et al. 2015; Francaviglia et al. 2019; Mazzoncini et al. 2016). However, no consequence of tillage practices on SOC accretion was seen as soil depth (>10 cm) increased (Mazzoncini et al. 2016). Soil erosion was allied to the SOC sufferers caused by tillage (Beniston et al. 2015). Besides, lowering mechanical instabilities improves soil health by increasing combined constancy, which decreases erosion (Abid and Lal 2009; Mikha and Rice 2004). By evaluating the complete soil profile (from 0 cm to 60 cm), the impacts of minimal and no-tillage practices on C sequestration are imperfect and inconsequential (Haddaway et al. 2017; Luo et al. 2010; Minasny et al. 2017; Powlson et al. 2014; Sanderman et al. 2009; Spiegel 2012). Biochar is completed by a thermal process of burning organic materials (animal or plant-based) at high temperatures prodigious 350 °C and with a low oxygen source called pyrolysis (Meena et al. 2020). Biochar delivers a long-term carbon sink in soils due to its strong resistance. Biochar treatment is said to boost SOC stocks in agricultural areas (Liu et al. 2016a, b; Maestrini et al. 2015) by cumulative primary output, (Lorenz and Lal 2014) rebellious fractions of SOC, and subsurface SOC pools (Lorenz and Lal 2014; Mao et al. 2012; Rumpel and Kögel-Knabner 2011; Solomon et al. 2012). Moreover, it also can advance soil water retaining, collective stability, soil erosion discount, and soil biota action (Liang et al. 2014; Palansooriya et al. 2019; Schmidt et al. 2014). Agroforestry is the combination of woody perennials like shrubs and trees with grasslands or an agricultural crop. Agroforestry, in all-purpose, assists various roles at the same time, comprising environmental (like better soil fertility and maximized SOC pools) and socioeconomic aids (e.g., increased crop efficiency and to deliver fodder, crops, or timber) (Shi et al. 2018; Sun et al. 2018; Wiesmeier et al. 2020). Deforestation is the loss of forest land for other purposes, such as agricultural crops, growth, or mining processes around the world. Deforestation has impaired the natural ecosystems, the biodiversity, and the climate and has been amplified by human activity since 1960 (Allen and Barnes 1985). Substantial amounts of carbon are stored in forests. As trees and other plants grow, they take carbon dioxide from the atmosphere. This is altered to carbon, which the plant stores in its leaves, trunks, branches, roots, and soil (Gorte and Sheikh 2010). When forests are expurgated or scorched, the carbon that has been deposited is released into the atmosphere, mostly as carbon dioxide. Because trees absorb and store CO_2 throughout their life, deforestation has an important impact on climate change. According to the World Wildlife Fund, tropical forests store more than 210 gigatons of carbon. What's more regarding is that the exclusion of these trees has two major negative consequences (Shukla et al. 1990). To begin with, chopping down trees results in CO_2 emissions into the atmosphere. Additionally, with a smaller number of trees, the general aptitude of planet to capture and sequester CO_2 is abridged. These both processes aggravate the greenhouse gas emission, which contribute to global warming and climate change (Moutinho and Schwartzman 2005).

4.5 Climate Change and Soil Health Indicators

Soil quality consists of active and inherent constituents. Inherent soil qualities, e.g., types of clay, depth to bedrock, and consistency, are difficult to change and take over thousands of years to form as a result of climate changes, such as topography, time, biota, and parent material (Wienhold and Awada 2013). On the other side, dynamic properties of soil quality are established due to human activities and human management practices and can be changed over a brief period. Soil quality comprises physical, chemical, and biological features required to nurture agricultural sustainability and environmental health (Cardoso et al. 2013). Soil is more complex than air and water because it is module part of solid, liquid, and gaseous phases and used in substantial number of variety of determinations assessed for natural ecosystems and efficiency having major focus is on the management biodiversity and environmental quality includes human activities, cultural and geographic heritance. Reaction of soil in comeback to the management practices is slow; thus, it is complex to understand the changes caused in the soil before nonreversible changes. The most significant part for evaluating soil health is the credit of diplomatic soil features that proves the job of soil to work and can be measured as the indicator of soil quality (Nortcliff 2002). The chemical indicators for soil quality evaluation are pH, available phosphorous, and available potassium. The physical indicators include aggregate stability and available water capacity. Biological indicators are represented by organic matter content and active carbon content. Indicators can be restrained from the composite sample of patent sites (Rashidi et al. 2010).

In recent views, soil health assessment is progressively integrated with land evaluation, because its policies are using multiple aspects and for a variety of designs involving sustainable land management. Common management are dependent on long lived land potential conditional on climate, topography and inherent soil properties and can be altered with respect to weather conditions and dynamic soil properties (Herrick et al. 2016). There are three soil indicators, and these are (i) soil physical indicators, (ii) soil chemical indicators, and (iii) soil biological indicators. Physical soil indicators include aggregate stability, porosity, bulk density and texture, and matchup with hydrological processes counting erosion, aeration, runoff, infiltration rate, and water holding capacity. Physical indicators of soil health overall comprise easy, quick, and low budget methods. A soil is reviewed poor in physical aspects when appears having low rates of root density, low aeration, water infiltration, difficulty of mechanization, enhanced surface runoff, and poor cohesion

(Dexter 2004). Soil particles with a size of less than 0.2 micron meter are assembled to make aggregates of 20–250 micron meter that are considered as microaggregates, and when these microaggregates cling together, they form macroaggregates. A substantial portion of soil organic matter is composed of carbohydrates that contribute up to 5–25% and is responsible for the stabilization of soil aggregates. Microaggregates have a low organic matter content and are very less disturbed by the microorganisms and more Fe and Al content responsible for the encouragement of microaggregation and, due to micro mass quality, are less disturbed by management practices (Cardoso et al. 2013) Plus, soil organic carbon in microaggregates is less responsive to changes (Zhou et al. 2020) than macro aggregates, which are more vulnerable to management practices and land use and specifically linked to the of the soil organic matter variations. Microbial activity in soil is understood indication toward more organic matter content also dispersion of soil aggregates following land use management practices is low intensive in soils. However, as the organic matter decreased, the accompanying aggregate dispersion lowers soil oxygenation and macroporosity and reduces the interpretation of microbiota causing decomposition and approach to the organic material. Air and water exist in the macro- and micropores of soil particles (Easton and Bock 2016), and soil texture plays a vital role in balancing between water and gases, which become substantial with time and management practices. However, the total porosity and bulk density can demonstrate the consequences of land management and usage on air and water relationships in a better way. Low bulk density of the soil particles are thought to be responsible for boosting up the structure of soil under low anthropogenic assumptions like local forests (Bini et al. 2013). The good amount of the SOM (soil organic matter) is also allowed to play a key role in boosting up the soil structure. In return, it improves soil macroporosity for plant roots, air, and water. The total soil porosity have relationship with texture (proportion of soil particles), and structure (biopores and macrostructure). The structure can easily get damaged by maximum use of land and plowing techniques, due to which distinctive soil water retention curve based on structural pores may change. Cropping methods and intensive management practice alert the structure, which is described as the arrangement of main soil particles (sand, silt, and clay) (Dexter 2004). Organic matter in soil imposes beneficial impact on soil structure in contrast to physical properties, including water infiltration, water retention, bulk density, porosity, and aeration; these are less responsive toward organic matter content. Soil aggregates regulate nutrient cycling, controls aeration and permeability, and acts as a home for soil microbes; as a result, the soil microbes, including microorganisms (bacteria, fungi, and virus), plants, and fauna, affect the soil aggregates. Organic matter (OM) and biological phase are the basic source of water and nutrient supply in soil; as a result, these factors allocate the physical structure of soil and hydrological processes (i.e., erosion, drainage, runoff, and infiltration). As a result, losses of soil function such as synthesis and mineralization of the soil organic matter, as well as consequences on biochemical cycles, may result from the reduction of the soil microbial activity owing to water limits (Bini et al. 2013). Different soil microbes act different on the restriction of water in soil. In the dry soil, water film is more strongly connected with the soil particles due to the restricted movement of bacteria, but, on the other side, in the dry soil, hyphae of fungi can travel in soil pores, which are filled with the air. Availability of the water depends on biological, chemical, and physical characteristics, but these characteristics are influenced by organic matter.

Chemical indicators of soil strength are coordinated with measurement of supplying the nutrients to plants and keeping of chemical elements that cause damages to the ecosystem. The chemical indicators pertaining toward soil strength evaluations are soil CEC, soil OM, soil pH, and nutrients availability (Kelly et al. 2009). Electrical conductivity (EC) and available nutrients in turn favor good crop production, nutrients availability, and microbial activity. Electrical conductivity is defined as the measurement of salt concentration; one of the chemical indicators for measuring soil health can easily be measured due to its very delicate and one-step conductivity measuring instrument. While soil pH is used to detect impact on soil by land use and plowing techniques and eventually climate change will impact on nutrient cycling, organic matter content, carbon cycling, water availability and plant productivity. Although a high amount of OM content also shows adverse impact on the health of soil by reducing the efficiency of pesticides. Electrical conductivity (EC) lets us know the current scenario in biological activity, crop performance, nutrient cycling, and salinity/sodicity in the soil (Arnold et al. 2005). CEC and sorption abilities of soil are important regarding assessment of soil chemical quality the retention of major nutrient cations calcium, magnesium, potassium, and immobilization of potentially toxic cations aluminum, and manganese. These characteristics reveal important signs of soil health, such as the soil ability to absorb nutrients and the presence of pesticides and pollutants (Ross et al. 2008). Due to the hot temperature, decomposition and loss of the soil organic matter will be increased, as a result, the CEC loss of coarse textured/sandy and clay soils with low biological activity, which results in low cation exchange capacity, and soils with low CEC causes poor holding of nutrients and leads to the leaching of nutrients in high rainfall and heavy irrigation applying areas. Nitrogen cycling closely associated with soil organic carbon cycling, consequently operators of change in climate, e.g., hot temperatures, irregular precipitation, and decomposition of atmospheric N cause effect on N cycling and changes the cycling of other plant-available nutrients like phosphorus and sulfur, from direction and exact magnitude of change in plant-available nutrients must be examined in detail. Heavy metals are collected in the soil through chemical and metallurgical industries (Pantelica et al. 2008), and that type of soil will eventually affect plant growth and human health, including adverse effect on soil ecology and agricultural existence of heavy metals in production quality and ground water quality. Concentrations of free metal ions in soil solution are significant to govern because these impact on bio availability to plants which in outcome are achieved by the metal ion speciation in the soil. The free metal ion concentration depends on the total metal content and metal species present in the soil. Irrigation with wastewater increases the amount of heavy metal adulteration in soil, and as there are large amount of heavy metal contaminants in the soil, plants will uptake more heavy metals, depending on the soil types. Other sources of heavy metal gathering are industrial production, mining, transportation, chemical industries, iron, steel industries, agriculture, and domestic activities responsible for the addition of excessive amounts of heavy metals into the water, including both surface and ground water; soils; and the atmosphere. Heavy metal growth in plants is of considerable responsibility because of the chances of food pollution through the soil-root interface. Some heavy metals, like Ni, Cd, and Pb, are not important for plant growth, and they are taken up and accumulated by plants in toxic forms. Soil chemical indicators are directly correlated with the crop production and soil health for higher plants production and sustainability and are quickly interpreted and improved by using fertilizers (Bini et al. 2013). The soil organic carbon is the basic chemical gauge for soil health and yield, as it affects the major functional operations in the soil like the storage of nutrients nitrogen, water holding capacity, stability of aggregates, and microbial activity. The applications of organic alterations in the soil are helpful even in the chemical maintenance of mine soil and the impact of microbial populations present in the adjustments on soil native microbial communities. Sheep and paper supplements are effective at raising the soil pH and decreasing the metal bioavailability and phytotoxicity, whereas poultry and cow dung resulted in greater soil microbial property values, including respiration and functional diversity. Beneficial effects reported under poultry at the start of the research because of the existence of easily degradable organic matter (microbial and chemical) and phytotoxicity to definitively diagnose bottlenecks during amendment selection for chemical stabilization in combination with low metal bioavailability and improved soil health (Galende et al. 2014). N is a required essential in the soil so that plants can accept to fulfill their required needs and is available in different chemical forms like mineral N (especially nitrate) and organic N stored in the soil organic matter. The use of nitrogen for the soil health indicating parameter put through the factors including climatic conditions, turning insufficient the analysis of the real availability for plants, based on soil chemical analysis. After N, phosphorus (P) is also a chief nutrient for crop growth and is essential in defining soil quality that limits the agricultural yields in tropical soils, particularly in highly weathered, oxidic soils, where the main part of the total soil P is fixed in clay minerals and oxides. The available P in the soil solution is found as orthophosphates, but the microbial P and organic P are also stocks that can rapidly become available (Bini et al. 2013).

Soil health pointers concerning biological indicators all needs sufficiently of soil bacteria, fungi and actinomycetes, earthworms, nematodes, protozoa, soil biomass carbon and N and biomass nitrogen. Soil biological indicators call attention to some actions and performances of microorganisms in the soil (Russo et al. 2012). Favorable activities of microorganisms present in the soil include the following: plant nutrients are unconfined from inexplicable inorganic substances; organic residues are decomposed and nutrients are released; beneficial soil humus is composed by breaking down residues that are organic in nature and application of fresh compounds; compounds that increase plant growth are produced; and nutrition of plant is enhanced symbiotically, which leads to the convert nitrogen from atmosphere into the form available to plants. Increasing surface area of roots for absorption of phosphorous; improving soil accumulation by the obligatory agent's production like glomalin and polysaccharides from mycorrhizal fungi and bacteria, respectively;

refining aeration of soil and infiltration of water; having toxic effect against pests and insects and against pathogens of plants weeds; and supporting degradation of pesticides and bioremediation. Soil organic matter indicators turned out to be used in long-time soil conduct experiment for the evaluation of change in climate; however, the reaction of soil organic matter toward elevated temperature is scientifically debatable. It is understood that the increasing temperature improves the decomposition rate of OM, increases the productivity of plant and supply of soil organic matter, as well as improves warmth and precipitation. Carbon dioxide fertilization and deposition of atmospheric nitrogen may promote productivity of plant and supply of organic matter to soil and hence enrich the soil organic matter. According to Kuzyakov and Gavrichkova (2010), the reason for soil organic matter loss is the availability of SOM to microorganisms, despite the rate modification in climate influence like temperature. The microbial biomass of soil is produced by the living portion of the SOM made by the living organisms, including bacteria, algae, fungi, and protozoa, which are the vital source of micronutrients and can be certainly cycled to fulfill the plants' demand. Soil microbial variety performs essential purposes in the sustainability for soil health, considering nutrient and carbon cycles. Microbial indicators are more responsive toward adjustments imposed to the land use and management (Masto et al. 2009). Not only microbial biomass but also soil exhalation has been used on a large scale in agricultural soils as bioindicator of soil health. Modifications in vegetation, including deforestation, reduces the microbial respiration for a long time, because of the low level of organic carbon inputs into the soil through land outer layer or rhizosphere. The less influencing management methods causes higher microbial activity (Babujia et al. 2010). The OM regulates the activity of microorganisms for the source of carbon, nutrients, and energy, which lead to the availability of CO_2 and mineralization, and the rate of mineralization relies on the quantity and quality of SOM. Balance between demands of farmer and needs of community can be fulfilled by healthy soils. Due to the deterioration in soil qualities, soil health is comprised of the complex network functioning as biological, chemical, and physical indicators. Soil organic matter supports to stimulate the soil health, maintain inactivate compounds that are toxic, and destroy pathogens and its implicit interactions between the internal and external soil elements to sustain agriculture. The soil has an ample variety of microbes. Concerning the global expertise of soil microbial dynamics, its function is enhancing rapidly, and the knowledge of rhizosphere complex is constrained to a limit, excluding its value in regulation soil plant systems (Sahu et al. 2017). Soil enzymes including dehydrogenase, urease, protease, phosphatase, and β-glycosidase (Mohammadi 2011) and enzymatic activity work as an indicator to variations occur in the soil plant system as it is nearly mention to the nutrients cycling and biology of soil, can be measured, combine information on the physicochemical status of soil and microbial level and show quick reaction to changes in management of soil (García-Ruiz et al. 2009). By modifying the quality and quantity of underground C input by plants, microbial enzyme activities may be stimulated by elevated CO_2, C change, and plenty of microbial enzymes affecting the function of microbial community in soil on a level. Plus, possibly soil aggregate size has the long-term effect on stimulation of microbial enzyme activities (Dorodnikov et al. 2009). Atmospheric N deposition causes impact on enzymes (extracellular), which are concerned in the processes of soil organic carbon decomposition and nutrient cycling. Soil faunae include the invertebrate community that may live their whole life or half of their life cycle in the soil, as soil fauna has become an important soil health indicator since recent years. Important in processes related to structure of terrestrial ecosystem, disintegration of residues of plants and creating relationships at different degrees with microorganisms. So, their active participation in processes causes effects on the soil properties, considered as great indicators of changes in the soil. OM is decomposed and transformed into various available forms of nutrients, which are conducted by the microorganism and microbial activities. Microbes will work more effectively as the organic matter quantity available to them at large and soil organic matter will be more shattered and spread out along the soil profile. Also, increasing the surface area of contact, earthworms enhance the distribution of organic material in the soil layers vertically or horizontally (Kostina et al. 2011). Higher permanence of soil accumulation has been seen in soil with elevated biomasses of microbes and earthworm. Further, the fauna actions combine particles of soil and generate blocks, tunnels, pores, and other biological chambers that make the movement of water and air, promote the microbial activity, and hence make the soil more accessible for agricultural creations and enhance plant harvests. On the other hand, soils having less activity of fauna reveals more compaction in soil fragments which makes complicated for plant roots for saturation have low accessible water content and less air in the soil triggers poor agricultural construction and have low variety of microbes. Soil fauna can be categorized by the food which they choose to eat, by flexibility, by diversity in their functions, and primarily by size. The most distinctive organisms examined as soil health indicators are members of mesofauna in soil that are present in places between soil macropores and in the soil, litter maintain feeding on organic matter and fungal hyphae and thus take part in process of nutrient cycling and soil accumulation. Some of the experiments have revealed that some species of springtail are good gauges of soil health. The macrofauna comprise bigger soil organisms, consisting of nematodes, proturans, and sauropods feeding on soil microorganisms, decaying plants, and animal materials, which intermittently are active in the soil ecosystem.. Differences in the environment may have different impacts on family, species, or functional group arrangement of the soil faunae. Practical groups as bioindicators have been preferred to use even though of the variety of total species because of the role which they are producing in biological performs. As some species of earthworm are distinct, the organic material accrued on the soil outside, and for that purpose, the activity of the species (individually) was deemed considered restrictive. In fact, in the presence of other functional groups of organisms, they are incompetent to change the role earlier performed by the earthworm species. But the existence or deficiency of some species may be constraining for an ecosystem operating directly influence on the vitality index is considered in evaluations of soil condition.

4.6 Soil Microbe Mitigating Climate Variability

The activity and growth of microorganisms is highly dependent upon the environmental factors, like moisture, temperature, and substrate disposal, and therefore the microbial responses and processes are influenced by climate change. The interests and growth of soil microorganisms may be directly and indirectly influenced by change in climate. The direct effects include change in precipitation pattern, temperature effects, and harsh climatic results, whereas ancillary effects comprise variants due to climate that amends the plant productivity and physicochemical estates of soil. Soil microbes play a key role in climate change through decomposition of organic matter in soil, and ratios of heterotrophic microscopic action stimulate the CO_2 effluence to the atmosphere that will improve global warming. The variety or diversity and population of soil microorganisms are indirectly influenced by changes in microclimate due to its effects on growth of plant and alignment of vegetation. On the first hand, the soil microorganisms are affected indirectly by increasing concentrations of CO_2 in the atmosphere, and in the second phase, there is enhanced photosynthesis and transport of carbon (photosynthate) to mycorrhizal fungi roots (Bardgett et al. 2008; Zak et al. 1993) and microbes that are heterotrophic in nature (Högberg and Read 2006). Because of excess concentration of CO_2, photosynthesis process in plant rises and plant growth may be doubled (Curtis and Wang 1998) that in return encourages the carbon flux in plant roots and microorganisms that are heterotrophic in nature through root exudation of sugars, which degrades it easily (Diaz et al. 1993; Zak et al. 1993). Soil microorganisms may be applied to support adaptation to change in climate by development and growth promotion and improving resistance against various abiotic and biotic stresses. Soil microorganisms take part in the formation of soil; maintain its properties; regulate its fertility, breakdown, and remediation of toxic contaminants; increase sustainable production; and eventually enhance ecosystem sustainability and resilience. Microbes are applied for management of soil health and resilience of ecosystem to lower the demand for production and transportation of synthetic fertilizers. Novel microbes and organic regulating agents can be applied to diminish the damaging influences of novel and advancing pests and pathogens in climate change setting. Frequently found natural managing agents comprise rust fungus *Maravalia cryptostegiae*, applied in country Australia for managing the weed rubber vine and *Neozygites fresenii* (parasitoid) applied for controlling the pest of cotton *Aphis gossypii*. The bacterium *Bacillus thuringiensis* is cast off at field condition, because it produces crystalline toxins, which demolish the *Diptera* and *Lepidoptera larvae*. Beneficial microorganism plant relations can efficiently enhance the growth of plant and increase their resistance to abiotic stresses and deteriorating diseases. Bacteria that are beneficial for plants help in the acquisition of nutrient, secrete PGP (plant growth promoting) hormones, and modify biochemical and physiological characters of the host plant and, so in this way, protect the plant roots from soil-borne deleterious pathogens. Bacterial genera like *Serratia*, *Bacillus*, *Azospirillum*, *Streptomyces*, *Rhizobium*, and *Pseudomonas* reduction in this class. These plant-growth indorsing useful bacteria can be applied for increased growth of plant and improved resistance against disease in altering conditions of climate. According to researches, right strains of mycorrhizal fungi, when inoculated with C4 plant, help against raised levels of CO_2 (Tang et al. 2009). Novel species of *Rhizobia* affiliated with *Medicago sativa* holds the potential to work under several circumstances (abiotic) like high or low pH or temperature, or low concentrations of SOM. The vast unmapped reservoirs of genetic and metabolic diversity of microorganisms offer a marvelous opportunity for the identification of novel genes to control the pest, biodegradation, and N_2-fixation with the help of the latest improved tools like metagenomics.

Soil microorganisms and their metabolism can impact the atmosphere-land carbon exchange cycles in several ways, which can be categorized into diverse groups like those which influence the ecosystem by CO_2 and methane uptake and which also affect the loss of carbon from the soil by respiration. Methane-oxidizing bacteria (MOB) or methanotrophs found in aerobic soils can function as effective biological sink to minimize emissions of methane to the atmosphere. They depend upon CH_4 for energy and carbon. About 15% of the total worldwide CH_4 is contributed by MOBs. They are sensitive to environmental calamities and hard to isolate because of their fixed attachment to soil particles and slow growth rate. A bacterial specie *Methylokorus infernorum*, which is present in geothermal zones in hot and acidic locations, exploits methane CH_4 gas. These bacteria have the ability to use a high amount of methane, which is up to 11 kg $year^{-1}$ and can also be used to reduce emissions of methane from CH_4-producing areas and factories. Moreover, *Methylobacillus* utilize carbon-containing compounds, like methanol, methylated amines, and methane. Additionally, there exist some natural microorganisms, which transform CO_2 into calcium carbonate ($CaCO_3$). Some species of microbes (denitrifying) are accountable to transform nitrous oxide (NO) into nitrogen (N_2) gas. The microorganisms have the propensity to reduce and mitigate emissions of GHGs. The microbial nutrients, gasses, and climate change pathway are explained in Fig. 4.1.

Soil microorganisms improved productivity, influencing the greenhouse gas budget in sense of discharges of greenhouse gas per part food fabrication. The advantage acquired by using the beneficial microorganisms in case of productivity can be thought as a role of microorganism to mitigate the change in climate. The world of microorganisms is very large, and only a very little portion <10% is characterized and identified so far (Bhattacharyya and Jha 2012). Soil microbes sense the biochemical created stimuli and releases the chemicals from their body, which can trigger complex mechanisms of plant defenses (Glick 2012). They effectively contribute in utilizing the greenhouse gases like N_2O, CH_4, CO_2, and nitric oxide (Bardgett et al. 2008). Microbes are essential for crop protection by promoting the capacity of disease resistance in plants opposed to the damaging pathogens and exposing destructive structures or auxiliary as biological elicitors against several biological and ecological influences. The fungi among microorganisms have the ability to colonize the external parts of plants and offer protection from several living and nonliving agents like pathogens, pests and insects attack, heat, and drought (Singh et al. 2011). Usage of microbial biofertilizer in agriculture system is

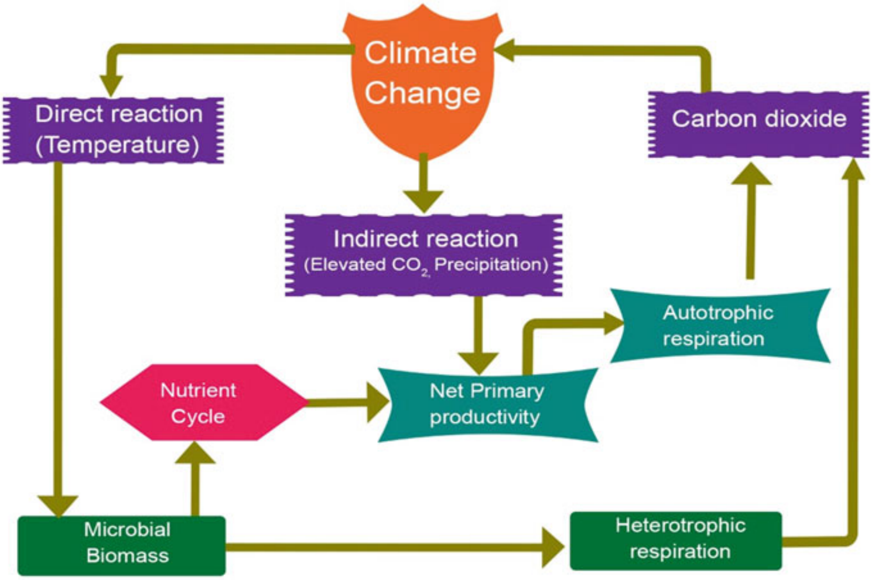

Fig. 4.1 The microbial nutrients, gasses, and climate change pathway. (Dutta and Dutta 2016)

not yet so common because of the problems of identification and tracking of inoculated strains and uncertainty of results. Nowadays, the application of microbial biotechnology is very important in sustainable agricultural development. Conserving the microorganism diversity is vital to maintain the species variety of higher living organisms and strategies for nutrient management and disease of plants (Colwell and Munneke 1997). Changes in climate encourage modification processes in the micro-organisms and plants (Grover et al. 2011) and therefore alter the efficiency of microbe-plant linkages. The concept of microclimate difference-microbe response and potential negative and encouraging position of microorganisms in worldwide environment difference is important to use them for changes in climate improvement and variation.

The three main factors affecting climate modification consist of natural, human, and atmospheric influence. The sun radiates solar energy that affects the planet and raises temperature; and rising temperatures cause global warming (Lean 1991). Improved amounts of human-generated glasshouse gases reason much more warming than current fluctuations in solar action. Satellites have been observing the sun's energy harvest for more than 40 years, and it has oscillated by less than 0.1%. The life on Earth exists due to the sun, which keeps its temperature warm and makes the conditions favorable for the survival of humans. It also influences Earth's atmosphere. However, the contemporary warming has been far too swift to be credited to the changes in Earth's orbit and far too huge to be caused by the solar endeavor (Assessment 2018). In a single solar cycle, which is of 11 years, the sun never brightens the same way it brightens and dims slightly. The sun undergoes various changes in activity and looks over each cycle. The level of the radiations coming from the sun changes, as does the quantity of material discharged into space by the sun, as well as the volume or size and number of solar flares and sunspots. Long- and short-term disparities in solar activity play only a minor effect on Earth's climate. Warming caused by the rising amounts of human-produced greenhouse gases is many times more commanding than any effects caused by the recent vagaries in solar activity. Satellites have been tracing the sun's energy output for more than 40 years, and it has been altered by less than 0.1% over that time. Since 1750, the warming produced by greenhouse gases unconfined by human use of fossil fuels has been more than 50 times more than the small extra warming caused by the sun (Birat 2021). Global climate change has been linked to huge volcanic explosions (Altman et al. 2021). Volcanic explosions have two major effects on the climate. First, they radiate the greenhouse gas carbon dioxide, which promotes global warming. However, the influence is negligible. Volcanic emissions have been projected to be at least 100 times lower than those from fossil fuel incineration since 1750 (Wilson 2021). Climate change is influenced by volcanoes. Massive quantity of volcanic gas, drips of aerosol, and ash are inserted into the stratosphere layer during a huge explosive outbreak. Although volcanic gases such as SO_2 can provide a cooling effect globally, on the other hand, volcanic gas like carbon dioxide, which is a greenhouse gas, has the ability to raise the temperature of the globe (Sigurdsson et al. 2015).

Climate alteration and air pollution have an intricate relationship. Pollutants, such as ozone O_3 and black carbon, raise the Earth temperature by entrapping the heat in the atmosphere, while others like SO_2 that form light-indicating elements cool the temperature (Stern 1977). Sustained decrease in air pollution and GHG emissions are dangerous because they cause significant health and ecological hazards around the world. Air property and climate lineups can be an advantage to one another: change in climate vindication enterprises can help decrease pollution of air, while policies related to clean air can help reduce greenhouse gas emissions, resulting in lower global warming. If decrease in a specific emission of pollutant results in increased atmospheric temperature rather than cooling, there may be trade-offs (Seinfeld and Pandis 2016). All through complex interactions in the environment, difference in climate, and pollution in air influence each other. raising levels of greenhouse gases interrupt the balance of energy between the atmosphere and the surface of Earth, which results in temperature changes that alter the atmosphere's chemical makeup. This balance of energy can also be influenced by direct emissions of air pollutants, for example, black carbon or those pollutants formed from emissions like sulfate and ozone. As a result, climate change and air pollution organizations have common impacts (Paoletti et al. 2007). The less gasoline we burn up, the better we are at decreasing air pollution and the dangerous effects of climate change. Make wise shipping verdicts. Walk, ride a bike, or operate public transportation wherever possible. Buying food in the vicinity decreases the quantity of fossil fuels need to transport or fly food across the country and possibly most prominently, "Support leaders who promoter for clean air and water, as well as accountable climate change action" (Mackenzie 2016). Water vaporization is the most plentiful GHG, but it also functions as a climate response. As the temperature of Earth increases, degree of water vapors increases, but, as a result, chances of clouds and rainfall also increase, making these two response mechanisms important to the greenhouse effect. CO_2 levels in the atmosphere raised from 280 ppm to 414 ppm in the last 150 years, due to the industries that underlie our modern society. Generated greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, are produced by humans, likely to be responsible for much of the rise in Earth's temperature during the past 50 years (Oreskes 2004; Karl et al. 2009). Increase temperatures result in higher evaporation costs, since the amount of energy required for evaporation decreases as the temperature rises. In a sunny, warm weather, water loss is increased due the high evaporation as compared to depressing and cool weather. As a result, when the weather is bright, hot, dry, and windy, evaporation rates are higher. Due to the water vapor functioning as a greenhouse gas in the atmosphere, evaporation might have a warm effect on the global climate. Increases in the evaporation intensity tend to induce clouds to develop low in the atmosphere, which function as a signal that the sun's warming rays are being reflected back into the space (Spracklen et al. 2018).

The emissions of greenhouse gas have a wide range of environmental and physical condition inferences. They contribute to respirational ailments due to air pollution and smog, along with triggering environmental difference through confining the heat up. Other consequences of climate change produced by greenhouse gases include extreme weather, food supply shortages, and more wildfires (Nunez 2019). Carbon dioxide is a minor but vital component of the environment. Ecological practices like respiration and volcano explosions emit carbon dioxide, as do human endeavors like deforestation, land use changes, and fossil fuels burning are only a few examples. Human has raised CO_2 level in the atmosphere by 47% since the beginning of the industrial revolution, which is the most significant long-term "forcing" of climate change (Fig. 4.2).

4.7 Climate-Smart Agriculture

Soil health is indispensable for creating more climate flexible agricultural systems, and it may be enhanced through an assortment of climate-smart agriculture (CSA) advances. Climate-smart agriculture (CSA) has been suggested as a general attempt to establishing agricultural practices to ensure long-term food insurance in the face of climate alteration (Palombi and Sessa 2013). One of CSA's pivotal goals is to minimize the emission of greenhouse gases while also enhancing the soil carbon appropriation and soil physical condition (Campbell et al. 2014; Lipper et al. 2014). Increasing the carbon consequences while lowering the carbon outputs is the key to distinguish more carbon in soils. Adding cover crops to the crop rotation, utilizing biochar to soils, and decreasing soil tillage are all often recommended ways for SOC

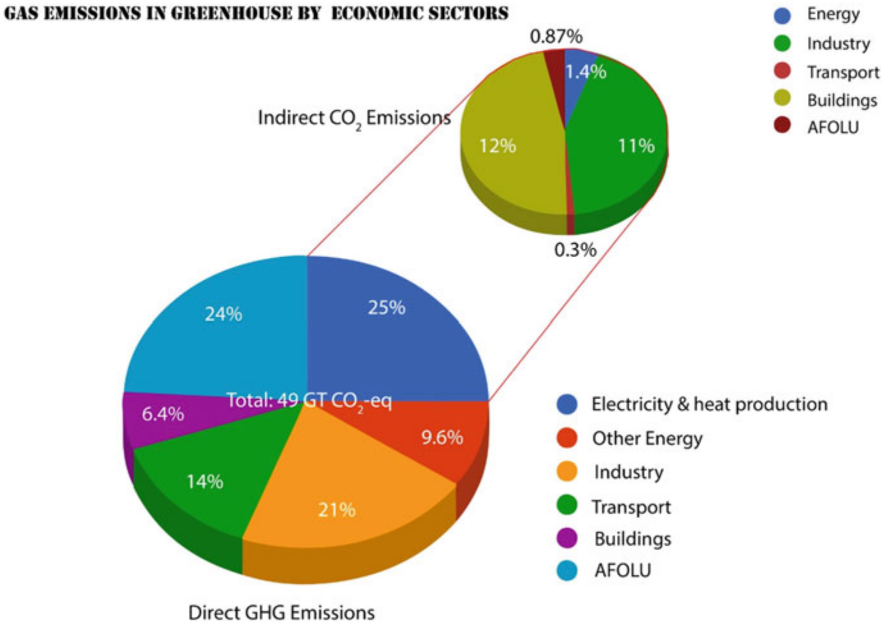

Fig. 4.2 The greenhouse gasses that affect climate change. (FAOSTAT 2022)

sequestration (i.e., conservation tillage). These administration tactics have been used in important agricultural zones around the world in the latest decades, developing in an enormous number of examinations and statistics (Chen et al. 2009; Clark et al. 2017). Encouraging effects of CSA regulating methods on SOC appropriation have been described by several processes. Conservation tillage, for instance, minimizes the organic matter rate in the soil and also minimizes the soil disturbance (Salinas-Garcia et al. 1997) and stimulates earthworm and mycological biomass (Fragoso et al. 1999; Briones and Schmidt 2017), thereby advancing SOC stability (Wang et al. 2021). Cover crop boosts carbon and nitrogen inputs, improving the agroecosystem biodiversity, and offers extra biomass inputs from above- and below-ground (Blanco-Canqui et al. 2011) (Lal 2004). Furthermore, cover crop can increase soil aggregation and structure (Sainju et al. 2003), reducing carbon loss from soil erosion indirectly (De Baets et al. 2011). Biochar alterations prejudiced the soil organic carbon diminuendos 2 ways: (1) enhancing soil combination and physical protection of aggregate related with soil organic matter from microorganisms attack; and (2) increasing the pool of intractable organic material, resultant in a low soil organic matter putrefaction amount and significant adverse priming (Du et al. 2017; Weng et al. 2017; Zhang et al. 2012). Even though these climate-smart agriculture governing techniques have been commonly utilized to improve the soil physical condition (Denef et al. 2007; Fungo et al. 2017; Thomsen and Christensen 2004; Weng et al. 2017), their effects on CO_2 sequestration change over time and are highly dependent on experiment design and site-specific factors, including climate and soil condition (Abdalla et al. 2016; Liu et al. 2016a, b; Paustian et al. 2016; Vickers 2017). The aptitude of CSA methods to sequester soil carbon differs widely. Some research has also claimed that CSA management techniques have a negative impact on SOC (Liang et al. 2007) (Tian et al. 2005). Most mathematical exploration intensive on the impacts of a single climate-smart agriculture practice on soil organic carbon (Abdalla et al. 2016; Liu et al. 2016a, b; Vickers 2017) and very few studies estimated the joint effects of varied CSA and conventional management practices. A combination of cover harvest and preharvest tillage, according to several recent research, may dramatically improve SOC when compared to a single management strategy. When no-tillage and cover crop practice were combined, soil carbon sequestration increased by 0.267 Mg C ha^{-1} $year^{-1}$, with the latter being a varied culture of hairy vetch (*Vicia villoma*) and rye (*Secale cereale*); when only no tillage was used, soil carbon sequestration decreased by 0.967 Mg C ha^{-1} $year^{-1}$ (Ashworth et al. 2014; Blanco-Canqui et al. 2013; Duval et al. 2016; Sheehy et al. 2015). When biochar was added to conservation tillage, Agegnehu et al. (2016) found that 1.58% and 0.25% more of SOC were sequestered in the midway and end season, respectively, under conservation tillage.

Climate-smart agriculture (CSA) is emerging progressively more popular as a solution in many nations. CSA is a comprehensive approach to landscape organization that improves productivity, improves flexibility, and lowers greenhouse gas emissions. The World Bank, as one of the major agricultural financiers, assists countries in their attempts to scale-up climate-smart agriculture. Climate-smart agriculture (CSA) is a management strategy for farmers in the face of climate change. The CSA wants to advance internationally relevant agriculture management practices for food security. The concept was initially introduced in 2009, and it has since grown based on feedback and interactions from a variety of stakeholders. The CSA strategy was established in response to arguments and disputes in environmental change and agricultural policies for long-term development (Lipper et al. 2017). Enhancement in mitigation by decreasing GHGs is an important CSA goal and a key to long-term efficient climate change adaptation; therefore, it comprises inventions and implementation of cultural techniques, varieties of crop, managing techniques, and organizations that will speed up improvement. Transitioning to no- or small tillage methods has already been recognized as a significant resource of carbon sequestration, and implementing more varieties of yields and conservation practices that decrease agriculture's land, ecological, and nonrenewable fuel resources is an additional significant reduction policy (Lal 2011; McCarthy et al. 2012). Climate-smart agriculture may work as an agent for developing resistance, better modification, and adaptation approaches within sociobiological structure (Steenwerth et al. 2014) (Fig. 4.3).

Precision agriculture is one such implement that is useful in making an agriculture more "climate savvy" by minimizing its environmental influence. Thus, precision agriculture is an intensive system that entails the usage of a world aligning system, several instruments for observing soil moisture content, nutrients availability, and geo reference map for various soil characteristics, but when implemented on a huge scale, it can support to increase productivity, reduce resource ingesting, and reduce ecological impact. Precision agriculture is a contemporary day climate-smart

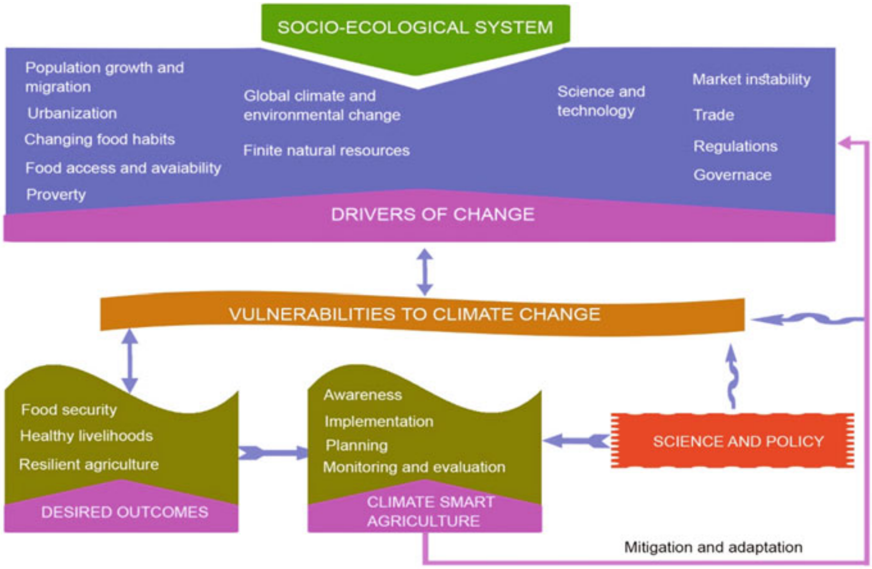

Fig. 4.3 Climate-smart agriculture for improving resilience, better mitigation, and adaptation. (Steenwerth et al. 2014)

agricultural technique that has the potential to address the food problems insecurity in poor nations and combine as a strong instrument and solution to the agriculture sector's numerous challenges (Roy 2020). The practice of "no-till farming," which avoids soil manipulation for crop production, is one approach to sequester carbon. No-till farming has numerous potential benefits for gardeners, farmers, and the environment when combined with cover cropping. The combination of no-till farming and cover cropping is always found suitable for increasing organic matter. Through this way, a shield is created over the soil to protect it during the driest times as well as a sponge in the soil to protect it during heavy rains. So, while the two activities combined generate organic matter and store carbon in the soil, they also offer additional advantages. Because all that organic waste is now decomposing, they give nutrients to the food. There are numerous environmental advantages to no-till farming. It increases carbon sequestration in the soil and reduces fossil fuel use in farm activities. The quantity of nutrients that the soil can contain increases as soil organic carbon levels rise, implying less petroleum-based fertilizers and runoff into nearby water bodies. Farmers would benefit from the method in the event of harsh weather, such as drought, because soil rich in soil organic matter absorbs water better than tilled ground. Agricultural practices in poor nations frequently result in poor soil quality. Climate change-related extreme weather may exacerbate the problem, unless better agronomic techniques are implemented. The goal of soil and land management must be to enhance yield while preserving soil and water resources. It also intends to sequester carbon. Organic fertilization, least soil disruption, residue absorption, terraces, water gathering, preservation, and agroforestry are all illustrations of this administration (Branca et al. 2013), but there are several

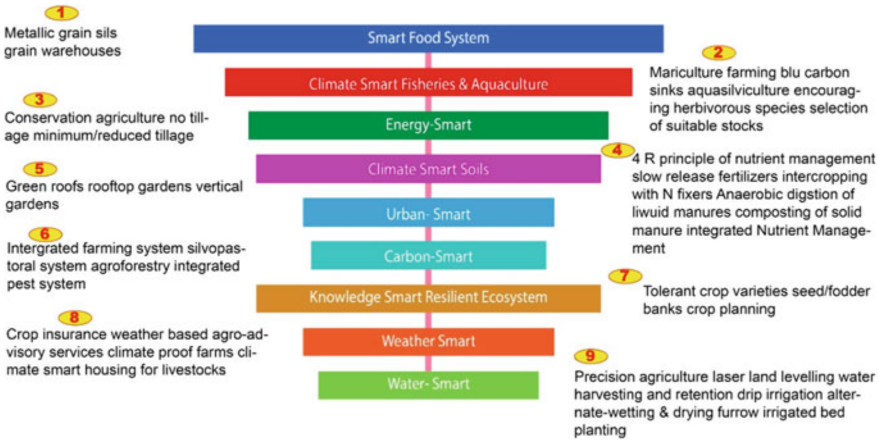

Fig. 4.4 Climate-smart agriculture technologies. (Adopted from Source: Khatri-Chhetri et al. 2017)

prospects for improving new management methods and improving existing ones to adjust spatial and climatic erraticism.

All agroecosystems require climate-smart agriculture (CSA) equipment, methods, and help. These approaches can help to improve agriculture, protect it from climate change, and ensure food security. The biophysical environment, farmer socioeconomic traits, and the benefits of CSA technology all play a role in CSA adoption (Khatri-Chhetri et al. 2017) (Fig. 4.4).

For countries that rely on agriculture for subsistence, CSA technologies provide at least two benefits in terms of production, resilience, and mitigation, with productivity being the most important. Metrics nested under these broad CSA categories can be used to track progress against a realistic baseline. For example, improved productivity could be assessed in terms of yields, income, or internal rate of return. CSA aspires to maximize synergies and minimize trade-offs across all of its pillars (Rosenstock et al. 2016). While boosting food security, CSA technologies manage climate- or weather-related risk. Extreme occurrences (such as floods) as well as slow-onset threats may be considered (such as delayed onset of seasonal rains). CSA technology should assist in mitigating the effects of these risks in the short term (by increasing the amount of production per farm, hectare, season, etc.) as well as in the long run (by increasing the amount of production per farm, hectare, season, and so on and decreasing the variability in production over time, despite climate change).

4.8 Soil Microbes and Global Agriculture

Food security becomes a major challenge in the twenty-first century in response to the increase in demand of sufficient food with respect to population rate. Nowadays, the other main factor influencing food security is climate change (Alamgir et al.

2020; Borrill et al. 2019). The alteration in environment, such as extreme temperatures and fluctuation in rainfall intensity, becomes a global aspect that concerns agricultural production (Abberton et al. 2016; Milus et al. 2009). These alterations have high impact on soil, microbiota, agricultural output, and global food security (Adger et al. 2009; Hill et al. 2009; Nelson et al. 2009; Campbell et al. 2016; Durán et al. 2016). As per contemplates, the normal world temperature has risen, and freshwater supplies will be fundamentally decreased before the end of the twenty-first century. Varieties in snowfall and territorial precipitation have additionally been noticed, and these variations are required to deteriorate in the coming days (Misra 2014; Reidsma and Ewert 2008; Reidsma et al. 2010; Stocker et al. 2013). Climate is fundamentally affected by farming. Farming emanates enormous volume of ozone-harming substances, i.e., GHGs like CO_2, CH_4, N_2O, and corona carbons into the environment, where they assume a critical part in ingest sun-powered energy (Valizadeh et al. 2014). Farming is responsible for an expected 17–32% of all worldwide greenhouse gas emanations (Cotter and Tirado 2008). Agribusiness can lessen GHG discharges and ease environmental change. While certain harvests may profit with environmental change in certain areas, expanding temperatures may in the long run lower rural yields on a worldwide scale, especially in dry and hot areas (Smith and Gregory 2013; Valizadeh et al. 2014). Moreover, extreme temperatures have increased weed and creepy crawly attacks, bringing about lower farming yields (Nelson et al. 2009; Reidsma and Ewert 2008). Without a debate, the combined impacts of environmental change on agribusiness are negative, representing a risk to worldwide horticultural creation and, thus, imperiling sanitation (Glenn et al. 2013; Malhotra 2017).

Farming usefulness is associated with conditions both straightforwardly and by implication, through giving and related cycles; environmental change will put a strain on this fragile equilibrium (Altieri et al. 2015; Smith and Gregory 2013). In spite of the fact that environmental change will impact our overall ability to get food, it is plausible that underestimated individuals in nonindustrial countries would be the most exceedingly awful hit (Sanchez and Stern 2016). It is clear that future requirements for food and environment administrations will require more extreme changes underway, utilizations, and strategies (Davidson 2016). CO_2 and other fellow gases are growing, and these additions will in the end affect the world's environment (Ortiz-Bobea 2021). Plant constructions and thus crop productions are prejudiced by various organic parts, and these components similar to suddenness and temperature may act either synergistically or ridiculously with various variable quantities in selecting yields (Yevessé 2021). Controlled field preludes can make information on how the yield of a specific gather arrangement responds to a given lift, like water or fertilizer. Nevertheless, by their disposition, such controlled tests consider only a confined extent of biological factors (Jiang et al. 2021). An elective method to manage and check out crop yield (changes) is the use of gather biophysical diversion models that introduce limits drawn from crop tests (Gurgel et al. 2021). Since natural change is likely to cut across a huge gathering of living components, such collect proliferation models give the most quantitative examinations of changes in ecology impacts on crop yields (Manzoor et al. 2021). However, the usage of gather reenactment models makes the examination of climate impacts over an area of yields logical; these kinds of models furthermore have limits, counting the separation from the grouping of components and state that impact creation in the field (Lal 2021). feasible ecological circumstances that changes, consolidate increased temperatures, variations in rainfall or snowfall, and increased air CO_2 obsessions. Regardless of the way that temperature additions can have both positive and antagonistic outcomes on crop yields, with everything taken into account, temperature increases have been found to diminish yields and nature of various harvests (Avagyan 2021).

A climate with greater CO_2 intensity would achieve higher net photosynthetic values (Horton et al. 2021). Higher centers may equally reduce arising (water disaster) as plants decline their stomata holes, the little cavities in the leaves through which CO_2 and water seethe are replaced with the air (Ortiz et al. 2021). The net change in crop yields is limited by the affability between these negative and positive direct ramifications for plant improvement and progress and by deceitful effects that can impact creation. These inadvertent effects have been usually disregarded in the examination of ecological change impacts (Zougmoré et al. 2021). Typical effects may rise up out of changes in the event and course of vermin and microorganisms, extended speeds of soil crashing down and defilement, and increased troposphere ozone levels in view of rising temperatures (Kehler et al. 2021). Extra deceitful effects may rise up out of changes in overflow and groundwater re-invigorate rates, which impact water supplies, and changes in capital or mechanical supplies, for instance, surface water accumulating and water support practices (Koutsoyiannis 2021) (Fig. 4.5).

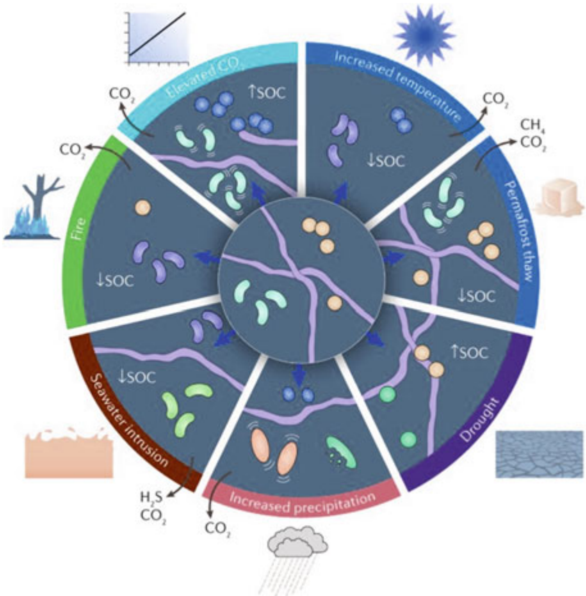

Fig. 4.5 Soil microbial response to climate change. (Jansson and Hofmockel 2020)

Naturally, more than 90 billion bacteria are preset in one-gram soil that promotes the plat growth by making the unavailable nutrients in the available form for plant uptake. Nowadays, the biotic stress is a big challenge for agriculture due to day-by-day increase in the world population, which causes increase in food demands. The use of chemical means of nutrients increases the crop production, but it also deteriorates the environment causing a reduction in soil fertility and plan growth (Armstrong and Taylor 2014). For agricultural production, the health of soil is very important, which depends on different reactions, such as chemical, biological, and physical, collaborated by microorganisms. The beneficial microorganisms are group of naturally occurring microorganisms, like plant growth-promoting rhizobacteria, fermenting fungi, actinomycetes, yeast, lactic acid bacteria, etc. These microorganisms play a very important role in improving the soil structure and soil fertility, suppressing soil-borne pathogen, fixing nitrogen, increasing the decomposition of organic matter, and enhancing the level of nutrients and of plant strength and ultimately crop yield (Joshi et al. 2019).

Soil microorganism is involved in different biogeochemical cycling of all major (N, P, K, S, etc.) and minor nutrients (Fe, Mn, Co, B, Zn, etc.) required for crop growth and other life (Jansson and Hofmockel 2020). The impact of climate change on soil microbes in different climate-sensitive soil ecosystem is illustrated in Fig. 4.1 (Dutaa and Dutta 2016). Mycorrhizal fungi and bacteria that live near the roots offer numerous advantages to the host plant, including faster growth, enhanced nutrition, better drought resistance, and defense against pathogens. Mycorrhizal fungi are broadly characterized into two groups. The first one is vesicular arbuscular mycorrhizas (VAM or AM) and the second is eco-mycorrhizas (EM), which differ extensively in structure and function. The structures produce by VAM within the roots of plants are known as arbuscules and vesicles, which participate in the transfer process of nutrients. This symbiotic relation benefits the host plants directly, through the solubilization of phosphate and other mineral nutrients from the soil by the fungus, while the fungus obtains a carbon source from the host plants. The symbiosis also improves the resistance of plants to biotic and abiotic stresses. Ectomycorrhizas (EM) frequently produce large aboveground fruiting bodies like that of a mushroom and toadstool as well as a hyphal net around the root of plant. Vesicles and arbuscules are absent, and the hyphal penetration of the root is incomplete. EM fungi are amenable to axenic culture. Potential inoculum can also be produced in the field from mycelium (Harrier 2001; Thomson et al. 1994). The soil microorganisms play a vital role in soil health and sustainability. The density and diversity of microorganisms' population indirectly depend on the level of organic matter, because it provides energy for soil microorganisms and improves the structure, stability, and moisture of the soil and plant nutrient availability and stops the occurrence of soil-borne disease (Zhang et al. 2007).

4.9 Microbial Contribution in Climate-Smart Agriculture

Worldwide, agriculture participate in and is an agriculture both promotes to and is endangered by climate change over. Corresponding to the account of IPCC, agriculture brings part in 58% and 47% of the total anthropogenetic constructions of N_2O and CH_4, respectively. Agriculture is previously facing the severe impacts of climate adjustment (Lobell et al. 2011), and consequently, the food production is also being affected directly and indirectly by it. Fluctuations in rainfall pattern, upsurge in mean temperature, and intensification in occurrence of intense climatic effects, like scarcity, floods, and cyclones, will highly affect the agriculture (Lee 2007). The growth of population in the world is forecasted up to one third by 2050, and most of the people (about 2 billion). The world's residents are expected to improve by one third by 2050, and most of the added two billion people will survive in improving states (Boettcher et al. 2015). With the aim to fulfill the constraints of food and feeding, agricultural production is predicted to grow by 60%. It is a big challenge for the upcoming food security, as the resources required to maintain the present agricultural growth are already being endangered. Furthermore, worldwide agriculture is already being harmfully impacted by global climate change, and climatic hazards to livestock, fisheries, and cropping are predicted to rise in the coming years. In the period of such rapid change in climate, alteration and redirection of agricultural production led to the strategy of climate-smart agriculture (CSA). Microorganisms are vital members of the soil-plant ecosystem, and simply no food production is possible without them. Microorganisms perform a vital role in the cycling of plant nutrients in the system of microbe plant soil and atmosphere. Microbes are crucial to nitrogen and carbon cycles and take part in the consumption and production of greenhouse gases (GHGs), like nitrous oxide, methane, and carbon dioxide. A vast diversity of microorganisms offers an unexploited way to improve the quality and quantity of agricultural products, leading to adaptation and mitigation of changing climate outcomes, thus helping to attain the target of climate-smart agriculture. The microbes that cause diseases to insect pest and weeds are utilized as biopesticides. There are many microbes in the soil, which promote plant growth through various biocontrol mechanisms. The free-living soil microbes help to maintain the soil structure, carbon sequestration, and nutrient storage and availability (Das et al. 2019).

Microbe variety in soil enhances the numerous mechanisms that are a vital part of biogeochemical cycles and henceforward promotes and maintains a lot of agroecosystem's biochemical reactions, such as decomposition of organic matter, nutrient availability to plants, and overall productivity of plant and soil. Many times, the microorganisms make associations, and many limiting resources are made available to plants by them. Furthermore, the host-specific microorganisms like mycorrhiza and N_2 fixers also make available limited and fixed plant nutrients to enhance plant growth. Consequently, microbes endorse the sustainability of agriculture and effective operation of agroecosystem (Das et al. 2019) (Fig. 4.6).

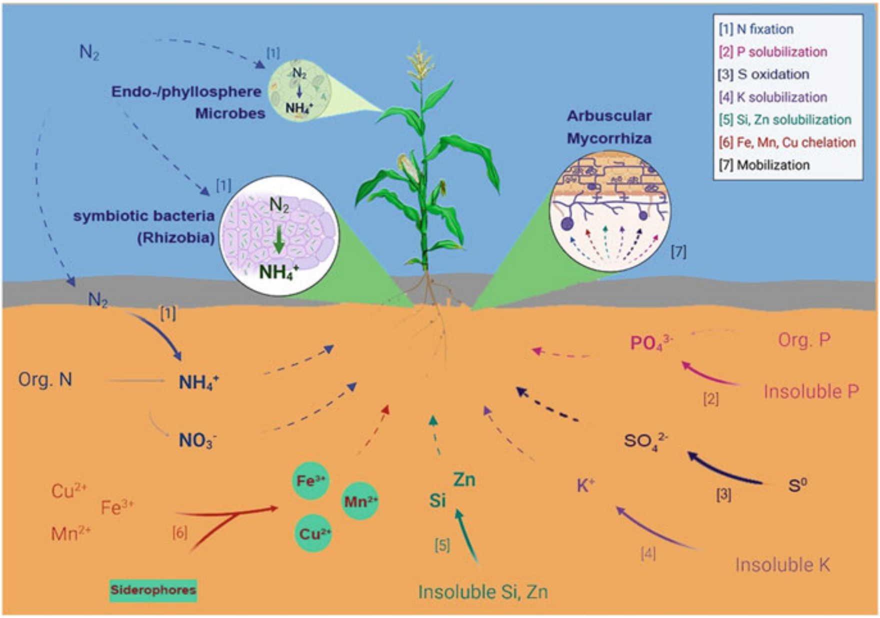

Fig. 4.6 Microbial-mediated nutrient transformation pathway. (Mitter et al. 2021)

The process in which complex organic biopolymers present in the dead remains, and residues of animals and plants are broken down into simpler inorganic and organic monomers through various biochemical reactions, referred to as organic matter decomposition (Juma 1998). During this microbial process of organic matter decomposition, nutrients and energy are recycled, and the surplus plant nutrients, like N, S, and P, are added to the soil in the plant-available form; this transformation is known as mineralization. Hence, in this way, microbes are crucial for the availability of essential plant nutrients and necessary inorganic compounds in the soil through the processes of nutrient recycling, by decomposing the plant residues and dead bodies of animals (Das et al. 2019). Fixation of atmospheric elemental nitrogen (N2) into plant-available forms is one of the most important biochemical reactions that is highly essential and beneficial for global agricultural sustainability and efficient ecosystem functioning. Worldwide, the annual incorporation of the fixed nitrogen through symbiosis between rhizobia and legume is assessed to be 18.5 million tones and 2.95 million tones for oilseed legumes and pulses, respectively (Howieson et al. 2005). However, the symbiotic bacteria nodulating the legume crops belong to the genera *Brady rhizobium*, *Ensifer*, *Rhizobium*, and *Mesorhizobium* that are conscientious of about 80% N accumulation in grains, causing high nutrition and profit. The bacteria, which live freely and do not form a symbiotic relation with the host crop, are known as free-living N2-fixing bacteria. Some of them are *Azospirillum*, present in temperate region cereal-growing soils; Beijerinckia, associated with sugarcane in tropical areas; and *Azotobacter*, prominent for N2 fixation in rice growing soil and also used as a biofertilizer for tobacco, tea, coffee, coconuts beetroot, sunflowers, oat, barley, maize, and wheat crops. Moreover, the species that belongs to the genera *Herbaspirillum*, *Gluconacetobacter*, and *Azospirillum* are endophytes of sugarcane and provide nitrogen to the crop. *Azorhizobium* strains that fix the N2 are isolated from the rhizosphere of wheat crop, while *Bradyrhizobium* and *Rhizobium* are from the roots of paddy. Additionally, there are specific diazotrophic bacteria that form a true beneficial mutualism (symbiosis) with some host plants by forming the nodules with its roots (García-Fraile et al. 2015). Phosphorus solubilizing microorganisms (PSMs) release the plant unavailable inorganic and organic soil phosphorus through mechanisms like solubilization and mineralization and make P available to crop plants, thus playing a vital role in soil fertility (Sharma et al. 2013; Walpola and Yoon 2012). In the P-deficient soils, a diversified variety of PSMs like fungi (*Penicillium* and *Aspergillus*) and bacteria (*Bacillus*, *Pseudomonas*, and *Actinomycetes*) can be inoculated in the soil to increase the P availability, through their mineralizing and solubilizing capability (Gyaneshwar et al. 2002). P solubilization by bacteria is more efficient than fungi (Sharma et al. 2013). *Penicillium bilaii* is also a beneficial P-solubilizing bacterium that effectively takes part in the phosphate solubilization in native soils. Secretion of organic acid by fungi solubilizes the phosphate reservoirs in soil, making P easily available to plant roots. Potential phosphate-solubilizing bacterial genera in the soil include *Pseudomonas*, *Rhizobium*, endosymbiotic rhizobia, and ectorhizospheric strains of *Enterobacter* and *Bacilli* (Khan et al. 2009). A mutual exchange of nutrients and carbon occurs between mycorrhizal symbiosis of arbuscular mycorrhizal fungi (AMF) and host plant. The host plant acquires nutrients, e.g., phosphate and nitrogen, from fungus, which promotes plant's resistance against abiotic and biotic stress, and, in response, fungi get 4–20% C fixed by photosynthesis. Mycorrhizal symbiosis is quite common, and its symbiotic functions depends upon the variations between the soil properties, host plants, and AMF species. Generally, the AMF symbiotic linkages are thought to be nonspecific and diffused due to their several linkages by many species to different plants (Selosse et al. 2006). AMF symbiosis is an important biological mechanism to remediate polluted soils and mining spots (S. E. Smith and Read 2010). The microbes that benefit the health when consumed are known as probiotics. The concept of probiotics was given by the Nobel Scientist Élie Metchnikoff, who recommended that food requirement by intestinal microorganisms helps to exchange the detrimental microorganisms by beneficial microbes and to follow measures to adapt the microbial flora in our bodies. Soil probiotics are normally thought as soil-based organisms (SBOs), since they are advantageous bacteria which live in the soil. As the plants do not genetically acclimatize in the rapidly changing environment, i.e., drought, limited nutrients, and toxins, therefore, they may utilize the microorganisms to build the capacity for fast growth in the fluctuating environmental conditions for shorter life period. Hence, in this way, plants show the same mechanism as humans using probiotics to progress their health. Stimulation of plant-specific microbial species in their rhizosphere region tells us that plants can support and stimulate tactically to certain microbes, which have the ability to produce antibiotics that defend the plants against diseases causing soil pathogenic organisms (Weller et al. 2002). The bacterial species of the genus *Pseudomonas* are universal in many soils and participate in a lot of reactions, like bioremediation, nitrogen (N2) fixation, nutrient cycling, control, and inhibition of diseases, therefore promoting the plant growth. Pseudomonads work as a potential biocontrol agent against oomycete and fungi pathogens over the last two decades (de Souza 2002). Their most frequent property is antibiosis that is responsible for their reactions against the disease-causing plant pathogens, and a variety of antipathogenic compounds are also recognized, e.g., biosurfactant, hydrogen cyanide (HCN), pyoluteorin, pyrrolnitrin, phenazines, and 2,4-diacetylphloroglucinol (2,4-DAPG) (Picard and Bosco 2008). Their quick response capability to variations in nutritional, carbon, chemical, and physical conditions in the soil is very highly beneficial in agriculture, environment, and ecosystem functioning.

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Chapter 5
Climate Change Impacts on Legume Crop Production and Adaptation Strategies

Mukhtar Ahmed, Aashir Sameen, Hajra Parveen, Muhammad Inaam Ullah, Shah Fahad, and Rifat Hayat

Abstract Climate change is a major constraint limiting legume production across the globe. Legume crops are a good source of food, feed and fodder, and they are grown on large scale in the arid and semi-arid tropics. Grain legumes provide great services to the ecosystem by fixing atmospheric nitrogen (N) through bacteria in root nodules, a process called biological N fixation (N-fixing symbiosis). Hence, legume can help to minimize emissions of greenhouse gases (GHGs), e.g. N_2O, CO_2 and CH_4, reduce fossil fuel energy and boost C sequestration in the soil. Climate models have predicted more occurrence of climate extreme events in the future. These events will impede the legume production by disturbing the growth and development of crop. Hence, in this chapter, we discussed the impact of heat stress, elevated CO_2 concentration eCO_2, drought and rainfall variability on legume crop production so that adaptation options can be suggested for the sustainable crop production. Results showed that legumes having C3 fixation pathway have shown higher rate of photosynthesis, reduction in photorespiration, more biomass production and higher water use efficiency under eCO_2. However, with the rise in temperature, plants show faster development rate, shorter life cycle, shorter grain filling duration and lower yield. Similarly, the positive impact of eCO_2 on nodulation was hampered by rise in temperature. In general, legume could cope eCO_2 even up to 1000 ppm by carbohydrate allocation in the form of sucrose and its storage as starch. Moreover, apart from starch mobilization, protein synthesis in legumes helps them to adapt in the

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changing climate. Water stress is another climate extreme event that limits the legume crop production at all phenological stages, but its impact is more severe during flowering and grain development phases, called terminal drought. Hence, adaptation options such as development of new climate-resilient legume crop cultivars, ideotype designing through use of process-based crop models, change in sowing dates, availability of short duration cultivars, use of precision agriculture tools for accurate application of irrigation and fertilization, intercropping, switching to better adapted legume cultivars and crop diversification are needed to combat the negative impact of climate extreme.

Keywords Climate change · Legume · Heat stress · Elevated CO_2 concentration eCO_2 · Drought and adaptation

5.1 Introduction

Legumes belong to the family Leguminosae or Fabaceae. The new name Fabaceae comes from the extinct genus *Faba* now part of *Vicia* genus (vetches). Faba word came from Latin which mean bean. However, the old name still works as it is related to a fruit name, i.e. legume. It is one of the agriculturally important large family of flowering plants. It includes trees, shrubs and annual/perennial herbaceous plants. Legume family has 765 genera and 20,000 species, and it is the third largest family on land. Legumes have worldwide distribution except Antarctica and the high Arctic. Legumes rank third in crop production after cereals and oilseeds. Legume crops are a good source of food, feed and fodder, and they are grown on large scale in the semi-arid tropics (Sita et al. 2017; Cernay et al. 2016). Legume plants can fix atmospheric nitrogen (N_2) through their symbiotic relationship with bacteria present in their root nodules. This fixation of N_2 is called biological nitrogen fixation (BNF). Legume plants are also called nodulated plants as well as additive or restorative plants as they can provide nutrients to the soil. These plants can be easily identified through compound stipulate leaves and dehiscent fruit, which can open in two sides. Legume seeds are also called pulse when used as dry grain, or pulse is the edible seed of legume. Legume is mainly used as a human diet as well as part of livestock forage and silage. Legumes as forage have two broad types: (i) pasture legume grazed by livestock, including alfalfa, clover, vetch, and arachis, and (ii) woody shrub or tree species, e.g. *Leucaena*/*Albizia*. Legumes have also been used as green manure crops, and they play a key role in crop rotation. Dominated legume plants across the globe include alfalfa, beans (black beans, guar or cluster bean, soybeans, mung bean, mashbean, kidney beans, faba bean, etc.), carob, clover, chickpeas, lentils, lupins, mesquite, peanuts, peas, tamarind, etc. Legume plants use C3 cycle to fix atmospheric carbon dioxide (CO_2). Legumes can be classified into cool season and warm tropical season legumes. Cool season legumes include lentil, lupin, chickpea, dry pea, grass pea, vetch and broad bean (Andrews and Hodge 2010). The legumes that can be grown in warm seasons and in hot and humid conditions are mung bean, pigeon pea, cowpea, common bean and urd bean (Singh and Singh 2011). Duc et al.

(2015) reported that grain legumes that have been consumed largely across the globe are lentil, chickpea, field pea, mung bean, common bean, broad bean, kidney bean and pigeon pea. Grain legumes are the biggest source (33%) of plant protein. Different types of legumes have been shown in Figs. 5.1a and 5.1b. Mainly, legumes can be divided into oilseed and non-oilseed legumes (Fig. 5.1b). Soybean and peanuts are the main examples of non-oilseed legumes, while oilseed legumes can be divided into fresh and dried legumes. Dried grain legumes are called pulses, and it can be further subdivided into lentil, dry bean, dry pea, chickpea and cowpea. Lentil's name came from the Latin word "lens" as the seed of these legumes looks like small lens. The list of legumes, which are available at FAOSTAT data set,

Fig. 5.1a Different types of dry legumes

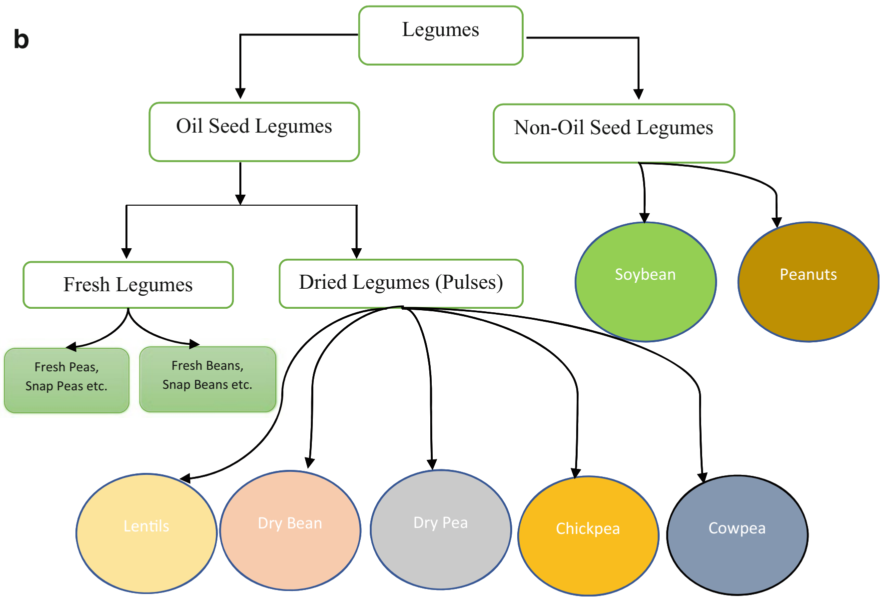


Fig. 5.1b Types of legumes

includes pulses, soybeans, pigeon peas, peas, lupins, lentils, groundnuts with shell, carobs, dry cowpeas, chickpeas, dry beans and Bambara beans. The production trends for these legumes have been shown in Figs. 5.2a and 5.2b. Furthermore, yield map of legumes with yield trend from 1980 to 2020 has been presented in these figures (Figs. 5.3a, 5.3b and 5.3c).

5.2 Nutritional Benefits of Legumes

Grain legumes are a rich source of protein (16–50%), dietary fibre (10–23%), essential elements (Fe, Ca, Mg, Zn and K) and vitamins. They are precious gifts to mankind and often known as the poor man's meat. Wang et al. (2009) reported that grain legumes are a storehouse of multiple nutritional components that include carbohydrates, sugars, vitamins, mono- and polyunsaturated fatty acids as well as more than 15 essential mineral elements. Grain legumes also contain folic acids, lectins, phytate, trypsin inhibitors and polyphenolic non-nutritional bioactive components. Pulse inclusion in a diet plan prevents a person from various health problems (e.g. type 2 diabetes, cardiovascular diseases and some forms of cancer), and it also reduces the risks of obesity. Pulses act as a tonic of the body as they digest slowly and provide slow-burning energy with a good supply of iron, which can help to provide oxygen throughout the body, thus boosting energy production and metabolism. Furthermore, the fibre in the pulses increases stool volume and transit, and it can also bind toxins and cholesterol in the gut so that it can be removed from the body. This helps to improve heart health and lower level of blood cholesterol. Pairing of pulses with grains prepares the ideal balanced diet, as pulses are rich in lysine protein and low in sulphur-containing amino acids, while grains are low in lysine and high in sulphur-containing amino acids. The top ten reasons to recommend pulses in diet plans are as follows: (i) low-fat, (ii) low sodium, (iii) good source of iron, (iv) good source of protein, (v) excellent supplier of fibre, (vi) excellent source of folate, (vii) good supplier of potassium, (viii) low glycaemic index, (ix) cholesterol-free and (x) gluten-free.

5.3 Area, Production and Yield of Grain Legumes

The grain legumes are grown on an area of more than 81 million ha with a global production of greater than 92 million tonnes (FAOSTAT 2022). India is the topmost producer of grain legume production, and it accounts for one-fourth of the global grain legume production. India is also the largest consumer of grain legumes. Other major grain legume-producing countries include China, Myanmar, Canada, Australia, Brazil, Argentina, the USA and Russia. Soybean is the top growing legume with an area of 126.95 million ha, production of 353.46 million tonnes and yield of 27,842 hg ha^{-1}. However, dry bean is the widely grown grain legume

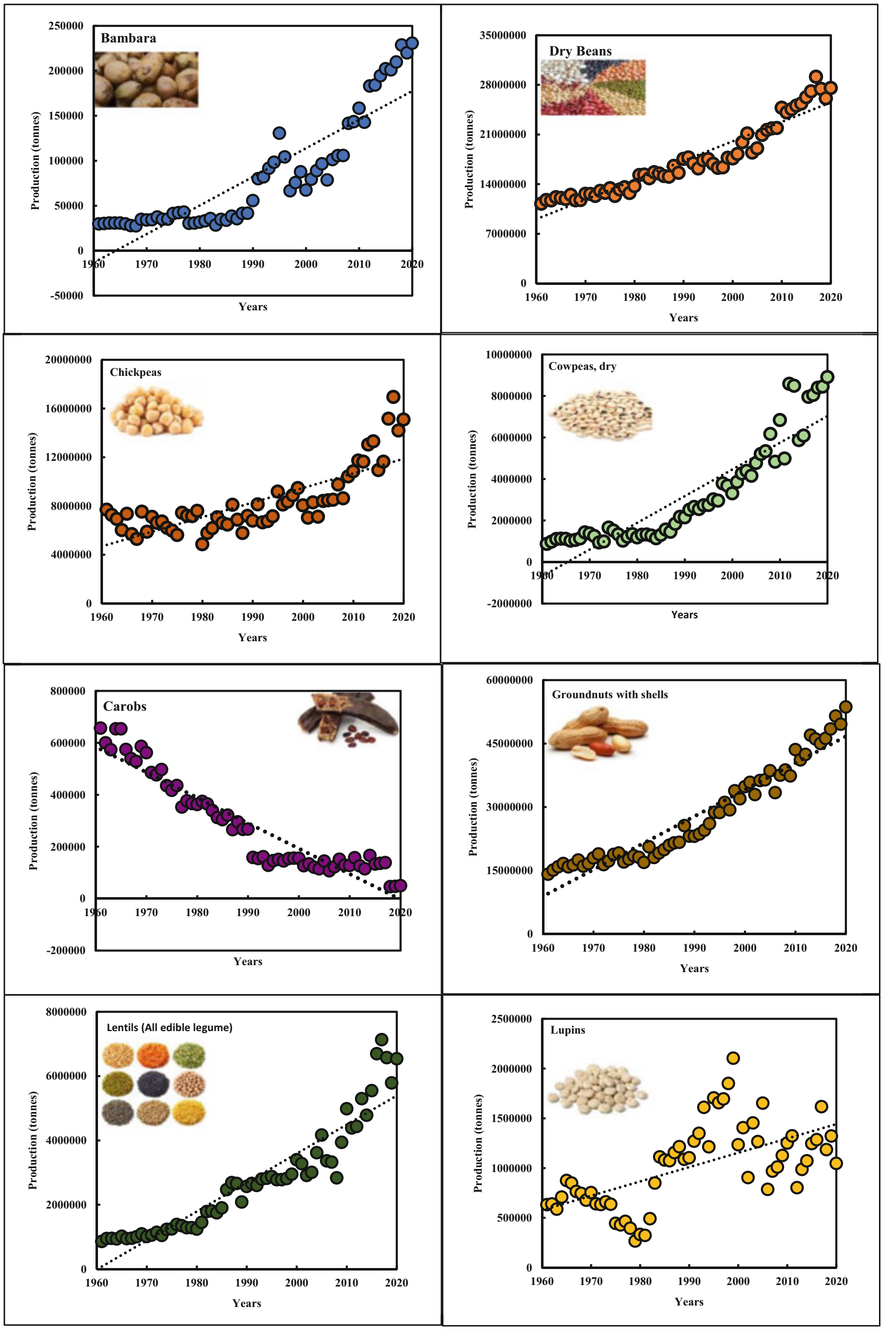


Fig. 5.2a Production trends for legume crops. (Source: FAOSTAT 2022)

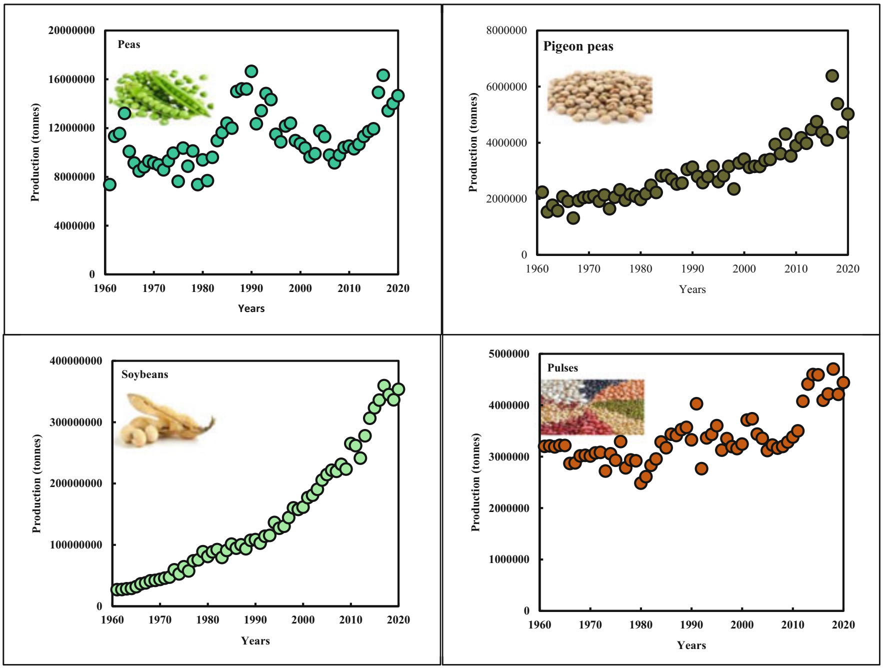


Fig. 5.2b Production trends for legume crops. (Source: FAOSTAT 2022)

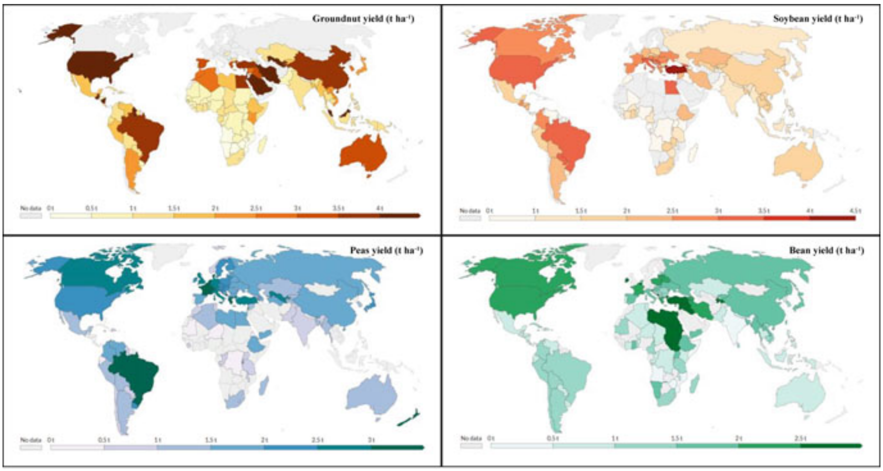


Fig. 5.3a Yield map of some legume crops. (Source: FAOSTAT 2022)

with an area, production and yield of 34.80 million ha, 27.54 million tonnes and 7915 kg ha^{-1}, respectively. Groundnut with shells is grown on an area of 31.56 million ha with production and yield of 53.63 million tonnes and 16,991 kg ha^{-1},

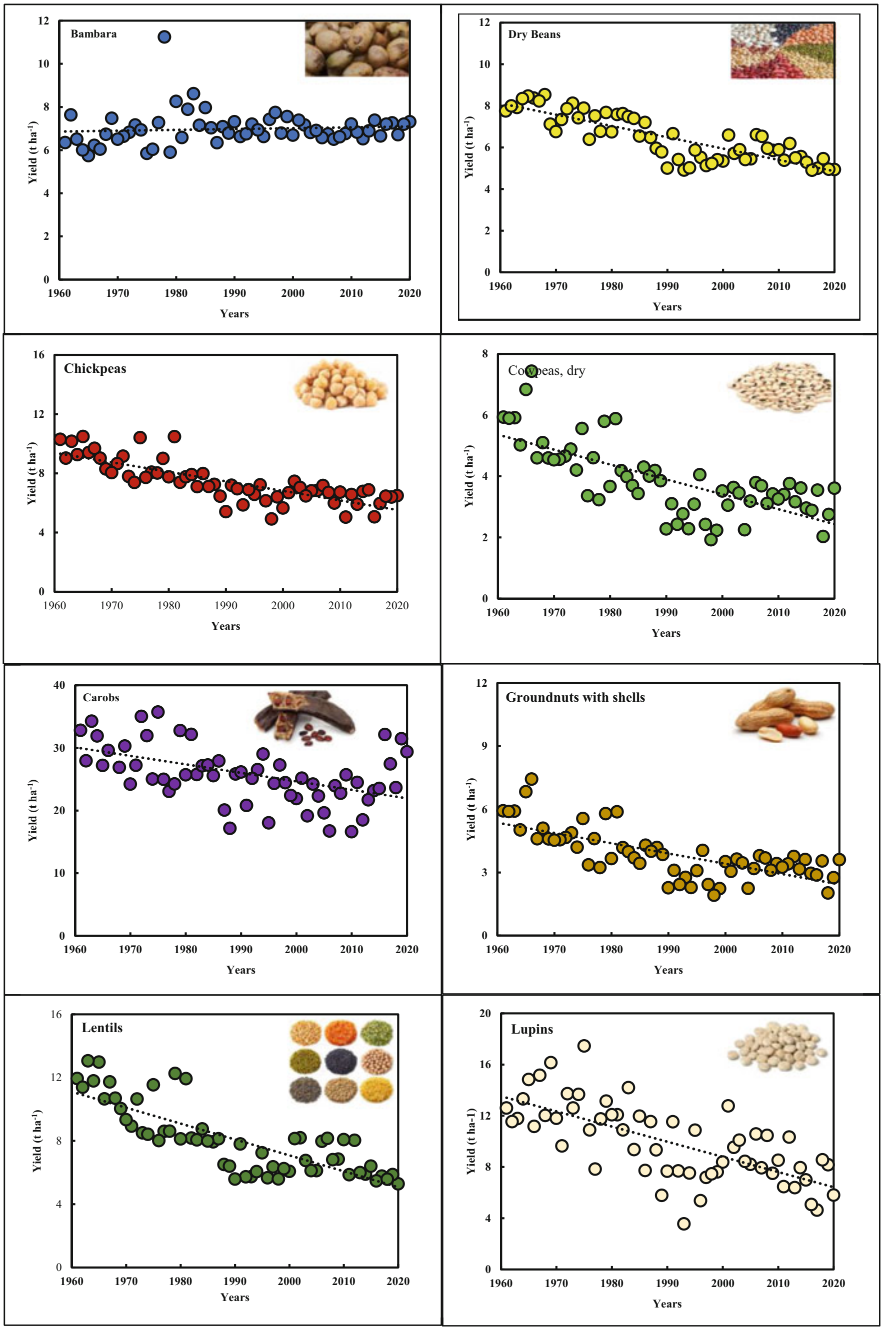


Fig. 5.3b Yield trends of legume crops. (Source: FAOSTAT 2022)

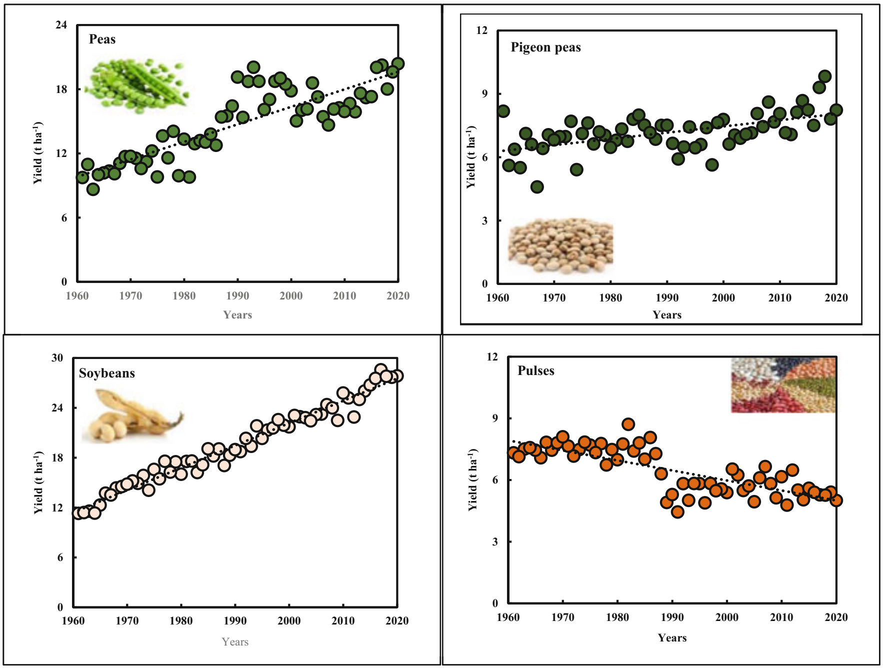


Fig. 5.3c Yield trends of legume crops. (Source: FAOSTAT 2022)

Table 5.1 Area, production and yield of main grain legumes across the globe (FAOSTAT 2022)

Crops	Area (million ha)	Production (million tonnes)	Yield (kg ha^{-1})
Beans, dry	34.80	27.55	7915
Chickpeas	14.84	15.08	10,163
Cowpeas, dry	15.05	8.90	5912
Groundnuts, with shell	31.57	53.64	16,991
Lentils	5.01	6.54	13,049
Peas, dry	7.19	14.64	20,364
Soybeans	126.95	353.46	27,842

respectively. Dry cowpeas occupy an area of 15.05 million ha with production and yield of 8.90 million tonnes and 5912 kg ha^{-1}, respectively (FAOSTAT 2022). Further details about other legumes have been given in Table 5.1.

5.4 Legumes and Ecosystem Services

Grain legumes provide great services to the ecosystem by fixing atmospheric nitrogen (N) through bacteria in root nodules, a process called BNF. This phenomenon can solve the problem of protein malnutrition across the globe as shown in the

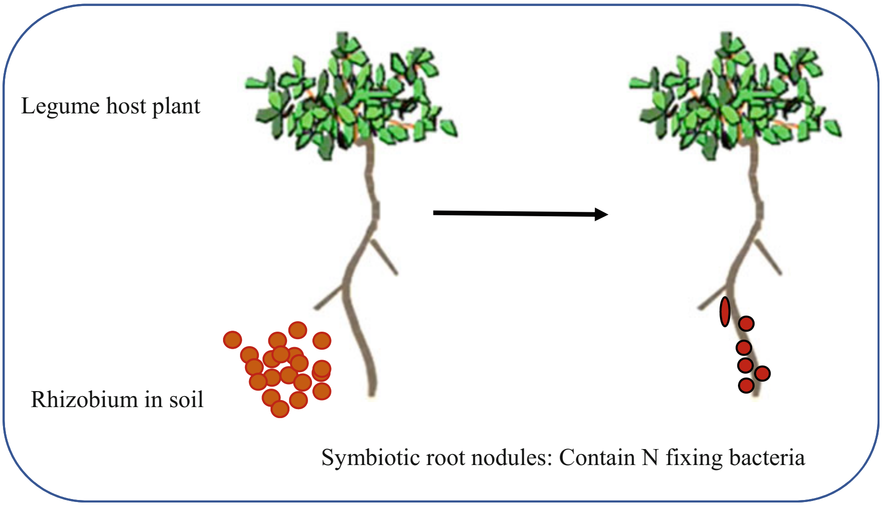


Fig. 5.4 Legume symbiosis with N-fixing bacteria

equation where legume plants in collaboration with *Rhizobium* bacteria can convert molecular nitrogen (N_2) to chemical N. However, these bacteria require energy that comes through plant photosynthesis, and they all are very species specific. Specialized root nodules are formed by legume plants to host N-fixing bacteria (rhizobia). These legume plants can grow without exogenous N fertilizer, and they are high in protein with ability to provide nutrition to the surrounding plants. Legume and bacteria symbiosis has been further elaborated in Figs. 5.4 and 5.5.

$$\text{Legume plants} + \text{Rhizobium bacteria} \rightarrow NH_3 \text{ produced inside root} \rightarrow \text{Protein}$$

Biological N fixation could help to minimize the emission of GHGs and groundwater pollution. Yue et al. (2017) reported from China that GHG emission from soybean production is 1% while it was 30%, 8%, 6% and 4% from cereals, vegetables, fruits and cash crops, respectively. Similarly, legumes can curtail global CO_2 emissions (>300 Tg year^{-1}) up to 50% that come from N fertilizer industries. Legume-rich feeds for ruminants can minimize CH_4 emissions as legume-based feeds contain less fibre, condensed tannins and saponins and have faster rate of passage. This leads to reduced cell wall digestion and modified rumen methanogenesis. Jensen et al. (2012) reported lower emissions of nitrous oxide in legumes (1.02 kg N_2O-N ha^{-1} year^{-1}) as compared to cereals (2.71 kg N_2O-N ha^{-1} year^{-1}) where N was applied. Schwenke et al. (2015) documented the positive impact of legume to reduce GHG emission in subtropical Australia. The work was carried out with the objective that introduction of legumes in cereal-based cropping system could help to mitigate nitrous oxide (N_2O) emissions. The results showed that cumulative N_2O emissions (CNE) from N-fertilized canola (624 g N_2O-N ha^{-1}) were much higher than legume crops, i.e. chickpea (127–166 g

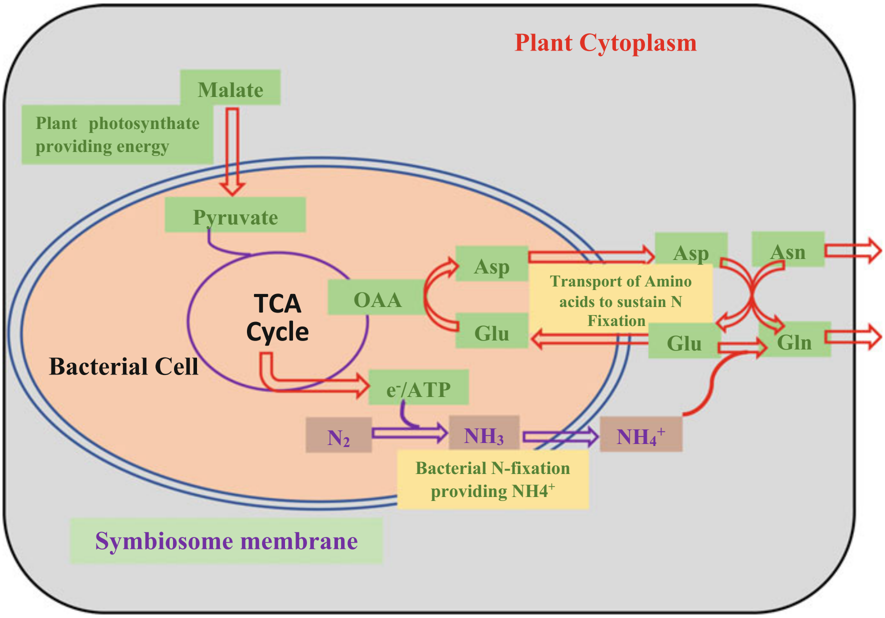


Fig. 5.5 Legume and bacteria symbiosis. *TCA* tricarboxylic acid, *OAA* oxaloacetate, *ATP* adenosine triphosphate, *Asp* aspartic acid, *Glu* glutamic acid, *Asn* asparagine, *Gln* glutamine

N_2O-N ha^{-1}), faba bean (166 g N_2O-N ha^{-1}) and field pea (135 g N_2O-N ha^{-1}). Similarly, N fixation provided higher total plant N biomass in chickpea (37–43%), field pea (54%) and faba bean (64%). Furthermore, the emission factor (EF) (percentage of input N emitted as N_2O) remained highest for canola (0.48–0.78%), while, in the case of legume, it was 0.13–0.31% for chickpea, 0.18% for field pea and 0.04% for faba bean. This study suggests that legumes should be part of all cropping systems as they have low EF. However, in another study conducted by Peyrard et al. (2016), higher N_2O emissions were reported due to legumes, which could be caused by faster decomposition rate of N-rich residues and denitrification. This exception in N_2O emission because of use of legumes could also be due to climatic conditions and management practices (Bayer et al. 2016). Ghosh et al. (2012) described C sequestration potential of legumes as they have deep root system, can fix N and have carbon-rich root exudates. Higher legume crop biomass and moderate rate of C mineralization have resulted to improve soil C retention in reduced tillage as compared to cereal crops (Bayer et al. 2016). Hazra et al. (2018) indicated legume potential to translocate C-photosynthate as root exudates and lignin-rich compounds, thus contributing largely to C sequestration and reducing C footprint. Legumes require less input to grow on marginal land and thus can bring prosperity to farming community living in problem soils. Legume can be a popular choice for farming community as they can withstand abiotic stress. Legumes are critical for the human nutrition as they can help to build resilience in combating system shocks such as COVID-19. It has now been proven that legumes have diverse application with unique properties; thus, their use could help in reducing GHG emissions and energy consumption, water conservation, C sequestration and soil health improvement. Furthermore, legume-rich diets provide greater health benefits with lower healthcare costs. Similarly, legumes could play an important role to fulfil the three important challenges in recent times, i.e. (i) population growth, (ii) urbanization and (iii) climate change.

5.5 Pulses: The Dry Edible Legumes

Edible dry grain seeds of legumes are called pulses. According to the Food and Agriculture Organization (FAO) (1994), plants that should be considered as pulses are given in Table 5.2. They grow in pods with variety of shapes, sizes and colours. Eleven types of pulses were recognized by the Food and Agriculture Organization (FAO). These are (i) Bambara beans, (ii) chickpeas, (iii) cowpeas, (iv) dry beans,

Table 5.2 Pulse plants as per FAO (1994) classification

Vernacular name	Scientific name
Common bean	*Phaseolus vulgaris* L
Lima bean	*Phaseolus lunatus* L
Scarlet runner bean	*Phaseolus coccineus* L
Tepary bean	*Phaseolus acutifolius* A Gray
Adzuki bean	*Vigna angularis* (Willd) Ohwi & H. Ohashi
Mung bean	*Vigna radiata* (L) R Wilczek
Mungo bean	*Vigna mungo* (L) Hepper
Rice bean	*Vigna umbellata* (Thunb) Ohwi & H Ohashi
Moth bean	*Vigna aconitifolia* (Jacq) Maréchal
Bambara bean	*Vigna subterranea* (L) Verdc
Broad bean	*Vicia faba* L
Common vetch	*Vicia sativa* L
Pea	*Pisum sativum* L
Chickpea	*Cicer arietinum* L
Cowpea	*Vigna unguiculata* (L) Walp
Pigeon pea	*Cajanus cajan* (L) Huth Lentil
Lentil	*Lens culinaris* Medik
Lupins	Several *Lupinus* L species
Hyacinth beans	*Lablab purpureus* (L) Sweet
Jack beans	*Canavalia ensiformis* (L) DC
Winged beans	*Psophocarpus tetragonolobus* (L) DC
Guar beans	*Cyamopsis tetragonoloba* (L) Taub
Velvet bean	*Mucuna pruriens* (L) DC
African yam beans	*Sphenostylis stenocarpa* (Hochst ex A Rich) Harms

(v) dry broad beans, (vi) dry peas, (vii) lentils, (viii) lupins, (ix) pigeon peas, (x) vetches and (xi) pulses nes (minor pulses). Pulse introduction in the cropping system is very beneficial and sustainable as they can minimize greenhouse gas (GHG) emissions, increase soil heath and use less water. In Pakistan the major grown pulses are chickpea, mung bean, lentil and mashbean, while on minor scale cowpea, faba bean, pigeon pea, common bean and moth bean are also grown.

Pulse production (0.7 Mt) in Pakistan is very low as compared to its requirement (1.5 Mt). Hence, Pakistan needs to import more than 50% of its pulses to fulfil its food requirements. The production and area of the major pulses during the last five decades in Pakistan have been shown in Fig. 5.6 (Ullah et al. 2020). The major reasons for low yield of pulses in Pakistan are as follows: (i) biotic and abiotic stresses; (ii) unavailability of quality seed and farm machinery; (iii) lack of crop improvements; (iv) competition with major crops; (v) soil issues, e.g. high pH, low organic matter and moisture; and (vi) support price and marketing issues. Moreover, climate extreme events, such as drought, heat waves and rainfall variability, are damaging pulse production in Pakistan. According to the Economic Survey of Pakistan, 2021–22 (https://www.finance.gov.pk/survey/chapter_22/PES02-AGRICULTURE.pdf), the area under pulse production is only 5% (1.5 mha), and due to

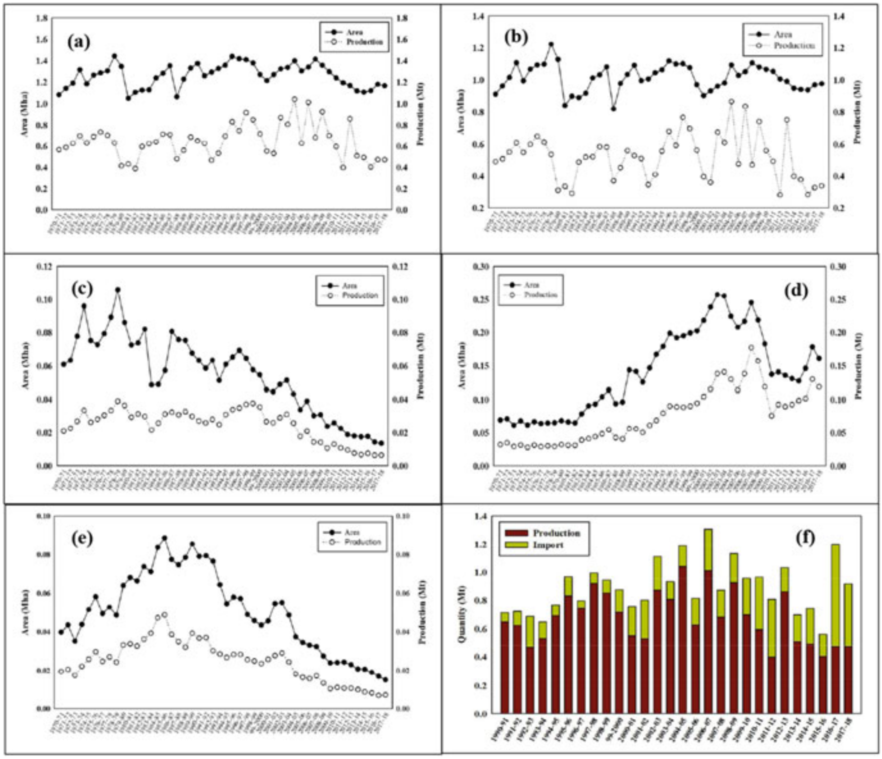


Fig. 5.6 Area and production statistics of (**a**) major pulses, (**b**) chickpea, (**c**) lentil, (**d**) mung bean, (**e**) mashbean and (**f**) import/deficit in Pakistan. (Source with permission: Ullah et al. 2020)

Table 5.3 Pulse area, production and yield during 2020–2021 in Pakistan

Crops	Area (000 ha)	Production (000 t)	Yield (kg/ha)
Chickpea	873	261	299
Lentil	6.5	4.9	754
Mung bean	231	204	833
Mash (black gram)	11	7	636

Source: Agriculture Statistics of Pakistan, 2020–2021

Table 5.4 Pulse area (hectares) in Pothwar region

Crops	Rawalpindi (ha)	Attock (ha)	Chakwal (ha)	Jhelum (ha)	Total (ha)
Chickpea	798	2500	9424	162	12,884
Lentil	1570	193	970	540	3273
Mung bean	618	191	1018	1337	3164
Mash (black gram)	2204	50	691	753	3698
Total	**5190**	**293**	**12,103**	**2792**	**23,019**

above-mentioned reasons, the area and yield declined drastically with the passage of time. The national average yield of pulses in Pakistan is less than one-fourth of the potential average yield of China, India, the USA and Australia. Generally, pulse production in Pakistan is centred in two regions, i.e. (i) Thal desert and (ii) Barani region. The pulse area, production and yield during 2020–2021 in Pakistan are given in Table 5.3. Similarly, pulse area in Pothwar region is given in Table 5.4. Distribution of pulses during kharif and rabi season of Pakistan has been shown in Fig. 5.7, which clearly illustrates that contribution of pulses to the total agricultural production is very low as compared to other kharif and rabi crops. Furthermore, pulse contribution in different cropping systems of Pakistan has been shown in Fig. 5.8. Pulses need attention in Pakistan as they are nature gifted crops, which can ensure food security, uplift human nutrition, improve soil health, bring sustainability in agriculture and help to mitigate climate change impacts. Since pulse production is very low, measures such as availability of quality seed and promotion of short duration pulses intercropped with major cereal crops could, therefore, help to boost pulse production. The Australian Centre for International Agricultural Research (ACIAR) is investing in the region to increase the pulse production in collaboration with the local stakeholders.

5.6 Pulse Benefits to Climate

Crop production, food security and climate change are interlinked with each other. Climate change has shown a profound effect on food production and quality of food. Similarly, climate change is shifting the production areas of food and non-food crops. Hence, urgent sustainable measures are needed to minimize the impact of

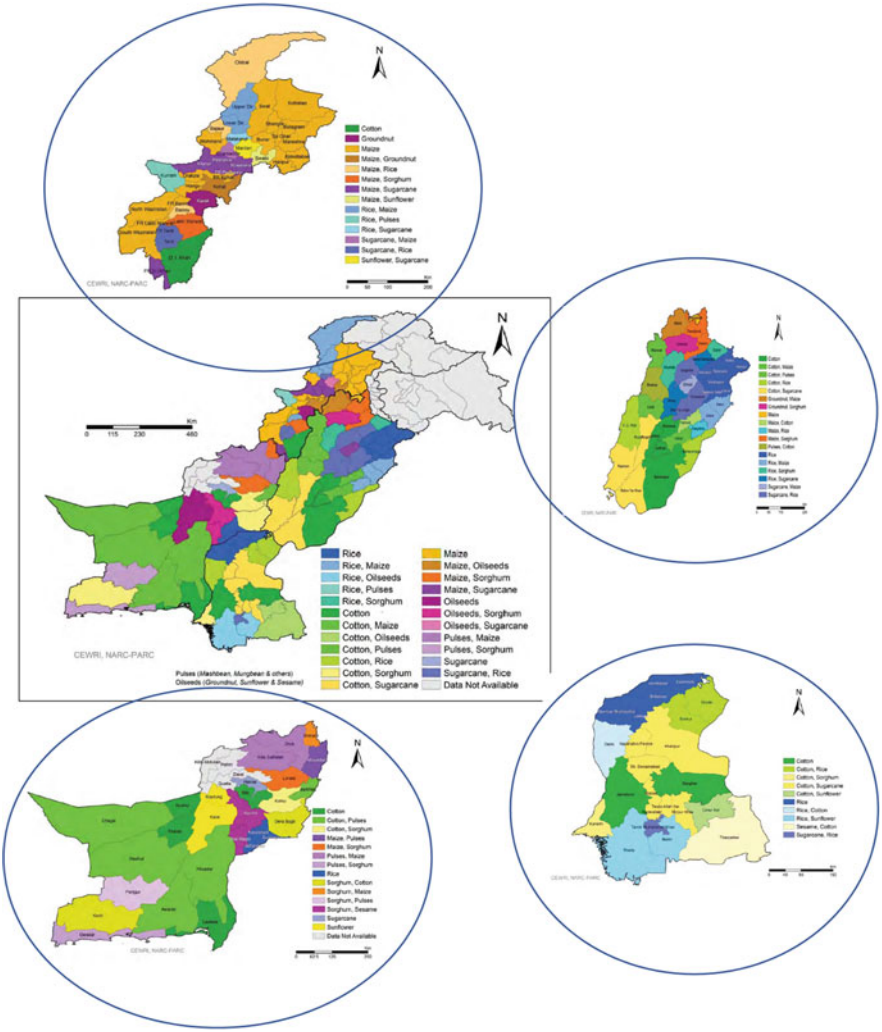


Fig. 5.7 Distribution of pulses in comparison with kharif crops in Pakistan. (Source: CIMMYT-Pakistan)

climate change, and under such circumstances pulses can be a good option. Pulse introduction in the cropping system will increase its resilience to climate change. Furthermore, pulses can increase crop productivity by nourishing the soil. Pulses are climate-smart crops as they can provide 5–7 million tonnes of N in soil, require less fertilizers, reduce the risks of soil depletion/erosion and promote higher C sequestration. However, improved pulse varieties will be required to minimize the impact of heat stress in the future. Pulses are very beneficial to minimize ecological footprint as introduction of pulses in the cropping system results to the fixation of N, which

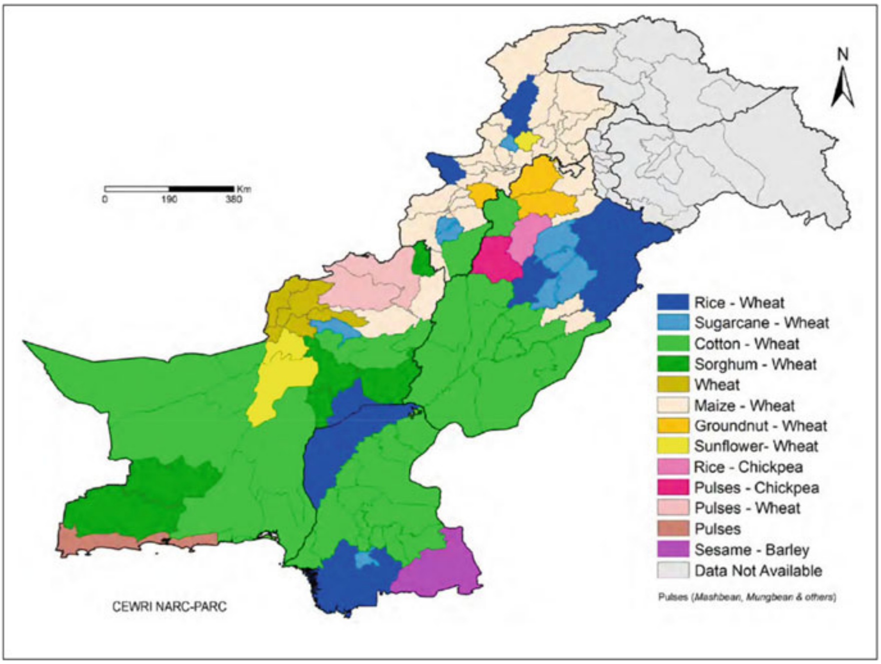


Fig. 5.8 Pulses share in different cropping system of Pakistan. (Source: CIMMYT-Pakistan)

increases grass yield and its feed values. Since grass grown as mixture with pulses resulted to the production of higher protein contents. This feed will further help to reduce GHG emissions from ruminants (Calles 2016) as it has already been well documented that agriculture is the fourth largest source of GHG emissions (Fig. 5.9) (IPCC 2007) and 4% of the global GHG emissions comes from the dairy sector (Gerber et al. 2010). Xu et al. (2021) reported doubled GHG emissions from animal-based foods as compared to the plant-based food. From animal-based foods it was 57% of the global GHG emissions (17,318 $\pm$ 1675 Tg CO_2 eq year^{-1}), while from plant-based foods it was 29%. The remaining 14% comes from other sources. Furthermore, they reported that farmland management contributes 38% to the total GHG emissions, while the share of GHG emissions from the land use change was 29%. South and Southeast Asia and South America are the largest emitters of the production-based GHG emissions as rice and beef production occurs in these regions. Smith et al. (2014) reported that 11% of the global GHG emissions comes from the agriculture sector and cattle produces 5335 Mt of CO_2 equivalents annually, which is almost 11% of the human-induced GHG emissions. Thus, it is essential to bring down all these GHG emissions, which is possible by adding legumes in the agricultural system as well as in the livestock feed. Furthermore, Rotz (2018) suggested that feeding protein (nitrogen)-rich diet to the cattle could help to reduce the emissions of NH_3, N_2O and nitrates in excreted manure. Data of GHG emissions per kilogram of food product shows that pulses release less GHGs (Fig. 5.10) as

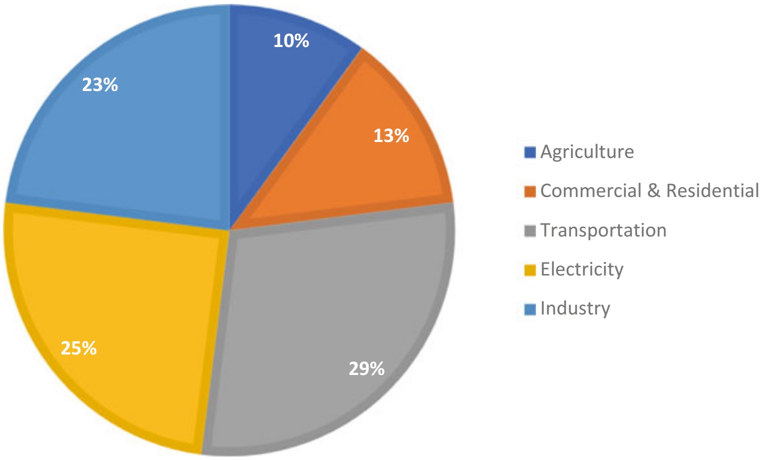


Fig. 5.9 Sector-wise emissions of greenhouse gases (GHGs)

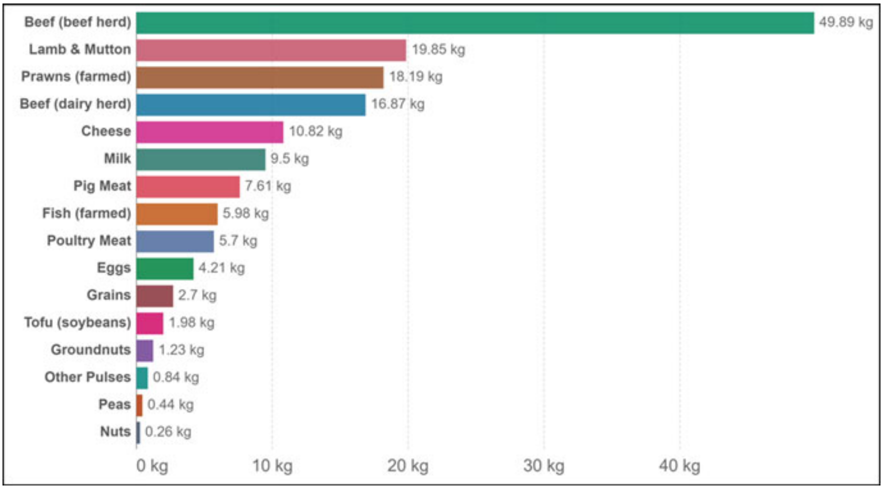


Fig. 5.10 Greenhouse gas emissions in kilograms of CO_2 equivalents (Kg CO_2 eq) per 100 grams of protein. (Source: https://ourworldindata.org/environmental-impacts-of-food)

compared to other sources. Furthermore, pulses can help to build sustainable food systems as they can be good alternatives in the production of bioenergy (Lienhardt et al. 2019). Pulses are environment-friendly crops as they help to reduce the application of synthetic N fertilizer (Jensen et al. 2012). This will help to minimize the emission of CO_2 in the air as synthetic N fertilizer production is also the biggest source of CO_2. Likewise, emissions of N_2O will be lower under pulses than crops and pastures where N will be applied. Leip et al. (2014) reported that the total N requirement to produce one N unit by pulse crop is very low, i.e. 1–2 kg kg^{-1} N product. Pulse acts as break crops in cereal-dominated crop rotations and could reduce insect, pest, disease and weed attacks (Liu et al. 2016).

5.7 Pulses as Food Security Boosters

Pulses have great potential to ensure food security and end hunger, which is a very important Sustainable Development Goal (SDG) of the United Nations, i.e. SDG2-Zero Hunger. Pulses can contribute to food security as it can be grown by small-holder farmers as an affordable source of protein, and due to their longer storability, they have low food wastage footprint (Bessada et al. 2019). Furthermore, pulses are suitable for marginal environments, and they are drought resistant with deep rooting features; thus, they have great potential to provide food and feed to dry environments. Pulses in the cropping system can give economic stability to the farming community. Farmers can get benefits from these crops by using them as feeds as well as storing them for longer period. Pulses also help to diversify the diets in developing countries. Furthermore, pulse incorporation in food systems could help to adapt to climate change.

5.8 Impact of Climate Change on Pulse Production

Climate change is one of the major threats to global pulse crop production. Pulse production from different regions of the world in the last two decades has been shown in Fig. 5.12. Around 25% of pulse production comes from the rainfed areas of the world where climate change is showing a significant impact (Fig. 5.11). India is the topmost producer of pulses followed by China (Fig. 5.12). According to the Intergovernmental Panel on Climate Change (IPCC), irreversible impacts of climate change will be more in the coming decades in the Asian subcontinent. This is already visible in the form of droughts, erratic rainfall and heat waves. Temperature during 2022 in India and Pakistan have reached at highest levels with April temperature (35.9 and 37.78 °C) broken the records of 122 years. This heat wave resulted to significant crop damage. It has been reported by experts that on average 7 °C increase in temperature in the month of April resulted to more than 500 kg ha^{-1} decline in the April wheat yield. Similarly, other crops, which include pulses, e.g. lentil and chickpea, have also been affected due to this rise in temperature. Since most of the pulse crops are heat sensitive, the sudden rise in temperature has, thus, shown significant damage to these crops. Furthermore, terminal heat stress at grain filling stages of rabi-sown pulse crops resulted to the declined yield. Thus, it is essential to develop proper mitigation strategies by considering both agronomic and breeding approaches. Similarly, intervention by the government is also needed to bring policies that can help to stabilize pulse crop yield in the future changing climate (Bera 2021).

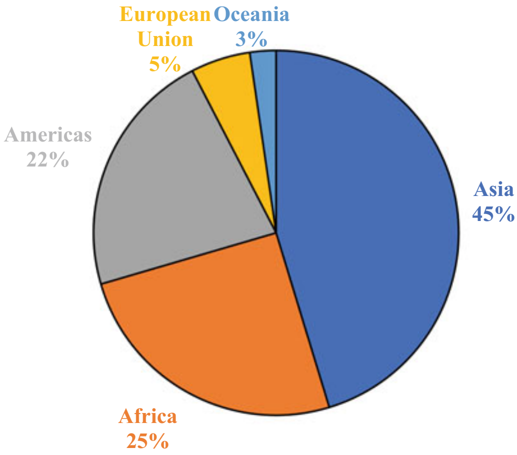


Fig. 5.11 Pulse production from different regions of the world in the last two decades

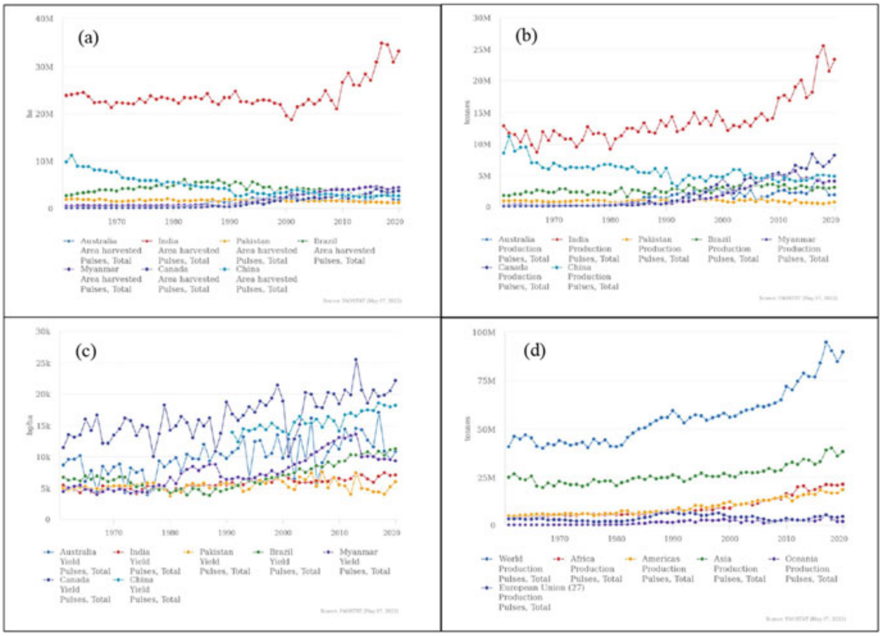


Fig. 5.12 Country-wise scenario of pulse harvested area (**a**), production (**b**), yield (**c**) and regional production in comparison with world production (**d**)

5.9 Institutes Working on Pulse Improvement

The International Center for Agricultural Research in the Dry Areas (ICARDA) is working, since quite a long time, for the promotion of sustainable agriculture in the dry areas of the world. It provides innovative science-based solutions to rural communities. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), headquartered in India (Hyderabad), is working on the improvement of pulses. ICRISAT is mainly conducting research for the improvement of dryland farming and agri-food systems. It was established in 1972 by the consortium led by the Ford and Rockefeller Foundations and was supported by the Government of India. ICRISAT provides innovative solutions in collaboration with the international partners to end hunger, poverty, malnutrition and environmental degradation in drylands of sub-Saharan Africa and Asia. ICRISAT has given early-maturing groundnut varieties (drought-escaping groundnut cultivar, ICGV 91114) that can produce higher yields by avoiding mid- and end-season drought. Similarly, high-yielding wilt-resistant chickpea variety was developed through genomics-assisted breeding. The Australian Centre for International Agricultural Research (ACIAR) is funding a lot to improve pulses in different countries. A large ACIAR project (CIM/2015/041) was implemented in Pakistan to increase productivity and profitability of pulses. Similarly, a scientific collaboration was established between ACIAR; National Agriculture Research Centre (NARC), Islamabad; Arid Zone Research Institute (AZRI), Bhakkar; and MNS-University of Agriculture, Multan to improve pulse production in rainfed areas of Pakistan. ACIAR is working hard in collaboration with the local stakeholders in Pakistan to reintroduce legumes in the ongoing cropping systems.

5.10 Quantification of Climate Variability Impacts on Legume Crops

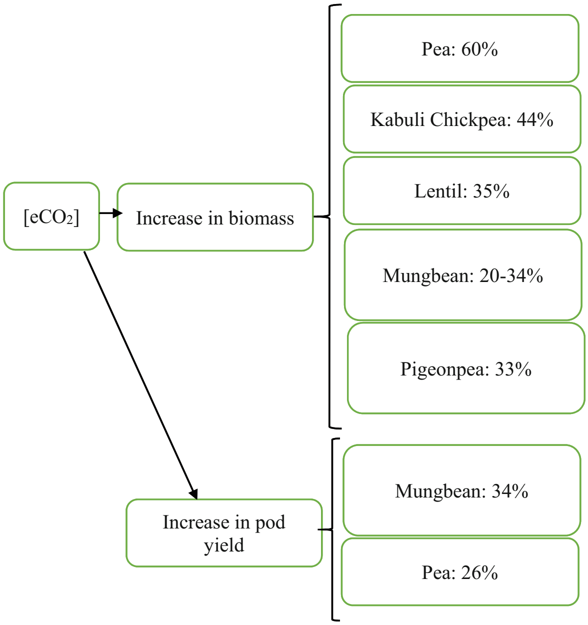
Climate is becoming hostile for food production, particularly in the semi-arid tropics (Cooper et al. 2008; Arunrat et al. 2022; Ahmed et al. 2022; Tui et al. 2021). Climate change in the form of rise in temperature, drought and variability in the rainfall has shown a significant impact on the agricultural production (Aslam et al. 2022; Bouabdelli et al. 2022; Arnell and Freeman 2021; Hernandez-Ochoa et al. 2018). Most of the prediction models had forecasted a 2–4 °C increase in temperature over the next century. Similarly, the concentration of CO_2 has been reached to 421 ppm as compared to pre-industrial time period when it was 278 ppm. CO_2 is now 50% higher than what it was before the industrial revolution. Furthermore, 10–20% increase or decrease in rainfall variability has been predicted. Annual variability in the climatic events is also increasing, and in the future crops will face more extreme events, e.g. heat waves and drought. Hence, it is essential to study the impact of heat stress, elevated CO_2 concentration eCO_2, drought and rainfall variability alone and in interaction on legume crop production so that adaptation options can be suggested for the sustainable crop production. Since legumes are dominantly grown in dryland conditions, drought will, thus, be the main yield-limiting abiotic stress for these crops. Therefore, to keep up the pace of agricultural production, improvement in the tolerance of legume crops to drought is an utmost important task. In the next sections, the response of legume crops to eCO_2, high temperature and water stress has been discussed so that prospects of grain legumes as climate-smart crops could be evaluated.

5.10.1 Impact of Elevated CO_2 Concentration eCO_2 on Legume Crops

Legume as a climate-smart crop sounds exciting, but the adverse effect of climate change on legume crop performance raises questions. eCO_2 has shown direct and indirect impacts on physiology and biochemical characteristics of grain legumes as reported in the past studies (Ainsworth et al. 2002; Mishra and Agrawal 2015; Palit et al. 2020). Legumes having C3 fixation pathway have CO_2 saturation point of 50–150 mg L^{-1} CO_2 as compared to C4 where it is 1–10 mg L^{-1} CO_2. Hence, under eCO_2 legume crops will do higher photosynthesis and maintain growth (Jin et al. 2012). Different studies confirmed the positive response of grain legumes to eCO_2 (Jin et al. 2012, 2013; Dutta et al. 2022; Singer et al. 2020; Sicher and Bunce 2015; Sulieman et al. 2015). Increasing CO_2 concentration from 350 ppm to 550 ppm in open-top chamber (OTC) resulted to 33% and 27% increase in the biomass of black gram and pigeon pea, respectively (Srinivasarao et al. 2016). Similarly, reduction in photorespiration due to eCO_2 was also reported by Srinivasarao et al. (2016). Furthermore, previous studies documented the positive impact of eCO_2 on growth and yield of other grain legumes, e.g. green gram, soybean, lentil, pigeon pea and chickpea (Pandey et al. 2016; Lam et al. 2012; Nasser et al. 2008; Saha et al. 2011; Bhatia et al. 2021). The impact of eCO_2 on biomass and yield of legume crops as reported earlier has been shown in Fig. 5.13.

Grain legume requires optimum supply of nutrients (N, P and K) and soil moisture to perform best as a climate-smart crop. Kimball (2016) reported complex relationship between eCO_2, crop performance and applied inputs through a meta-analysis of FACE (free-air CO_2 enrichment) experiments. Outcomes showed that the availability of N and water in C3 legumes, i.e. soybean and clover, resulted to 25% increase in shoot biomass while increase in C3 cereals (barley, rice and wheat) was 19%. eCO_2 resulted to 10% decrease in evapotranspiration in both C3 and C4 plants. Butterly et al. (2015) reported higher wheat biomass (55%) as compared to field pea (36%) due to eCO_2 and other input application. This higher benefit in wheat was due to dilution of tissue nutrient (Wang and Liu 2021). Furthermore, different past studies reported that in the future plants could be exposed to nutrient imbalance with lower N or higher C:N and C:P ratios due to eCO_2 (Sardans et al. 2012; Cotrufo et al. 1998; Yuan and Chen 2015). Decrease in nutritional quality due to eCO_2 was illustrated by Myers et al. (2014) and Loladze (2014) in their work and depicted Mg (9.2%), Fe (16.0%) and Zn (9.4%) deficiency in wheat, rice, vegetables and other C3 plants. Newton et al. (1996) stated that, in general, legumes (dicots) performed well as compared to cereals (monocots) under eCO_2 but cereals are more prone to water

Fig. 5.13 The impact of $[eCO_2]$ on biomass and yield of legume crops



stress than legume. Phosphorus (P) is a very important major macronutrient, which plays a critical role in the synthesis of ATP (adenosine triphosphate), the currency of energy as well as other biochemicals. Higher availability of P in the presence of eCO_2 resulted in the increase in biomass of field pea and chickpea, but the compensatory impact of eCO_2 under lower P was also reported for green gram (Zhang et al. 2014; Pandey et al. 2016). However, there was no consistent correlation observed between P and plant biomass under eCO_2 due to a number of reasons. One reason could be duration of exposure to eCO_2 as prolonged exposure to eCO_2 resulted to photosynthetic downregulation (plants acclimate and show a reduction in photosynthetic activity), which leads to lower crop yield (Sanz-Sáez et al. 2010). Other reasons for the downregulation under eCO_2 could be due to poor stomatal conductance and declined activity of rubisco (ribulose-1,5-bisphosphate carboxylase/oxygenase) (Rosenthal et al. 2014). Furthermore, C-sink limitation theory and N limitation hypothesis were given by Rogers et al. (2009) to provide other reasons for this downregulation. According to C-sink limitation theory, additional sinks are needed to translocate the carbon to the linked microbes; otherwise, this excessive carbon will limit the activity of rubisco. However, as per N limitation hypothesis, legumes fulfil additional N requirements by improving nitrogenase activity and nodule mass, which resulted to the overall increase in BNF (Sulieman et al. 2015; Goicoechea et al. 2014). Rogers et al. (2009) illustrated the positive (+), negative (−) and no effect of eCO_2 and nutrient supply on legume leaves, nodules and pods per seed parameter as shown in Fig. 5.14. This supports the hypothesis that greater photoassimilate production at eCO_2 resulted to higher nodule biomass and N fixation (Rogers et al. 2006; Ross et al. 2004).

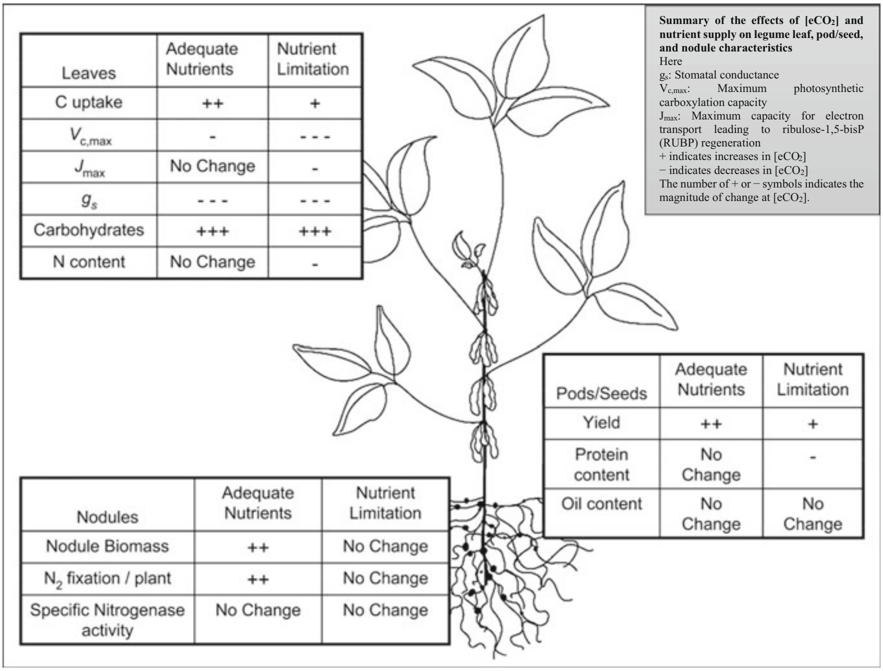


Fig. 5.14 Effect of eCO_2 on legume nodules, pods per seed and leaves. (Source with permission: Rogers et al. 2009)

5.10.2 Impact of High Temperature on Legume Crops

Temperature is the determinant factor of plant development, and rise in temperature is happening across the globe due to climate change (Song et al. 2022; Allan et al. 2021). Hence, plant productivity is on decline due to extreme temperature (Aslam et al. 2022; Hatfield and Prueger 2015). Small change in temperature can affect production of those crops, which are already growing close to optimum temperatures (Prasad and Jagadish 2015). Flowering is the most sensitive phenological stage among all crops, and rise in temperature during this crop developmental stage significantly affects crop production. Hatfield et al. (2011) provided cardinal temperature (Tc) values for different annual crops, which showed that vegetative development increases with increase in temperature and has higher optimum temperature. However, with the rise in temperature, plants show faster development rate, shorter life cycle, shorter grain filling duration and lower yield (Hatfield and Prueger 2015; Aslam et al. 2022; Naz et al. 2022; Fatima et al. 2020; Ahmad et al. 2019; Ahmed and Ahmad 2020). Legume crops, e.g. soybean, which is a photoperiod-sensitive crop, have also shown disruption in the phenological development due to rise in temperature. Similarly, extreme high temperature also resulted to a significant effect on pollen viability, fertilization and fruit or grain formation (Hatfield et al.

2011, 2020; Boote 2011). Furthermore, temperature rise (2–4 °C by the end of century) due to the global climate change will also result to the change in the weather parameters, such as solar radiation, wind speed, pan evaporation and vapour pressure deficit (VPD). According to Vadez et al. (2012), VPD and evapotranspiration (ET) are very important climatic variables that determine crop water use efficiency (WUE). Under the changing climate, plants must transpire huge amount of water to sustain biomass accumulation, but it will not be sustainable both environmentally and economically. Hence, drought-tolerant legume cultivars with lower transpiration under higher VPD should be screened to increase WUE under extreme temperatures (Sinclair et al. 2008). The nitrogen fixation potential of rhizobia is very sensitive to temperature, and it performs well at the optimum temperature of 20–25 °C. However, if there is any minor change in soil temperature, it could destroy the symbiotic relationship and BNF (Aranjuelo et al. 2014). Similarly, the positive impact of eCO_2 on nodulation could be hampered by rise in temperature. In general, legume could cope eCO_2 even up to 1000 ppm by carbohydrate allocation in the form of sucrose and its storage as starch. Furthermore, apart from starch mobilization, protein synthesis in legumes helps them to adapt in the changing climate.

5.10.3 Impact of Water Stress on Legume Crops

Water stress limits the legume crop production at all phenological stages, but its impact is more severe during flowering and grain development phases, called terminal drought (Farooq et al. 2017). This kind of drought has shown significant damage to legume crops in the arid and semi-arid tropics (Pushpavalli et al. 2015). Drought reduces biomass, yield and yield components of legume crops as shown in Fig. 5.15. However, the magnitude of reduction depends on the intensity and duration of the drought stress, crop phenological stage and genotypic variability. For example, in chickpea, stress at pod filling stage shows higher yield loss as compared to flower initiation. Terminal drought also leads to leaf senescence, oxidative damage, reduced C fixation, sterility of pollen, inhibition of flowering and reduced pod filling and development (Vadez et al. 2012; Sita et al. 2017; Farooq et al. 2009, 2017).

5.11 Modelling and Simulation

New legume crop varieties are required that can perform well under the changing climate. Plant breeders are targeting specific traits to provide climate-resilient cultivars. However, early assessments of such traits are necessary to get potential benefits to minimize significant investment losses. Process-based crop models can be used to design site-specific crop ideotypes by using crop, soil, environment and management data (Boote et al. 2003). These models have crop coefficients that represent genetic

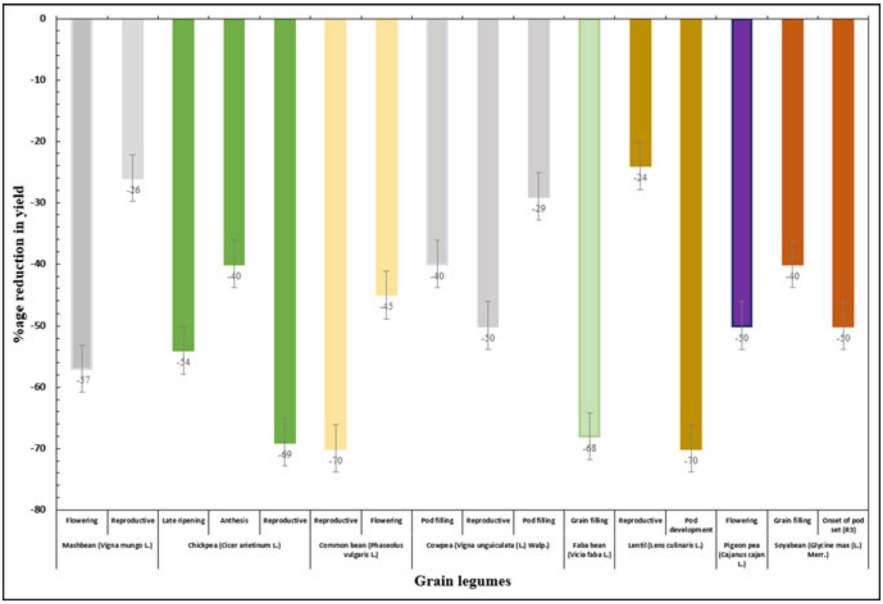


Fig. 5.15 Percentage reduction in the yield of grain legumes due to water stress

traits of cultivars, which can be modified within observed limit of genetic variability to evaluate the potential benefits of incorporating traits singly or in multiple combinations for the target site (Singh et al. 2012). Crop models have already been used by different researchers to suggest genetic improvement of crops under different climate change scenarios (Stöckle and Kemanian 2020; Boote 2011; Boote et al. 1996, 1998, 2001, 2003; Varshney et al. 2020; Hammer et al. 1996, 2002, 2010; Suriharn et al. 2011). Furthermore, the use of omics approaches (e.g. genomics, transcriptomics, epigenomics, proteomics and metabolomics) in combination with modelling and computational analysis could help to understand biological systems accurately (Lavarenne et al. 2018).

CROPGRO-Groundnut model was used by Singh et al. (2014b) with the objectives to develop high-yielding groundnut cultivars under heat and drought stress. Drought and heat tolerance and yield-enhancing traits were incorporated into the commonly grown chickpea cultivars. For drought tolerance enhancement in cultivars, changes were made in the relative root distribution function (WR) and lower limit (LL). Generally, the following equation is used to calculate WR for different soil layers:

$$\mathrm{WR}_{(L)} = \exp\left(-0.02 \times Z(L)\right)$$

where $Z(L)$ is the depth in metres to the midpoint of soil layer L. For the drought-tolerant cultivars, it was assumed that they will have greater rooting density and depth in soil profile; hence, the roots of drought-tolerant cultivars will go deeper to extract soil water. Therefore, the following equation was used to compute greater rooting density:

$$\mathrm{WR}_{(L)} = \left[1.0 - Z_{(L)}/5\right]^{P}$$

where P:6 and 5 was used for all soils. This increases WR with depth in soil profile. Furthermore, water in soil layer was also increased by 5% by reducing the LL using the following equation:

$$\mathrm{LL}_{(\mathrm{TOL})} = \mathrm{LL} - 0.05 \times (\mathrm{DUL} - \mathrm{LL})$$

where LL(TOL) is the LL for the drought-tolerant cultivar.

For the incorporation of heat tolerance traits, changes were made in the species file as there is no heat tolerance coefficient in the groundnut model. Thus, temperature tolerance of the three processes, i.e. (i) seed set, (ii) individual seed growth rate and (iii) partitioning of assimilates to reproductive organs, was increased by 2 °C to have heat-tolerant cultivars. The outcome of the study depicted that CROPGRO-Groundnut model could be used to develop heat- and drought-tolerant virtual cultivars, which can be a useful adaptation strategy under the changing climate.

Genetic traits of groundnut were evaluated by Singh et al. (2012) using CROPGRO to suggest adaptation options for the future climate. Modification in crop traits was made by changing crop phenological traits at first. The traits used were emergence to flowering duration (EM-FL) and seed filling to physiological maturity (SD-PM). These traits were increased by 10% alone and in combination. Similarly, SD-PM was increased by 10%, but EM-FL was reduced to keep the maturity the same. Furthermore, crop growth traits, i.e. maximum leaf photosynthesis rate (AMAX), specific leaf area (SLA) and leaf size (SIZLF), were increased by 10%. However, N mobilization from the leaves (NMOB) was reduced by 10%. Among the reproductive traits, pod adding duration (PODUR) was reduced by 10% to make the cultivar more determinant, while seed filling duration (SFDUR) and coefficient for maximum partitioning to pods (XFRT) were increased by 10%. In the case of root traits, the relative distribution of roots in the soil profile (SRGF) was decreased by 10% for 30 cm soil layer, and afterwards below 30 cm layer, it was increased by 10%. Similarly, the rate of rooting depth (RTFAC) was increased by 10%, while assimilate partitioning to the roots were increased by 2% via reducing partitioning to the leaves and stems. Furthermore, the turgor-induced shift of partitioning from shoot to root (ATOP) was reduced from 0.80 to 0.0. The ATOP value of 0 shows no shift, i.e. the root is less adaptive to plant water deficit, while the ATOP value of 1.0 represents maximum adaptive shift. The simulation outcome showed that increasing AMAX, XFRT and SFDUR resulted to higher pod yield in all climates. Similarly, productivity of groundnut under the changing climate could be increased by adjusting the duration of crop life cycle phases, particularly SD-PM. Moreover, under water stress conditions, shorter PODUR is recommended. This study recommended that CROPGRO model should be used to assess the potential of crop traits alone and in combination for multiple environments to design crop ideotypes under multiple stresses. Sennhenn et al. (2015) suggested that well calibrated and evaluated models can be a good tool for ex ante assessment of agricultural management interventions under the changing climate. Furthermore, they recommended that short-season grain legumes can contribute more to climate-resilient and productive farming system in dryland agriculture.

5.12 Adaptation Options for Legumes to Climate Variability

Ideotype to genotype approach can help to adapt crop phenology to climate change (Gouache et al. 2015). Different simulation models can be used to fulfil this task as model parameters could be linked to the markers. The model outcomes showed that earlier phenology can be a good stress-avoidance strategy in the future (Boote 2011; Singh et al. 2012; Boote et al. 1998, 2003, 2011; Suriharn et al. 2011). Similarly, the models themselves can be useful for developing crop adaptation strategies under the changing climate (Singh et al. 2014b). Other adaptation measures that can be useful to cope climate change impacts on legume crops include change in sowing dates, availability of short duration cultivars, application of precision agriculture tools for accurate application of irrigation and fertilization, intercropping, switching to better adapted legume cultivars and crop diversification (Ali et al. 2022; Ejaz et al. 2022; Tsegay et al. 2015; Ge et al. 2011; Thorp et al. 2008; Basso et al. 2001; Weih et al. 2022; Kherif et al. 2022; Wang et al. 2022; Singh et al. 2014a, b; Ahmed et al. 2022; Kollas et al. 2015; Jensen et al. 2012; Ghosh et al. 2012). Boote (2011) suggested use of cultivars with lower leaf area per plant and cultivars with earlier transition ability to reproductive phase in his work about improvement of soybean cultivars for adaptation to climate change and variability. Pulses have potential to outperform others under the changing climate by adopting strategies in which they can allocate more photoassimilates to the roots (Nie et al. 2013). Modification in root architecture under the changing climate is a very good adaptation option by which legumes can explore additional soil volume for water and nutrients. Hence, the investigation of root to shoot ratio in legumes should be considered to develop climate-resilient cultivars (Pritchard 2011). Kumar et al. (2019) emphasized on the use of systematic screening approach for the development of climate-resilient smart pulses.

5.13 Conclusion

Climate change has shown a significant impact on legume production, and risk is likely to increase in the future. The response of future legume crops will not only be dependent on eCO_2, but it will also be having strong association with other abiotic factors. Thus, it is essential to select and develop cultivars that can cope with climate extremes. It might also include cultivars with early vigour, shorter duration and higher root to shoot ratio. Similarly, genotypes with better WUE could help to give sustainable yield under dryland conditions. Furthermore, development of climate-resilient agrotechnologies is needed to adapt legumes to the changing climate and fulfil the food demand of rising population. The agrotechnologies could be adoption of conservation agriculture, use of plastic mulching, screening for heat- and drought-tolerant cultivars, application of precision agriculture, merging modelling with genetics and use of omics techniques in combination with modelling.

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Chapter 6
Cereal Crop Modeling for Food and Nutrition Security

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Abstract Rapid population growth, climate change, and limited natural resources have widened the gap between food production and consumption, contributing to global hunger. Improving cereal crop production is a critical hot spot challenge for closing this gap and ensuring global food security and nutrition. Previous data and findings from published literature demonstrated that cereal crop models have been applied and developed globally over the last 30 years under a wide range of climate, soil, genotype, and management conditions. However, when the models are applied to pests, diseases, phosphorus fertilization, potassium fertilization, iron, and zinc, further improvements are required. Furthermore, the integration of genotypes and phenotypes is critical for food security, necessitating careful consideration in crop models. We examined about 31 cereal crop models for increasing crop production and ensuring food and nutrition security. Furthermore, we discussed the current limitations in crop model application, as well as the critical need to integrate with

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other cutting-edge sciences, such as remote sensing, machine learning, and deep learning. This will undoubtedly improve crop model accuracy and reduce uncertainty, assisting agronomists and decision makers in ensuring food and nutrition security. In this chapter, we discussed the current and further improvements of cereal crop models in assisting breeders, researchers, agronomists, and policy makers in addressing current and future challenges related to global food security and nutrition.

Keywords Cereal crops · Crop models · Food security · Model limitations and improvements · Uncertainty · Machine learning · Remote sensing · Production

6.1 Introduction

Food security is suffering from many issues worldwide including but not limited to rapid population growth, limited soil and water resources and climate change (Godfray et al. 2010; Kheir et al. 2021), which definitely affected also on nutrition (Godfray et al. 2011). Agriculture provides food security as one of the most significant ecosystem services (Zhang et al. 2007). A sustainable food system (SFS) is a food system that provides food security and nutrition for all while ensuring that the economic, social, and environmental foundations for future generations are not jeopardized (FAO 2018). This means that it is profitable all the time (economic sustainability), has broad-based societal benefits (social sustainability), and has a positive or neutral impact on the natural environment (environmental sustainability). As a result, agricultural intensification and expansion have increased in recent decades to meet global food demand. Given the rising population's demand for food, the agriculture industry has a significant challenge in raising food crop productivity. As the three staple grains of wheat, rice, and maize represent about two-thirds of total daily calorie intake, improving their yields is essential (Cassman 1999). Globally, many attempts worked on enhancing crop production and decreasing the environmental impacts. Such experiments have faced by other encountered factors, such as weather, soil, and genotypes (Basso et al. 2011). Because of the variation in place and time, it's challenging to move crop dataset from region to another for the farming policy makers (Jones et al. 1998). Crop models (CM) are regarded as powerful tools for exploring the complex integration of soil, crop, climate, and management in order to provide valuable recommendations to decision makers that are difficult to provide in trial-and-error experiments (Ali et al. 2020; Asseng et al. 2018, 2019; Ding et al. 2021; Kheir et al. 2019).

During the initial decades, the Crop Environment Resource Synthesis (CERES) models were improved. CERES-Wheat (Otter and Ritchie 1985; Ritchie 1985), CERES-Maize (Jones et al. 1986; Ritchie 1985), and CERES-Rice (Ritchie et al. 1986) were developed first to predict grain yield only and then promoted as decision support tools when Decision Support System for Agrotechnology Transfer (DSSAT) was released (Jones et al. 2003). The CERES models are dynamic crop system models that predict the crop phenology and development on a daily time series (Ahmad et al. 2012, 2013, 2019; Abbas et al. 2017). The main components of water, nitrogen, phenology and soil are important for models to predict yield (Kheir et al. 2022). The most often tested and utilized crops are maize, wheat, and rice, although CERES models also include barley, grain sorghum, and pearl millet (Ritchie 1985). In addition, the crop modeling platforms also include Agricultural Production Systems Simulator (APSIM) (Keating et al. 2003), Environmental Policy Integrated Climate (EPIC) (Kiniry et al. 1995), CropSyst (Stockle et al. 2003), as well as STICS model (Brisson et al. 1998).

Crop models have been developed to investigate the yield gap and highlight potential challenges to food security (Ammar et al. 2022). Applications of the models included quantification of the yield gap (Schils et al. 2018; van Ittersum et al. 2016), gaps between available and consumption of food (Keating et al. 2014), and land reclamation is required to meet the population growth current and in the future (Gerten et al. 2020). However, the use of CM for soil fertility, particularly with potassium and phosphorus, pets, and diseases has received less attention thus far (Donatelli et al. 2017; Kheir et al. 2020). This chapter outlines the global challenges of food security, the role of cereal crop models to address such challenges, and the consequent policy recommendations.

6.2 Global Challenges and Solutions to Ensure Food Security

The United Nations' Sustainable Development Goals (SDGs) outlined the big issues for the coming decades (UN 2015). Based on SDG axes, it was required from the agricultural system to end the hunger and food insecurity and to enhance the nutrition, as well as to protect, restore, and promote the terrestrial ecosystem and alleviate the biodiversity loss (SDG 15) and thus combat climate change (SDG 13). Diverging paradigms about what to produce, where to produce it, and how to produce it will be the fourth major problem for agricultural science in the coming years.

6.3 Food Security and Nutrition

The food wedge analysis highlighted that even if the policy recommendations reduced the food losses and demand via changing the diets, about 46% of food demand in 2050 will be taken from increasing the crop productions (Keating et al. 2014). Understanding the difference between the potential or water-limited yield and the actual yield is required to meet the additional production needed for closing the future food demand (van Ittersum et al. 2013). In the analysis of food systems, health, nutrition, and quality are becoming increasingly important (Brouwer et al. 2020). This is critical in broadening the discourse on food security beyond staple (cereal) crops and evaluating the function of nutritional variety as a crucial component of agricultural systems. It also helps to put health and nutrition into context with other macroeconomic changes such as rising earnings and an expanding middle class.

6.4 Keeping Away from Diversity Loss and Changing Land Use

Land reclamation is important and required to close the food gap by meeting the required food demand (Foley et al. 2011). For the period 2002–2014, global reclamation land grew at a rate of 12.6 million hectares per year, indicating a significant shift that had not occurred previously (Cassman and Grassini 2020). More than half of this increase in farmland was dedicated to cereal crops. Despite the global vast agricultural land resources (Chamberlin et al. 2014), it is critical to conserve land for wildlife and avoid greenhouse gas emissions connected with land removal. This is especially true considering that the majority of biodiversity is situated outside of protected areas in human-managed production landscapes, where agricultural growth poses a substantial danger (Baudron and Giller 2014). Both land sparing and land sharing are viable choices for increasing agricultural productivity while limiting negative impacts on biodiversity, but the best method relies heavily on local conditions.

6.5 Adaptation and Mitigation to Climate Change

Due to its detrimental impact on agricultural yields, climate change is anticipated to place the world's food supply on a knife's edge (Rosenzweig et al. 2014), coupled with decreasing the suitable agricultural land. Increasing CO_2 and other greenhouse gases is the main driver to increase the global temperature, variability of rainfall, and extreme events. Climate change's detrimental effects on cereal wheat output have been assessed using CM (Asseng et al. 2015; Bassu et al. 2014), but this can be offset using appropriate CO_2 fertilization (Long et al. 2006). A considerable number of crop model applications deal with climate change adaptation, but there is an imbalance with other areas that could benefit from crop model insights. Exploratory studies mapping the suitability of a given region to introduce new crops are examples of the latter (Silva and Giller 2021), or regional resource use efficiency. Noticeably, most crop models target the field scale cropping systems (Table 6.1). Extrapolating from field to region is straightforward and appealing, but it ignores explanatory factors at the farm level, which is the most significant decision-making level. To address this constraint, spatially explicit crop models have been integrated with agricultural systems to assess trade-offs in management alternatives while taking farm heterogeneity into account (Antle et al. 2018; Capalbo et al. 2017).

Table 6.1 What can and cannot crop models do for predicting the yield and cluster levels at which they have been used

Item	Can do	Cannot do	References
Radiation	Yes		Chapman et al. (2020)
Temperature	Yes		Albasha et al. (2020)
Sowing	Yes		Bassu et al. (2020)
Water	Yes		Lopez-Bernal et al. (2020)
Nutrients (largely N)	Yes		Falconnier et al. (2020)
Pests		Yes	Rasche and Taylor (2020)
Diseases		Yes	Bregaglio et al. (2020)
Weeds		Yes	Colbach et al. (2020)
Field scale	Yes		ten Den et al. (2020)
Farm scale		Yes	Ngwira et al. (2020)
Cropping system	Yes		Kersebaum et al. (2020)
Farming system		Yes	None
Food system		Yes	None

Adapted from Silva and Giller (2021)

6.6 The Role of Cereal Crop Models

The CM could be applied to avoid the management problems following appropriate calibration and uncertainty quantification. Dynamic models are fundamentally complex hypotheses, and their testing and development entails identifying and changing the explanatory processes in the model that are responsible for an unsatisfactory representation of reality. The improvement and development is a complexed cycle of simulation experiments to generate and test the hypothesis (Rötter et al. 2018). Different crop models have been created exclusively, and the majority of CM exercises have focused on cereal crops. This is mainly due to the importance of cereals in food security and nutrition in most regions worldwide. Crop models have been applied to support plant breeding and improve cereal crop production and to reduce resource use in various environments (Dingkuhn et al. 2007; Kropff et al. 2013). In the last few decades, there has been evidence of changes in crop cultivar features and their responses to weather in many parts of the world. The creation of new rice varieties, such as semidwarf variants in the 1960s and hybrid rice varieties in the 1970s, has resulted in a rise in rice grain output across Asia. Because of the creation of semidwarf rice varieties, for example, China's rice output potential improved by around 30% (Fang et al. 2004), achieving 20% increase in yield when heteros are used (Virmani et al. 2003). In China, it was found that the vegetative growth in spring wheat decreased by 30% due to warming effect (Tao et al. 2012). Many studies have been conducted to demonstrate the importance of cereal crop models in simulating yield for use in food security strategies and policy recommendations for decision makers (Gautam et al. 2015; Liu et al. 2013; Zhang et al. 2016).

6.7 Principle Disciplines and Integrating Innovations

Most of CM have been used for simulating crop growth and development based on plant physiology and biology. However, combining crop models with other innovations such as remote sensing, machine learning, big data, and deep learning has less attention so far. These innovations frequently necessitate the creation of new sorts of models or the repackaging of current models in new programming languages (i.e., Python, R, C++) that enable their integration with new forms of data and big dataset (de Wit et al. 2019). This integration will undoubtedly improve the accuracy of CM in designing sustainable food systems, especially in light of population growth and large datasets (Basso and Antle 2020). Recently, a big dataset derived from remote sensing images has been generated, which could be used for CM to be applied at a wide range of spatial and temporal resolutions (Dharmawan et al. 2021; Sishodia et al. 2020). For example, spatial satellite image data combined with crop models improved crop yield, water use, N uptake, and resource use efficiency predictions (Huang et al. 2019). Machine learning has also proven useful in calibrating crop models based on big phenotyping data for specific genotypes (Chapman et al. 2020).

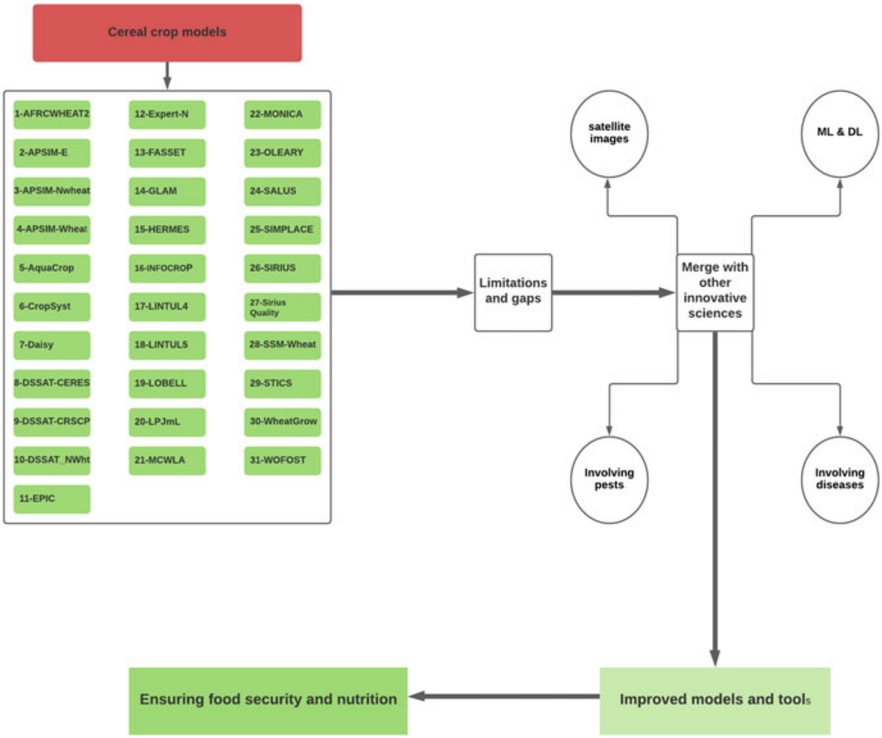

Fig. 6.1 Analytical framework highlighting the cereal crop models in literature and the potential for improvement for ensuring food security. (Own preparation by authors)

Nonetheless, this important field still requires a great deal of attention with multi-machine learning models in various environments. Therefore, we summarized cereal crop models from the literature and developed an analytical framework highlighting the potential for improving such models to ensure food security and nutrition (Fig. 6.1). Furthermore, the relative references for each model were gathered and summarized in Table 6.2.

Table 6.2 Cereal crop models in literatures

No.	Model	References
1	AFRCWHEAT2	Porter (1993)
2	APSIM-E	Keating et al. (2003) and Wang et al. (2002)
3	APSIM-N wheat	Asseng et al. (1998, 2004) and Keating et al. (2003)
4	APSIM-wheat	Keating et al. (2003)
5	AQUACROP	Stedduto et al. (2009) and Vanuytrecht et al. (2014)
6	CropSyst	Stockle et al. (2003)
7	DAISY	(Hansen et al. (1991, 2012)
8	DSSAT-CERES	(Hoogenboom and White (2003), Jones et al. (2003) and Ritchie et al. (1985)
9	DSSAT-CROPSIM	Hunt and Pararajasingham (1995) and Jones et al. (2003)
10	DSSAT-N wheat	Holzworth et al. (2014) and Kassie et al. (2016)
11	EPIC	Kiniry et al. (1995) and Williams et al. (1989)
12	Expert-N	Biernath et al. (2011), Ritchie et al. (1987) and Stenger et al. (1999)
13	FASSET	Berntsen et al. (2003) and Olesen et al. (2002)
14	GLAM	Challinor et al. (2004) and Li et al. (2010)
15	HERMES	Kersebaum (2007, 2011)
16	INFOCROP	Aggarwal et al. (2006)
17	LINTUL4	Shibu et al. (2010) and Spitters and Schapendonk (1990)
18	LOBELL	Gourdji et al. (2013)
19	LPJmL	Beringer et al. (2011) and Gerten et al. (2004)
20	MCWLA-wheat	Tao and Zhang (2013) and Tao et al. (2009)
21	MONICA	Nendel et al. (2011)
22	OLEARY	Latta and O'Leary (2003) and O'Leary et al. (1985)
23	SALUS	Basso et al. (2010) and Senthilkumar et al. (2009)
24	SIMPLACE	Angulo et al. (2013)
25	SIRIUS	Semenov and Shewry (2011)
26	Sirius quality	He et al. (2010)
27	SSM-wheat	Soltani et al. (2013)
28	STICS	Brisson et al. (2003)
29	WHEATGROW	Pan et al. (2007)
30	WOFOST	Boogaard and Kroes (1998)
31	LINTUL5	Shibu et al. (2010) and Spitters and Schapendonk (1990)

Adapted from Kheir et al. (2020)

6.8 Conclusion

The world's food systems face significant challenges, including gaps between food production and consumption caused by land degradation, rapid population growth, climate change, and limited natural resources, such as soil and water. These challenges necessitate the use of unconventional methods to meet the technology trend, large datasets, and the pressing need for food security and nutrition. Cereal crops are the most common and important crops for quantifying and addressing food security but require further improvements in production. The defined cereal crop models can investigate potential future of yield production, and adaptation for stresses. However, with new trials and cultivars, the current crop models will need to be improved and developed further. Furthermore, simulating processes at the cropping system level and contextualizing global model application and food systems should also be considered. Consequently, combining new innovative sciences such as remote sensing, machine learning, and deep learning with crop models will improve prediction accuracy and reduce uncertainty, assisting in the preparation of policy recommendations for decision makers. Integrating cereal crop models with other cutting-edge sciences will improve yield predictions and help policy makers make appropriate adaptation recommendations to ensure food security and nutrition.

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Chapter 7
Changing Climate Scenario: Perspectives of *Camelina sativa* as Low-Input Biofuel and Oilseed Crop

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Abstract High population shifts and climate change are putting thrust on the food industry, especially edible oil production. Monoculture of high-input crops certainly affects the crop yield and soil health. The import of edible oil is increasing in the major part of the world, putting some burden on the national exchequer of the countries. The current oil crops are unable to meet the deficit to address the problems; a crop with distinct features must be incorporated in the cropping system.

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[*Camelina sativa* (L.) Crantz], a unique profiled biodiesel crop, is famous as gold of pleasure, and its oil is famous as a golden liquid. Camelina oil is an outstanding feedstock for the bio-based industry since its unique composition allows multiple applications. It is a rich source of oil >43%, which comprises a huge amount of unsaturated fatty acids, which accounts for 90%, containing 30–40% of alpha-linolenic acid and 15–25% of linoleic acid. The revival of this unique oilseed crop was based on (a) numerous inherent promising physiognomies, vigorous agronomic characteristics, eye-catching oil profile, genetic continuity with *Arabidopsis*, and the comfort of genetic remodeling by floral dip; (b) the investment in camelina which is understood as it merits serious considerations as potential biodiesel and oilseed and which shares a big role toward the sustainability along with increasing the diversity and production of plant oils; and (c) a univocal and descriptive portrayal of the different growth stages of camelina which will be used as an important apparatus for agronomy and research. In this review, the extended BBCH (Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie) scale was used to describe the phenological stages. The best use of camelina in the industrial sector as a drop-in product of packing materials, coatings, and adhesions can be achieved by further research to enlarge the camelina market.

Keywords Agronomic aspects · Industrial products · and biodiesel · BBCH scale · *Camelina sativa* · Diversification · Morpho-phenology · Attainable yield potential

7.1 Introduction

Agriculture productivity has many major challenges including increasing resource depletion, ever-growing cost pressure (Iqbal et al. 2021a), ongoing structural change, and increasingly adverse impacts of climate change (IPPC 2011). Oil crops are high-value agricultural commodities used in refined edible oil products, and with the rising global population, the demand for high-quality seed oils continues to grow (Gupta 2015). Despite numerous efforts to enhance the productivity of oil crops, there is still a huge gap between the demand and supply of oil in the bio-based and edible oil markets extracted from different oilseed crops (Iqbal et al. 2021b). Sustainable oil crops produce high amount of edible oil which could be used in human nutrition and the feedstock could be used in animal feed. Most extensively grown oilseed crops, i.e., rapeseed (*Brassica napus* L.), soybean (*Glycine max* L.), and sunflower (*Helianthus annuus* L.), mainly retrieve the economic values of their oil related to its quality. Having even, or at least predictable, oil quality would

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characterize an added value for emerging oilseed crops, such as camelina, which has a huge potential in the bio-based market under the eyes of its unique fatty acid profile, as it permits a plethora of numerous applications (Berti et al. 2016). The introduction of a new crop in the existing cropping system to enhance productivity and profitability is directly associated with crop diversification. This is a vital part of the process of structural transformation of the economy of the country. The improvement in the productivity of oilseed crops in the country is the need of the hour. The introduction of the latest technologies brings crop diversification, which results in a positive shift in the area under oilseed crops (Abro 2012). These efforts were fruitful, but still, there is a huge gap between the demand-supply of edible oil in the country. *Camelina sativa* is a golden crop, which is a success story due to its salient features, i.e., environmentally sustainable source of energy (Chaturvedi et al. 2017). The introduction, adoption, and implementation of new technology always need special attention due to certain factors such as economic situation of the farmers. So, it is a challenge to penetrate a new crop into the rural market and agriculture infrastructure. Furthermore, the adoption of the new crop must be superior in a particular section, plus it must have the ability to be a value-added commodity which can give early and handsome returns to the stakeholders. This will also help in resolving the problems associated with monotonous crop rotation and also will enhance the systems health and productivity. To overcome these problems, there should be an alternative solution like another oilseed crop that can compete in the production race and maintains the quality of edible oil and other purposes. In this scenario, *C. sativa* may be used as a commercial, sustainable, and terrestrial source of longer-chain fatty acids and for human food and as aquaculture feedstock (Righini et al. 2019).

C. sativa is a rediscovered oilseed crop that belongs to the family Brassicaceae (Righini et al. 2016); originated from Finland, Northern Europe; and spread around the globe (Schillinger 2019). This crop has gained tremendous attention from stakeholders and re-emerged as an important oilseed crop. It has numerous attributes that give it unique status among other oilseed crops. For instance, it can be grown successfully under suboptimal growth condition and has been reported to perform well under water-deficit environment than major oilseed crop, e.g., rapeseed (*Brassica napus* L.) (Zubr 1997; Gugel and Falk 2006). It requires low inputs compared to other crops (Righini et al. 2019) that makes *C. sativa* the best fit on less fertile and moisture-deficient lands. Its oil has comparatively low glucosinolate content than other members of the Brassicaceae family, making it relatively better option to use its oil in different feed formations (Matthäus and Zubr 2000b).

Biodiesel production from vegetable oils is a great alternative to conventional petroleum-biodiesel due to its remarkable environmentally safe quality. It has a huge market as it can be used in agricultural machinery, automobiles, power generation, and the stationary power sector (Xue et al. 2011). Almost 95% of the world's biodiesel is produced from vegetable oils like canola, sunflower, and soybean (Gui et al. 2008). In recent years, the demand for *C. sativa* has increased due to its ability to grow with few inputs, and its oil can be utilized for a nonfood purpose (Putnam et al. 1993). The fatty acids pattern in *C. sativa* is very particular with the characterization of 30–40% linolenic acid (C18:3), almost 4% of erucic acid, and 15% of eicosenic acid (C20:1) (Budin et al. 1995), making it highly suitable for drying oil, which is used to form environment-friendly paints and coatings (Zaleckas et al. 2012; Kasetaite et al. 2014). Despite its ability to be grown as an alternate oilseed crop for semiarid regions, *C. sativa* remains underexploited due to the limited attention of researchers despite its unique agronomic and industrial potential. The present review describes the agronomic potential of *C. sativa* provided under semiarid conditions as an alternate oilseed crop. It further underscores the industrial potential of *C. sativa* and its nutritive values. Moreover, it also discusses the challenges and projections for future research to ensure the economic feasibility of *C. sativa* production.

7.2 Oilseed and Biofuel Crops Under Changing Climate

The climate change is characterized by various indicators and manifests itself as global warming, CO_2 enrichment of the atmosphere, ozone depletion, melting of glaciers, and permafrosts resulting in rising of sea level and changing of weather patterns (Abbas et al. 2021a; Iqbal et al. 2021a, b; Siddiqui et al. 2019). The net impacts of climate change include erratic rainfalls, emergence of drought spells of varying intensity and duration along with disruption of modern cropping systems with respect to sowing time, and emergence of new insect pest of food and nonfood crops (Iqbal et al. 2020). Besides food and oilseed crops, biofuel crops have also been seriously affected by changing climatic scenario in a direct or an indirect way (Abbas et al. 2021b; Iqbal et al. 2020). The direct influence of climate change and global warming has been significantly adverse for most of C3 crops compared to C4 crops (Iqbal et al. 2020). The indirect impact of changing climate on biofuel crops might be attributed to lesser area available for cultivating nonfood crops owing to uncertain and highly variable productivity of food crops especially wheat, rice, maize, etc. Currently, intensive research is being undertaken to develop strategies for reducing CO_2 emission into the atmosphere, while bioenergy may serve as one of the promising substitutes of the fossil fuels (Somerville et al. 2010). For instance, the USA is using the starch component from 40% of maize for the production of ethanol having consumption in transportation sector. However, optimum amount of fertilizer needs to be applied in addition to field preparation for growing biofuel crops such as maize that ultimately requisite fossil fuel consumption, thus tempering carbon savings strives (Hossain et al. 2020).

Recently, researchers are striving to develop liquid fuel (ethanol) from lignocellulose of crops like camelina that hold potential to mitigate adverse effects of climate change through lesser use of fertilizers and tillage, avoiding numerous disadvantages associated with traditional biofuel crops such as corn which require intensive management and contribute to greenhouse gases emission into the atmosphere. The biofuel term encompasses grown fuels like corn ethanol that might be utilized in transportation sector instead of fossil fuels (like petroleum products). In addition, biofuel term is also used for any fuel synthesized from various types of plant materials belonging to crops such as maize, sorghum, soybean, etc. The biggest advantage of biofuel crops especially camelina is that they greatly suck CO_2 from the air as they grow and thus might be declared as zero net emitter. But considering camelina like biofuel crops as zero emitter crop is not too simplistic as its cultivation requires application of fertilizers, use of fossil fuel-run tractors for performing different operations, transportation of farm inputs to field, and energy for converting the plant material into liquid fuels. Under changing climate, cultivation of camelina can also increase carbon storage in the soil. However, a careful and precise life cycle analysis of camelina encompasses fossil fuel consumption for crop cultivation, harvest, plant material conversion into fuel, transportation of biofuel to distribution facilities, and their combustion effect on environment.

Climate change tends to trigger most of oilseed crop growth and development on the cost of shortening the crop growth duration (Farooq et al. 2022). It has been reported that increased air saturation and vapor pressure owing to higher temperature in the longer run restrict moisture exchange among crop leaves and atmosphere (Faisal et al. 2020). Additionally, high temperature as a result of climate change gives rise to heat stress that is detrimental to crop plants especially at reproductive crop stage which leads to notable reduction in crop yield (Sabagh et al. 2020; Raza et al. 2022). Moreover, warmer climate coupled with CO_2-enriched environment invites significantly higher pests and diseases (both indigenous and exogenous). Oilseed crops have witnessed a sharp decline in their productivity owing to the adverse effects of climate change during the last decade. In particular, heat stress and erratic precipitation have served as the most vital climatic factors determining the seed yield as well as oil concentration of seeds (Ahmad et al. 2021). Therefore, there is a dire need to investigate alternative oilseed crops such as camelina that are either preadapted or hold potential to thrive well under rising temperature and erratic precipitation levels as predicted by numerous climate change models. Despite due recognization of the need to produce biodiesel and cooking oil from alternative crops including camelina, the agroecological requirements of alternative crops and degree of adaptive variation in their seeds and ecophysiological characteristics have remained unclear. Thorough investigations pertaining to determining the ecological requirements for biofuel-cum-oilseed crops like camelina might be used for identification of suitable present as well as future cultivation areas. Moreover, there is need to develop viable analytical tools for appropriate modeling of camelina like crops niches and their potential distributions enabling the projection of changes for their cultivation in climatically suitable areas.

7.3 History

Camelina (*Camelina sativa* L.) originated from Finland to Romania and east to Ural Mountains. The very first cultivation of *C. sativa* was done after the bronze ages (between the stone ages and the iron ages) in Northern Europe (Francis and Warwick 2009; Toncea 2014). It is native to Northern Europe. According to Francis and Warwick (2009), the *Camelina* spp. in the cards originated in southwestern Asia and southeastern Europe, while the exact origin of *C. sativa* is still undefined (Larsson 2013). A number of its species got under the molecular analysis that suggested the center of its origin is Russia and Ukraine (Ghamkhar et al. 2010). According to archaeologists, the origin of *C. sativa* is southern Europe, and its cultivation is started in Neolithic times. Till the iron ages, it was a famous cultivated crop all over Europe (Knörzer 1978). Its introduction to North America is a contaminant in the seed lots of different crops (Francis and Warwick 2009). It was deliberately introduced in Canada in 1863 in Manitoba and then cultivated in the Peace River district during the mid-1990s (Francis and Warwick 2009). In North America, its proper cultivation was started in the late 1990s (Robinson 1987). It belongs to the family Brassicaceae and is famous as "false flax" and "gold of pleasure." It was a well-known oilseed crop before World War II, but after the explosions, the cultivation of *C. sativa* declined and was replaced by other oilseed crops (Ehrensing and Guy 2008; Séguin-Swartz et al. 2013). The very initial trial that was carried out in North America renowned that *C. sativa* bearing a high level of oil content, economic yield, and short duration lifecycle which assets grave consideration as a potential crop (Plessers et al. 1962) and three trials were carried out in Ottawa and Ontario. The second trial was performed at Fort Vermillion, Alberta (Plessers et al. 1962), and found that camellia is performing better than other oilseed crops of the area like rapeseed and flaxseed. These trials were followed, and additional trials were conducted in Denmark, England, and Finland, showing that *C. sativa* has an oil content of 40–44% (Zubr 2003a, b).

7.3.1 Native Range

The native region of *C. sativa* in Asia includes Pakistan, Armenia, Georgia, Azerbaijan, India, Mongolia, Russian Federations, Turkey, Tajikistan, Kazakhstan, and Turkmenistan (USDA 2011), and in Europe, Albania, Macedonia, Austria, Slovakia, Belgium, France (including Corsica), Bosnia and Herzegovina, Montenegro, Bulgaria, Czech Republic, Croatia, Ukraine (Crimea), Denmark, Greece (Crete), Germany, Hungary, Italy, Spain (Sardinia, Sicily), Russian Federation, Moldova, Slovenia, the Netherlands, Switzerland, Sweden, and the UK (USDA 2011).

7.3.2 Range

In Asia, the *C. sativa* was first introduced in China and Japan (USDA 2011), while in Africa, it was introduced in Tunisia (USDA 2011). In Australasia, *C. sativa* was first introduced in Australia (Southern regions of the country, Tasmania, Victoria, and Western regions) and New Zealand (Western Australian Herbarium, 2010, USDA-ARS 2011). In the USA, it was introduced in almost 38 states, including California, Indiana, Arkansas, Florida, Mississippi, Tennessee, Nevada, Colorado, etc. (USDA 2011). The introduction of *C. sativa* is reported in South America in Uruguay, Chile, Mexico, and Argentina (Francis and Warwick 2009; USDA 2011). In Canada, it was introduced throughout the whole country except Newfoundland province (Govt. of Canada 2011; Francis and Warwick 2009), and in Europe, it was reported as a naturalized crop in Belarus, Ireland, Finland, Estonia, Lithuania, Latvia, Poland, Norway, Romania, and Ukraine (Milbau and Stout 2008; USDA-ARS 2011)

7.4 Classification

7.4.1 Taxonomy and Genetics

The genera Camelina belongs to the tribe Camelineae and family Brassicaceae (mustard family) (Al-Shehbaz et al. 2006). Camelineae tribe also includes the model plant known as *Capsella bursa-pastoris* and *Arabidopsis thaliana*. It is polyploidy in nature, evidenced by the genetic mapping of its genome (Galasso et al. 2011), and the hexaploid genome is also reported (Hutcheon et al. 2010). Chromosome numbers for *C. sativa* are 14 or $n = 6$ or 26 or $2n = 12$, or 40, with $2n = 40$, a common count (Gehringer et al. 2006). USDA-NRCS (2010) stated the taxonomic position of *C. sativa* as it belongs to the kingdom Plantae, subkingdom Tracheobionta, superdivision Spermatophyta, division Magnoliophyta, class Magnoliopsida, subclass Dilleniidae, order Capparales, family Brassicaceae, tribe Camelineae, genus *Camelina* Crantz, and species *Camelina sativa* (L.) Crantz (gold-of-pleasure) (Al-Shehbaz et al. 2006).

7.5 Plant Growth

7.5.1 Morphology

It is assumed that *C. sativa* was originally cultured as a winter oilseed crop (Waraich et al. 2017) that can attain height up to 30–90 cm (Putnam et al. 1993). After germination, the initial growth is conceded on the conical room having axial branches. In the initial growth phase, the plant part above the ground consists of rosettes of leaves. These rosettes then will be turned into an erect stalk having several leaves. Its stem becomes woody when the plant reaches maturity with glabrous or sparse hairs (Klinkenberg 2008). The stem is non-branched most of the time, but sometimes it has branches (Klinkenberg 2008). In the case of hairy stems, the starlike hairs are more in numbers than normal hairs. Leaves are narrow in shape with pointed edges and are 2–8 cm long (Putnam et al. 1993). During the consequent stage of growth, flowering and axial branches having flowers develop from the apex. Its flowers are small and prolific, known as racemes, which are greenish-yellow (Putnam et al. 1993), pale yellow, or white (Klinkenberg 2008) in color. Camelina flowers consist of four petals with 4–5 mm length and sepals with 2–3 mm, style length is 2–2.5 mm, and length of flower stalk is 10–25 mm. Its fruit is known as silique, which is shaped like a pear pod or teardrop-shaped having 5–6 mm width and 7–9 mm in length with a squared-off tip, 0.7–2.5 mm in diameter, brown to orange in color, and results from self-pollination, though they can be cross-pollinated by different pollinator insects. Seed pods resembled the bolls of flax and range 6–14 mm in length, containing 10–25 seeds. The seeds are pale yellow, tiny in size (0.7 mm × 1.5 mm) (Klinkenberg 2008), and oblong with a tough surface (Putnam et al. 1993). Seedling emergence takes around 6 days after sowing, while fluorescence appeared and seed formation initiates 37 and 57 days after sowing and plant takes ~80 days after emergence to reach maturity (Alina and Roman 2009). At harvesting time, the plant reached a height of 51.4 cm, with an average of 87–121 siliques per plant having ~739 seeds/plant and ~6.55 seeds per silique (Alina and Roman 2009; Waraich et al. 2017).

7.5.2 Phenology

C. sativa has got much attention due to its salient features, but the exact depiction of its phenological growth stages is not understood yet. Martinelli and Galasso (2011) planned an experiment to elaborate the phenological growth stages based on the extended BBCH scale (Hack et al. 1992). The knowledge of growth stages is essential and supposed to be fundamental for studying the ability of crops to adopt different environmental conditions, for development of highly suitable and appropriate agronomic techniques, for different breeding programs, and for the setup of application protocols of different fertilizer and herbicide.

7.5.3 Growth of Camelina: Overall Depiction

It can be subdivided into three subspecies on taxonomic bases (*pilosa*, *foetida*, and *sativa*) (Angelini and Moscheni 1998). So, its cultivation extended from overwintering to spring period. *C. sativa* ssp. *pilosa and sativa* were supposed to be good in an agronomic context. *Pilosa* is known for its character of verbalization requiring the maximum growth of stem and consequent flowering. One of the main characteristics of camelina is its morphological plasticity. This species is characterized as a short-growing seasonal crop that completes its life cycle with 110 days in spring, and it might be shortened under adverse conditions.

7.5.4 BBCH Scale for C. sativa

Table 7.1 shows the ten different growth stages of *C. sativa* based on two- and three-digit BBCH scales. For the overall depiction of development, the two-digit code is

Table 7.1 Depiction of the *C. sativa* phenological growth stages in accordance with the extended BBCH scale (Used with permission of Martinelli and Galasso, 2011)

BBCH codes		
Two digits (00)	Three digits (000)	Explanation
Germination: the principal growth stage 0		
00	000	Dry seed
01	001	Imbibition of seed starts
03	003	Imbibition finished
05	005	Emergence of radicle from seed
07	007	Hypocotyl emergence from seed with cotyledons
08	008	Hypocotyl along with cotyledons mounting toward the soil
09	009	Cotyledons emergence through the soil surface
Leaf enlargement: principal growth stage 1		
10	100	Unfolded Cotyledons (node 0)
11	101	True leaf pair on first node
12	102	Single true leaf on second node
13	103	Single true leaf on third node
14	104	Single true leaf on fourth node
15	105	Single true leaf on fifth node
16	106	Single true leaf on sixth node
17	107	Single true leaf on seventh node
18	108	Single true leaf on eighth node
19	109	Single true leaf on ninth node
	110	Single true leaf on tenth node
	118	Till stage 199 the coding lasts with the same trend
	119	Single true leaf on 19th or succeeding node
Development of side shoots[a]: principal growth stage 2		
21	201	One-sided shoot developed
22	202	Two-sided shoots developed
2.	20.	Coding continues with the same scheme up until stage 29 (209)
29	209	Nine or more side shoots visible
	21.	Till 219 the coding lasts with the same trend
	219	19 or >19 side shoots developed
Elongation of main stem: principal growth stage 3		
31	301	Stem elongated 10% of final extension
32	302	Stem elongated 20% of final extension
3.	30.	Till 39 the coding lasts with the same trend
39	309	Maximum stem elongation
Harvestable vegetative parts development[b]: principal growth stage 4 (mislaid)		
Emergence of inflorescence: principal growth stage 5 (main shoot)		
50	500	Enclosed inflorescence in leaves
51	501	Visible inflorescence
55	505	Enclosed individual flower buds
59	509	First petals visible but still all flowers enclosed

(continued)

Table 7.1 (continued)

BBCH codes		
Two digits (00)	Three digits (000)	Explanation
Flowering: principal growth stage 6 (main shoot)		
60	600	First flower opened
61	601	10% flowers opened
62	602	20% flowers opened
63	603	30% of flowers opened, first petal dried or fallen
64	604	40% flowers opened
65	605	Complete flowering: 50% flowers opened
67	607	Flowering ending: most petals dried or fallen
69	609	Flowering ended: Visibility of fruit
Fruit development: principal growth stage 7 (main shoot)		
71	701	10% siliques touched maximum size
72	702	20% siliques touched maximum size
73	703	30% siliques completed maximum size
7.	70.	Till 79 the coding lasts with the same trend
79	709	All siliques touched maximum size
Ripening: principal growth stage 8		
81	801	Ripened silique 10% (seeds are deep yellow/orange and hard)
82	802	Ripened silique 20%
83	803	Ripened silique 30%
8.	80.	Till 89 the coding lasts with the same trend
89	809	Almost every silique is ripe; the crop is prepared to be reaped
Senescence: principal growth stage 9		
97	907	Plant death and dryness
99	909	Harvested produce[c]

[a]In *C. sativa*, the side shoot development generally happens either concurrently or after inflorescence emergence. Consequently, the second principal growth stage ordinarily mislaid. If formation of side shoot is taken a feature of specific attention, then principal growth stage 2 can be counted in along with principal growth stage 5 by using diagonal stroke

[b]As vegetative part was not harvested, so principal growth stage 4 has been omitted

[c]Storage treatments were applied at this stage

used, but the three-digit code is used in case of more accuracy. The application of three-digit code permits for selecting 19 leaves (Hack et al. 1992), thus allowing the precise depiction of plant growth before the emergence of an inflorescence. This is predominantly essential as in camelina, the scoring of stem enlargement, a phase that generally happens concurrently with the development of leaf, doesn't allow the instant valuation of the existing growth stage stated as a percentage of the final plant height. The accurate knowledge of the growth stage developed before the emergence of fluorescence then goes for the three-digit growth stage. The main-stem elongation can be directly assessed by the scoring of clearly protracted internodes on the main stem, but this is very difficult in the case of *Camelina sativa* as the identification of enlarged internodes is habitually equivocal and mainly operative dependent. To address this problem, main-stem elongation capacity as a percentage of the final stem length was taken as a highly suitable means to measure stem elongation in camelina. As different growth stages in *Camelina sativa* overlapped, like fluorescence emergence and formation of side shoot that take place simultaneously, the operator might skip the advanced stage or consider both the BBCH codes alienated by a diagonal stroke.

7.6 Reproduction

7.6.1 Floral Biology

C. sativa is considered an autogamous, self-compatible species (Mulligan 2002). The selfing process in camelina starts at dusk; stamen turned toward the stigma in the evening and deposited its pollen that lasts for the whole night that results from withering the flower that falls in 2–3 days. The same thing happens next to the stem, which grows longer as a new flower blooms (Schultze-Motel 1986). Out of 10,000 plants, the cross-pollinated were less than 3% (Tedin 1922). Contrastingly results were published by those who erroneously stated that camelina benefited from different pollinators (Goulson 2003).

7.7 Seed Production and Dispersal

7.7.1 Planting Time

Planting date is a key aspect in the satisfactory production of camelina due to favorable and unfavorable environmental conditions, i.e., temperature and soil moisture, which affects seed yield and seed quality. Generally, high-temperature stress might result in plant sterility, seed abortion, reduced number of seeds, and grain filling duration (Hatfield and Prueger 2015). Studies showed that camelina oil content is greater under cool environmental conditions (Obour et al. 2017; Zanetti et al. 2017), as grain weight is affected by seeding date and lower thousand seed weight has been reported in late seeded crop (Liu et al. 2021). Contrastingly, Urbaniak et al. (2008) stated that the seeding date has no effect on the 1000-grain weight and yield in field trials of Canada. Due to climatic variations among different regions globally, it defines the optimum planting time of camelina (Table 7.2).

Table 7.2 Optimum planting times of camelina around the world

Country	Planting time	References
USA/Montana	Late February or early March	McVay and Lamb (2008)
USA/Minnesota	Mid-April to mid-May	Gesch (2014)
USA/Minnesota	Mid-April to mid-May	Sintim et al. (2016a)
USA/Western Nebraska	Late March to end of April	Pavlista et al. (2011)
USA/Kansas State	April	Obeng et al. (2019)
USA/Nevada	Mid-March	Neupane et al. (2019)
Chile	April 30	Berti et al. (2011)
Europe	Mid-March and mid-April	Zanetti et al. (2017)
Canada	Mid-April to mid-May	Gesch (2014)
Pakistan	Mid-November	Waraich et al. (2017)
Poland	September 1	Czarnik et al. (2018)

7.7.2 Seed Rate

Optimization of the seed rate of a crop is a critical aspect for balancing seed cost with proper crop stand establishment to improve yield and, particularly for camelina, to contend with weeds because there are only a few herbicides used for its better performance (Sobiech et al. 2020; Gesch et al. 2018). Urbaniak et al. (2008) demonstrated that 1000-grain weight and yield are significantly affected by seed rate in field trials in Canada. They reported seed yield of 1.34, 1.50, and 1.60 ton ha^{-1}at seed rate of 200, 400, and 600 seed m^{-2}, respectively. They also observed more silique and branches per plant at lower seed rate. In another 3-year trial in Germany, 1.34, 1.16, and 1.80 ton ha^{-1}average yield was recorded each year, respectively, while seed rate of 400 m^{-2} and 120 kg N ha^{-1} application produced the highest yield (2.28 ton ha^{-1}). However, a higher seed rate (800 seed m^{-2}) reduced the total branches plant^{-1}, number of silique plant^{-1}, seeds silique^{-1}, and seed weight plant^{-1}. The positive effect of N application on yield and yield contributing traits was also affirmed by other field studies (Gao et al. 2018).

7.7.3 Seed Banks, Viability, and Germination

C. sativa is not a novel crop in the field, but unfortunately it was being ignored by the researchers despite its unique characters. The literature on seed dormancy and crop volunteers in camelina is very rare. Zhang and Auer (2019) have little information about seed dormancy in camelina as the seeds have shown little dormancy period, and seed emergence was recorded after 2 weeks of harvesting in a 3-year experiment in Ireland by Crowley (1999). Ellis et al. (1989) found that the germination of camelina was related to the dose of white light photon and was subdued by high radiation, which generally hinders emergence, and was significantly stimulated by gibberellic acid (GA_3). In Maritime Canada, the rate of germination of camelina was

>95%, although the seedling emergence rate was dependent on the environment (Urbaniak et al. 2008).

7.8 Camelina: Agronomy, Prospects, and Challenges

C. sativa is a short-day plant and completes its life cycle within 100 days (McVay and Lamb 2008). It can't reach the lower soil surfaces in search of water because of the shallow root system (Putnam et al. 1993). It can either be grown as an annual spring or biannual winter crop. It can be successfully grown under various soil and climatic conditions due to its high adaptability.

7.8.1 Sowing Date

The production of *C. sativa* can be optimized by following the basic principle of crop production, starting from the optimum sowing date. Sowing of camelina at an optimum time prevents pod abortion by preventing its exposure to severe heat and drought in early summer. Soil moisture and environmental conditions are the main driving forces behind the optimization of sowing date. Pavlista et al. (2011) did not find any effect of sowing date on the crop yield in western Nebraska. In the summer crop, the sowing after mid-April despite late March or mid-April negatively impacts the yield. The winter sowing in September and October (Gesch and Cermak 2011) bears the chilling conditions of winter and resumes its growth with favorable conditions. Winter-sown camelina has distinctive benefits like proper stand establishment of crop leads to better plant growth which lowers the weed pressure (Gesch and Cermak 2011) and it permits the crop to mature before the start of severe summer leading to early harvesting which helps in soil moisture conservation for the succeeding crop (Gesch and Archer 2009; Gesch and Cermak 2011).

7.8.2 Tillage

This would be best suited in winter-based nonirrigated traditional cropping systems where crop failure could be prevented by moisture availability. Soil preparation must be done carefully. Before the sowing of the crop, multiple harrowing must be done to eliminate the weed infestation. Camelina has the potential to perform under no-till and traditional tillage (Enjalbert and Johnson 2011). However, under no-till/ excessive crop residue, the seed rate needs to be increased as emergence rate can be negatively effected (Enjalbert and Johnson 2011).

7.8.3 Seed Rate

Optimal seed rate is very crucial for proper stand establishment, active plant growth, and high economic yield. There must be 210 plants m^{-2} (20 plants ft^{-2}), which can be achieved with optimal seed rate (6 kg ha^{-1}); seed must be incorporated into the soil. Its seeds must be planted at shallow depths (6–8 mm) due to small seeds for a better crop stand. Primary and secondary tillage, seed rate, sowing method, and sowing depth are the key dynamics that affect the plant population and consequent yield (McVay and Khan 2011). It is known as a drought- and chilling-tolerant crop as compared to canola and can thrive and give satisfactory yield under these conditions (Putnam et al. 1993; McVay and Lamb 2008; Berti et al. 2016). The seedling of camelina can tolerate the freezing temperature up to −2 °C, whereas the seedlings of rapeseed, mustard, and flax cannot survive (Robinson 1987). Schulte et al. (2013) published that the temperature fluctuations do not influence the lipid profile of camelina. However, there is a possibility that the sowing date might affect the lipid profile as late sowing exposes the crop to high summer temperatures.

7.8.4 Herbicide Control

There is no proper post-emergence herbicide of camelina, so pendimethalin and glyphosate could be the better option for pre-emergence control. Camelina is a short-duration biofuel crop having consistent yield without using many weedicides and pesticides (Razeq et al. 2014; Iskandarov et al. 2014). Unlike *Brassica*, camelina is not affected by birds and flea beetle damage (Pavlista et al. 2011). It is also resistant to insect pests (Iskandarov et al. 2014; Kirkhus et al. 2013). Quizalofop is used for post-emergence chemical weed control, while glyphosate is useful for pre-emergence weed control (Jha and Stougaard 2013). Prior researchers had used bonanza and treflan as pre-plant herbicides to restrict weed invasion (Yang et al. 2016). The only labeled herbicide for camelina is sethoxydim, which is ineffective on broad leaves (Obour et al. 2015). *Sclerotinia sclerotiorum* is also documented in *Camelina* fields, reducing its production (Yang et al. 2016). The literature on pre-emergence herbicide (PRE) usage is very limited for weed control in camelina (Schillinger et al. 2012). Consequently, existing substitutes of weed control have to use a labeled pre-emergence broad-spectrum herbicide, while mechanical removal of weeds is a very time-consuming practice (Froment et al. 2006). Sethoxydim is the only registered herbicide for camelina, but it controls narrow-leaf herbs, and quinclorac is suitable for broadleaf herbs (Jha and Stougaard 2013). The lower rates of S-metolachlor, dimethenamid-P, and pendimethalin, keeping in view the toxic level for use, could be approved for camelina (Jha and Stougaard 2013). However, certain residual herbicides from sulfonylurea are reported to affect the crop stand of camelina (Enjalbert and Johnson 2011).

7.8.5 Fertilizer Applications

Optimum nutrient application is a driving force behind better growth and development, yield quantity, and quality. Depending upon soil type, fertility, and soil moisture, 20–50:10–25:0 kg ha^{-1}of nitrogen (N) and sulfur (S) are required for camelina, respectively (Jiang et al. 2013). Soil organic matter and moisture are the main factors behind the response of *C. sativa* toward N and S (Jankowski et al. 2019). As camelina has shown maximum yield at 45–56 kg N ha^{-1}. *C. sativa* does not need any intercultural practice from the seedling stage till harvesting. The response of camelina toward phosphorus (P) application was not good even in P-deficient soil (Obour et al. 2012), and P at 15–30 kg ha^{-1}might be suitable for the *C. sativa* production.

7.8.6 Harvesting

The plant reached its harvesting maturity when 50–75% of silique got brown, which is the best time to harvest the crop (Sintim et al. 2016b). Harvesting at a proper time decreases the chances of yield loss by shattering, so swathing of the crop must be considered for harvesting at uneven maturity. Regular grain combine harvester can be used to harvest camelina with certain adjustments like the height of header must be fixed at the highest spot to deny the plugging and airflow adjustments to minimize the chances of seed to blow away. However, the cleaning of seed might be needed due to this slow airflow as a seed might be mixed with plant material. The mixing of plant material with seeds could be fixed by installing a 0.35 cm screen before the lower sieves beneath the harvester (Enjalbert and Johnson 2011).

7.8.7 Seed Yield

The nonirrigated areas where the total precipitation recorded was 400–500 mm gave seed yield of 1.68–2.02 ton ha^{-1}and 0.50–1.34 ton ha^{-1} in low rainfall areas (McVay and Lamb 2008). Seed yield of 0.45–1.30 ton ha^{-1} has been recorded in trials in years 2013 and 2014. The trial conducted in Eastern Europe gave 2.88 ton ha^{-1} of seed yield (Vollmann et al. 2008). Camelina seed yield varies in different continents (Table 7.3).

7.9 Potential of *C. sativa* Over Nonirrigated Areas Compared to Other Oilseeds

C. sativa has greater potential in nonirrigated areas due to its lower requirements of water. The intercropping of camelina has been tested in wheat-based cropping systems in dryland regions. The trials under dryland regions resulted that camelina

Table 7.3 The difference in seed yield and oil content of *C. sativa* in experiments conducted in different parts of the world

Location	Oil content range	Yield range (kg ha^{-1})	Major source of variation	References
Iran	33–34.4%	1868–3209	Irrigation levels, sulfur	Amiri-Darban et al. (2020)
Nevada, USA		594–961	Sowing dates, years	Neupane et al. (2019)
Kansas, USA	290 g kg^{-1}	317–483	Sowing dates, years	Obeng et al. (2019)
Germany	32.0–49.0%	1100–2650	Breeding lines	Gehringer et al. (2006) and Berti et al. (2011)
Romania		1761–2892	Cultivars	
Austria	40.5–46.7%	1574–2248	Breeding lines, seed size	Vollmann et al. (2007)
Ireland	43.1–44.7%	1630–3200	Sowing date, N rates	Crowley and Fröhlich (1998) and Berti et al. (2011)
Chili		420–2390	Sowing dates, NPS, Fertilization	
Denmark	40.4–46.7%	1270–2360	Spring/fall sowing	Zubr (1997)
Pakistan		300–400	Drought, selenium	Ahmad et al. (2020)
Germany	34.3–42.4%	1290–3230	Breeding lines	Seehuber et al. (1987)
Germany	32.1–42.3%	500–2620	Genebank accessions	Seehuber (1984) and Katar et al. (2012)
Turkey		572–997	Accessions and breeding lines	
West Canada	37.0–46.3%	1000–3000	N fertilizer rates, environments	Malhi et al. (2014)
Minnesota, USA	37.7–41.0%	800–1900	Cultivars, sowing date	Gesch (2014)
Pacific Northwest USA	29.6–36.8%	127–3302	Cultivars, spring/fall planting	Guy et al. (2014)
East Canada	35.5–37.8%	1400–2050	N, S fertilization	Jiang et al. (2013)
Nebraska, USA	29.8–34.3%	556–1456	Sowing date	Pavlista et al. (2011)
East Canada	35.5–40.1%	426–2568	Cultivars, N rate	Urbaniak et al. (2008)
West Canada	35.8–43.2%	962–3320	Genebank accessions, environments	Gugel and Falk (2006)
Minnesota, USA	34.3–37.5%	1007–1218	Genebank accessions	Putnam et al. (1993) and Rode (2002)
Slovenia		400–800	Cultivars	

yielded more or somewhere the same as other oilseed crops, but the shattering, lodging, disease, and insect factors were minimal compared to others (Putnam et al. 2009; Gao et al. 2018). Likewise, Johnson et al. (2009) stated that the performance of camelina under nonirrigated conditions was way better than rapeseed as camelina produced more seed yield than rapeseed. *C. sativa* can be used as a potential fallow crop in cereal-based crop system, which results in crop diversification, minimizes pest population, and increases the profit of the farmer, log-term crop sustainability, and farm in the region. *C. sativa* proved a potential crop with minimum reduction in yield as it can replace fallow in the wheat-fallow system (McVay and Lamb 2008). Cultivation of *C. sativa* on underutilized fallow wheat-based production systems strips to evade uninterrupted competition for land use.

7.10 Constraints

Several restraints affect the outcome and economic feasibility of *C. sativa* regardless of its capability as a substitute potential bioenergy crop for dryland regions. Information regarding the agronomic practices, production systems, and adapted spring and winter genotype is scarce. *C. sativa* is facing problems regarding the benefit-cost ratio and lack of marketing system that could lose the productivity of the crop. Like other constraints, uneven maturation results in the harvesting problems that might cause shattering, and postharvest losses are another significant constraint in the profitability of camelina (McVay and Khan 2011; Lenssen et al. 2012). Certain fungal infections have been reported in camelina, like downy mildew infestation in Pacific Northwest in the USA (Putnam et al. 2009; Harveson et al. 2011), and the control of downy mildew has not been reported yet for camelina. All these challenges bring much-needed attention of researchers to conduct more research on camelina to optimize its production and profitability.

7.11 Camelina Agronomic Performance, Oil Quality, Properties, and Potential

C. sativa oil has many advantages over other oilseeds. One of them is the presence of unsaturated omega-fatty acid (80%) of total fatty acid and 35–40% of linolenic acid (18: 3n·3) (Belayneh et al. 2015). Camelina oil has many advantages over other oilseeds. Its oil is a rich source of omega-3 fatty acid (80%) of total fatty acid and 35–40% of linolenic acid (18: 3n·3) (Budin et al. 1995; Abramovič and Abram 2005; Abramovič et al. 2007; Schwartz et al. 2008), and it has more than 50% polyunsaturated fatty acids in cold-pressed camelina oil (Budin et al. 1995; Abramovič et al. 2007), and it has tenfold of more oil as compared to other oilseeds (Alice et al. 2007; Tabără et al. 2007). The fatty acids pattern in camelina is very particular with the characterization of 30–40% linolenic acid (C18:3), almost 4% of erucic acid, and 15% of eicosenic acid (C20:1) (Budin et al. 1995). Member of order Brassicales, especially the Brassicaceae family, has a secondary metabolite known as glucosinolates (Clarke 2010). There are almost 120 types of glucosinolates discovered yet which are naturally present in the plants. These secondary metabolites are responsible for the sharp and bitter taste in cruciferous vegetable oil and also release chemicals that act as defensive agents against herbivores and natural pests (Fahey et al. 2003). Glucosinolates can cause damage to plants, and plants compartmentalize this compound to avoid the damage. Camelina also does the same and accumulates the glucosinolates (glucoarabin (9-(methylsulfinyl)nonylglucosinolate – GS9), glucocamelinin (10-(methylsulfinyl)decylglucosinolate – GS10), and 11-(methylsulfinyl)undecylglucosinolate (GS11) in its seeds. Camelina oil is also known as golden liquid, which contains more than 50% of polyunsaturated essential fatty acids primarily linoleic acid and alpha-linoleic acid, and it also contains tenfold more fatty acids than other oilseed crops (Alice et al. 2007; Tabără et al. 2007). It has a significant shelf life due to the presence of Vit-E (tocopherol) that saves it from oxidation (www.simplunatura.ro), and it also plays a vital role in slenderness recovery, the elasticity of skin, and regeneration of cell (Vollmann et al. 1996). The basic properties of camelina make it specifically suitable, which are (1) exceptional aroma and taste, (2) color, (3) chemical and physical composition, and (4) extended conservation duration (up to 2 years). Table 7.4 has shown the fatty acid composition in the camelina oil.

The camelina oil yield and quality has shown variations on different location. Though the modern breeding history of *C. sativa* is relatively little, *C. sativa* trials have shown a satisfactory seed yield and other promising agronomic features than other novel crops that may be due to the long adaptation history of *C. sativa*. A

Table 7.4 Fatty acid profile of *C. sativa* oil (research conducted in the Constanta County, 2009) (Imbrea et al. 2011; El Sabagh et al. 2019; Borzoo et al. 2020; Yuan and Li 2020; Amiri-Darban et al. 2020)

Fatty acids	Bonds ratio	Oil content (%)
Myristic acid	C14:0	0.10
Palmitic acid	C16:0	6.51–8.1
Palmitoleic acid	C16:1	0.18
Stearic acid	C18:0	2.15
Oleic acid	C18:1n–9	16.27–16.38
Linoleic acid	C18:2n–6	20.99–21.52
Linolenic acid	C18:3n–6	32.20–35.58
Conjugated linoleic acid	C18:2	1.06
A-Linolenic acid	C18:3n–3	11.59
Arachidonic acid	C20:4n–6	1.11
Erucic acid	C22:1n–9	1.6
Docosadienoic acid	C22:2n–3	2.24
Gadeolic acid	C20:1	14.4
Eicosadienoic + eicosatrienoic	C20:2	2.64
PUFAs/MUFAs		1.83
Polyunsaturated fatty acid		90.0
Other fatty acids		0.61
Glucosinolate		15.7–28.2

detailed number of published research on the difference of camelina seed yield and oil content in European and North American locations are presented (Table 7.4). The use of camelina oil in the human diet has been established in many European countries like the UK, Germany, Finland, Denmark, and Ireland. Camelina is found to be used in the bread of human consumption. It has a specific composition that enriches the bread with essential amino acids (Zubr 2003b), omega-3 fatty acids (Amiri-Darban et al. 2020), fatty acids (Zubr 2003b), dietary fibers (Zubr 2003a), and other minor compounds. It is also rich in oil (Sehgal et al. 2018), fatty acids (Anderson et al. 2019), tocopherols (Zubr 2009; Fernández-Cuesta et al. 2014), bioactive compounds (Matthäus and Zubr 2000b), and amino acids (Zubr 2003b).

7.12 Camelina Response to Insects, Disease, Herbivory, and Higher Plant Parasites

7.12.1 Insects

The insect attack on *C. sativa* is not very extensive because the insect damage has never been enough to warrant control measures (Robinson 1987) for flea beetles (Soroka et al. 2015). It was found that the possible reasons behind the resistance against insects shown by camelina could be due to either the occurrence of repellents or the nonexistence of volatile stimulatory compounds, probably because of the low concentration of glucosinolates (Henderson et al. 2004). The European tainted plant bug is the possible insect species connected with camelina developed as a potential crop (Palagesiu 2000). Further studies have proved that camelina insects susceptibility depends upon the host specificity (Soroka et al. 2015).

7.13 Diseases

7.13.1 Fungal Diseases

Downy mildew, botanically known as *Peronospora parasitica* (Pers. ex Fr.) Fr., was found on camelina in Canada (Conners 1967). *C. sativa* was found resistant to various fungal diseases due to the production of camalexin, methoxycamalexin, and phytoalexins (Browne et al. 1991). The concentration of these compounds can be increased by the inoculation of *A. brassicae* inoculum (Jejelowo et al. 1991), which is the first reported antifungal compound. Pedras et al. (2003) suggested that the resistance in camelina against blackleg could be found by the mixture of phytoalexin production and the destruxin B detoxification pathway. Camelina has also shown massive variability toward different diseases as the variability toward leaf spot was 34% and 10% toward black rot (Westman and Dickson 1998; Westman et al. 1999). The resistance of *Camelina* against several diseases is stated in different regions as Camelina was found resistant to blackleg fungus from Australia (Salisbury 1987) and Poland (Karolewski 1999), and no virulence reported yet (Li et al. 2005). *C. sativa* was also found susceptible to *Botrytis* spp. and *Sclerotinia* in Poland (Crowley 1999) and downy mildew in Austria and the USA (Vollmann et al. 2001; Dimmock and Edwards-Jones 2006).

7.13.2 Viral Diseases

C. sativa has shown susceptibility to aster yellows phytoplasma (Zhao et al. 2010), turnip yellow mosaic tymovirus (TYMV) and *erysimum* latent tymovirus (ELV), beet western yellows virus (BWYV) in Germany, and radish mosaic virus (RaMV) in the Czech Republic. TYMV was also transmitted by *C. sativa* seed (Brunt et al. 1996; Špak and Kubelková 2000).

7.13.3 Bacterial Diseases

In Germany, Camelina was reported to be infested by bacterial blight caused by *Pseudomonas syringae* pv. *camelinae* (Mavridis et al. 2002).

7.13.4 Phytoplasmas

C. sativa was reported to be infected by the aster-yellows-phytoplasma disease (Khadhair et al. 2001) from Alberta, Canada.

7.13.5 Invertebrates

In mixed crop with wildflower, *Camelina* seeds have shown big damage by *Arion lusitanicus* Mabille and *Deroceras reticulatum* Muller by destroying more than 50% of seed, but this did not happen in the crop grown in harrowed plots (Kollmann and Bassin 2001).

7.14 Nutritional Values of Camelina Seed

The nutritional values of camelina seed have been shown in Table 7.5. The analysis of water-soluble B series vitamins has found the contents of thiamin (B1), riboflavin (B2), niacin (B3), pantothenic acid (B5), pyridoxine (B6), biotin (B7), and folate

Table 7.5 Amount of different compounds, amino acids, sugars, vitamins, and minerals in camelina seed oil (Rode 2002; Bătrîna et al. 2020)

Compounds	Amount (%)	Compounds	Amount	Minerals	Amount
Glucose	0.42	Flavonoid	143 mg/kg of seed	Ca	1%
Fructose	0.04	Polar phenolic	439 mg/kg	Mg	0.51%
Sucrose	5.5	Sitosterol	1884 μg/g of oil	Na	0.06%
Raffinose	0.64	Stigmasterol	103 μg/g of oil	K	1.6%
Stachyose	0.36	Brassicasterol	133 μg/g of oil	Cl	0.04%
Starch	1.21	Campesterol	893 μg/g of oil	P	1.4%
Pectin	0.96	Cholesterol	188 μg/g of oil	S	0.24%
Lignin	7.4	Thiamin	18.8 mg/g	Cu	9.9 mg/g
Crude fiber	12.8	Riboflavin	4.4 mg/g	Mn	40 mg/g
Mucilages	6.7	Niacin	194 mg/g	Ni	1.9 mg/g
		Pantothenic acid	11.3 mg/g	Zn	69 mg/g
		Pyridoxine	1.9 mg/g	Fe	329 mg/g
		Biotin	1.0 mg/g		
		Folate	3.2 mg/g		
Amino acids (%)					
Histidine	4.06	Lysine	4.46	Threonine	2.89
Isoleucine	4.38	Methionine	2.70	Tryptophan	1.21
Leucine	7.04	Phenylalanine	5.06	Valine	6.10
Alanine	6.14	Glutamate	16.03	Proline	5.88
Arginine	8.45	Glycine	5.44	Serine	5.84
Aspartate	8.96	Cysteine	1.84	Tyrosine	3.52

(B9). Camelina oil also possessed phenolics such as polar phenolic compounds (Abramovič et al. 2007; Chaturvedi et al. 2017) and flavonoid (Matthäus and Zubr 2000a). Its oil has a significant amount of sterols as sitosterol, cholesterol, campesterol (Shukla et al. 2002; Szterk et al. 2010), brassicasterol, and stigmasterol (Shukla et al. 2002). Topically applied, a healing effect on bruises, skin scratches, squeezing, and sprains, and skin diseases (e.g., acne) and inflammations, is described in the literature (Rode 2002).

7.15 Agro-industrial Uses

The huge oil content in camelina seeds makes it a special product for industrial use and nutritional application. The seed meal of defatted *C. sativa* has a substantial level of carbohydrates, proteins, and a number of phytochemicals, which can be used in the feed and agriculture sector (Gugel and Falk 2006; Zubr 2009). Its oil has great potential for industrial applications. It is reported that camelina has a unique fatty acid profile that makes it early drier, making it good in making polymers, paints, varnishes, dermatological products, and cosmetics (Kasetaite et al. 2014; Zaleckas et al. 2012). Its epoxidized oil has great industrial uses, like in the making of pressure-sensitive resins, adhesives, and coatings (Kim et al. 2015). Its oil content (106–907 L ha^{-1}) is far more as compared to sunflower (500–750 L ha^{-1}) and soybean (247–562 L ha^{-1}), which make it best fit agriculture industrial growth medium (Moser 2010). Due to the presence of omega-3 fatty acid in such a high percentage, camelina oil is being promoted as a dietary supplement in animals (Ponnampalam et al. 2019) and human diet (Rahman et al. 2018). The composition of hen egg can be changed through alteration in diet. If their feed is rich in long-chain fatty acids like omega-3 fatty acids, their concentration will be increased in the yolk, and flax is the best source of omega-3 fatty acid (Jiang et al. 1992; Pilgeram 2007).

7.16 Camelina and Animal Feed

Oilseed crops can also be used as a source of feed for humans and animals like *C. sativa* (Sawyer 2008), which is a source of protein-rich meal having a unique amino acid profile including cysteine, methionine, glycine, arginine, threonine, and lysine which are more in concentration than soymeal (Pekel et al. 2009). This unique profile of amino acids made the camelina meal a good feed source for poultry. Camelina meal consists of 5–10% lipid content that enhances its nutritive values and provides a high-value meal as compared to soymeal (Zubr 1997). This makes the camelina meal one of the best additions to feeding the livestock and poultry (Frame et al. 2007).The first publication on the use of camelina meal for livestock feed was published in 1962 reported that its meal has more proteins than rapeseed and flaxseed (Plessers et al. 1962). A study has been reported on camelina meal usage as a starter diet in turkey production at 5%, 15%, and 20%, a good source of protein, and 5% is recommended for starter diet (Frame et al. 2007). The replacement of soymeal with *C. sativa* in the ruminant (beef steer) diet resulted in a significant decrease in the stress-responsive hormones (Cappellozza et al. 2012). Its meal contains 23–40 glucosinolates μ moles g^{-1} (Singh et al. 2014), 1–6% phytate (Adhikari et al. 2016), and 100–150 g kg^{-1} crude fiber (Kakani et al. 2012). In addition to this, there was no change noticed in the function of the thyroid. However, camelina meal reduced the acute-phase reduction protein reactions, which are normally enhanced during transportation or when animals are subjected to a feed lot setting (Cappellozza et al. 2012). This research is evidence of the positive role of camelina meal in reducing the stress response in cattle. A fat reduction was observed in the cow milk by using camelina meal (2 kg of DM), but it did not reduce the milk yield (Hurtaud and Peyraud 2007). After oil extraction, the by-products of *C. sativa* seeds can be used as a nutritious feed meal with high levels of crude protein (>45%), omega-3 fatty acids (>35%), fiber (10^{-11}), and vitamin E (Meadus et al. 2014) for livestock.

7.17 Biofuel

Total global fossil reserves are 1707 billion barrels, which is an alarming number because it will only be able to fulfill of global supply for 50.6 years (BP 2017). Due to limited resources, conservation of fossil fuels, and climate change, renewable energy sources such as camelina are under the limelight (Sainger et al. 2017). Oilseed feedstocks counting camelina are estimated to contribute 0.5 billion gallons of the 36 billion gallons of conveyance fuel required by the US economy by 2022 (USDA 2010; Mohammed et al. 2017). The worldwide emphasis on energy security accompanied by the determinations to subordinate the greenhouse gas emissions (GHGs) has pushed many governments to begin with inflexible policies on cleaner-energy production, predominantly biofuels' production goals and utilization, joined with continuous efforts that focused on research and progress of bioenergy crops (e.g., Glithero et al. 2012; Radzi and Droege 2014). Past literature indicated that camelina is apt for aviation fuel and biodiesel production (Keshavarz-Afshar and Chen 2015; Yang et al. 2016). Biodiesel production from vegetable oils is an excellent alternative to conventional petroleum-biodiesel due to its remarkable environmentally safe qualities. It has a huge market as it can be used in agricultural machinery, automobiles, power generation, and stationary power sector (Xue et al. 2011; Tabatabaie and Murthy, 2017). Almost 95% of the world's biodiesel is produced from vegetable oils like canola, sunflower, and soybean (Gui et al. 2008). Besides other advantages and use of oilseed crops, they are projected to play a vital part in alleviating greenhouse gas emissions by their capacity to produce biofuel. USDA report has lightened up the potential of camelina to produce biofuel (USDA 2010). The properties (acid value, the lubricity of the oil, permeability at low temperature, kinematic velocity, and acid value) of biodiesel produced by camelina have the same properties of biodiesel produced by soybean (Moser and Vaughn 2010). This shows the potential of high-quality biodiesel production in camelina. Mineral diesel fuel can produce a power of 38.5 kW, which is less than that of camelina (43.5 kW), which is produced by coldly pressed neat oil of camelina seeds. However, mineral diesel fuel has less consumption efficiency as compared to camelina (Bernardo et al. 2003). In the recent few years, the demand for camelina is increasing due to its ability to grow in fewer input requirement, and its oil can be used for a nonfood purpose (Seehuber 1984; Putnam et al. 1993; Mohammad et al. 2018). The fatty acids pattern in camelina is very particular with the characterization of 30%–40% linolenic acid (C18:3), almost 4% of erucic acid, and 15% of eicosenic acid (C20:1) (Budin et al. 1995); this will make it best for the utilization of drying oil which is used to form environment-friendly paints and coatings same as of linseed oil (Zaleckas et al. 2012; Kasetaite et al. 2014). Camelina oil can be used as biodiesel and can also be an alternative to petroleum due to its huge production ability. Its oil can be utilized in different vehicles as biodiesel (Fröhlich and Rice 2005). As camelina is known for its diverse use in industrial products, that makes it a profitable enterprise (Table 7.6).

Table 7.6 Research has been done in different countries to evaluate the uses of camelina oil in different industries and products

Products	Country	References
Chemicals, paints and coatings, resins, adhesives	Poland, USA	Nosal et al. (2015), Kim et al. (2015) and Li et al. (2015)
Cosmetics and soaps	USA	Obour et al. (2015)
Film, fibers, and thermoplastics	China	Reddy et al. (2012)
Bio-Gum	USA	Li et al. (2016)
Bioplastic	USA	Kim et al. (2015)
Cuticular waxes and suberins	USA	Razeq et al. (2014)
Shelf life enhancer	Ireland	Eidhin et al. (2003)
Phytoremediation	India	Tripathi et al. (2016)
Bio-alkyd resin	Poland	Nosal et al. (2015)
Bioadhesive	USA	Kim et al. (2015) and Obour et al. (2015)
Animal feed	Romania, Turkey, Denmark, India	Ponnampalam et al. (2019), Ciurescu et al. (2016), Pekel et al. (2015) and Singh et al. (2014)
Fish	Canada	Bullerwell et al. (2016) and Booman et al. (2014)
Jet fuel	USA, Canada	Drenth et al. (2015), Li and Mupondwa (2014) and Vollmann and Eynck (2015)
Food and supplements	Egypt	Ibrahim and El Habbasha (2015)
Bio-oils	USA, Ireland, Spain	Mohammad et al. (2018), Drenth et al. (2015) and Gómez-Monedero et al. (2015)
Herbicide, fungicide	USA	Cao et al. (2015) and Ma et al. (2015)
Medical use		
Cancers and tumors	USA	Das et al. (2014)
Ulcers	USA	Cuendet et al. (2006)
Cholesterol reduction	Finland	Karvonen et al. (2002)
Neurological abnormalities	USA	Trumbo et al. (2002)
Coronary heart diseases	Turkey	Gogus and Smith (2010)
Burns and inflammations	USA	Sampath (2009)
Antioxidant	Germany	Terpinc et al. (2012)

7.18 Alternative Uses

The *C. sativa* meal is very nutritious and is used as feed for ewe's milk (Salminen et al. 2006), cattle's, hens, turkey's, rabbits, etc. If we want to expand this industry, we must find new alternative uses of camelina meal. There must be strong collaboration among universities, research wing, and stakeholders to find new ways of camelina meal uses as bio-based products like adhesive, coating, and packing materials (Li et al. 2015; Kalita et al. 2018; Liu et al. 2018). The dearth of a marketing system and less productivity when related to several other oilseeds are currently impeding its adoption. The government policy must be clear about the rates and marketing of *C. sativa* and its products. This will boost camelina production. An extended marketing system will be able to improve the cost-effective feasibility of camelina as a profitable oilseed.

7.19 Camelina in the Fallow Season

This crop can be used as a replacement for the fallow season before sowing wheat in the main winter fallow and can also be sown in the wheat summer fallow system (Obour et al. 2015; Berti et al. 2016; Obour et al. 2018). It will be a big success for agronomic assistance; the crop management is comparatively very easy because the insect pest infestation is very low and no extra mechanization is required which will result in high economic yield. Crops that could replace the wheat-summer crop-fallow phase system must have some unique features, including agronomic assistance, companionable with available technology, comparatively easy to handle, lowest disease and invasion, and increasing the final profitability. In the cereal-based cropping system of dryland area, the incorporation of camelina will diversify the cropping system and increase profitability (Johnston et al. 2002). A yield reduction has been reported in wheat yields following camelina in drier years might be due to sustained fallow period (Hess et al. 2011; Sintim et al. 2014).

7.20 Prospects for Future Research

Unfortunately, price and low seed yield contributed to the decline in camelina production acreage (NASS 2015). Camelina is being grown under contracts in Canada, with about half in the province of Saskatchewan (Li and Mupondwa 2014). Because there is no established market for camelina, many economic studies have used canola prices for economic feasibility evaluations (Gesch et al. 2018). Barriers to wide-scale adoption of this crop as feed or feedstock for biofuels include low seed yield, lack of an open market, low price for the seed, perception as a weed by farmers (Jewett 2015), and anti-nutritional aspects in both the meal and oil.

7.20.1 Agronomic Research

The main concern with camelina is that very little effort is being made in technology development and transformation regarding breeding efforts to updated genotypes, the latest and appropriate production systems, and best agronomic practices. In contrast, many trials have been conducted to produce elite germplasm via conventional breeding efforts to improve the potential of *C. sativa* in field conditions. Several efforts should be made to conduct multi-locational experiments to check its response in water shortage conditions, thermal stress, salinity, or heavy metal stress conditions as were being made for canola by Pavlista et al. (2011). Studies must be made on the optimum fertilizer requirements of *C. sativa* on different soils to enhance its productivity and must try to incorporate it into an existing cropping system. Trials must be conducted to investigate weed and disease control. *C. sativa* is reported to be highly susceptible against residual class two herbicide. Nonetheless, efforts were made to address this problem; they transformed it by *Arabidopsis acetolactate* synthase (ALS) engineered with a number of particular changes/mutations in various combinations in the active site of camelina (Ala122Thr, Pro197Ser, and Trp574Leu). The studies on the camelina issue like shattering, harvesting, and postharvest management must be done to improve its response. Most of the oilseed crops are raised in marginal and submarginal lands which are having poor fertility status. So, it's an agronomist's job to convince the farmers and increase the cultivation area on fertile and productive soils. Agronomic research to recognize the appropriate spring and winter genotypes, seeding dates, and soil fertility requirements are desired to optimize the site-specific production technologies for camelina.

7.20.2 Plant Breeding Efforts

Unlike other oilseed crops, there is a minimum number of breeding efforts being made in *C. sativa*. Most of the cultivars being used in the USA are from their native origin, with minimum improvements that were screened and adjusted to regional conditions. If we want to increase the camelina seed yield, oil content, and oil quality, we need to make plant breeding efforts to develop new high potential varieties. These cultivars must have the ability to cope with environmental stresses effectively. The ability to outcross in *C. sativa* is minimal so efforts must be needed to explore this wing (Julié-Galau et al. 2014). The genotypic research in camelina was very limited because of the self-pollinating nature of camelina that makes it a complex process, so biotechnological techniques could give a breakthrough. However, scientists have forged the utilization of an agrobacterium-mediated transformation by spending ex-plants of camelina and floral dip procedure to incorporate bacterial strains in camelina plant. So, we need to use plant breeding approaches to improve the performance of *C. sativa*.

7.21 Climate Change

A growing global population is driving up the demand for food. This challenge is intensified in agriculture by extreme vulnerability to climate change. Climate change noticeably affects crop productivity and global food security by increasing temperatures, atmospheric carbon dioxide and ground-level ozone concentrations, weather variability, shifting agroecosystem boundaries, invasive crops and pests, and more frequent extreme weather events. However, the changing climate is having far-reaching impacts on agricultural production, which are likely to challenge food security in the future. Therefore, extensive actions will be needed for increasing yield and quality food to meet the future demand.

Agriculture is a foremost part of the climate problem (climate change) and also a major source of greenhouse gases (GHGs) which contribute to the greenhouse effect. Agriculture contributes toward climate change through *anthropogenic* GHG emissions and by the conversion of nonagricultural land such as *forests* into agricultural land (Sarkodie et al. 2019). Blanco et al. (2014) estimated that agriculture, forestry, and land-use change contributes 20–25% of global annual emissions. The food system as a whole contributes 37% of total GHG emissions estimated by *European Union's Scientific Advice Mechanism*, and this figure will increase up to 40% by 2050 due to population growth and dietary change (SAPEA 2020). However, crop insecurity will increase over time and with rising GHG emissions. Therefore, climate change will affect in agriculture, and the potential agrobiodiversity can provide resilient solutions in future agriculture.

7.22 Role of Camelina to Mitigate Climate Change Issues

Camelina can endorse biodiversity, decrease soil erosion, improve water infiltration (Gaba et al. 2015; Meyer et al. 2019), and encourage the sustainable intensification of cropping systems (Sindelar et al. 2017; Struik and Kuyper 2017). Mixed or relay cropping with camelina is valuable and widespread organic farming to overcome weed pressure (Leclère et al. 2019).

The production of plant-based liquid fuels has major implications to improve the environment and to mitigate climate change. Camelina is well known as advanced biofuel producer crop. A biofuel qualifies as an "advanced biofuel" if the fuel reduces GHG emissions by at least 50% compared to baseline petroleum fuel (EISA 2007). In 2013, the US Environmental Protection Agency identified the fuel pathways for biofuels produced from camelina oil and stated that camelina biodiesel could qualify as an advanced biofuel (USEPA 2013). It was estimated that use of camelina biodiesel reduces GHG emissions by 69% compared to 2005 baseline diesel (Dangol et al. 2015). Biofuels have the potential to emit less pollution compared with fossil fuels and, if implemented correctly, could help alleviate the rise of CO_2 levels and climate change (Bernardo et al. 2003). It is often reported that oilseed crops are the most efficient and effective biofuel source (Hill et al. 2006). In another study using camelina in place of mineral-diesel to power trucks showed that emissions of carbon monoxide (CO), carbon dioxide (CO_2), and smoke were significantly less from trucks powered by camelina oil (Bernardo et al. 2003).

7.23 Conclusion and Suggestions

The worldwide alimentary-oil requirement is increasing; thus, despite the development of hybrids and cultivars, improvement in production machinery, and technologies of oil-bearing crops, we need to incorporate the novel species in the cropping system that have the unique fat profile as reserve substances. Camelina as an oilseed holds a promise with the ability as the commercial oilseed, animal feed, and other industrial uses. As camelina has important agronomic characters that must highlight its scope as a new addition in a cropping system. BBCH's two- or three-digit coding system that described the phenological growth stages of a crop provides the phenological information and is complemented by depictions of most descriptive stages. Existing approaches for adjusting endogenous lipid profile and oil yield in camelina have a huge success, and it can also offer industrial products derived from it. The abiotic stress tolerance and low-input requirements are novel characters of this crop that makes it best fit in semiarid and arid conditions like Pakistan. The one biggest harmer of camelina adoption is the lack of a proper marketing system and low productivity in competition with other oilseed crops. The economic yield of camelina needs to improve the challenges relating to seed yield and new lipids. Novel approaches are being instigated to understand the intricate metabolic fluctuations over time and space with synthetic biological apparatuses to fine-tune lipid metabolism for explicit requirements. So, there is a dire need to develop a proper marketing system and a government policy for its production. Research on *Camelina* is limited, and its production systems are not being fully optimized. Agronomic research to identify suitable winter and spring *C. sativa* genotypes, seeding dates, and soil fertility requirements are needed to develop site-specific production recommendations for camelina. A prolonged proper marketing system will improve the financial feasibility of camelina as a salable oilseed. The latter will guarantee the grower's adoption of camelina in the semiarid regions due to its desired agronomic features as a dryland crop.

To attain numerous high-valued lipid foodstuffs, it is vital to reform the enzyme with enhanced activities or precise characteristics. Numerous methods can be employed to alter or produce innovative enzymes essential for the specific lipid amalgamation and accretion, together with focused protein alteration and upright-translation amendments. Lastly, modified metabolic paths for elevating innovative and high-esteemed lipids would be shared with additional breeding plans in camelina, for instance, cumulative harvest and seed oil contents and enlightening resistance to numerous environmental stress circumstances.

Conflict of Interest Authors declare that they have no conflict of interest.

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Chapter 8
Greenhouse Gas Emissions and Mitigation Strategies in Rice Production Systems

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Abstract Methane (CH_4) and nitrous oxide (N_2O) are the two critical greenhouse gases (GHGs) that absorb radiation, affect atmospheric chemistry, and contribute to global climate change. Rice being the second largest cultivated food crop around

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the world is also a leading anthropogenic source of GHG emissions from agriculture sector. It accounts for 18% CH_4 and 11% N_2O emissions of the total agricultural GHG additions. In the face of rising population, rice production is estimated to be increased by 40% in 2030 along with higher CH_4 and N_2O release to the atmosphere which needs to be reduced on priority basis. We attempted to develop a mechanistic understanding on CH_4 and N_2O production from rice fields and different factors influencing their emission. It has been found that modifications in traditional crop cultivation practices manifested enormous potential to minimize GHG emissions from rice fields. However changes in the existing management practices can simultaneously influence more than one gas, and their effects may be opposite. After assessing the possible mitigation options to abate CH_4 and N_2O emissions, it has been found that modifying irrigation and tillage practices, improving fertilizer management, using low-emitting rice varieties, incorporation of fermented cow dung and leaf manures, addition of nitrification inhibitors, and slow-release fertilizers manifested great potential to abate methane and nitrous oxide emissions. Incorporation of biochar, straw compost, and straw ash could have better results in curtailing GHG emissions compared to direct straw additions. Adoption of these proposed mitigation options singly or in combination is likely to minimize GHG emissions and helpful in sustainable rice production. However successful execution of these practices at farmer's level demands the removal of all social, economic, educational, and political barriers.

Keywords GHG emission · Rice production · CH_4 · N_2O · Climate change · Nitrification · Methanogenesis

Abbreviations

AFOLU	Agriculture, forestry, and other land use
CH_4	Methane
CO_2	Carbon dioxide
FAO	Food and Agriculture Organization
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
IRRI	International Rice Research Institute
N_2O	Nitrous oxide
RFESs	Rice field ecosystems

8.1 Introduction

Climate change is a major environmental concern of the twenty-first century largely driven by rising greenhouse gas (GHG) emissions (Wang et al. 2017). Rising sea levels, food security, health problems, severe storms, migration, and increasing economic losses are just some of the immediate repercussions of climate change (Yoro and Daramola 2020). This devastating situation advocates the adoption of certain strategies to minimize the GHG emissions and limit the impact of climate change. The three most important GHGs are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), absorb infrared radiation in the atmosphere, retain heat, and warm the surface of the Earth, therefore potentially contributing toward global warming (Synder et al. 2009). Global warming potential (GWP) of these three GHGs differ significantly as GWP of N_2O is 298 times higher than CO_2, while GWP of methane is 265 times greater than CO_2 on a 100-year time span (Shakoor et al. 2020). According to IPCC (2014), power sector (electricity and heat production) accounts for 25%; agriculture, forestry, and other land use (AFOLU) sector 24%; industrial sector 21%; transportation sector 14%; other energy sectors 10%; and building sector 6% contribution in global GHG emissions, respectively (Fig. 8.1).

Agricultural production systems are vital anthropogenic sources of GHGs having share of about 10–14% in global GHG emissions, and agriculture alone contributes about 42% of total CH_4 and 75% of N_2O emissions (FAO 2020). In worldwide agricultural ecosystems, CH_4 emissions are 3.22×10^6 Gg CO_2-eq year^{-1}, while nitrous N_2O emissions amounted 5.99×10^6 Gg CO_2-eq year^{-1} (FAO 2020).

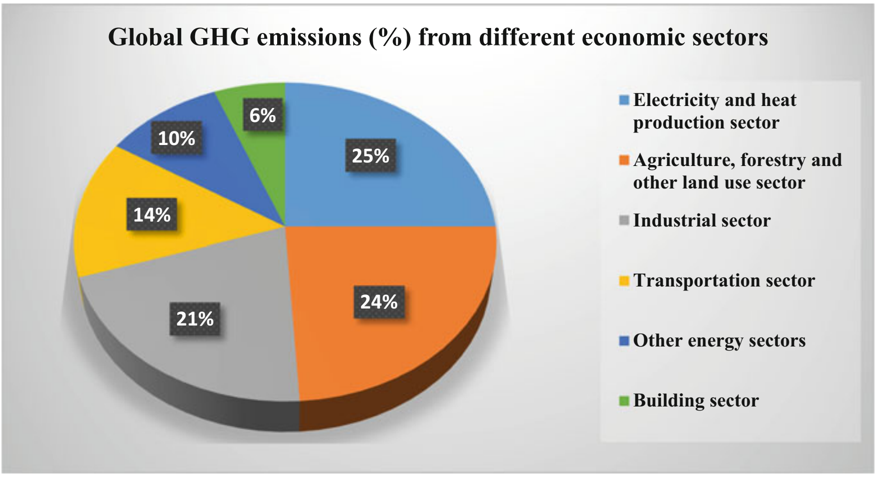

Fig. 8.1 Contribution of different economic sectors in global greenhouse gas emissions. (Source: IPCC 2014)

Rice (*Oryza sativa* L.) is a vital component of agricultural production systems encompassing a harvest area of about 23% of the total area of global cereal farming (FAO 2020). Rice is widely cultivated as a staple food crop globally (Carlson et al. 2017) covering 160 million hectares (ha) of land with 740 million tons of annual production (Pathak et al. 2018). About 92% of the global rice production and consumption occurs in Asia, and it satisfies nearly 35–80% of total calorie consumption of the Asian people (Sarwar et al. 2022). Almost 75% of the global rice supply is dependent on 79 million hectares of irrigated cropland in Asia. Therefore, current and future food security particularly in Asia and around the globe will largely depend on irrigated rice systems (Kumar et al. 2019). Irrigated rice cropping systems significantly contribute toward CH_4 and N_2O emissions into the atmosphere. Global estimates revealed that CH_4 accounts for 18%, while N_2O accounts for 11% emissions of the total agricultural emissions that come from paddy fields (IPCC 2014; FAO 2020). Furthermore, GWP of GHG emissions from rice production systems is approximately four times greater as compared to wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) (Linquist et al. 2012). According to an estimate, rice production will be increased by 40% at the end of 2030 in response of enormously increasing population (FAO 2009). Hence increase in production will escalate the CH_4 and N_2O emissions to the atmosphere, thereby raising serious concerns regarding climate change and sustainable rice production (Wang et al. 2017). Therefore for sustainable rice production in the future, we have to combine the increase in rice yield with reduced GHG emissions (Faiz-ul Islam et al. 2018). Nonetheless CH_4 and nitrous oxide ejections from rice fields are significantly persuaded by crop production practices such as soil tilling methods, land leveling, plant residue management, irrigation scheduling, drainage system, and organic and inorganic soil modifications. Therefore the appropriate strategy to manage the GHG emissions with gains in rice yields is to modify or improve the traditional crop management practices. It will help to maintain appropriate soil carbon pools and improve nutrient use efficiency with substantial reduction in CH_4 and N_2O productions from paddy fields.

8.2 Rice Ecosystems

Rice crop is widely grown under diverse climatic conditions around the globe. The International Rice Research Institute (IRRI) has classified the rice field ecosystems (RFESs) into four categories: (i) upland, (ii) irrigated, (iii) rain-fed lowland, and (iv) flood-prone rice ecosystems (IRRI 1993) (Fig. 8.2).

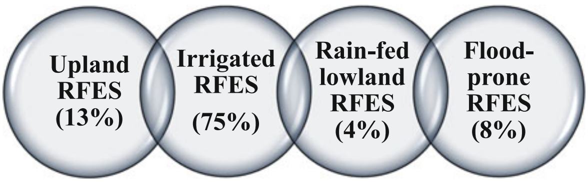

Fig. 8.2 Different types of rice field ecosystems (RFESs) in the world. (Source: IRRI 1993)

Upland RFES The upland rice field ecosystems comprised of low-lying valleys with undulating steep slopy land having high runoff and sideways water movement. Such kind of system represents less than 13% of the global rice land.

Irrigated RFES Irrigated RFESs have ample quantity of water to support single or more crops annually. Lands under irrigated RFES cover about 50% of world's rice lands controlling nearly 75% of the world's rice production.

Rain-Fed Lowland RFES The rain-fed lowland RFES encounters both drought and flooding problems. Rain-fed low lands cover about 25% (one quarter) of the world's rice fields.

Flood-Prone RFES The rest of the rice fields are categorized as flood-prone RFES holding an area of about 8% of the world rice lands. Uncontrolled flooding is a primary feature of this RFES. The land may remain submerged with water (0.5–4.0 depth) for about 5 months, whereas in some areas get alternate flooding with brackish water caused by tidal fluctuations. These RFESs face multiple problems such as plant nutrition, weeds, and pest problems; therefore they require different rice crop management strategies.

8.3 Paddy Soil Characteristics

Paddy soils represent the second largest manmade wetlands after natural wetlands (Yoon 2009). Primarily paddy soils are characterized by heavy texture with reduced soil horizon indicating continuous or inconsistent signs of waterlogging like splitting of iron and manganese in the soil solution (Kirk 2004). Moreover presence of a hard pan with higher bulk density at a depth of 15–25 cm substantially decreases water percolation and promotes flooding. Utilization of paddy soils through puddling constitutes the artificial submerged conditions accompanying reduced soil conditions hiding the original soil characteristics (Kirk 2004). Management of paddy soils mediates the creation of pedogenetic horizons (Fig. 8.3) a characteristic of paddy soils (FAO 2006).

W: This horizon is characterized by thin layer of standing water containing bacteria, macrophytes, phytoplankton, and small fauna. This horizon is primarily oxic.
Ap: It represents the interface of the soil and standing water with oxic conditions. Thickness of this zone may range from several millimeters to several centimeters.
Arp: It is the top portion of an anthraquic horizon having reduced puddled and flooded layer, indicating a reduced soil matrix with some oxidized root channel. It represents an oxidation reduction site during the period of alternate flooding and drainage of soil. This layer is usually 15 cm thick.
Ardp: It is the lower part of an anthraquic horizon with plough pan. It is compact with high bulk density having platy structure that hinders the water infiltration. Hence stagnant and reduced conditions are retained in this layer.
B or C: A hydragic horizon carrying redoximorphic properties.

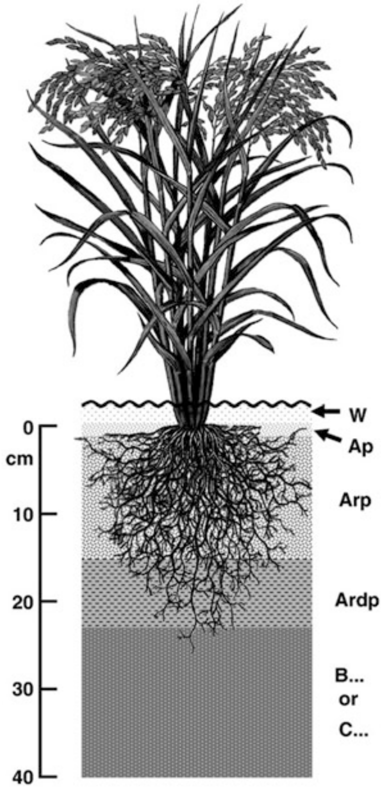

Fig. 8.3 Horizon sequence of a typical paddy soil. (Source: FAO 2006)

Paddy soil management-induced fluctuations in redox potential control the microbial community structure, function, and therefore short-term biogeochemical processes. Microbial reduction processes after flooding utilize NO_3^-, Mn^{4+}, Fe^{3+}, and SO_4^{2-} as electron acceptors and emit gases including N_2O, N_2, H_2S, and CH_4 and due to reduction-mediated increasing pH-NH_3. This is the main reason of N losses and low N fertilizer use efficiency. Meanwhile, rice roots acquiring atmospheric O_2 via aerenchyma cells modify the rhizosphere environment, causing nitrification and CH_4 oxidation along with precipitation of Mn and Fe oxides. High content and fluxes of dissolved organic matter (DOM) in rice soils from plant remains initiate microbial activity and GHG. DOM confinement by soil minerals and consequent steadiness against microbial decay is highly dependent on the prevailing redox state (e.g., DOM precipitation by Fe^{2+} under anaerobic conditions). Fluctuations in redox conditions may prolong the retention and stabilization of DOM by Fe oxy hydroxides (Kögel-Knabner et al. 2010).

8.4 Methane (CH_4) Production and Emissions from Paddy Soils

CH_4 is the second crucial GHG after CO_2 in terms of GWP and the dominant GHG emitted from rice fields. Its concentration in atmosphere has greatly increased from preindustrial level of 722 ppb to the current level of 1830 ppb (Wang et al. 2017). The cumulative annual CH_4 emission from both anthropogenic and natural sources is estimated about 600 CH_4 Tg year^{-}1 out of which 20% is added by paddy fields. Globally rice cultivation alone adds up approximately 46 Tg year^{-1} CH_4 emissions to atmosphere (James and James 2010).

8.4.1 Methanogenesis and Methanogens

Production of CH_4 through bacterial breakdown of complex organic matter under anaerobic conditions in flooded rice is called methanogenesis, whereas the bacteria/archaea accomplishing this process are called methanogens (Penning and Conrad 2007).

Methanogens from Archaea domain are strictly anaerobic obligate in nature (Fazli et al. 2013). Methanogens are also unique as they obtain their energy from CH_4 production by utilizing substrates like ethanol, formate, acetate, CO_2, and H_2 (Conrad 2007). Methanogens are mesophilic in nature, capable of producing CH_4 in a temperature range of 20–40 °C (Dubey 2005). Ammonium ion (NH_4^+) is the preferred nitrogen source used by all the methanogens, although they can fix molecular nitrogen and also contain nitrogen fixation genes (nif) (Dubey 2005; Serrano-Silva et al. 2014). CH_4 formation by methanogens requires some unique enzymes and coenzymes to accomplish this procedure (Nazaries et al. 2013).

Weeds, weed and rice roots, rhizo-deposition by weeds and rice, algal biomass, rice litter, rice stubbles, biomass of microbes, aquatic animals, and organic fertilizers act as organic matter sources. Conversion of this organic matter into preferable food forms (acetate) or alcohols (desired after acetate) for methanogens is executed through following processes (Malyan et al. 2016).

8.4.1.1 Hydrolysis

Both humus and humic components constitute the organic matter in rice soils. The humus consists of specific matter and water-soluble materials. This granular matter comprising of cellulose, hemicellulose, lignin, and proteins is provided by living component, whereas substances such as amino acids, sugars, and nucleotides which are water soluble either contributed by disintegration of the particulate matter through hydrolysis of extracellular enzymes or by rhizo-deposition (Conrad 1999; Brune et al. 2000; Kimura 2000; Liesack et al. 2000; Kimura et al. 2004).

8.4.1.2 Acidogenesis

In acidogenesis the hydrolytic products (monomers) are transformed into volatile fatty acids, ammonia, organic acids, alcohols, hydrogen, and CO_2 (Cairo and Paris 1988). Fermentative bacteria convert monomers of hydrolysis into acids. This kind of fermentative bacteria may be strictly anaerobic or can be facultative aerobic.

8.4.1.3 Acetogenesis

During acetogenesis volatile fatty acids convert themselves into acetic acid, CO_2, and H by acetogens. Acetogen bacteria are primarily obligatory anaerobic bacteria found largely in rice fields (Rosencrantz et al. 1999). Wood–Ljungdahl or reductive acetyl-CoA pathway is used by acetogens to synthesize acetyl-CoA and cell carbon. Formation of acetate from the preformed metabolites (acids) is accomplished by bacteria at a temperature range of 15–50 °C. Globally this range of temperature usually exists in majority of the rice fields across all geographical regions (Malyan et al. 2016).

8.4.1.4 Methanogenesis

Methanogens consume C from formic acid, alcohols, methylated sulfides, methylamines, dimethyl sulfide, acetate, methanethiol, and CO_2/H_2 as substrates producing CH_4 (Nazaries et al. 2013; Dubey 2005). The acetate or CO_2/H_2 acts as an instant methanogenesis precursor. Methanogenesis occurs as a result of decline in non-methanogenic electron-accepting agents (oxygen, nitrate, manganese (IV), iron (III), and sulfate) and transforms thermodynamic conditions (Malyan et al. 2016).

8.4.2 Methane Emission Pathways

CH_4 can be found in rice soils either as dissolved CH_4 or in gas phase (Tokida et al. 2005). An estimation revealed that approximately 33–88% of the total subsurface CH_4 exist in gas form. In contrast dissolved CH_4 content found to be quite low is less soluble (17 mg/l) in water (at 35 °C) and not having any ionic form (Green 2013). Association of methanogens, methanotrophs, and atmospheric-soil CH_4 completely governs the CH_4 cycle in soil. Generally three possible processes facilitate the CH_4 release from soil to the atmosphere.

8.4.2.1 Diffusion

Movement of gas molecules in the most active layer is called diffusion. CH_4 emission through diffusion is relatively slow with less and CH_4 flux from soil because it is less soluble in water. The highest CH_4 diffusion is observed in sandy soil, while in clay soil CH_4 diffusion is negligible mainly due to pore-space differences. In deepwater rice, diffusion operates only in the top portion of water column (Neue 1993), and it also impedes the CH_4 transfer from plants to atmosphere when CH_4 partial pressure in the root zone reaches to its threshold level (Denier van der Gon and Breemen 1993).

8.4.2.2 Ebullition

When CH_4 is transported in the form of bubbles, this process is known as ebullition, and it may be steady or sporadic (Green 2013; Tokida et al. 2005; Strack et al. 2005). Ebullition is much faster compared to diffusion and occurs under high CH_4 production especially during early growth period of rice. Loss of CH_4 during ebullition is common from rice soils, particularly in clay textured soils. It is also noted that ebullition process is largely influenced not only by gaseous pool of CH_4 but also by the plant-derived flux capacity (Tokida et al. 2013). Additionally, CH_4 emission through ebullition is so quick that opportunity of CH_4 oxidation becomes limited.

8.4.2.3 Plant-Mediated Transport

This process of CH_4 emission is assisted by aerenchymatous tissues of rice. Arenchymatous tissues also liberate CH_4 gas (nearly 80–90% of total methane) to air from rhizosphere in paddy fields (Malyan et al. 2016). CH_4 is primarily liberated via micropores present in the leaf sheath on the lower side of the leaf while it is released secondarily through leaf blade stomata (Nouchi et al. 1990). Additionally, Chanton et al. (1997) and Das and Baruah (2008) highlighted the correlation between CH_4 emission rates and stomatal density and further linked this emission with transpiration.

8.4.3 Methane Oxidation

Methane oxidation occurs under both aerobic and anaerobic circumstances (Nazaries et al. 2013). This bacterial oxidation is mediated by methanotrophs (either aerobic or anaerobic). Methanotrophs usually consume CH_4 or methanol to obtain energy for their growth (Malyan et al. 2016). Details about both oxidation processes are presented below.

8.4.3.1 Aerobic Methane Oxidation

In aerobic oxidation CH_4 is changed into CO_2, via stepwise action of enzymes. In the first step, CH_4 is converted into CH_3CHO by methane monooxygenase (MMO) enzyme. Methanol dehydrogenase then oxidizes CH_3CHO to formaldehyde, which is further oxidized to generate formate and lastly to CO_2. The process of CH_4 aerobic oxidation is catalyzed by MMO enzymes. A brief depiction of CH_4 oxidation process to CO_2 is as under:

$$CH_4 \rightarrow CH_3OH \rightarrow HCHO\ (Formaldehyde) \rightarrow HCOOH \rightarrow CO_2$$

8.4.3.2 Anaerobic Methane Oxidation

Anaerobic CH_4 oxidation (AOM) is accomplished through physical combination of anaerobic methanotrophic archaea (ANME) and sulfate-reducing bacteria (SRB) (Nazaries et al. 2013; Chowdhary and Dick 2013). CH_4 oxidation to CO_2 took place via SRB in the presence of sulfate as an electron acceptor agent (Caldwell et al. 2008; Thauer and Shima 2008). Ettwig et al. (2010) described that an anaerobic bacterium *Methylomirabilis oxyfera* that oxidizes CH_4 has been found to reduce nitrite into dinitrogen in pure cultures. Moreover, reduction of nitric oxide to dinitrogen without forming N_2O is mediated by an unknown enzyme (Serrano-Silva et al. 2014). Despite utilization of sulfate and nitrite being electron acceptors, AOM in marine environment largely depends on iron and manganese (Beal et al. 2009).

8.4.4 Factors Affecting Methane Production from Paddy Soils

Methane emission from paddy soils is largely dependent on the production and oxidation rates that are mainly governed by methanogens and methanotroph population dynamics in the system. Interplay of various factors (Fig. 8.4) regulates these processes like SOM content, soil pH and soil texture, redox potential, fertilizers, and soil temperature. These emission processes are also influenced by diurnal and seasonal variation, increasing ozone and carbon dioxide concentration, management practices such as cultivar selection, nutrient application, water management, and pesticide application (Table 8.1) (Malyan et al. 2016).

Fig. 8.4 Factors related to CH_4 production

8.5 Nitrous Oxide (N_2O) Production and Emission from Rice Fields

N_2O is a leading anthropogenic GHG and plays a key role in stratospheric ozone depletion. Its share in enhanced global warming effect is approximately 6% (IPCC 2007a, b). Agriculture sector is the largest source of N_2O among all the anthropogenic sources (Reay et al. 2012). Rice (*Oryza sativa* L.) farming is an important component of agriculture sector because it fulfills the food needs of nearly half of the global population (Maclean et al. 2013). Paddy fields also contribute toward atmospheric N_2O emissions (Maclean et al. 2013; Linquist et al. 2012). Rice fields have a share of about 11% in total global agricultural emissions of N_2O (IPCC 2014; FAO 2020). In addition to that on global scale, one-seventh of the nitrogen (N) fertilizer and one-third of irrigation are utilized by paddy globally (Heffer 2009). It creates a

Table 8.1 Factors affecting the CH_4 production from rice fields

Factor		Effect on CH_4 production and emission
Water regimes	Submergence	Submerged conditions found to enhance CH_4 production and emission (Ponnamperuma 1972)
	Intermittent drainage	It decreased the CH_4 formation through O_2 influx in soil; consequently CH_4 emission is reduced (Sass et al. 1992; Corton et al. 2000)
Soil	Soil texture	Heavy-textured soils may capture more CH_4 and allow more oxidation, thus releasing less CH_4. Sandy soil manifested high methane emission as compared to clayey soil. CH_4 production also increases with increase in aggregate size of the soil (Neue 1993; Jackel et al. 2000)
	Soil pH	Optimal soil pH range lies between 7.5 and 8.5 for CH_4 production. However soil pH above 8.8 and below 5.8 completely inhibits CH_4 production (Parashar et al. 1991; Pathak et al. 2008)
	Soil redox potential (Eh)	Production of Eh starts at −150 to −160 mV. Production escalates with reduction in Eh maximum production noted at Eh −250 mV (IPCC 2001; Ali et al. 2008)
	Soil temperature	Emission rate doubled when soil temperature ranges between 20 and 25 °C and maximum production takes place at 30 °C of soil. Rising temperature makes gases more soluble in water, thereby increasing the gas emission chances (Holzapfel-Pschorn and Seiler 1986; Lu et al. 2015)
Organic matter application	FYM, straw compost, and green manure	Drastic increase in production and emission occurred with organic matter addition (Yagi et al. 1997; Majumdar et al. 1999; Pandey et al. 2014; Sander et al. 2014; Haque et al. 2013)
	Biochar and cattle manure	Addition of these amendments decreased the CH_4 emission (Feng et al. 2012; Pramanik and Kim 2014)
Land preparation		Intercultural operations can increase emissions, but it is less prevalent in direct-seeded rice because of higher plant density, less weed growth, and mechanical weeding which restrict emissions (Neue 1993)
Fertilizer (type, rate, and mode)		Urea enhances CH_4 emissions, while ammonium sulfate, ammonium thiosulfate, and super single phosphate reduce CH_4 emissions in paddy fields (Wang et al. 1993; Serrano-Silva et al. 2014; Rath et al. 2002; Adhya et al. 1998)
Nitrification inhibitors		Nitrification inhibitors (NI) like dicyandiamide and nitrapyrin inhibit the formation of CH_4 in rice fields. Use of urease inhibitor (hydroquinone), nitrification inhibitor (dicyandiamide), and hydroquinone plus dicyandiamide have been found to decrease CH_4 release by 30, 53, and 58%, respectively (Lindau et al. 1990; Salvas and Taylor 1980; Boeckx et al. 2005)

(continued)

Table 8.1 (continued)

Factor		Effect on CH_4 production and emission
Rice cultivars		CH_4 flux changes from cultivar to cultivar; increase in production occurs due to root exudate availability; resultantly emission rises by providing conduits (Mitra et al. 1999; Jain et al. 2000)
Diurnal variation		Maximum production noted at 12:00, whereas minimum production was observed at 18:00 (Zhang et al. 2015)
Elevated CO_2 concentration		No significant effect was noted on CH_4 emission (Tokida et al. 2010)
Pesticide effect		15 to 98% decrease in CH_4 emission with butachlor application has been observed compared to control (Mohanty et al. 2004; Jiang et al. 2019)

strong N_2O formation zone, because both N fertilizer application and irrigation management practices promote N_2O emissions (Zhao et al. 2019; Jiang et al. 2019). Hence, chances of rise in global N_2O emissions from paddy in the future are considerably high (Ussiri et al. 2012). Therefore, understanding of N_2O production mechanisms under paddy fields is quite necessary so that promising mitigation strategies should be evolved that could help to curtail rising global warming affect and resultant climate change.

8.5.1 Nitrogen Transformation in Flooded Soils (Volatilization, Leaching)

Some important characteristics of flooded rice soils responsible for N conversion are (i) restricted exchange of atmospheric gases with flooded soils, (ii) rise in pH of acidic soils and decline in calcareous and sodic soil pH, (iii) reduction in soil redox potential, (iv) higher ionic strength and electrical conductivity (EC), and (v) anaerobiosis combined with decomposition of soil organic matter (Savant and De Datta 1982).

Behavior of nitrogen in flooded soils is completely different as compared to dry soils. Flooding in aerobic soils causes rapid depletion of soil O_2, so soil NO_3^- becomes vulnerable to be lost through denitrification and leaching. Soil flooding results in NH_4^+-N accumulation mainly because of inhibited nitrification, unstable NO_3^{-} $^{-}$-N, and less N needed for OM breakdown. Flooding also reduces the utilization efficiency of added nitrogen. In flooded soils conversion of $NH_4^+$to NO_3^- is restricted by O_2 deficiency that stops the mineralization at NH_4^+. Therefore, NH_4^+ becomes the leading form of N that gets accumulated. Hence it can be found in three sections: (i) NH_4^+ in exchange sites (ii), NH_4^+ in soil solution, and (iii) non-exchangeable NH_4^+ (De Datta 1995). NH_4^+ present in soil solution and at the exchange sites is easily taken up by rice. The NH_4^+-N may be fixed by clays, lost through volatilization, runoff, leaching, seepage, and nitrification followed by denitrification.

In puddled soils, runoff and leaching losses are less common. Thus, in flooded rice soils, the N_2 and NH_3 gas emissions are the main reason for fertilizer inefficiency. Higher N losses are noted when applied fertilizer yielded ammoniacal N in large amounts under flooded conditions (Simpson et al. 1988), which revealed that NH_3 volatilization is a vital process of N loss. Soil-applied N restricts NH_3 volatilization; however it cannot limit N loss, because after its application, NH_4^+ is transformed to NO_3^-, which is denitrified and lost in the form of N_2 and/or N_2O (Freney et al. 1990). In tropical transplanted rice, NH_3 volatilization losses may range between 10% and 56% of urea nitrogen broadcasted in flooding conditions (Buresh and De datta 1990; Freney et al. 1990). Different factors affecting the pattern of NH_3 loss include fertilizer source, temperature, pH, CEC of the soil, wind speed, and ammoniacal [NH_4^+ + NH_3]-N concentration (Freney et al. 1990; De Datta 1995; Cai et al. 2002). During volatilization process, gaseous NH_3 is formed, i.e.,

$$NH_4{}^+(aq) \rightarrow NH_3 + H^+$$

H^+ ion is liberated in this reaction. Therefore, in both oxidized and reduced soil layers, pH and buffering capacity affect the process of volatilization. In wetland soils, pH dynamics reveal that submerged conditions regulate the pH values in reduced acid and alkali soils within a range of 6.5 and 7.2. Thus volatilized NH_3 may exacerbate indirect N_2O emissions.

Reduced plow layer in flooded soils exists in between thin oxidized surface and somewhat oxidized subsurface soil layers. Reduced soil layer represents a specific pattern with aerobic and anaerobic microsystem in which rice roots get flourished and derive nitrogen. O_2 diffusion from rice roots makes the root rhizosphere somewhat oxidized as compared to the rest of the plow layer soil. Nitrification operating in oxidized soil zones, root rhizosphere, and floodwater transforms ammonical N into NO_3^-, which travels to reduce soil zones and further converted into N_2 and N_2O after denitrification (Reddy and Patrick 1986). Denitrifying bacteria require soil organic matter as an energy source, but the type and quantity of soil organic matter mainly govern the denitrification rate.

Wetland rice soils also experience alternating wet and dry phases, particularly in rain-fed circumstances or in continuous flooding situation. These soils remain saturated during the production period of rice, but become dry and aerated when there is an interval between rice crops. In this interval time, soil is either fallow or under crop cultivation. Under dryland aerobic conditions of soil, NO_3^--N from nitrification of N fertilizer or NH_4^+ after mineralization of soil organic nitrogen may become deposited in the soil or may be utilized by the plants. Although processes of mineralization and immobilization operate at the same time in wetland soils, they are affected by various soil and environmental elements. Near the harvest of rice crop, the amount of soil NO_3^- is minute, whereas soil NH_4^+ also becomes low owing to N taken up by rice plus volatilization losses (Buresh and De Datta 1991).

8.5.2 Processes Enabling Nitrous Oxide Emission from Rice Fields

Intermingling of different biophysical processes of biotic and abiotic origin derives the N_2O production and release from soils (Firestone and Davidson 1989). Flooded rice fields after fertilization facilitate denitrification to produce N_2O and N_2, but the same conditions further promote N_2O reduction to N_2, which is the vital output of denitrification. Soil flooding displaces O_2, and any O_2 in water is used by microbial and root respiration, ultimately depriving the soil from O_2. Rice paddies with anaerobic conditions prevent nitrification and support accumulation of NH_4^+.

8.5.2.1 Nitrification

Nitrification is not a common phenomenon in paddy soils mainly because of unfavorable water environment that favors anaerobic conditions. However, aerobic rice soils or alternatingly flooded soils may facilitate higher nitrification. When rice soils are intermittently flooded, it makes surface soil layer fully or partial aerobic during drainage and for a short time when next irrigation carries dissolved O_2 with water. In this situation with presence of NH_4^+ in the field, substantial amount of N_2O can be produced through nitrification in rice fields.

Nitrification is a microbial process accomplished through ammonium (NH_4^+) oxidation into nitrate (NO_3^-) through nitrite (NO_2^-) (Hayatsu et al. 2008). Nitrification consists of two steps: oxidation of ammonium ($NH_4^+ \rightarrow NO_2^-$) and oxidation of nitrite ($NO_2^- \rightarrow NO_3^-$). Ammonium oxidation can be performed by *Nitrosomonas* spp. and *Nitrosospira* spp. of bacteria and *Nitrosococcus* spp. of *Gammaproteobacteria* called as ammonia-oxidizing bacteria (AOB). Moreover, some archaea known as ammonia-oxidizing archaea (AOA) can also perform ammonia oxidation. Many studies revealed that AOA is more abundant than AOB in the ocean (Francis et al. 2007), while it is assumed that AOB could be more responsible for nitrification than AOA in agricultural soils. In rice paddy soils, a positive relationship has been noticed between nitrification activity and AOB abundance (Li et al. 2007); therefore, AOB might have more important role than AOA in ammonium oxidation in paddy soils. Nitrite oxidation, the second step of nitrification, is completed by nitrite-oxidizing bacteria (NOB) belonging to the genera *Nitrobacter*, *Nitrospina*, *Nitrococcus*, and *Nitrospira* (Hayatsu et al. 2008). Hydroxylamine, an intermediate of ammonia oxidation, and N_2O can be produced as a byproduct of hydroxylamine oxidation (Ishii et al. 2011).

8.5.2.2 Denitrification

Denitrification can occur in significant amount under field during drainage of water at anaerobic microsites containing nitrate and when demand for O_2 surpasses supply (Arah and Smith 1989). This phenomenon takes place either inside the soil mass or in fully saturated areas inside a structureless soil when O_2 diffusion is restricted or when there is unusual O_2 demand. Denitrification process simultaneously serves as both source and sink for N_2O because it forms and uses N_2O in the soil.

Denitrification is a microbial respiratory process, where after stepwise reduction, nitrogen oxides (NO_3^- and NO_2^-) are transformed into gaseous forms (NO, N_2O, and N_2). Nitrogen oxides may work as substitute electron acceptors for oxygen under anaerobic conditions. N_2O can also be consumed as an alternative electron acceptor, but it can be reduced by non-denitrifiers (Zumft and Kroneck 2006). Although N_2O is an intermediate product of denitrification ($NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$) the final product can be N_2O if a denitrifier is not able to reduce it (Tiedje 1994).

Microorganisms containing assimilatory NO_3^- reduction generate N_2O, whereas respiratory NO_3^- and dissimilatory NO_3^- reduction to NH_4^+ (DNRA). All these metabolic processes normally produce N_2O, and they also produce N_2 without any gain in energy; therefore they are called as non-respiratory N_2O producers (Tiedje 1988). A chemical reaction in which NO_2^- or NH_2OH are decayed in acidic soil can also produce N_2O in small amounts.

8.6 Factors Influencing N_2O Emission from Rice Fields

N_2O emission is a primary outcome of nitrogen source (Eichner 1990). A number of factors can influence the N_2O emission from soils (Table 8.2). Interaction and interplay of these factors actually regulate and determine the N_2O emission rate from paddy soils. However, the main emission curtailing factors are water regimes, fertilizers, plant population, soil texture, management, and cultural practices.

8.7 Strategies to Mitigate CH_4 and N_2O Emissions from Rice Fields

Agriculture is among the largest sectors contributing CH_4 and N_2O gases to atmosphere. For that reason experimentation to develop mitigation strategies of methane and N_2O formation and release from agricultural ecosystems are pretty much in vogue in recent days. It is quite obvious that mitigation of either of these gases from the irrigated rice fields through better management practices may probably give rise to the emission of others. Several studies have reported a negative correlation between the emissions of these two gases (CH_4 and N_2O) from rice soils. A

Table 8.2 Factors influencing N_2O formation and release from paddy fields

Factor		Effect on N_2O production in soil	Influence on N_2O liberation to the atmosphere
Water	Submergence	Water controls oxygen amount and diffusion process in soil; it promotes anaerobic conditions and accelerates denitrification process	Controls diffusion process; flooding increases complete denitrification to N_2 and curtails N_2O emission (Granli and Bockman 1994; Majumdar et al. 2000; Hou et al. 2000; Akiyama et al. 2005)
	Intermittent drainage	Switching of aerobic-anaerobic conditions drives switchable processes of nitrification and denitrification. Consequently N_2O production increases	Switching of anaerobic and aerobic processes promotes N_2O emission as compared to constant anaerobic or aerobic conditions (Majumdar et al. 2000)
Fertilizer	Types and application rate	Large amounts of N content scale up the nitrification and denitrification production. Hence N_2O formation is increased due to higher N content	Taken together emissions of N_2O increase in response of higher N application rate rather than type of nitrogen fertilizer applied (Cai et al. 1997)
	Ammonium sulfate vs. urea fertilizers	NH_4^+ facilitates N_2O liberation through nitrification	High amount of N_2O is produced by ammonium sulfate compared to urea with same amount of fertilizer application (Cai et al. 1997; Hua et al. 1997).
	Nitrate fertilizers vs. urea	In flooded soils N_2O formation is favored by NO_3^- via denitrification (Cai et al. 1997)	Nitrate fertilizers increase N_2O emissions compared to ammonium sulfate and urea (Cai et al. 1997)
	Farm yard manure vs. inorganic N fertilizers	FYM is a slow releaser of nitrogen via mineralization compared to inorganic nitrogen fertilizers	It reduces N_2O emissions compared to inorganic nitrogen fertilizers (Pathak et al. 2002, 2003)
Soil texture	Heavy texture	Trapping of high N_2O content leads to slow diffusion	Decline in N_2O emissions occurs because N_2O is completely denitrified to N_2 (Cai et al. 1999; Xu et al. 2000)
	Sandy soils	N_2O diffusion is faster in sandy soils	N_2O emissions are high due to easy movement of N_2O
Nitrification inhibitors		Delay in nitrification minimizes N_2O formation	Controlled nitrification facilitates reduced N_2O emissions (Majumdar et al. 2000)

prominent trade-off effect between CH_4 and N_2O discharges from paddy fields has suggested that it is inevitable to examine the holistic effects of various management practices for minimizing GHG emissions in order to tackle the greenhouse effect backed by rice croplands. Hence the management practices should be adjusted in such a manner that emissions of these greenhouse gases may effectively be mitigated with least atmospheric radiative forcing contribution. Generally farmers give preference to economic crop production over mitigation. However CH_4 and N_2O mitigation controlling factors start from small scale and reach to global scale. Some extensively discussed management strategies may be employed to mitigate CH_4 and N_2O that are exclusively given below.

8.7.1 Water Management

Appropriate management of irrigation practices such as intermittent flood irrigation, midseason drainage (5–20 days) before reaching the maximum tillering stage, controlled irrigation, and multiple short-duration drainages (2–3 days after 3-week interval during the entire growth period) have been found to be effective in minimizing the CH_4 and N_2O emissions (Hussain et al. 2015; Malyan et al. 2016).

CH_4 in puddled soil is produced due to anaerobic decomposition of organic material following the flooding event in rice fields. However, performing field drainage activities completely diminishes the anaerobic condition for a time that not only prohibits the production of CH_4 but also reduces its total quantity to be released into the atmosphere during the entire growing season. On the other hand, N_2O production in rice fields is also regulated by the existence of oxygen. Unlike CH_4, the interchanging aerobic and anaerobic conditions favor bacterial conversion of various nitrogenous compounds to N_2O in the soil and its release to atmosphere. Additionally N_2O production in cropland is synergistically linked with the available nitrogen content in the soil (Hussain et al. 2015).

As far as midseason drainage is concerned, a 43% decrease in CH_4 emission owing to oxygen influx in soil is noted, thus providing conditions suitable for methanotrophic bacteria. Similarly intermittent drainage practice can reduce CH_4 discharge by 47% than flooding. Intermittent irrigation practice consisting of 20- or 40-day period can substantially minimize CH_4 emission compared to continuous flooding. According to an estimate, alternate wetting and drying with 5 cm irrigation depth (3 days and/or 4 days drying in a week) can successfully reduce CH_4 discharge up to 28% compared to continuous flooding with sustainable grain yield (6.71 t/ha). Likewise, midseason drainage has proven to be a good practice to control CH_4 and nitrous oxide emissions from paddy soils (Malyan et al. 2016).

8.7.2 Rice Varietal Selection

Selection of an appropriate variety can successfully regulate the methane emission from paddy croplands. Numerous studies have revealed that cultivated rice varieties having less sterile tillers, short rooting system, high root oxidation capacity, maximum harvest index, and less root excretion tendency and having timely maturing characteristics are best suited for curtailing CH_4 emissions from rice soils (Wang and Adachi 2000; Aulakh et al. 2001). Cultivars differing in CH_4-emitting capacity have differences in their morphological traits and physiological activities, methane gas carriage and root exudation potentials, etc. (Jia et al. 2002; Setyanto et al. 2004). Additionally, qualitative and quantitative transformations in the composition of root exudates among various rice cultivars can significantly influence CH_4 generation rate (Jia et al. 2002). Besides these, it is also narrated that root aerenchyma and root oxidation capacity substantially adjust the methane source strength in the rhizosphere. Conclusively these disparities in rice cultivars could develop significant direct or indirect changes in CH_4 emission rates.

8.7.3 Planting Methods

Adoption of direct-seeded rice (DSR) technique and using system of rice intensification (SRI) planting method are found effective in minimizing GHG emissions. Puddling and seedling transplanting operations are avoided in DSR, and rice seeds are directly sown in plowed or no-tilled soil. The DSR planting significantly reduces CH_4 emissions compared to transplanted rice (TPR) with slight increase in N_2O emission. Cumulative reduction in CH_4 liberation in DSR over transplanted rice has been ranged between 82% and 98% (Gupta et al. 2016; Pathak et al. 2012). Taking into account comparable GWP, higher grain yield and lower GHGI advocate that the DSR substantially lowers the resultant radiative forcing of CH_4 and N_2O releases as compared to TPR cropping system. In SRI planting 15–20-day-old rice seedlings are transplanted per hill in well-puddled soil by avoiding soil flooding but maintaining the soil field capacity level. SRI planting technique showed potential to decrease CH_4 emission by 61% when compared with TPR (Jain et al. 2014). Hence selection of suitable planting techniques can be useful in minimizing the GHG emission rates from rice fields.

8.7.4 Fertilizer Management

CH_4 and N_2O emissions are largely affected by fertilizer management. Type, amount, and fertilizer application method affect CH_4 emission from rice croplands. A recent finding revealed that proper nitrogen management in rice crop can reduce

CH_4 discharge by 30–50% relative to control treatment (Dong et al. 2011). Ammonium-based N fertilizer application as compared to urea showed higher potential to minimize CH_4 emission mainly due to higher CH_4 oxidation rate in the rhizosphere (Bodelier et al. 2000; Ali et al. 2012; Linquist et al. 2012). Sulfate-based fertilizers compel sulfate-reducing bacteria and methanogens to compete for substrate, which results in less CH_4 discharge under anaerobic conditions (Hussain et al. 2015). When ammonium sulfate applied as N source in rice crop, it caused 23% reduction in CH_4 emission (Ali et al. 2012). However in reduced zone, it does not affect CH_4 oxidation, so nitrification and denitrification will be minimum to produce N_2O. Application of potassium fertilizer decreases soil redox potential, reduces CH_4 formation, and stimulates CH_4 oxidation, consequently releasing less CH_4 (Hussain et al. 2015; Babu et al. 2006). Babu et al. (2006) reported a cumulative 49% reduction in CH_4 emissions with 30 kg K ha^{-1} as compared to control in rice crop. Split application of N at critical crop growth stages, especially low N amounts, is recommended because N uptake is low and it will reduce N_2O emission (De Datta and Magnaye 1969; Pillai et al. 1986).

Belowground (8–10 cm deep) application of urea super-granules, urea pellets, and urea briquettes in reduced zone can maximize N recovery and decrease N_2O loss (Pillai et al. 1986). Subsurface application of urea super-granules reduces methane flux over control (Rath et al. 1999).

Bio-fertilizers have capability to improve soil and increase yields on sustainable basis together with CH_4 mitigation in rice crop (Pabby et al. 2003). Bio-fertilizers include *Azolla*, mycorrhizae, cyanobacteria/blue green algae (BGA), and diazotrophs. BGA/*Azolla* with photosynthetic ability provides oxygen to rice soils. Azolla (aquatic pteridophyte) having N_2-fixation ability and symbiotic association with *Anabaena azollae* are widely applied bio-fertilizers in China, India, Bangladesh, and Vietnam in rice field. *Azolla* has curbing effect on CH_4 ejection from flooded soils, as it increases the dissolved oxygen content at the soil-floodwater interface. Lowest CH_4 emission has also been observed, when cyanobacteria applied in combination with *Sesbania* biomass, urea, and silicate fertilizers.

Pre-composted organic matter when added to soil has shown less CH_4 production per unit of carbon as compared to readily mineralizable carbon sources. In contrast, animal dung compost showed more N_2O emission when compared to chemical fertilizers (Chao and Chao 2001). However composts consisting of cow dung and leaves have reduced CH_4 fluxes (Agnihotri et al. 1999). Organic matter-induced aerobic degradation can significantly decrease CH_4 emission, but simultaneously it can increase N_2O emission through nitrification of liberated ammonium. Proper straw management via surface retention/mulching or converting it into biochar or compost rather than burning or incorporation showed potential to curtail GHG discharges from rice soils (Hussain et al. 2015).

8.7.5 Nitrification Inhibitors and Slow-Release Fertilizers

Nitrification inhibitors (NI) or slow-releasing N-based fertilizers have ability to minimize rice field greenhouse gas emissions (Majumdar 2003). NI restricts NH^{+4}-N conversion into NO_3^--N, which directly reduces N_2O emissions via nitrification and availability of NO_3^- for denitrification is also reduced. Aside from artificially prepared materials, some plant-based products have also shown potential to lessen N_2O emissions from rice fields. Dicyandiamide (DCD) and nitrapyrin nitrification inhibitors prevented CH_4 formation and minimized the emissions of CH_4 and nitrous oxide from paddy fields (Lindau et al. 1993; Salvas et al. 1980).

A significant decrease (30, 53, and 58%) in CH_4 emission has been observed with hydroquinone, dicyandiamide, and hydroquinone plus dicyandiamide applications, respectively (Boeckx et al. 2005). Many natural nitrification inhibitors like neem cake and urea coated with neem oil have been found to reduce CH_4 release by 8% and 11%, respectively, than urea fertilizer alone. Application of encapsulated form of calcium carbide (ECC) also reduced CH_4 emission by 13% in rice soils (Malla et al. 2005). Slow-release fertilizers can mitigate N_2O emissions; however slow-release (coated urea) and fast-release (compound fertilizer) N sources did not reveal any significant difference regarding methane emission (Hussain et al. 2015).

8.7.6 Tillage Practices

Soil tillage practices significantly affect the soil physical properties and GHG balance. Looking at GHGs together, soil tilling caused 20% higher net global warming compared to zero tillage indicating climate change mitigation potential of zero tillage system. Compared to conventional tillage system, no or reduced tillage practices significantly lessen (by 6.6%) the overall GWP of methane and N_2O emissions. The possible controlling effect of reduced tillage on CH_4 oxidation may facilitate CH_4 emissions mitigation. Adoption of zero tillage practices on regular basis may promote CH_4 oxidation and conversely minimizes CH_4 emission. In contrast some researchers have the viewpoint that no tillage practices can enhance N_2O emissions from rice soils (Zhang et al. 2011; Nyamadzawo et al. 2013). On the basis of C sequestration and CH_4 mitigation abilities, zero tillage practices have capacity to offset overall GHG emissions. Overall less GWP of zero or reduced tillage compared to conventional tillage practices in rice croplands (Ahmad et al. 2009) suggested that practicing reduced tillage has potential benefits of GHG mitigation and C-smart agriculture, which should be endorsed in rice-based cropping systems. However, the effectiveness of no tillage will largely depend on tillage methods, type of land use, and other management practices. No tillage considerably reduced the overall GWP when the percentage of basal N fertilizer (PBN) was >50% and when tillage duration was >10 years or rain-fed in upland, while when PBN < 50%, tillage duration ranged between 5 and 10 years, or with continuous flooding in paddy fields. Reduced tillage practices also decreased the overall GWP in monoculture system in upland. Therefore, while adopting no tillage or reduced tillage practices to curtail GHG emissions, their interaction with other agronomic practices should also be considered (Feng et al. 2018).

8.8 Conclusion

Rice (*Oryza sativa* L.) is a vital component of agricultural production systems, and its cultivation significantly contributes toward GHG (CH_4 and N_2O) releases and leads to global warming. Increasing population and escalating rice demand in the future raised serious concerns to curtail GHG emissions from rice cultivation without compromising the yield. By understanding the production mechanisms of CH_4 and N_2O from paddy fields, different mitigation strategies have been proposed to decrease methane and N_2O emissions. Site-specific nutrient management, changing irrigation practices like excess water drainage, performing recurrent irrigation, and adoption of DSR are helpful in minimizing the CH_4 and N_2O emissions. Use of fermented cow dung and leaf manures, changing N fertilizer sources (such as urea with ammonium chloride and use of ammonium sulfate in place of prilled urea), application of NI, and slow-release fertilizers are capable to alleviate methane and nitrous oxide releases. Similarly biochar, straw compost, and straw ash incorporation showed more promising results as compared to direct straw incorporation. However, the farmers will accept only those mitigation strategies which will not affect their grain yield.

The abovementioned mitigation possibilities are scientific findings, but to attain full implementation of these options singly or in combination at the farmer level needs a decisive policy and substantial government support. The policy to alleviate or lessen CH_4 and N_2O releases to atmosphere will vary according to a specific region or country, and it will highly be dependent on financial aid given by the government. However for effective and fruitful implementation of such practices to curtail GHG emissions and to sustain rice productivity under changing climate, all social, economic, educational, and political hurdles must be removed.

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Chapter 9
Fiber Crops in Changing Climate

Muhammad Tariq, Muhammad Ayaz Khan, Wali Muhammad, and Shakeel Ahmad

Abstract About 2000 plants have been reported in the world as fiber sources; however, only few are being utilized. Cumulatively fiber crops including cotton, jute, flax, agave, sisal, manila fiber, and ramie are being grown on 34.2 million hectares with the annual production of 29.5 million tonnes. The cotton is the leading fiber crop which shares more than 90% area and 80% production across the world. Despite the importance of the other fiber crops, most of the climate change studies were limited to cotton. There is uncertainty in climate of the future as the human actions responsible for greenhouse gas emission are not accurately predicted. The chemicals used for fiber extraction are deteriorating the environment quality, and proper treatments must be performed prior to disposal. Climatic factors are driving force for the crop growth, reproduction, and movement of insect pests. Increase in temperature, concentration of carbon dioxide in air, and rainfall pattern are distinguished climatic factors responsible for change in crop production. The cotton and hemp contributions in greenhouse gas emission are high; however, cotton is more victim of climate change in terms of phenology, yield, and quality. The accelerated development in response to high temperature reduces the duration of various developmental stages, thus reducing the yield as well as quality. Due to weakening of plant protection mechanism in current scenario of climate change, cotton bollworms, mealy bug, mirid bugs, and fall armyworm will be the widely distributing pests of fiber crops in the world. The phenomenon of the climate change is regulated by

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multiple factors, has multiple effects, and requires multiple approaches to strengthen fiber availability.

Keywords Fiber · Greenhouse gas emission · Quality · Pests

9.1 Global Fiber Production

The fibers are important component of the human lives in addition to shelter and food. The fiber crops were primarily grown for raw material of textile industry; however, non-textile applications have been identified since the last few decades back. Some of future uses of fiber crops may be in form of biopolymers, insulation board, particle board, cosmetics, etc. The natural fibers are mainly classified as bast fiber, seed fiber, and leaf fiber. About 2000 species were reported as fiber crops but the number of cultivated species is very few (Pari et al. 2015). The sclerenchyma fibers associated with phloem of the plant are known as bast fiber. The bast fiber accounts 16% in total global production of natural fiber crops. The other categories of fiber crops are seed and leaf fiber. The seed and leaf fibers originated and are extracted from seed and leaves, respectively. The other examples of these fiber categories are listed in Table 9.1.

The latest reports of International Cotton Advisory Committee (ICAC 2021) showed that the global cotton lint production in 2020–2021 was 24,189,000 metric tonnes which was harvested from 32,045,000 ha. The India ranks first in production (6,026,000 metric tonnes) and area (13,477,000 ha); Australia in yield (1905 kg ha^{-1}); China in beginning stock (8,938,000 metric tonnes), consumption (8,400,000 metric tonnes), imports (2,801,000 metric tonnes), and ending stocks (9,219,000 metric tonnes); the USA in exports (3,571,000 metric tonnes); and Hong Kong in ratio of ending stocks (34.08). The cotton is grown in many countries of the world with the prime objective of source of natural fiber along with many other associated uses as raw material in edible oils, bioenergy, and feed industry (Tariq et al. 2018, 2021; Afzal et al. 2018, 2020; Saranga et al. 2001; Mubeen et al. 2021; Abbas et al. 2020).

The fiber of jute is also known as allyott and golden fiber. There are two most common species of jute *Corchorus capsularis* (white jute) and *Corchorus olitorius* (tossa jute). It is believed that the former originated from India and later originated from South Asia. The jute is the major fiber crop followed by cotton. It is mainly grown in Asia (99.7%) particularly India, Bangladesh, and China along with some contribution from South America. Worldwide, 3,375,884 tonnes were harvested in 2019 from an area of 1,437,939 ha. It is a short-season (120–150 days) crop, it is sown in summer season, and irrigation requirements are fulfilled with precipitation. The flax was sown on 259,424 ha with the total production of 1,085,734 tonnes. The Europe (France) is the main producer with share of 74.4% followed by Asia (China and Russian Federation) with global share of 24%. The total agave fiber production was 38,173 tonnes from an area of 64,360 ha. The America contributes about 91.9% in total production and Asia contributes only 8.1%. It is mainly produced from

Table 9.1 Description and uses of fiber crops

Fiber crop	Scientific name	Other species	Fiber type	Family	Principal uses
Cotton	*Gossypium hirsutum* L.	*G. arboreum* L., *G. barbadense* L., *G. herbaceum* L.	Seed fiber	Malvaceae	Principal raw material for textile
Flax	*Linum usitatissimum* L.		Bast fiber		Fashionable clothing, raw material for linen, packaging materials, cigarette paper
Sunn hemp	*Crotalaria juncea* L.		Bast fiber	Leguminosae/ Fabaceae	Bags, shoes, insulation material, ropes or cords
Kenaf	*Hibiscus cannabinus* L.		Bast fiber	Malvaceae	Composites for automotive cordage, woven
Ramie	*Boehmeria nivea* L.		Bast fiber	Urticaceae	Industrial sewing threads, fishing nets, filter cloth
Jute	*Corchorus capsularis* L. (white jute)	*C. olitorius* L. (black jute)	Bast fiber	Malvaceae	Cloth for wrapping bales, sacks, carpets, curtains
Sisal	*Agave sisalana* L.		Leaf fiber	Asparagaceae	Hats, bags, carpets, rope and twine, geotextile
Manila hemp (abaca)	*Musa textilis* L.		Leaf fiber	Musaceae	Ships' rigging, fishing line, paper making

Columbia, Mexico, and Cuba. The sisal is being grown on 235,670 ha with the production of 602,509 tonnes. Both the area and production of sisal are decreasing since 2011. The Americas share 69.4%, Africa 23.7%, and Asia 6.9% in world total production of sisal. Brazil ranks first in sisal production followed by Mexico and the United Republic of Tanzania. The worldwide Manila fiber (abaca) was grown on 173,206 ha with the global production of 108,582 tonnes. It is mainly produced in Asia (68.9%), America (30.7%), and Africa (0.4%). It is mainly grown in the Philippines followed by Ecuador. Ramie is being grown on 31,587 ha with the production of 60,610 tonnes. Its production and area are continuously decreasing since 2007. It is mainly grown in China and Asia shares about 99.2% global production. The kapok fiber production in the world was 101,300 tonnes in 2013. It is mainly grown in Asia in Indonesia and Thailand (FAO 2019).

9.2 Fiber Crops Contribution in Climate Change

Like other crops, the energy, fertilizer, and pesticide use is an important aspect of fiber crops. Therefore, the greenhouse gas emissions are also linked with production practices of fiber crops. It was concluded that carbon footprint of natural fiber is

Table 9.2 Carbon footprints of fiber crops

Fiber crops	Carbon footprints (CO_2-eq/tonne)
Cotton[a]	2150[c]
Jute[b]	566
Flax[b]	520
Kenaf[b]	445
Sunn hemp[b]	423

[a]Agarwal and Jeffries (2013); [b]Singh et al. (2018b); [c]Average of both Australia and the USA

20–50% lower than those of synthetic fiber. Producing one tonne of jute fiber (carbon footprint) results an emission of 566 kg CO_2-eq (Singh et al. 2018a). The carbon footprints of other fiber crops are given in Table 9.2.

The kenaf plant has ability to absorb very high amount of CO_2, and it was concluded that every tonne of kenaf absorbs 1.5 tonnes of CO_2. The CO_2 requirement of kenaf was regarded much high than other crops (Kimball and Idso 1983). The nitrous oxide (N_2O) from agriculture field is linked with nitrogen fertilization. Since, the nitrogen requirement (50–100 kg N ha^{-1}) of kenaf is very low and very low N_2O emissions are thus reported. The N_2O emissions value for kenaf is 0.7–1.3 kg N ha^{-1} $year^{-1}$ which is very low, and its cultivation did not result in a significant amount of greenhouse gas emissions (Cherubini et al. 2009). It was also further confirmed that 10% of total nitrogen applied to kenaf field is lost through volatilization, loss through runoff/leaching is 5–10 kg ha^{-1} $year^{-1}$, and N_2O emissions are 0.6–1.2 kg ha^{-1} $year^{-1}$, which is only negligible part (IPCC 2006). The hemp has capacity to absorb CO_2 which will reduce the intensity of climate change (Vosper, 2011). It can be successfully grown without irrigation water supply which makes it the future crop of the area which is likely to be affected by drought (Gedik and Avinc 2020).

The study conducted to evaluate the greenhouse gas emissions from various cotton production steps showed that about 400.7 kg CO_2 e/ha. The further fragmentation revealed that harvesting/module building, road cartridge, and primary tillage contribute 141.8, 68.6, and 56.7 kg CO_2 e/ha, respectively. Among the agro-inputs, the nitrogen fertilizers are the main source of greenhouse gas emission followed by insecticides (Maraseni et al. 2010). The pollution during retting process is a common environmental issue of those fiber crops in which retting is essential. It consumes lot of water and pollutes the surface water. The decortication is an essential process of fiber extraction from sisal. Generally wet decortication is used which generates lot of wastewater, i.e., 100 m^3/ton fiber, which require effluent treatment prior to disposal. The pesticide and fertilizer use is very low in Manila hemp; hence, its contribution to greenhouse gas emission is minor. The sodium hydroxide, sodium sulfide, and hydrogen peroxide are used for fiber extraction which is dangerous for environmental quality.

9.3 Impact of Climate Change on Fiber Crop Production

9.3.1 Cotton

Worldwide, cotton is already broadly adapted to growing in temperate, subtropical, and tropical environments, but growth may be challenged by future climate change (Bange et al. 2016). Climate change is likely to affect cotton production both positively and negatively. Temperature influences cotton growth and development by determining rates of fruit production, photosynthesis, and respiration. The high temperature at critical stages during June to September reduced the yield due to flower shedding and less boll setting (Tariq et al. 2017; Ahmad et al. 2017). In addition, high temperature coupled with high humidity boosted whitefly population which is a major cause of yield reduction in 2019. Higher temperatures in cotton-producing areas and regions already suffering from high temperatures could have a negative impact as a result of increased shedding of flower buds. The rise in temperature could have a positive effect on yields, though, in those areas and regions where the effective fruiting period is squeezed between two phases of lower temperatures: one early in the season to start effective flowering and boll formation and one at maturity that results in termination of fruit formation. It has been projected that CO_2 concentration in the atmosphere will rise. Since CO_2 is an important substrate for photosynthesis, there should be increased yield in the future. However, various control environment studies highlighted that crops cannot take the full benefits because of high temperature. The similar findings were confirmed in control experiments in cotton conducted by Reddy et al. (2002).

Another impact of higher atmospheric CO_2 is that weeds will be growing more vigorously as well. When cotton is in the seedling stage, competition with weeds is critical. In spite of the fact that cotton planting and development will start earlier as temperatures rise, the same development will be observed in weeds. The critical period in the development of cotton and weeds will coincide. Unlike cotton (which is a C_3 plant), most weeds are C_4 plants and will show less reaction to CO_2 as C_4 plants let in even more carbon dioxide than C_3 plants, and this reduces, and sometimes eliminates, carbon losses by photorespiration. That is why cotton can compete with weeds more effectively under conditions where there is enough water and nutrition (Kaynak 2007).

There is a global warming phenomenon in the world and same is the case with cotton-growing areas. There are implications of rising temperature on growth and development processes and input requirement. The irrigation requirement is linked with prevailing temperatures and rainfall. The temperature stimulates the evapotranspiration and hence regulates the irrigation requirement, while rainfall serves as supplement to irrigation and support to reduce irrigations. The other impact of warming appears with respect to accelerated crop development, leading to reduce the duration of phenological stages (Ahmad et al. 2017). The earliness of 2.30–5.66 and 4.23 days per decade have been reported for sowing to boll opening and sowing to maturity in Pakistan (Ahmad et al. 2017) (Figs. 9.1, 9.2 and 9.3). The same trend

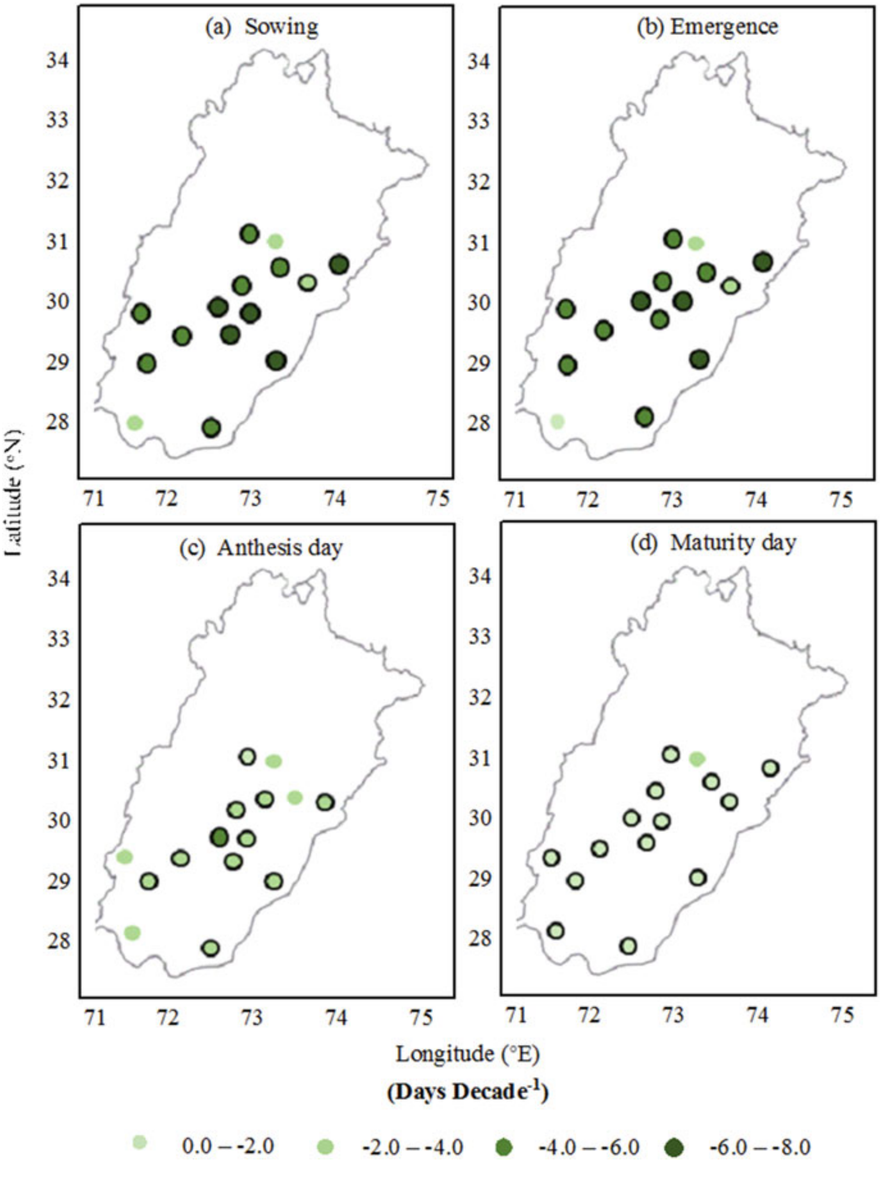

Fig. 9.1 Observed trends in phenological stages of cotton sown from 1980 to 2015 in Punjab, Pakistan: (**a**) sowing, (**b**) emergence, (**c**) anthesis, and (**d**) maturity. Circles with black border indicate statistically significant trends at $p = 0.05$ probability level. (Source: Adapted from Ahmad et al. 2017)

was observed in China where a reduction of 2.16 days from sowing to harvesting was observed. In the future, the temperature in China will increase by 2.3 °C–3.3 °C, and precipitation may change by 5–7% (Arshad et al. 2021). The precipitation during

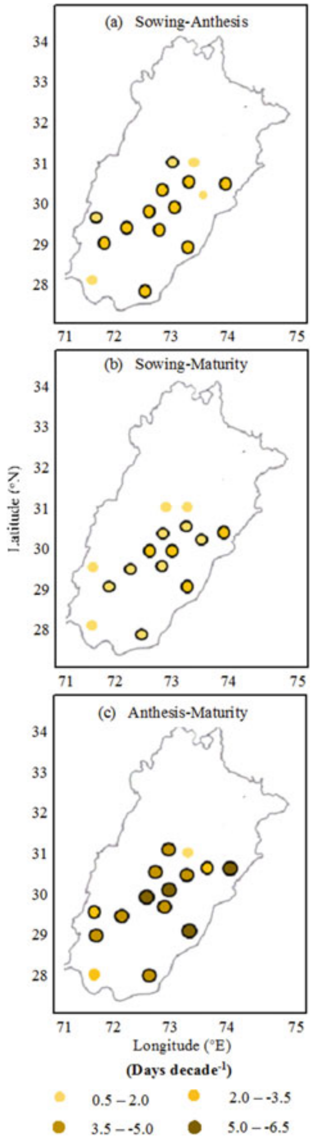

Fig. 9.2 Observed trends in the length of phenological phases for cotton from 1980 to 2015 in Punjab, Pakistan: (**a**) sowing-anthesis, (**b**) anthesis-maturity, and (**c**) sowing-maturity. Circles with black border indicate statistically significant trend at $p = 0.05$ probability level. (Source: Adapted from Ahmad et al. 2017)

the months of September, October, and June will change by 6–20% and 13–44% in Punjab (Pakistan). Temperature will increase in this region by 0.5 °C–1.7 °C in 2025 and 0.5 °C–3.7 °C in 2050 (Amin et al. 2018). The earliness in various stages due to higher temperature have also been confirmed in the Punjab, Pakistan, in the results of study on the impact of quantification of climate warming in cotton (Ahmad et al. 2017).

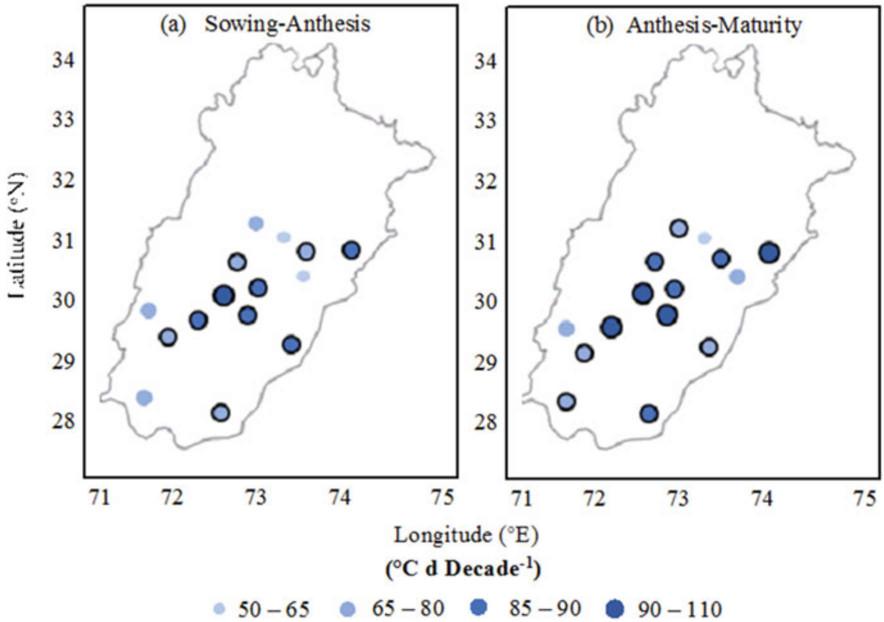

Fig. 9.3 Observed trends in thermal time required for cotton in Punjab, Pakistan, to advance from (**a**) sowing-anthesis and (**b**) anthesis-maturity. Circles with black border indicate statistically significant trend at $p = 0.05$ probability level. (Source: Adapted from Ahmad et al. 2017)

9.3.2 Jute

The temperature and rainfall are two principal factors of climate change which will affect the jute growth performance. Historical weather data of the last 100 years show a noticeable increase in ambient temperature and large variation in monsoon rainfall in the lower Indo-Gangetic Plain (IGP) region where jute is grown. An increase of 1.04 °C in annual average surface air temperature has been recorded (Singh et al. 2017), and by the 2050s, average ambient temperature is expected to rise by another approximately 2 °C (MEF 2004). In recent years, the impact of climatic variability is causing significant fluctuations in jute production and is likely to affect its yields in the long term. The jute is mainly grown under rainfed condition and about 500 mm rainfall is required for its successful growth. The rainfall has been reduced by 40–50% from 12th week to 15th week of the year (Singh 2017). The uneven distribution of rainfall exposes jute to early season drought, a serious abiotic limiting factor inhibiting nutrient acquisition by roots and restricting jute production (Geethalakshmi et al. 2009).

9.3.3 Hemp

Hemp can adapt and grow in different climate circumstances but is also vulnerable to several climate-related events. The early flowering and probable drought stress resulted in decreased stem/fiber yield in the study by Amaducci et al. (2008). The crop does not like wet soils that are prone to soil crusting and soil compaction. In case of high precipitation, these soil conditions increase the chance of waterlogging and full saturation of the soil, which can decrease yield or cause total crop failure. The hemp is a crop of temperate region which may shift to North as a result of climate change in the future (Rubel and Kottek 2010). It showed that farmers should be kept alert for future climate and is most likely that some new areas may be brought under hemp cultivation, while the area in core zone may be reduced. The water requirement of hemp is comparatively high during first 6 weeks of the growth; reducing the precipitation during this period may reduce the growth and yield, particularly in rainfed cultivation.

9.3.4 Flax

Higher accumulated temperatures cause lignin generation within the plant, however, and pose problems during the retting and mechanical separation of fibers. Meanwhile, flower bud differentiation and pollination of flax were influenced by temperature increasing in the reproductive growth phase, which would affect the number of capsules and the seed setting rate per plant and lead to the decrease of flax yield. The annual precipitation also influences the growth of fibers. It has been suggested that during the growing period, the precipitation should be about 110–150 mm (Heller et al. 2015). In climate change scenario, sudden temperature rise, precipitation fluctuations, and floods with windstorms not only affect the crop growth but also have negative impact on flax fiber quality.

9.4 Impact of Climate Change on Fiber Quality

The cotton is a raw material of various textile products in which fiber length determines the yarn quality. There are increasing trends of global warming over the world, and of course it has implications on cotton fiber quality as the crops are already suffering heat stress in arid and semiarid regions. For this controlled environment, experiments were performed for evaluating the impact of increased day and night temperature. The results demonstrated the negative impact of high temperature on fiber length, and the main reason behind these results was identified that high temperature shortened the duration of rapid fiber elongation. The enzymes and genes responsible for fiber elongation had been responsive to high temperature.

It was further investigated that increased night temperature has great influence on reduction of fiber length. Therefore, it was suggested that future projection must be made on the basis of rising trends of night temperature (Dai et al. 2017). In another study, Lokhande and Reddy (2014) concluded on the basis of controlled environment experiment that fiber length linearly increased in response to increased temperature from 18 °C to 22 °C and decreased with further rise in temperature. Similarly, fiber uniformity and micronaire improved with temperature up to 26 °C followed by decline, while fiber strength linearly increased with rising temperature. The immature fiber contents, short fiber contents, and seed coat nips decreased with rising temperature levels up to certain level followed by improvement, whereas maturity ratio improved with rising temperature. Changing temperature has great impact on micronaire followed by fiber strength, length, and uniformity. The decrease in natural water resources during jute harvesting time affects fiber quality, as large volume of clean and slow moving water is required for appropriate retting (Majumdar et al. 2013). In kenaf, the fiber length and core fiber length improved from 2.68 to 3.10 mm and 0.92 to 0.98 mm by increasing concentration of CO_2 from 400 to 800 μmol mol^{-1}. The bast holocellulose, bast α-cellulose, core holocellulose, core α-cellulose, and core lignin had negative association with CO_2 levels (Mahdi et al. 2014). Water stress delays plant growth and fiber maturation in hemp (Abot et al. 2013). Stem height and stem diameter decrease, while fiber layers become thinner in the year with drier conditions.

9.5 Fiber Crop Production Opportunities in Climate Change Scenarios

The concerns about the environmental impacts of various synthetic fibers are growing over time. Therefore, the demand for natural fiber crops is increasing due to ease of biodegradability and recycling. The predicted demand for fiber is likely to increase by 60% (130 million tonnes) in 2050 over 1990 (50 million tons) (https://cordis.europa.eu/).

The flax fiber production though has high pesticides and energy requirement but has minimum global warming impact, eutrophication, and acidification (Yan et al. 2014). The climate change potential of flax fiber production is low as it produces 316 kg CO_2-eq for each tonne of fiber production (Dissanayake et al. 2009). The climate change potential of flax fiber is also low in comparison with hemp because each tonne of hemp fiber production is accompanied with 2600 kg CO_2-eq, while this value is 2000 kg CO_2-eq for flax fiber (van der Werf and Turunen 2008). In another study, the hemp was reported an efficient tool of conversion of CO_2 into biomass as estimated that 1 ha can absorb 2.5 tonnes of CO_2. Moreover, if the crop is grown twice a year, this absorption can be doubled (Kolodziej et al. 2012). The hemp has ability to withstand the waterlogged (Satriani et al. 2021) and drought conditions (Gao et al. 2018); therefore, it may be a potential crop of the future keeping in view the fluctuations in precipitations in changing climate scenarios. The greenhouse gas emission during textile processing does not vary for synthetic and natural fiber. However, synthetic fiber manufacturing from various raw materials resulted in higher emissions than natural fiber. During 120-day growth cycle, the jute plants in 1 ha consume 15 MT CO_2 and release 11 MT of O_2 in the atmosphere (IJSG 2013).

9.6 Climate Change Impacts on Pests

Pest profiles are changing with the change in climate for all the agricultural crops. Fiber crops are also most affected due to climate change. Aphid was a serious pest of cotton crop in Australia, and it was observed to cross Europe, disturbing the cotton crop (Hulle et al. 2010). With early warming of climate, the cotton crop is not much disturbed, and the potato crop in the USA is damaged due to aphids and plant hoppers (Nelson et al. 2013). Temperature has warmer 10 days before in the last 65 years, posing a serious effect on interaction of crops and pests due to interaction of biotic and abiotic factors essential for crop growth and pest population (Baker et al. 2015). Among the fiber crops, cotton is the most sensitive and vulnerable to the climatic factors.

Plant material becomes less nutritive after increase of temperature and decrease of carbon accumulation within the plant tissues. To cope with these changes, insects consume more plant materials for their survival resulting in more damage of crops. Farmers are using more and more insecticides for better pest management. These pesticides are even increasing after the introduction of Bt cotton and pest pressure still increasing specially on genetically engineered cotton verities. In the last 10 years, pink bollworm on cotton crop is remarkably increasing. Similarly, whitefly is also on alarming situation in Pakistan.

9.6.1 Cotton Bollworm

Cotton bollworm (*Helicoverpa armigera* L.) was a common pest of cotton crop in many countries including Australia, Pakistan, and India. This pest goes into the winter diapause into the soil surface depending on the temperature and sunlight availability. After climate change and increasing of mean temperature, adult survival rate of cotton bollworm has decreased, and it is decreasing on cotton crop each year. The increase in carbon dioxide in air causes longer larval stage of *H. armigera* L. (Kriticos et al. 2015). Advanced modeling shows that the coastal areas of southern Australia will receive less attack of this pest in 2090. Similarly, attack will be more in western and northern Australia.

9.6.2 Natural Enemies

The reported changes in phenology of fiber crop pests are also supportive for higher survival of natural enemies of any pest hibernation in winter. Aphid and *H. Armigera* L. survival patterns are totally changed, and the population dynamics of stated pets needs further research to mitigate with climate change adopting the advanced pest management options (Li et al. 2015).

9.6.3 Fall Armyworm

The fall armyworm (*Spodoptera frugiperda* L.) is a moth belonging to the family Noctuidae. It has a host range of hundreds of plant species, inflicting severe damage in grasses – particularly maize and sorghum, which are the preferred hosts – along with other crops, such as rice, cotton, and soybean preferred by different species strains. It is native to tropical and subtropical areas of the Americas, and during summer it migrates into southern and northern temperate American regions (FAO 2021). Still fall armyworm has most choice of maize, but with change of preference, it can be converted to cotton and other fiber crops.

9.6.4 Cotton Mealybug

Mealybugs are severe agricultural pests which reach up to 350 species, but only 158 (about 35 are polyphagous) species are identified as pests worldwide (Franco et al. 2009). Cotton mealybug (*Phenacoccus solenopsis*) has been introduced as serious and alarming pest for cotton crop in Pakistan and India (Noureen et al. 2016). This pest was first time reported in 1991 from the state of Texas and spread throughout the world (Franco et al. 2009). During the initial years of the twenty-first century, cotton mealybug emerged as the most destructive pest of cotton crop, and it was spreading high in high-temperature areas (Arif et al. 2009). With the changing environment of cotton areas, adaptation was carried out from leaves to roots in hottest and dry areas, while it was foliage pest on moderate climate (Hodgson et al. 2008).

9.6.5 Minor Pests

Numbers of mirid bugs (insects of the Miridae family), previously only minor pests in northern China, have increased 12-fold since 1997, they found. Mirids are now a main pest in the region. Mirids can reduce cotton yields just as much as bollworms, up to 50% when not controlled. The insects are also emerging as a threat to crops such as green beans, cereals, vegetables, and various fruits. The rise of mirids has driven Chinese farmers back to pesticides. According to ecologists, genetic modified crops are not a magic bullet for pest control. They have to be part of an integrated pest management system to retain long-term benefits. Whenever a primary pest is targeted, other species are likely to rise in its place. For example, the boll weevil was once the main worldwide threat to cotton. As farmers sprayed pesticides against the weevils, bollworms developed resistance and rose to become the primary pest. Similarly, stink bugs have replaced bollworms as the primary pest in the southeastern USA since *Bt* cotton was introduced (Lu et al. 2010).

9.7 Fiber Crop Diseases

Increased carbon dioxide concentrations and change in mean temperature are also favoring the spread and damage of plant pathogenic bacteria and fungi. Cotton wilt has been increased manyfold in the last 10 years of Pakistan crop history due to which crop gets early matured and farmers can't attain natural maturity of crop.

9.8 Future Recommendations and Conclusion

The detailed studies on the impact of climate change were mainly focused on cotton; however, these studies must be extended to other fiber crops to evaluate the integrated effects of temperature, humidity, CO_2, and water stress on growth, yield, and quality. The development of cultivars tolerant to abiotic stresses including water availability (deficit and waterlogged), heat stress, and capabilities to efficiently utilize the elevated CO_2 to maximize production and minimize losses in variable environments.

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Chapter 10
Estimation of Crop Genetic Coefficients to Simulate Growth and Yield Under Changing Climate

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Abstract Global climate change has several implications on food security. The task of feeding the growing human population with limited resources is a challenging mission. With modern climate-resilient cultivars and optimized management practices, agronomists are trying to provide solutions to optimize the demand and supply balance in the food system. Crop simulation models play a vital role in assessing cultivar's performances with extrapolated conditions (soil and weather types) and resources (management practices), at varying spatiotemporal scales as large and multilocation field experiments with scarce resources are challenging. New cultivars need to be updated with their genetic coefficients to simulate crop growth and development and hence prediction of phenology and yield under different environments. Most of the modeling studies rely on the calibrated genetic coefficients of crops from different geographical regions and do not calibrate it properly which brings biasness in the model output. Different optimization methods for parameter estimation play a crucial role in meeting these requirements in short period. The selection of methods to estimate genetic coefficients also requires careful cataloguing of input data using standardized and appropriate protocols. With robust estimates of genetic coefficients, the reliability on simulation model will be boosted after proper statistical evaluation on the need of parameterization, testing model symmetry, and improving modeling metrics. Moreover, properly calibrated and validated model can be used to assess crop potential yield analysis, yield gap assessment,

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projection of climate and economic, and other decision support analysis which helps growers to enhance profitability and strengthen environmental stewardship. In this chapter, we discuss and describe different method of estimating crop genetic coefficients for simulation models. We also highlight advantages and disadvantages of the individual methods with special emphasis on the need of ensembling methods to minimize bias and inherent uncertainties in the estimation of these coefficients. This chapter will provide crop model developers and users an insight over different optimization methods and ensembling needs.

Keywords Crop modeling · Climate change · Genetic coefficient · Optimization · Calibration · Validation

10.1 Introduction

Global food security has become a growing challenge and will be critical to meet several Sustainable Development Goals (SDGs) (United Nations 2015). The ever-increasing demands for food, water, and energy for growing population are influenced by multiple factors which led to instability in global food production and supply. These factors are compounded by climate change, one of the significant drivers of instability in global food production. The increasing frequency of extreme climate events is of key concern and poses risk to food security (Mehrabi and Ramankutty 2019). To offset the instability in food production, breeders develop climate-resilient crop cultivars, which tend to achieve its potential yield with innovative agronomic interventions including optimal use of inputs such as seeds, nutrients, and water.

Global efforts during the last few decades have shown that yield gain is attributed ~50–60% to improved genetics and ~40–50% to management practices (Sacks and Kucharik 2011). Moreover, the process of developing better crop cultivar with improved tolerance to abiotic (heat and drought) and biotic (pests, diseases, and weeds) stresses along with other consumer-preferred traits demands time and resources. Despite these accomplished traits, cultivars attain lesser yield under field conditions than their potential. Although breeders have leveraged the interaction of genotype and environment (Elias et al. 2016), optimized agronomic management practices help in overcoming the challenges of yield gap (i.e., gap between potential and attainable yields). To realize the interactions of genotype, environment, and management (G × E × M), traditional agronomic experiments are designed for optimizing management practices to minimize the yield gap (Vilayvong et al. 2015). However, these voluminous experiments are constrained by time, spatial scale (heavily focused in a specific site), and resources.

To overcome these constraints, simulations of crop growth and development can facilitate these G × E × M interactions by extrapolating field experiments at spatiotemporal scales having varied location and multiple seasons (Lobell et al. 2009). Dynamic process-based crop simulation models can potentially quantify the physiological behavior and responses of crop cultivars under different G × E × M scenarios. The expression of cultivar to the individual environment is controlled by specific cultivar traits, termed as "genetic coefficients." Crop model algorithm identifies these coefficients to express the interaction among weather, soil characteristics, and management practices for crop growth and development. Moreover, these coefficients define and differentiate crop varieties, and hence estimation of the genetic coefficients is required while introducing new cultivar and when evaluating a known cultivar to a new region within the crop model. Obtaining these coefficients accurately at the field conditions is difficult as it is vulnerable to environmental disturbances within and during seasons and prone to human error while replicating field experiments.

The purpose of this chapter is to describe (a) crop genetic coefficients and their role in simulating crop growth and yield, (b) different methods of estimating the crop genetic coefficients, and (c) statistical evaluation of the performance of genetic coefficients. This chapter also highlights the advantages and disadvantages of different methods of estimating crop genetic coefficients.

10.2 Crop Simulation Models and Genetic Coefficients

The interaction of genetics (G), the biophysical environment (E), and management practices (M) resulting in crop phenological development can be simulated by process-based dynamic ecophysiological models, popularly known as crop models. These models are widely used as a support tool for research and decision-making at a scale, where we need to assess roles of G x E x M scenarios on crop development and yields. The physiological processes are simulated using state- and rate-variable approaches, which are associated and characterize the rate of change in the physiological processes. At the end of crop duration, the total biomass production is determined by the product of the average growth rate and total duration of the crop. And later, economic yield can be quantified as partitioned portion which goes into grain with a certain fraction that depends on environment under which crops are grown. Hence, physiologically, once rate variables are estimated, the state variables are calculated at time interval (Δt) following numerical integration (Forrester 1961) for total crop growth duration. It can be simply represented as Eq. 10.1 and can be depicted as Fig. 10.1:

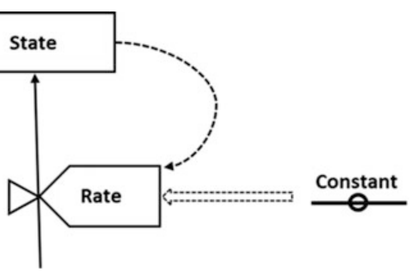

Fig. 10.1 A relation diagram of dynamic exponential growth

$$\text{Rate} = \text{Constant} \times \text{State} \tag{10.1}$$

These rate variables and constant in models are controlled by the genetic characteristics of the cultivar and are represented as genetic coefficients. These coefficients represent differences among cultivars, and their values are empirically estimated through extensive field experiments (evaluated under varying soil × weather conditions). To better represent genetic information of cultivar into models, cultivar parameters are estimated as a function of the alleles at different loci. A large set of germplasms are evaluated which vary in loci of interest to quantify their specific effects. In case of limited variation, for pure inbred lines, dominant and recessive alleles are scored 1 and 0, respectively, and their expression under different environments are estimated through linear regression with a physiological rationale. Once cultivar coefficients are determined, the field evaluation data are used to calibrate them conventionally by adjusting and comparing simulated and observed values of crop phenology and yield. This is a tedious task for all specific parameters of a cultivar as many modelers and/or agronomists are not familiar with genetics to evaluate these parameters following these approaches.

10.3 Common Methods of Estimating Genetic Coefficients

10.3.1 Field Experimentation

The development of new cultivars requires a selection of desired traits from screened pool of genotypes. The estimation of desired genotypic characteristics from breeding and field trials usually follows a liner model in the form of

$$Y = X\beta + Z\mu + e \tag{10.2}$$

where y is observed values; β and μ are fixed and random effects of gene under consideration, respectively; X and Z are design matrices for experiment; and e is a random residual error.

As evident from Fig. 10.1, yield is the product of the duration of crop growth and rate of biomass accumulation, both governed by light intercepted over a range of temperatures (Ritchie and Nesmith 1991). Hence temperature and photoperiod response function are critical in determining genetic coefficients. Moreover, for modern cultivars duration of growth is of highest significance than rate of growth, which is of relatively less significance (Evans and Fischer 1999). Temperature is the prime factor for growth duration; however, photoperiod and vernalization also impact growth significantly. Mostly the genes that regulate photoperiod and temperature response are scrutinized for estimating genetic coefficients and are part of fixed effects, β (Eq. 10.2). The randomness, μ (Eq. 10.2) of genotypic values of desired genes, is of major concern for breeders, and hence they look for shrinkage of those values toward desired means and are estimated through best linear unbiased prediction (BLUP) (Henderson 1985).

Photoperiod response function (PRF) is of prime focus for breeders while estimating genetic coefficients. The PRF is a function of basic vegetative phase, maximum optimal photoperiod, and photoperiod sensitivity (Rood and Major 1981). Basic vegetative phase is the time to anthesis under optimum photoperiod. Maximum optimal photoperiod is the longest photoperiod that does not delay flowering time. Photoperiod sensitivity is the delayed anthesis beyond maximum optimal photoperiod. The appearance of leaf, total leaf number, and time to anthesis are influenced by photoperiod. The evaluation under controlled environment is a good source for retrieving this data by determining duration of sensitive phases (Craufurd et al. 2013).

The dynamic nature of photoperiod response and its impact on growth stages and yield attributes have been studied extensively for major crops and their PRF, for example, rice (*Oryza sativa* L.; Yin et al. 1997; Nakagawa et al. 2005; Guo et al. 2020; Clerget et al. 2021; Zong et al. 2021), wheat (*Triticum aestivum* L.; Masle et al. 1989; Miralles and Slafer 1999; Slafer and Rawson 1996; Aslam et al. 2017; Arjona et al. 2020; Hyles et al. 2020), maize (*Zea mays* L.; Kiniry et al. 1983; Warrington and Kanemasu 1983a, b; Kiniry 1991; Birch et al. 1998; Van Bussel et al. 2015; Lin et al. 2021), soybean (*Glycine max* L. Merr.; Hadley et al. 1984; Jones et al. 1991; Sinclair et al. 1991; Mavromatis et al. 2001; Nico et al. 2019; Ohigashi et al. 2019; Bu et al. 2021), and sorghum (*Sorghum bicolor* L. Moench; Alagarswamy and Ritchie 1991; Craufurd et al. 1999; Clerget et al. 2004; Folliard et al. 2004; Dingkuhn et al. 2008; Wolabu and Tadege 2016; Clerget et al. 2021).

Temperature response function (TRF) can be developed by estimating crop phasic development with respect to temperature. Prediction of the crop developmental stages using temperature summation or total heat accumulation which translates into assimilate production leading to growth of plants was first suggested by Reaumur in 1735 (Wang 1960). With that idea, the concept of growing degree days or thermal time has been used extensively by researchers (Gallagher 1979) in the form of

$$t_d = \sum_{i=1}^{n} \left(\overline{T}_a - T_b \right) \quad (10.3)$$

where $\overline{T_a}$ is the daily mean air temperature, T_b is the base temperature at which crop ceases its development, and n is the total number of days used for defining phasic development.

The effects of temperature on crop development have been extensively studied by developing temperature response curve for major crops, for example, rice (Yin et al. 1997; Baker 2004; Prasad et al. 2006; Han et al. 2009; Puteh et al. 2010; Van Oort et al. 2011; Sánchez et al. 2014), wheat (Porter and Gawith 1999; Prasad and Djanaguiraman 2014; Cammarano et al. 2016; Prasad et al. 2017; Maiorano et al. 2017; Wang et al. 2017; Nuttall et al. 2018), maize (Cutforth and Shaykewich 1990;

Ritchie and Nesmith 1991; Stewart et al. 1998; Wang et al. 2018, 2020), soybean (Wilkerson et al. 1983; Hodges and French 1985; Jones et al. 1991; Setiyono et al. 2007; Boote et al. 2018; Alsajri et al. 2020), and sorghum (Hammer et al. 1989; Craufurd et al. 1999; Kumar et al. 2009; Prasad and Djanaguiraman 2011; Boote et al. 2018; Clerget et al. 2021; Liang et al. 2021). Field and controlled environment experiments have been conducted to assess and quantify the effect of temperature and photoperiod or their interactions (Erskine et al. 1990; Jagadish et al. 2007; Prasad et al. 2008; Tao and Zhang 2010). Field experiments measuring key phenological and physiological processes and their interaction primarily generate valuable information on sensitive stages and secondarily the quantification of varietal response which form a basis to estimate genetic coefficients for crop models.

10.3.2 Trial and Error (TE)

The conventional and subjective methodology for parameter estimation is manual trial-and-error (TE) method. In this method the cultivar's genetic coefficients are adjusted by the users until the observed and simulated yield matches or have least root mean square error (RMSE) (Willmott 1981). Although the process is cumbersome and considerably time-consuming, the results are more questionable when parameters of the model are arbitrarily changed to match the observed results – without following more functional approaches of the natural variation for the crop traits. Manual iteration requires expertise and careful calibration. The final estimates vary with the model users, despite with the same dataset and model structure. However, if calibration can be performed carefully, users might get better results in TE than automated optimization as the latter has sometimes been locally optimal and unreliable. An optimization algorithm for estimating genetic coefficients is a complicated process and demands advance programming and computing knowledge; hence the TE method is commonly used and preferred by agronomists. Several modelers have compared different methods of estimation and found the TE method promising and better than others. Mereu et al. (2019) used 10-year datasets to optimize the genetic coefficients and found the TE method performed better in simulating phenology and yield than the objective optimization methods of the generalized likelihood uncertainty estimation (GLUE) (He et al. 2009). The TE method was found to be better than parameter optimization tool PEST (Parameter ESTimation; Doherty et al. 1994) for phenology and yield prediction for wheat and soybean experiments conducted by Ma et al. (2020).

10.3.3 GENotype Coefficient Calculator (GENCALC)

Crop models have been used to simulate growth and development of crops from field scale (Jha et al. 2018; Saravi et al. 2021) to watershed (Eeswaran et al. 2021) and regional scale (Therond et al. 2011). The decision support system for agrotechnology transfer (DSSAT) model is one of the most widely used models (Hoogenboom et al. 2019) which has incorporated the GENotype Coefficient Calculator (GENCALC) method for estimating genetic coefficients based on sequential or gradient search method (Hunt et al. 1993). The basic idea behind a gradient search algorithm is to achieve an optimal solution within a defined search space of set experimental data and initial cultivar. This follows a hill-climbing optimization pattern which consists of moving solution from one point θ_n (phenology coefficients) to θ_{n+1} (growth coefficients) with a gradient of deterministic objective function $J(\theta)$. It is feasible for continuous domain (datasets from cultivar and field experiment), not for multidimensional or nonlinear. The GENCALC estimates cultivar coefficients by iterating them in a preset sequence of coefficients first which controls phenology and then the yield. Iteration involves comparison of outputs based on the simulated and observed variables (phenology and yields) in a sequential manner until it achieves best model fit, i.e., least RMSE between simulated and observed variables.

The GENCALC reads through a set of experimental data using coefficients from a startup cultivar (a closely related cultivar which functions as a reference for desired calibration). With initial startup coefficients, it adjusts and modifies genetic coefficients for best fit, i.e., least RMSE for target variable in each run or search cycle. Several researchers have used GENCALC and compared with other methods to assess its performances. The GENCALC has been used to estimate genetic coefficients of major crops including groundnut (*Arachis hypogea* L.) (Anothai et al. 2008), soybean (Bao et al. 2015), rice (Buddhaboon et al. 2018), wheat (Ibrahim et al. 2016), and maize (Román-Paoli et al. 2000; Hassanien and Medany 2007; Yang et al. 2009; Bao et al. 2017; Adnan et al. 2019). This approach has main limitations of the relatively small sampling area of search space, not optimum for wide ranges of desired targets (Pabico et al. 1999), and the overall inability to estimate uncertainties of the derived parameters, obtaining the crop genetic coefficients as deterministic values (He et al. 2010).

10.3.4 Downhill Simplex Method

Downhill simplex method (Nelder and Mead 1965) is an optimization algorithm which does not use derivatives for optimization and performs optimization quickly. The idea of getting geometric search space in simplex method, with N+1 vertices in N-dimensional space is to get same dimension of simplex and search space. The simplex moves through search space once starting cultivar is defined. Using the initial coefficients, it generates initial simplex, and the target or objective function (phenology and yield) is evaluated for each vertex of simplex (here vertices represent combination of genetic coefficients) by computing RMSE between simulated and observed values. The simplex movement ceases once it achieves lowest RMSE for one of the vertices as compared to others. With a goal of quick optimization, it sometimes captured into local minimum of the target of objective function (phenology and yield) which is determined by genetic coefficients. It is advisable to repeat the process with different initial cultivar to avoid local minima. To overcome this limitation, several evolutions have been practiced in this method; however, it makes this method more complex for crop models (Matsumoto et al. 2002). Researchers have used this method to estimate genetic coefficients for different crops, for example, soybean (Grimm et al. 1993; Piper et al. 1996), maize (Wei et al. 2009), rice (Gilardelli et al. 2019), and sunn hemp (*Crotalaria juncea* L.; Parenti et al. 2021). Correndo et al. (2000) investigated the pros and cons of choosing model to estimate errors and highlighted about the paradox of choices of model users.

10.3.5 Simulated Annealing Method

As the name annealing connotes, optimization is performed akin to annealing in thermodynamics, as first by melting at high temperatures and then slowly lowering the system until it freezes and at each temperature simulation search space runs at its maximum capacity to get best solutions with the lowest RMSE for target function (Brooks and Morgan 1995). Researchers have used this method to estimate genetic coefficients for different crops, for example, soybean (Mavromatis et al. 2002), maize (Ferreyra 2004), and rice (Zha et al. 2021), and soil root parameters (Calmon et al. 1999).

10.3.6 Generalized Likelihood Uncertainty Estimation (GLUE)

The uncertainty in data input and model parameters give biased model output. Likewise, associated uncertainty in cultivar datasets, field experimental datasets, and the derived parameters are difficult to be accounted during optimization. A Bayesian framework that assesses uncertainty of parameters using Monte Carlo technique, called generalized likelihood uncertainty estimation (GLUE), overcomes the limitation of associated uncertainties (Mertens et al. 2004; Candela et al. 2005; He et al. 2010). This method employed the genetic coefficients database of the DSSAT (Hoogenboom et al. 2019) to generate prior parameter distributions (He et al. 2010) and then can be used to develop the posterior distribution based on Bayes' theorem (Makowski et al. 2006). The prior parameter distributions are developed by fitting them to a multivariate normal distribution and then estimate the posterior distributions of each parameter using Bayes' theorem (Eq. 10.4):

$$P(\theta|O) = \frac{P(O|\theta)P(\theta)}{P(O)}, \tag{10.4}$$

where θ and O represent the parameter set and observations, respectively. $P(\theta|O)$ is the posterior distribution. $P(O|\theta)$ is the likelihood, $P(\theta)$ is the prior probability, and $P(O)$ is a normalizing constant.

To calculate likelihood values, random parameter sets θ_i are generated from the prior distributions. A likelihood value $L[\theta_i|O]$ for each observation (anthesis date, maturity date, and yield) is estimated based on Gaussian likelihood function (Eq. 10.5) (He et al. 2010):

$$L[\theta_i|O] = \prod_{j=1}^{M} \frac{1}{\sqrt{(2\pi\sigma_o^2)}} \exp\left\{-\frac{\left[O_j - Y(\theta_i)\right]^2}{2\sigma_o^2}\right\} \tag{10.5}$$

where θ_i is the ith parameter set, M is the number of observations, O_j is the jth observation, $\sigma_o{}^2$ is the variance of model error, and $Y(\theta_i)$ is the output of the model. In addition, Eq. 10.6 calculates the probability of the parameter set:

$$p(\theta_i) = \frac{L(\theta_i|O)}{\sum_{j=1}^{N} L(\theta_i|O)} \tag{10.6}$$

where $p(\theta_i)$ is the probability or likelihood weight of the ith parameter's set θ_i and $L(\theta_i|O)$ is the likelihood value of parameter set θ_i, given observations O (He et al. 2010).

The empirical posterior distributions were constructed from the pairs of parameter's set and probabilities (θ_i, $p(\theta_i)$, $i = 1\ldots,N$). The means and variances of those chosen parameters were calculated as in Eqs. 10.7 and 10.8 (He et al. 2010):

$$\mu_{\text{post}}(\theta) = \sum_{i=1}^{N} p(\theta_i) * \theta_i \tag{10.7}$$

$$\sigma_{\text{post}}^2(\theta) = \sum_{i=1}^{N} p(\theta_i) * \left(\theta_i - \mu_{\text{post}}(\theta)\right)^2 \tag{10.8}$$

where $\mu_{\text{post}}(\theta)$ and $\sigma^2{}_{\text{post}}(\theta)$ are the mean and variance of the posterior distribution of parameters θ and $p(\theta_i)$ is the probability of the ith parameter set.

GLUE estimate parameters in similar sequence as GENCALC does, first phenology and then growth. At the end of optimization, the set of parameters having maximum likelihood values is selected as final coefficients. GLUE has been applied in the field of hydrology extensively (Beven 2018) and crop sciences (He et al. 2010) for parameter estimation. It has been used to estimate genetic coefficients of major crops including maize (He et al. 2009; Ahmed et al. 2018; Sheng et al. 2019; Jha et al. 2021), rice (Buddhaboon et al. 2018; Prasad and Mailapalli 2018; Tian et al. 2018; Tan and Duan 2019; Gao et al. 2020; Hyun et al. 2021; Jha et al. 2022), wheat (Ji et al. 2014; Ibrahim et al. 2016; Li et al. 2018; Mereu et al. 2019; Yan et al. 2020), soybean (Rodrigues et al. 2012; Salmerón and Purcell 2016; Nath et al. 2017; Memic et al. 2021), and sorghum (Vieira et al. 2019).

10.3.7 Parameter ESTimation (PEST)

Automatic optimization like GLUE takes lot of time to get results due to high number of runs required and of longer duration. To expedite the estimate process, the Parameter ESTimation (PEST) software (Doherty et al. 1994) has been developed and coupled with DSSAT as DSSAT-PEST package (Ma et al. 2020). With an advantage of quick convergence of search space, high efficiency, and transferability of codes in any language, it is easy to use for parameter estimation in crop models. The underlying algorithm of this software is Gauss-Marquardt-Levenberg nonlinear algorithm (Liang et al. 2016) which estimates parameter by reducing the number of objective functions (Eq. 10.9):

$$\phi = (c - Xb)^t Q(c - Xb) \tag{10.9}$$

where X is the model action, b is the desired parameter, c is the observed value of objective function, and Q is the cofactor matrix which weighs parameters based on observation. This PEST software runs with DSSAT input (cultivar, parameter output, and simulation control) and output files (cultivar coefficient and error) with control file of optimization (Ma et al. 2020). Ma et al. (2020) extensively applied PEST for maize, rice, wheat, soybean, and cotton (*Gossypium hirsutum* L.). Song et al. (2015) used PEST for parameter estimation and compare it with GLUE for maize. Maize coefficients are estimated for simulating irrigation strategies using PEST software (Fang et al. 2019).

10.3.8 Evolutionary Algorithm: Multi-objective Evolutionary Algorithm

The optimization involves multiple objective functions during the process, for example, anthesis and maturity date and yield in case of crop modeling. Cultivar's genetic coefficients control the objective function in synchrony rather than in silo. To simplify in terms of mathematical equation (Eq. 10.10),

$$F(x) = (f1(x),\ \ldots, fm(x))T \tag{10.10}$$

where main function $F(x)$ consists of m number of objective functions in the decision search space.

The single objective in Eq. (10.10) often intersects or complements to generate final result and hence conflicts with other objective functions. Calibrating one objective function may disturb other objective functions. Hence, a single solution cannot be achieved by optimizing all objective functions altogether. To overcome this problem, the best trade-off is designed and called as the Pareto optimality concept of Edgeworth and Pareto (Stadler 1979). It involves the principle of population-based nature and hence is considered as evolutionary algorithm. A powerful yet simple algorithm, a non-dominated sorting genetic algorithm-II (NSGA-II) (Deb et al. 2002), has become popular in the last two decades for multi-objective optimization for crop models. It employs non-dominated ranking rule to set objective functions and diversified population through crowding distance ranking. Sarker and Ray (2009) used this algorithm for crop models to estimate parameters. However, all these methods are used to optimize resource use at the field for best set of management practices. Recently it was used for parameter estimation for crop model (Kropp et al. 2019). Despite that it is not popular in crop modeling community, it has immense potential to explore for optimizing genetic coefficients of the cultivar. It needs a programmer to rearrange codes to design the Pareto fronts for optimizing coefficients.

10.3.9 Noisy Monte Carlo Genetic Algorithm (NMCGA)

Genetic algorithm (GA; Goldberg et al. 1989), a multidimensional, a multimodal, a discontinuous search algorithm having vast search space, outperforms other optimization techniques (Wu et al. 2006). The noisy Monte Carlo genetic algorithm (NMCGA; Ines and Mohanty 2008) earlier used in hydrology was first used in crop modeling to estimate genetic coefficients of maize (Jha et al. 2021). It estimates fitness of set of parameters based on the prior distribution and range from dataset (set of cultivar coefficients of all cultivars for the given crop in the model) using Monte Carlo resampling (Ines and Mohanty 2008). Based on lowest RMSE between simulated and observed values, the resampled parameter sets are evaluated under a noisy space (Wu et al. 2006). For optimal solution, fittest parameters go through crossover and mutation with several generations.

The objective function of the parameter set for the ith ensemble is formulated as Eq. 10.11:

$$\mathrm{Obj}(K)_i = \mathrm{Min}\left(\frac{1}{T}\sum_{t=1}^{T}\left|\frac{1}{N_{\mathrm{resample}}}\left(\sum_{r=1}^{N_{\mathrm{resample}}}\mathrm{Sim}\ (K^r)_{\mathrm{ti}}\right) - \mathrm{Obs}_t\right|\right)\forall_i \qquad (10.11)$$

where K^r is the set of K parameters combinations with r realizations generated from Monte Carlo resampling, N_{resample} is the total number of realizations for simulated (Sim (K^r)) and observed variables (Obs_t), and t_i is the running index for time T (Ines and Mohanty 2008). Noisy fitness is calculated using the inverse of the modified-penalty approach of Hilton and Culver (2000) (Eqs. 10.12 and 10.13):

$$Z(K)_i = \mathrm{Obj}(K)_i\left(1 + \mathrm{Penalty}\ (K)_i\right)\forall_i \qquad (10.12)$$

$$\text{fitness}(p^*)_i = \frac{1}{Z(K)_i} \forall_i \tag{10.13}$$

where p^* is the chromosome and fitness (p^*) is the noisy fitness of that chromosome sampled from each ensemble i from the Monte Carlo resampling. A chromosome realization is penalized (Penalty (K)) if its predicted variables violate some preset rules against the goodness-of-fit evaluation (Ines and Mohanty 2008). Sampling fitness is calculated based on Eq. 10.14 to reduce the noise in fitness:

$$\text{Sfitness } (p^*) = \frac{1}{R}\sum_{i=1}^{R} \text{fitness}(p^*)_i \tag{10.14}$$

where R is the total number of ensemble i. The arrays of parameter set (chromosome) of means and standard deviations undergo through the search process until the best chromosome is generated.

Jha et al. (2021) employed sequential optimization, first for phenology and then for growth coefficients for maize cultivars. Pabico et al. (1999) used GA to determine genetic coefficients of soybean cultivars. Xu et al. (2016) have used genetic algorithm to calibrate parameters of the soil-water-atmosphere-plant (SWAP)–Environmental Policy Integrated Climate (EPIC) coupled model.

10.3.10 Markov Chain Monte Carlo (MCMC)

A formal Bayesian approach, Monte Carlo, is a computational technique for sampling independent random sequence with a defined probability distribution function. However, Markov chain Monte Carlo (MCMC) draws sample from a distribution where the next sample is dependent on the previous sample, hence forming a chain called Markov chain (Shapiro 2003). It is capable of distinguishing the effect of input, output, model structure, and parameter. Comparison of formal Bayesian, MCMC, and pseudo-Bayesian, GLUE, underlies in the difference in estimating model residual error. The latter has no strong assumptions on residual error distributions (Tan et al. 2019). Iizumi et al. (2009) employed MCMC to estimate model parameters for rice. Sexton et al. (2016) used MCMC and GLUE to estimate parameters for sugarcane (*Saccharum officinarum* L.) and found both could be able to simulate biomass accurately. A modified MCMC, Metropolis-Hastings algorithm (López-Cruz et al. 2016), used for greenhouse crop models and differential evolution adaptive Metropolis (DREAM) algorithm have been used to estimate model parameters (Dumont et al. 2014).

10.4 Other New Promising Parameter Estimation Methods

There are several evolving algorithms which are used in global optimization of parameters in the field of crop resource planning and hydrology and can be used for genetic coefficient estimation and optimization after carefully revising same basic codes and testing. Some of them are highlighted here.

10.4.1 Differential Evolution (DE) Algorithm

DE algorithm is a global optimization method which focuses on multi-sampling objective function (target: phenology and yield) for optimizing the population (parameter sets) starts with random selection from the initial population (Storn and Price 1997). Zúñiga et al. (2014) used this algorithm to calibrate SUCROS model (van Ittersum et al. 2003) and later used for husk tomato crop (*Physalis ixocarpa* Brot. ex Horm.). Recently, Martínez-Ruiz et al. (2021) used DE algorithm to calibrate HORTSYST model (Martínez-Ruiz et al. 2012).

10.4.2 Covariance Matrix Adaptation Evolution Strategy (CMA-ES)

A special numerical optimization method for nonlinear problems is based on biological evolution where new individuals are generated by variation and selection in each generation. A maximum likelihood and covariance matrix of each generation is updated, and new evolution path is generated till the final solution is achieved (Hansen and Kern 2004). Zúñiga et al. (2014) used CMA-ES for husk tomato and compared with other methods.

10.4.3 Particle Swarm Optimization (PSO)

Inspired by social psychology, in this method (Kennedy and Eberhart, 1995), particles (here parameter) are placed in search space with defined objective function, and it evaluates the objective function at each location (Kennedy and Eberhart, 1995). Movement of particle is determined by current and best location (solution). Once all particle is optimized individually, then swarm like birds flock move for optimal solution. Jin et al. (2017) used PSO algorithm to feed AquaCrop model (Vanuytrech et al. 2014) for winter wheat yield estimation. Kaleeswaran et al. (2021) used PSO to inform crop selection based on resource availability.

10.4.4 Artificial Bee Colony (ABC)

Based on flying and dancing communication pattern of honeybees, food location represents an optimal solution, and nectar represents fitness of the solution. The total number of bees for food search is equivalent to number of optimal solutions. The artificial bee colony (ABC) algorithm generated a randomly distributed population for all the employed and onlooker bees, and they pass information about food source to other bees. Similarly, optimal solution is fitted based on food source, and nectar amount represents solution and fitness, respectively (Karaboga and Akay 2009). Chen et al. (2016) employed ABC for designing irrigation scheduling for multiple crops. Zúñiga et al. (2014) used ABC compared to other bioinspired algorithm explained in previous sections.

10.4.5 Ensembling Approach

Every method has its own advantages and disadvantages when it comes to measuring uncertainty in simulated values. Parameters estimated by individual method can simulate phenology in a better way than the growth simulation and vice versa. Empirically, it is evident that ensemble averages have better results than even the best single method (Chen et al. 2015; Martre et al. 2015). In the crop modeling community, after successful results from climate ensembling, scientists have started ensembling model results to get ensembled simulations through Agricultural Modeling Intercomparison and Improvement Project (AgMIP, Rosenzweig et al. 2013). However, a very few researchers have started ensembling parameter estimation methods instead of ensembling model itself. The basic questions that arise while doing ensembling are (1) relatedness and target of parameter estimation methods, (2) assigning weights to each method, (3) ensemble based on single vs multiple model input and output, (4) evaluating uncertainty estimates of all methods, and (5) compatibility of methods with models.

Several researchers have tried to compare parameter estimates and highlighted advantages and disadvantages of individual method (Ibrahim et al. 2016; López-Cruz et al. 2016; Buddhaboon et al. 2018; Tan et al. 2019; Gao et al. 2020). Jha et al. (2021) employed ensemble approach in parameter estimation for maize cultivar for the first time rather than ensembling model output. The detailed approach of ensembling by weighted average and simple average is explained in Jha et al. (2021). They compared GENCALC, GLUE, and NMCGA (two variants, with standard deviation and without standard deviation: NMCGA_SD and NMCGA_NO_SD). The results of genetic coefficients of maize cultivar are shown in Table 10.1; and the model performances are shown in Fig. 10.2.

Table 10.1 Genetic coefficients estimated by different methods. GENCALC, GLUE, NMCGA_SD, NMCGA_NO_SD, and ensembling approach in 2017 and 2018

Methods	P1	P2	P5	G2	G3
GENCALC	143.8	0.54	780.0	750	8.5
GLUE	133.2 (30.7)	1.7 (0.5)	767.5 (40.1)	762 (176)	12.6 (2.6)
NMCGA_SD	134.4 (8.4)	1.714 (0.2)	758.6 (73.1)	779.7 (20.6)	13.2 (0.2)
NMCGA_NO_SD	134.9	1.7	666.4	806.6	14.8
Arithmetic average	136.6	1.4	743.1	774.6	12.3
Weighted average	137.5	1.4	749.0	777.4	11.4

Source: Jha et al. (2021)

Note: P's are phenology parameters and G's are growth parameters; values in () are standard deviation of parameter estimates. NMCGA_SD (noisy Monte Carlo genetic algorithm with standard deviation); NMCGA_NO_SD (noisy Monte Carlo genetic algorithm without standard deviation). P1 = juvenile phase coefficient (°C-d); P2 = photoperiod sensitivity coefficient (days); P5 = grain-filling duration coefficient (°C-d); G2 = potential kernel number coefficient; G3 = kernel filling rate (mg/day)

10.5 Statistical Evaluation of Performance of Genetic Coefficients

Crop models are based on empirical equations, and a set of hypotheses describing dynamic growth and development can be resulted in biased simulation or error as compared to the observed values. It is advisable to have in season observed value in addition to end season observed data for statistical evaluation (Sinclair and Seligman 2000). Hence, the performance of the model should be evaluated statistically with the observed data (Willmott 1982). R^2 is a measure of the correlation of simulated and observed values and used to evaluate the fitness of the linear model (Correndo et al. 2021). It misrepresents the under- or overestimation of the observed data as it is insensitive to proportional difference between observed and simulated data (Legates and McCabe 1999; Krause et al. 2005). Hence deviation and test statistics are required to evaluate the model performances.

Test statistics includes coefficient of determination (R^2; Eq. 10.15), and deviation statistics include mean bias error (MBE; Eq. 10.16), root mean square error (RMSE; Eq. 10.17), and index of agreement (d-index; Eq. 10.18) (Willmott 1982) to measure the performances of the calibration methods:

$$R^2 = \frac{\left[\sum_{i=0}^{n}\left(O - \overline{O}\right)\left(M - \overline{M}\right)\right]^2}{\sum_{i=0}^{n}\left(O - \overline{O}\right)^2 \sum_{i=0}^{n}\left(M - \overline{M}\right)^2} \tag{10.15}$$

$$\text{MBE} = \frac{1}{n}\sum_{1}^{n}(M - O) \tag{10.16}$$

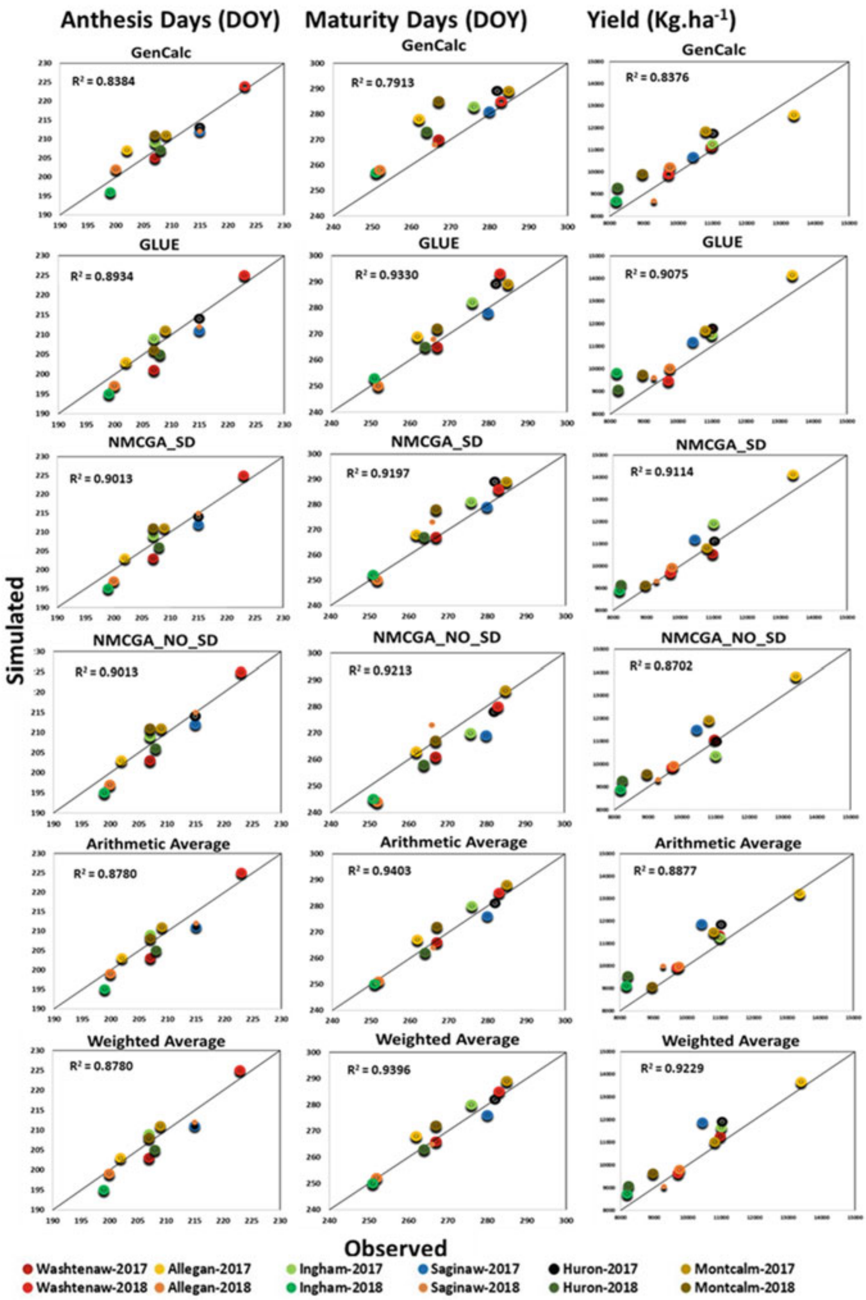

Fig. 10.2 Comparison of simulated and observed phenology and yield of maize for all the methods and ensemble for different validated sites. (Source: Jha et al. 2021)

$$\text{Root Mean Square Error} = \sqrt{\frac{\sum_1^n (M-O)^2}{n}} \tag{10.17}$$

$$\text{Index of Agreement } (d - \text{index}) = 1 - \left[\frac{\sum_1^n (O-M)^2}{\sum_{i=0}^n \left(|M-\overline{O}| + |O-\overline{O}|\right)^2}\right] \tag{10.18}$$

where M and O are simulated and observed variables (e.g., ADAP (anthesis date), MDAP (maturity date), or HWAM (yield)), respectively.

These objective functions are determined by crop genetic coefficients and help in simulating crop growth, development, and yield and help in assessing impact of climate change. Jha (2019) and Jha et al. (2021) compared the performance of CERES-Maize (Attia et al. 2021) using different parameters estimated by selected methods (e.g., GENCALC, GLUE, and NMCGA) and compared with ensembling approaches. They found that ensembling of genetic coefficients improved phenology and yield predictions once calibrated over multiple seasons rather than using an individual method. Better MBE, RMSE, and d-index for ensembling method have more effectiveness in simulating phenology and yield as compared to other individual method as shown in Table 10.2 (Jha et al. 2021). Further details on the pros and cons of different metrics for model performance and evaluation can be found at Correndo et al. (2021).

10.6 Conclusions

Increasing food demand of growing population must be met by enhancing food production to synchronize the dimension of food security by the end of the century. Climate vulnerability along with other major global issues impedes the target of food security globally. With limited resources, we need to produce more food with climate-resilient cultivars. Crop models play a vital role in testing cultivars under varying G x E x M scenarios. New cultivars need to be updated with their genetic coefficients to simulate their growth and development and hence prediction of phenology and yield under different environments. Field experiments are scarce with current limited extent of land resources, and hence estimating genetic coefficients is laborious, costly, and therefore a daunting task. Different optimization methods for parameter estimation play a crucial role in meeting these requirements. The selection of methods to estimate genetic coefficients also requires careful cataloguing of input data and protocols. To avoid biasness on accounting uncertainties, we should emphasize on ensemble methods rather than using the individual method of parameter estimation as discussed above in this chapter. The additional benefit of applying ensemble approach is to improve the prediction performance by reducing variance error of different methods. The performance and robustness are two critical components which are desirable for all model users in predicting

Table 10.2 Performance of CERES-Maize using parameters estimated by GENCALC, GLUE, NMCGA, and ensembling approach during calibration in 2017 and 2018

	ADAP (DOY)			MDAP (DOY)			HWAM (kg.ha^{-1})		
	MBE	RMSE	d-index	MBE	RMSE	d-index	MBE	RMSE	d-index
GENCALC	−1	4	0.93	6	12	0.84	604	784	0.96
GLUE	−2	5	0.89	4	12	0.84	1065	1093	0.93
NMCGA_SD	−2	5	0.88	2	10	0.87	81	665	0.97
NMCGA_NO_SD	−2	5	0.88	−8	11	0.84	594	833	0.95
Arithmetic average	−2	4	0.91	−1	9	0.90	861	1107	0.90
Weighted average	−2	4	0.91	−1	9	0.90	801	937	0.94

Source: Jha et al. (2021)
Note: ADAP (anthesis day after planting), DOY (day of year), MDAP (maturity day after planting), HWAM (yield at harvest maturity (kg/ha))

phenology and yield. Fine-tuned and evaluated model can be used to assess crop potential yield analysis, yield gap assessment, projection of climate, and economic and other decision support analysis which helps growers to enhance profitability and strengthen environmental stewardships.

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Chapter 11
Climate Change Impacts on Animal Production

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Abstract Change in climate presents a serious peril to the animal species. Long-term deviations in the global or regional climate patterns have evident repercussions on the environment. Variance in the climatic pattern has a direct and indirect impact on animal production, so for this reason, it is requisite to perceive the appropriate way out not only to maintain the economy but also to reduce the hazardous environmental pollutants that will mitigate the negative impacts of climate change. The science of climate change signifies an increase in temperature of the sea surface, plummeting of air quality, and disruption of the natural systems due to elevation in the emission of greenhouse gases. Climatic variations are the utmost stressors of animal production as it exerts great influence on the forage quality, water accessibility, breeding, milk production, and the overall cattle farming sector. Salination of freshwater river systems due to the upsurge in sea level lessens the hygienic status of the production. Any transition in the temperature threatens the fish resources equally. Besides warming, climatic variability generates acidic conditions in the water bodies, which in turn curtail the global fish supply. Rising temperature hastens the growth of parasites that intensifies the potential for morbidity and death. Augmentation in heat stress reduces the yield in the dairy, beef, and poultry industry and thus induces heavy economic loss. The animal industry in the USA witnessed a loss of between 1.69 and 2.36 billion dollars annually due to heat stress. Animal products are the principal agricultural products of food security across the globe. These products provide 17% of worldwide consumption of energy in kilocalories and 33% of protein consumption globally. Climate change has adverse implications on animal production and productivity which accordingly influence food security.

Keywords Animal industry · Climatic pattern · Food security · Heat stress · Morbidity

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11.1 Introduction

11.1.1 Global and Country Scenario of Climate Change

Climate change has a great influence on animal and plant lives, in every continent of the world. Variation in the degree of warming by every small fraction makes a difference, and any climate change is a serious threat to biological diversity in the succeeding years. Global warming is considered the serious cause of the extinction of species. Loss of species due to climatic changes may range from 0% to 54% (Urban 2015). There is a reduction in the viability of species due to climate changes. According to the Intergovernmental Panel on Climate Change, 2013 rise in global temperature due to an increase in the concentration of greenhouse gases will lead to a decrease in the snow and glaciers, and eventually sea level will also rise. There has been a decline in Arctic sea ice extent by 7.4% per decade, and in both the Southern and Northern Hemisphere, snow cover and glaciers have lessened (Yatoo et al. 2012). According to the United Nations Intergovernmental Panel on Climate Change, there will be an increase of 1.8 to 4.0 °C in temperature, and sea level is expected to rise between 18 and 59 cm in the next 90 years. Rising levels of greenhouse gases, i.e., CO_2, CH_4, and N_2O, in the atmosphere because of the activities of humans is the key factor of climate change. The last 6 years, i.e., from 2014 to 2020, are recorded as the 6 warmest years. There is a surge in the sea level, which further increases by the melting of glaciers. With the increasing carbon dioxide concentration in the atmosphere, the concentration of carbon dioxide also increases in the ocean which decreases the pH level of the water body, and the phenomenon is called ocean acidification. All these climatic changes have an impact on the biotic components present on the Earth's surface. According to IPCC, an average rise of 1.5 °C increases the risk of extinction of about 20–30% species. Various plant and animal species will not be able to adapt themselves to climate change. Climate change has pernicious repercussions on animal life, which can prove disastrous in the upcoming times (Fig. 11.1). According to Food and Agriculture Organization (2020), there is a dire need to intumesce the livestock sector globally owing to the escalating demand for animal-origin foods. Change in climatic conditions poses a serious threat to animal production.

11.1.2 Animal Production Under Climate Variability

Livestock production plays a significant role in the maintenance of the food supply. Change in climate conditions vitiates the production and quality of meat, milk, and eggs as it influences the reproductive behavior, metabolism, health conditions, and immunity of an animal. Conversion of forest land into barren lands due to drought and deforestation decreases the food availability for grazing animals. In developing countries, the livestock sector is growing expeditiously because of the elevated

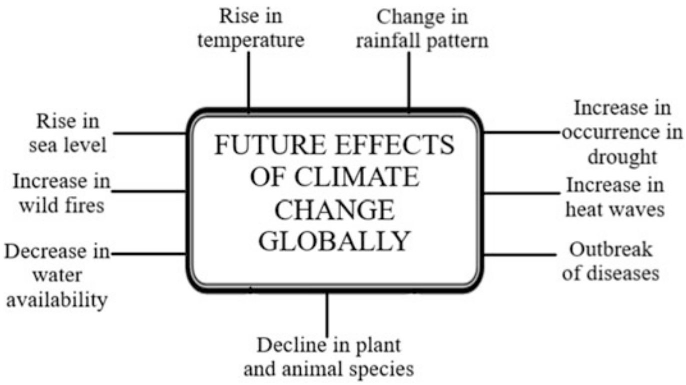

Fig. 11.1 Effect of alterations in climatic conditions

demand for animal products. However, in developed countries, this sector is endeavoring to become more efficient. It is predicted that in the near future, animal production will get adversely affected in view of competition for land, water, food, feed, and other changes looming in the environment. In developing countries, the livestock sector is one of the rapidly thriving agricultural subsectors. Demand for animal products in such countries is soaring at a rate of knots due to an increase in the population growth, movement of people from the rural to urban areas, and increase in per capita income (Delgado 2005). Animal production is the engine of development in various countries across the globe. The majority of the people, especially those dwelling in the developing countries, depend on animal production to boost up the several attributes of their livelihoods (Thornton et al. 2006; Thornton and Gerber 2010). Approximately, 30% of the Earth's ice-free land surface area is occupied by the livestock system (Steinfeld et al. 2006). The livestock sector proffers employment to 1.3 billion people across the globe, and in the developing countries, this sector directly augments the sustenance of 600 million poor farmers (Thornton et al. 2006). Globally, animal products accord 17% to kcal consumption and 33% to the consumption of proteins, although striking differences exist between the poor and rich countries (Rosegrant et al. 2009). Fisheries form the primary source of food for the increasing population across the world. They contribute to 17% of the world's total animal protein. They are important in developing tropical countries that depend on the fish for 70% of their nutrition. Loss of fish as a source of protein will put up an increased pressure on forests and other croplands.

11.1.3 Demand for Animal Products

There is an increased demand for animal productivity due to various reasons as follows.

11.1.3.1 Population Growth

According to the UNDP Annual Report (2008), it has been estimated that in the year 2050, the human population would be in the range of 7.96 to 10.46 billion, and much increase in population will be espied in developing countries. This alacritous surge in the population enunciates an increase in the food supply, which can be accomplished by improving the production of animal products. Animal products will provide nutrition security to the surging population. According to a report generated by Alexandratos and Bruinsma (2002), over the next 40 years, it is expected that the world population will increase by 2.25%, and so the global food production needs to be increased by 70% with doubling the production from developing countries.

11.1.3.2 Growth in per Capita Income

In a country, an increase in per capita income by 1% effectuates growth in the output of animal production by 0.21% (Chand and Raju 2008). Food preferences have been changed owing to the rise in per capita income in developing nations. World GDP revealed an annual increase of 3.85% between 1950 and 2002, which according to Maddison 2003 resulted in an increase in the per capita income growth rate by 2.1%. Across the globe, over the period of 40 years, global real per capita is expected to augment by over 10,000 US dollars per capita.

11.1.3.3 Urbanization

Across the globe, more than four billion people reside in urban areas, and it has been estimated that by the year 2050, approximately seven billion people will live in urban areas. With the rise in income, people begin to migrate from rural to urban areas. According to Yitbarek (2019), migration of people from rural space to urban centers will continue at a rapid pace, and it is expected that 70% of the world's total population will be living in urban areas in the near future. In developing nations it is prophesied that urbanization will continue at a swift rate, which in turn will influence the consumption habits of the people, and evidence support that an increase in the rate of urbanization may lead to an increase in consumption of animal products (Rae 1998; Delgado 2003). According to the studies done by Delgado (2005), urbanization often whets improvements in technologies like cold chains, to allow the trade of perishable animal products more widely and easily. In developing nations, due to rapid urbanization, animal production plays an indispensable role in accomplishing food security (Godber and Wall 2014).

Worldwide, more than 60 billion land animals are utilized for the production of meat, egg, and dairy products. According to Yitbarek (2019), animal production will depict a significant increase by the year 2050, viz., pig meat by 290%, egg meat by 90%, poultry meat by 700%, milk by 180%, sheep and goat meat by 200%, and buffalo and beef meat by 180%. Approximately, one-third of the global human protein consumption is met by the food obtained from animals and other animal products (Popp et al. 2010). The livestock sector acts as the source of livelihood across the world for around one billion of the poorest people (Hurst et al. 2005). According to the International Fund for Agricultural Development (2007) and Kabubo-Mariara (2009), whenever there is a failure in crop production, at that time animal products come to the rescue of the people by acting as an important food source. Yawson et al. (2017) reported that the average per capita consumption of meat is prognosticated to upsurge from about 34 kg in 2015 to 49 kg in 2050. Demand for animal products is predicted to rise considerably in the near future. According to the data provided by the Agricultural and Processed Food Products Export Development Authority (2018), India accounts for approximately 5.65% of egg production and 3% of the meat production over the world. India has the largest population of milk-producing animals in the world. Various animal species are important as they form the important food source having high nutritive value; some species are important for industrial purposes as they supply hides, skin, and fiber. Even some valuable by-products such as dung for fuel and manure and the horns are also obtained for the production of fancy items. Animal production can be a small-scale cottage industry or large-scale manufacturing industry and so helps in providing part-time or full-time employment to the people. The livestock sector is the source of regular income because of the quotidian production of dairy and poultry products. Fluctuations in climatic conditions have a tremendous effect on the fisheries sector. In the next few years, the air temperature and water temperature will continue to rise, due to which the level of the sea will surge up as the glacial mass will begin to melt. This will lead to acidification of water bodies owing to increased absorption of carbon dioxide emissions (Bindoff et al. 2007). Climate change even affects the distribution of fish in water bodies.

11.1.4 Institutes Working on Animal Production Under Changing Climate

The Indian Council of Agricultural Research (ICAR)-National Institute of Animal Nutrition and Physiology (NIANO), set up on November 24, 1995, at Bangalore, plays a pivotal role in conducting elementary analysis with respect to resource management of animal forage using various physiological-nutritional perspectives to ameliorate the animal productivity. Animal Production Research Institute (APRI) was established in the year 1908. Since then it is working to increase per capita animal productivity and profitability of farmers involved in livestock production.

This institute also aims to optimize the utilization of natural resources such as land and water to safeguard and preserve the environment. The National Research Institute of Animal Production was set up in Poland in 1950 and is authorized to carry out development and research work related to genetics and breeding of animals and all the issues related to animal production. Animal Production Research Institute-Giza situated in Egypt facilitates innovative and effective research on agri-food issues to achieve sustainable development outcomes. The Institute of Animal Sciences and Pastures (IZ) at Sau Paulo State, Brazil, works with an aim to research increasing animal productivity by using new technologies. This institute is committed to face any kind of challenges in the near future. Post Graduate Institute of Animal Sciences, Kattupakkam, situated in Chennai city, Tamil Nadu, was founded in the year 1957. The institute aims to improve livestock productivity by using various scientific techniques in the management of livestock. National Dairy Research Institute-National Innovations on Climate Resilient Agriculture (NDRI-NICRA), in Karnal, Haryana, effectuates pioneering research for animal welfare while sustaining the animal productivity in changing climate conditions. The institute is striving hard for increasing livestock production by fighting against both biotic and abiotic stress conditions. International Livestock Research Institute (ILRI), a global research center based in Kenya, was established in the year 1994. This institute is a member of the Consultative Group on International Agricultural Research (CGIAR). The research work focuses on various livestock challenges such as the vaccine for animal diseases, animal genetics, changing climatic conditions adaptation and mitigation, rapidly emerging infectious diseases, and markets for animal products. The Institute of Animal Husbandry was founded in 1948, in Belgrade (Zemun), and it carries out research activities in the areas of animal breeding, feeding, genetics, and physiology to enhance the productivity of animal products. The National Animal Production Research Institute was set up in Zaria (Nigeria) to develop new appropriate technologies for increasing animal production to assure food security to the growing population.

11.1.4.1 Livestock Census

The 20th livestock census was set in motion during October 2018 in both the rural and urban cities. This census was performed in approximately 6.6 lakh villages and 89,000 urban places across India and included more than 27 crore households and non-households:

- Total livestock population = 535.78 million.
- Total bovine population = 302.79 million.
- Total cattle population = 192.49 million.
- Total cow population = 145.12 million.

11.2 Quantification of Climate Change

11.2.1 Overview of Responses to Temperature, Drought, and Carbon Dioxide

11.2.1.1 Temperature

According to the report generated, the US livestock industry suffered a loss of 1.69 to 2.36 US billion dollars due to warm conditions of the environment. Increased temperature reduces the sperm quality and concentration in bulls, poultry, and pigs (Karaca et al. 2002; Kunavongkrita et al. 2005). Temperature increases between 1 and 5 °C can whip up the mortality rate in grazing cattle (Howden et al. 2008). An increase in the temperature of water alters the physiology and male-female ratio of the fish species. Increasing temperature accelerates the rate of transmission of communicable diseases. According to Tubiello et al. (2008), forage supply gets affected by high temperature as it shifts C3 grasses to C4 grasses. Howden et al. (2008) reported that the temperature rise has shifted *Kobresia* communities, the highly productive alpine, to the *Stipa* communities that are less productive. In the swine industry, Mayorga et al. (2019) reported huge loss linked with heat stress as this decreases feed efficiency, carcass quality, and reproductive performance and increases infection and death rate. Above a certain maximum limit of temperature, intake of feed, production of poultry, milk, reproduction, hormonal activity, and the immunity of an animal get suppressed (Das et al. 2016). Temperature changes decrease the production of dairy and beef products that incur a striking loss in the economy (Nardone et al. 2010).

11.2.1.2 Drought

Besides being affected by an increase in temperature due to changing climate, livestock is susceptible to extreme events such as drought (Kanwal et al. 2020). Drought poses a serious risk to the environment that influences the production of livestock negatively. This prolonged period of scanty rainfall is considered a momentous natural menace and is generally acknowledged as one of the dominant causes of damage to the environment, farming, and ecosystem (Vicente-Serrano et al. 2010). Dzavo et al. (2019) recorded water shortage as the most common cause for the loss of cattle in semiarid and subhumid areas. Starvation was found to trigger cattle loss due to lack of food. Fodder supply becomes sparse due to lack of rainfall as a result of which the price of fodder also rises. In India, approximately 68% of the sown area is at the risk due to drought, and every year it affects about 50 million people. The deficiency of nutrition in the diet of livestock is balanced by the fat resources in the body. Drought leads to fluctuations in the populations of livestock by increasing death rate and decreasing birth rate (Ellis and Swift 1988; Oba and Kotile 2001). According to the United Nations Environment Programme (1989), India is vulnerable to utmost events due to changing climate. The effect of a dry spell is noticeable even in lactating animals (Kanwal et al. 2020). The scarcity of rainfall has a strong influence on the sheep. Research studies have shown that drought leads to depletion in offspring production and lessens milk production, and infertility issues even cause serious diseases and death of an animal in certain cases. Studies conducted by Salmoral et al. (2020) revealed that the drought that occurred in the UK in the year 2018 imposed a remarkable impact on the growth of grass that affects the availability of feed, prices, the income of farmers, and thus animal welfare. Nanson et al. (2002) reported that more than 50% of the world's surface area is drained by the dryland rivers. The abundance of fish in these dryland rivers is affected by the drought conditions as the water flow stops and most of the river channels dry up (Knighton and Nanson, 2000). The drought conditions threaten the resistance of the fish population which eventually leads to mass mortality in fish (Hopper et al. 2020; Vertessy et al. 2019).

A decrease in abundance and biomass of trout in streams was observed in water systems near Western Cascade Mountains during the drought year (Kaylor et al. 2019). Hakala and Hartman (2004) reported that in response to drought-like conditions, the abundance of adult brook trout decreased by 60%. On similar lines, James et al. (2010) observed a decline in population biomass of adult brown trout following drought. Drought also presents an acute risk to the livestock sector as such condition lowers the production of hay and fodder (Schaub and Finger 2020). Smit et al. (2008) and Webber et al. (2018) had observed considerable diminution in the production of grassland and feed crops. Changing climatic conditions have an indirect effect on the production of poultry as it greatly affects the maize yield production. Availability and the price of poultry feed get affected due to climate change as reported by Liverpool-Tasie et al. (2019).

11.2.1.3 Carbon Dioxide

The livestock population is facing a serious challenge due to changing atmospheric conditions. Over the last previous 200 years, levels of carbon dioxide in the atmosphere have been increased by approximately 30%. Semple (1970) reported that natural ecosystems act as the source of the majority of food supply to ruminants and 95% of the livestock food is supplied by the rangelands (Holochek et al. 1989). Plants produce their food by the process of photosynthesis and so act as the primary producers. During this process, carbon dioxide is transformed into sugars such as glucose; thus CO_2 is vital for the growth of plants. But the increased levels of CO_2 drop the level of nitrogen in the leaves, which is considered as a most crucial nutrient for animals that depend on plant-based food (Ehleringer et al. 2005). Under elevated concentrations of carbon dioxide in the atmosphere, it has been reported that the plants elevate the release of secondary metabolites due to which animals feeding on such plants show a decrease in growth rate and increase in death rate (Percy et al.

2002). Roughly, one-third of the CO_2 that is produced due to human activities dissolves in the oceans which causes ocean acidification. Elevated levels of CO_2 lead to difficulty in breathing in marine fishes, and as a result, it inhibits their food-capturing ability and they become prone to predators. The most drastic effects of the elevated CO_2 concentration are prophesied in oxygen minimum zones in the oceans, where oxygen is found at very low concentrations (Brewer and Peltzer, 2009).

The quality of forages has been reduced due to morphological changes linked with elevated CO_2 (Owensby et al. 1996). Due to the increased concentration of carbon dioxide, more waxes get deposited in the plant leaves, which further lessen the forage quality for livestock (Thomas and Harvey, 1983). In the future, the production of livestock will most likely get distressed by increasing temperature and increasing CO_2 levels as they modify the growing conditions of plants that are used by animals for feeding purposes (Loholter et al. 2012). Preliminary analysis has revealed that in 2020, the average concentration of carbon dioxide in the atmosphere all over the globe was 412.5 ppm, which indicates a surge of 2.6 ppm over the levels of CO_2 recorded in the year 2019. Levels of CO_2 have depicted an increase of 12% since the year 2000.

11.2.2 Overview of Responses to Biotic Stress Such as Parasites

Livestock animals such as sheep and goats act as the vital component of the dairy farming section. Various helminths act as parasites in these animals and thus affect the farming systems across the world. These parasites lessen the productivity of these animals as they feed on the body or the blood of the host. Greer (2008) reported that *Haemonchus contortus* absorbs nutrients from the gastrointestinal tract of the host species, and this way the parasite damages the lining of their GI tract. As a result, the host shows various symptoms such as a decrease in weight, hyperoxia, and death in certain cases. Climate affects the copiousness and survival rate of infective stages of parasites, thus increasing the infection rate of animals (O'Connor et al. 2006). Stress triggered by the direct and indirect effects of bacteria, viruses, insects, and nematodes is referred to as biotic stress. This stress leads to loss due to pathogenicity and death in animals (Jaya et al. 2016). Changing climatic conditions have a great influence on the infectious diseases in animals as they alter their spatial distribution, disturb the seasonal and annual cycles, modify the vulnerability of animals to diseases, and also change the prevalence and severity of diseases in them (Patterson and Guerin, 2013; Bagath et al. 2019 and Filipe et al. 2020). Various transmissible disease-causing organisms responsible for causing various diseases in animals are sensitive to climate change especially rainfall, temperature, and moisture. Pathogens transmitted through food, water, and soil are most probably affected by the change in climatic conditions (McIntyre et al. 2017).

11.3 Impact of Climate Change on Livestock Production Systems

Long-term change in the climate of the Earth due to an increase in the average temperature of the atmosphere is called climate change. Animal production is an indispensable resource for the people living in poorly developed communities. Any change in the environment of an animal affects the efficaciousness of the animal production system as these changes markedly influence the growth, development, and reproduction of all animals (Fig. 11.2).

11.3.1 Quality of Feed

Change in the climatic conditions such as fluctuating temperature, intense heat waves, wind, precipitation, etc. in a certain region presents a great threat to the animals. Animal production gets affected because of the decreased quality of the forage available for feeding. Decrease in the production of herbs and increase in lignification of plant tissues vitiate the forage digestibility by animals. Furthermore, the area under the shrub cover is increasing with the change in climate that tends to diminish both the quality and quantity of feed available to the animals (Hidosa and Guyo 2017). The research findings have suggested that with the increase in temperature and carbon dioxide levels, the primary productivity of greensward and grazing lands decreases. Climate change decreases the productivity and grazing capacity of pasture lands. Moreover, it changes the pasture composition and also increases the offset of biomass yield (Attia-Ismail 2020). Plants growing on pasturelands entirely rely upon rainfall, so any change in the pattern of rainfall will affect the plants. Climatic changes such as reduced rainfall and the increase in drought-like conditions will decrease the primary productivity of rangelands/pastures, which will lead to overgrazing which may result in conflict over the scarce food resources. There is a growing probability of an increase in weather events, and that will have a great impact on the grazing systems in arid and semiarid areas especially at altitudes (Hoffman and Vogel 2008). Similar kinds of effects can be expected in the

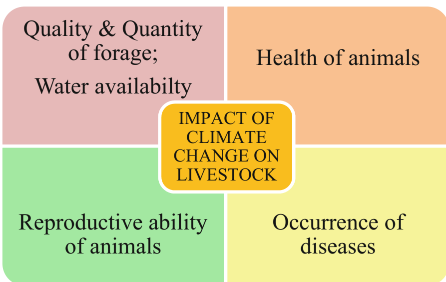

Fig. 11.2 Effect of climate change on animals

non-grazing systems where the animals are confined to climate-controlled buildings. Decreased agricultural production and the increase in the competition for food resources will surge the prices of oilcake and grains, which are considered major feed sources in non-grazing systems. In various regions of the world, wide fluctuations in the pattern of rainfall will have a great impact on forage production (Sejian et al. 2016). Studies done by Giridhar and Samireddypalle (2015) suggested that any climatic change has an adverse impact on productivity, quality of species, production of forage, and also the ecological roles of grasslands.

A dry spell over a long period also poses a great threat to pasture and feed supplies, as this leads to a decrease in the availability of quality forage to the grazing animals. Decreased precipitation and high temperature in the summer season in certain areas cause intense droughts, which may affect crop production and thus pose a significant problem for the animals that rely on grains for their food. So, it is evident that climate change has a negative impact on the animal production system.

11.3.2 Health of Animals

Change in climate may have a direct or indirect influence on animal health. Studies conducted by the National Research Council revealed that at a temperature above 30 °C, feed intake of cattle, sheep, goats, pigs, and chickens lessens by 3–5% with a single-degree rise in temperature. The secretion of stress hormones is also provoked by the temperature change. Reduced intake of feed due to prolonged exposure to high air temperature dwindles the production of catecholamines, growth hormones, and glucocorticoids. Studies done by Itoh et al. (1998a, b), Moore et al. (2005), and Sano et al. (1983, 1985) depicted the change in the metabolism of glucose, lipids, and proteins in animals that were under heat-stressed conditions. A decrease in the intake of feed and availability of forage leads to acute rumen acidosis, which increases the risk of laminitis and milk fat depression in animals. Heat stress impairs the protective value of the colostrum in cows and pigs. Animals require different types of nutrients such as minerals, vitamins, protein, and energy which vary with the region and the type of animal (Thornton et al. 2009). Any disruption in the availability of these nutrients due to heat stress affects both the process of digestion and metabolism in animals (Mader 2003). The deficiency of sodium and potassium in dairy cattle engenders metabolic alkalosis and increases the rate of respiration (Chase 2012). The reproductive capability of hens decreases because of heat stress, which has a significant effect on the production of eggs due to interference in the process of ovulation. Change in climatic conditions in the different regions of the world presents a great threat to the sustainability of animal production systems. Under cold stress conditions, animals overfeed on the protein-rich feed to increase the production of heat; howbeit it causes complications in the gastrointestinal tract. Increased temperature reduces the activity of chymotrypsin, trypsin, and amylase which decreases the nutrient digestibility in poultry (Amundson et al. 2006). An increase in the temperature of water jeopardizes the existence of various fish species.

Le Quesne and Pinnegar (2012) reported that ocean acidification decreases the development of otolith and calcified structures in fishes.

11.3.3 Reproduction in Animals

Unpredictable changes in the rainfall pattern and temperature influence the maturity and gonadal development of fishes during the breeding season. An increase in temperature influences the spawning and maturation of fishes. So the overall productivity of marine and freshwater ecosystems gets decreased due to any change in climatic conditions. The transfer of energy between the animal and its surrounding gets altered due to extreme changes in the climate which has an adverse effect on the reproduction in animals. The time period of the estrous cycle varies due to seasonal fluctuations in the environment of any animal. Heat and cold stress conditions bring down the rate of conception. Moreover, the functioning of the endocrine system also gets disrupted. Singh et al. (2013) reported that heat stress induces an increase in the secretion of adrenocorticotrophin hormone and cortisol that results in obstruction of sexual behavior induced by estradiol. According to Roth et al. (2000), ovarian follicles get damaged and are not able to survive when the temperature of the body surpasses 40 °C. Bilby et al. (2008) reported that high-temperature conditions lead to infertility due to an increase in the production of uterine PGF (2 alpha). In the cold season, the rate of conception was recorded to be 40–60%, whereas it decreases to 10–20% in hotter months (Cavestany et al. 1985). Balic et al. (2012) reported that an increase in temperature alters hormonal balance, sexual behavior, and quality of semen that has a significant impact on the overall reproductive performance of bulls. Seasonal infertility has also been reported in pigs because of the changes in photoperiod and temperature conditions (Auvigne et al. 2010), due to which the swine industry suffers a lot. Change in climate affects the process of reproduction in most of the fishes (Pankhurst and Munday 2011). According to Pankhurst and King (2010), in autumn-spawning fish species, increased temperature impedes the inception of ovulation, thus swaying the process of reproduction.

11.3.4 Diseases in Animals

The risk for the outbreak of diseases increases due to changes in the temperature of water systems; thus this may incur huge economic losses in the aquaculture sector. Prathap et al. (2017) reported that the temperature of the udder in dairy cows increases due to heat stress which is recognized as the fons et origo of mastitis disease. Animal productivity across the globe gets decreased by 25% due to various livestock diseases (Grace et al. 2015). Heat stress can lead to acidic conditions in the rumen of animals that cause lameness in dairy and beef cows (Cook and Nordlund 2009). A biting midge species, *Culicoides imicola*, serves as a vector for

Schmallenberg virus and bluetongue virus in ruminants, and the studies done by Wittmann et al. (2001) revealed that 2 °C rise in air temperature spreads this species tremendously. These animal viruses are proliferating at a faster rate due to change in climatic conditions. According to Caminade et al. (2019), with ascend in humidity to about 85%, reproduction in ticks increases; thus climate change accelerates tick infestation in animals. Clearing away of forests and decreasing the area under vegetation lead to an imbalance in the ecosystem due to an increase in humidity and temperature that augment the spread of vector-borne diseases. Fox et al. (2012) reported that the larvae of *Haemonchus contortus*, a nematode, show an increase in the development with the increase in temperature, thus causing severe anemic conditions in sheep as this worm is responsible for the bloodsucking from the stomach of the sheep. Animal diseases caused by the helminths are known to increase with climate change. According to data generated by WHO (2008), alterations in the climatic condition such as an increase in rainfall, temperature, and humidity can augment the spread of spores of *Bacillus anthracis* that cause anthrax disease in animals. Salinity affects the water that animals use for drinking purpose, thus causing diarrhea in animals. Alam et al. (2017) revealed that changes in the salinity of water bodies cause malfunctioning of the immune system and various diseases related to the skin in animals, thus having a negative impact on the health of animals. White et al. (2003) performed studies on Australian livestock and concluded that outbreak of ticks leads to an 18% decrease in the bodyweight of animals. In sheep, cutaneous myiasis increases with elevation in humid conditions and rainfall during the summer season (Sutherst 1990). Due to a surge in humidity and temperature, the developmental rate of parasites and the disease-causing organisms increases as reported by Mashaly et al. (2004). Thus, it can be concluded that the economy of the nation gets disturbed due to decreases in animal production owing to various diseases with climatic changes. The aquaculture sector gets equally affected by the change in the climate. Altered weather conditions have a negative influence on both the wild and cultured fish population due to an increase in susceptibility to sundry diseases. Elevated water temperature increases the risk of furunculosis and white spot disease in fishes (Lopez et al. 2010). Alteration in climatic conditions has a proclivity for various diseases in animals.

11.4 Impact of Climate Change on Animal Productivity

11.4.1 Milk Production

Heat stress has a great impact on animal productivity. Temperature-humidity index lesser than 68 is apt for the performance of cattle in a temperate climate (Gauly et al. 2013). The temperature-humidity index of approximately 72 is desirable for high milk-producing cows in the subtropical and tropical climate. Panting, sweating, and standing for long periods indicate heat stress in dairy cows (Koirala and Bhandari 2019) due to which the cows eat less forage. Both composition and the quality of milk decrease due to climatic changes. Various constituents of milk such as percentage of fat, amino acids, lactose, and casein content change due to an increase in the temperature of the body that influences the synthesis of fat in the mammary gland. Prathap et al. (2017) reported the production of milk is affected by the increase in temperature as it causes an imbalance of various hormones such as lactotropin, estrogen, birth hormone, growth hormone, and progesterone hormone. There is a decrease in milk production in the animals when the temperature increases above 35 °C (Wheelock et al. 2010). Valtorta et al. (2002) recorded a 10–14% reduction in the production of milk in dairy cows in response to heatwave conditions. Heat stress has a negative effect on the production of milk and meat. According to Bernabucci (2019), the hot environment negatively affects the quality of animal products besides its quantity. Summer et al. (2018) pointed out that both the organic and inorganic constituents of milk get affected by heat stress.

11.4.2 Wool Production

Unevenness in the rainfall pattern and concentration of carbon dioxide in the atmosphere affects the quantity and quality of forage available to the animals. The amount of water resources are declining, and so it is envisaged that the health of animals will be badly affected by increasing temperature. Alterations in the forage quality will lessen the productivity of clean wool. Reduction in the availability of pasturelands will affect the diameter and strength of wool fiber (Howden et al. 2004).

11.4.3 Poultry Production

Climate change has a similar impact on the poultry industry. Tankson et al. (2001) reported that an increase in temperature will decrease the body and carcass weight of poultry which has a significant impact on the energy and the protein content of the birds. Moreover, the rate of reproduction also declines due to climate changes. Obtrusion of ovulation and decrease in the feed intake affect egg production (Nardone et al. 2010). An increase in temperature also reduces the quality of eggs.

11.4.4 Meat Production

The findings of Nardone et al. (2010) have revealed that beef cattle with thick and dark color coats are at more risk of increased temperature. In ruminants, global warming can lessen down the size of the body, the thickness of fat, and the weight of the carcass. Lucas et al. (2000) observed that the survival rate of the young ones of pigs decreases when the temperature rises above 25 °C. Moreover, there will be a reduction in feed intake and carcass weight due to changes in climatic conditions.

11.5 Climate Change and Mortality

When the body temperature of an animal increases by 3 to 4 °C above normal, then it may lead to heatstroke, heat cramps, and organ dysfunction in animals. Extreme weather conditions increase the death rate among animals (Vitali et al. 2015). In the year 2003, during the summer season in Europe, thousands of poultry, pigs, and rabbits died due to severe heat waves. According to Howden et al. (2008), a rise in temperature between 1 °C and 5 °C above-average levels leads to high mortality in grazing animals. An increase in the death rate in Mecheri sheep was observed by Purusothaman et al. (2008) in India during the summer months due to thermal stress or heat stress conditions. Various events are on the record that depicts that extreme weather conditions increase the mortality rate in animals. In Ethiopia, a drought occurred in the years 1973–1974, which leads to mortality of 30% goats, 50% sheep, and 90% cattle due to a decrease in the availability of water and feed (Kidus, 2010). Elevated carbon dioxide concentration in water bodies has a detrimental impact on the growth and viability of early life stages of fishes that inhabit the bottom of water bodies as they do not possess a regulatory system for the maintenance of pH (Frommel et al. 2014).

11.6 Modeling and Simulation

Changing climate leads to precariousness in livestock production. Climate models apprise humans about the rising unevenness in the climate patterns. Climate change adaptation has gained huge attention, and it is managed by making high-tech innovations and new policies (Crane et al. 2011). Based on different climate scenarios, various models such as regional circulation models (RCMs), general circulation models (GCMs), economic models, etc. are used to depict the impact of changing climate in the near future (Hein et al. 2009; Olson et al. 2008). General circulation models figure out the potential causes of climate variability and project climatic variations in the coming decades. GCMs are also called global climate models. Sutherst et al. (1999) and Sutherst (2000) described CLIMEX, a bioclimatic modeling software that validates the evolution of models which outline the abundance and distribution of any species based on climate. Regional climate modeling (RCM) is another alternative for global modeling, which simulates smaller portions instead of the entire globe. According to Maure et al. (2018), CORDEX regional climate models predicted that the western part of South Africa will receive less rainfall and heat waves will increase that have a negative impact on various productivity sectors like utilization of wildlife, apiculture, the fisheries sector, and livestock as the effective temperature for living species may surpass. Harrison et al. (2016) utilized farm systems and economic modeling for predicting the effects of climate change on the production and economy of dairy products. They used historical climate data and regional climate change projections for the years 2040 and 2080 to determine the upcoming climate conditions. Biophysical modeling has been used to predict the impact of climate change on consumption of pasturelands, additional feeding, and milk productivity and also determines the risks to the corporate sectors that are related to varying prices of milk and other input costs (Harrison et al. 2017). Global Livestock Environment Assessment Model (GLEAM) has been developed by the Food and Agriculture Organization (2020) that quantifies the productivity and utilization of natural resources in the animal production sector. This model identifies the impact of environmental changes on the animals, thus contributing toward the evaluation of alteration and reduction scenarios to develop a more sustainable animal sector. This modeling framework can be used both at the regional and global levels.

11.7 Adaptation Options

Changing climate conditions undoubtedly have a negative impact on the health of animals. Under the conditions of heat stress, modifications in the diet composition in such a way that it either increases the feed intake by animals or compensates for the less consumption of feed can help in improving animal productivity. Alteration in the frequency and time of feeding can help in eluding excessive load of heat and thus increases the chances of survival, particularly in poultry (Renaudeau et al. 2012). Efficient cooking systems can be applied to decrease heat stress in animals. A combination of cooling with other treatments can be used to ameliorate the fertility rate in heat-stressed livestock (Bernabucci 2019). Climate change induces heat stress, increases the incidence of disease, and brings a reduction in the availability of the pasturelands, and the livestock tolerates these environmental constraints through morphological, behavioral, hormonal, biochemical, and cellular adaptation (Sejian et al. 2017). Adaptation strategies include modification both in the production and management systems, breeding practices, amendment in policies, advancement in technologies, and modifying the perception of farmers (Rowlinson et al. 2008; USDA 2013). According to IFAD (2010), integrating livestock animals with crop production and forestry and altering the time and site of farm operations acts as an adaptative measure for livestock production. Diverseness of livestock and variety of crops can surge the tolerance for heatwaves and dry spell which intensifies the production of livestock even when the animals are vulnerable to stresses of temperature and rainfall. Besides this, crop and livestock animal diversity are effectual in combating the diseases related to climate change (Batima et al. 2005; Kurukulasuriya and Rosenthal 2003). According to the studies conducted by Renaudeau et al. (2012), Thornton and Herrero (2010), and Havlík et al. (2013), changes in feeding practices such as alteration of diet composition, modification of feeding time, and inclusion of agro-sylviculture species in the diet of animals can help them to adapt in the changing climate conditions. All these practices lessen the risk of changing climate by reducing feed insecurity during drought conditions, decreasing extreme heat load, and reducing malnutrition and death rate in animals. Transition in breeding practices can surge the tolerance for heat stress and diseases in animals by ameliorating their breeding and growth (Henry et al. 2012). The development of genebanks can enhance the breeding programs which will act as an insurance policy for livestock animals (Thornton et al. 2008).

11.8 Conclusion

Certain steps are required to be taken by the government by focusing on the advancement to lessen the effect of climate change on the livestock and aquaculture sector. Climate change is viewed as a substantial threat to the continuance of life on the earth, and it is one of the serious challenges of this century. The cognizance of change in climate conditions and their impact on animal health is very limited across the world. Climatic events have a serious impact on the biotic components of the ecosystem. It is necessary to understand the alterations in climate, and certain policies should be developed in response to these climatic variations. Varieties of fodder that are resistant to drought-like conditions need to be developed so that good-quality feed remains available to the animals. Shelter for animals should be designed in such a way, keeping in mind the heat stress, comfort, and behavior of animals (Ali et al. 2020). Climate alterations jeopardize the existence of the livestock system. Adaptation to climate changes and framing various policies at the regional, national, and international levels are ultra-critical to defend animal production. One of the most propitious adaptations is to use various crop varieties as feed for the livestock (Downing et al. 2017). Diversification of feed increases the tolerance toward the alterations in climate changes. Advanced technologies can be utilized to link data on climate change with the outbreak of various diseases.

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Chapter 12
Climate Change and Global Insect Dynamics

Raman Jasrotia, Menakshi Dhar, Neha Jamwal, and Seema Langer

Abstract Diversification of insects has occurred through 450 million years of earth's fluctuating climate, yet swiftly deviating patterns of temperature and rainfall present unexpected obstacles along with the anthropogenic stresses. Climate variance and extreme weather events have a considerable impact on insect population dynamics. Insects are very sensitive to the ongoing climate warming. The temperature has a direct impact on the maintenance of essential life functions in insects such as survival, growth, development, metabolism, voltinism, and even availability of the host. A decrease in precipitation leads to drought-like conditions, which affect the abundance and diversity of soil insects. Global warming supports the manifestation of insect-transmitted plant diseases, and the population of the insect vectors gets increased. Research findings suggest that with a rise of temperature by 2 °C, insects experience more than the expected life cycles in a season. Elevation of carbon dioxide levels affects the behavior and production of insects as the host plant grown in such conditions is less nutritious for the insects. Alteration in the pattern of precipitation influences the insect pest predators, parasites, and diseases emanating in complex dynamics. Climate change incites the change in insect dynamics across the globe, and every day about 45–275 species of insects are becoming extinct. Beetle incidence in a protected forest in New Hampshire, USA, has decreased by 83% in a resampling project spanning 45 years, apparently as a function of warmer temperatures and reduced snowpack. In a subarctic forest in Finland, negative associations with a warming climate were detected for subsets of the moth fauna to name a few. Climate change is itself not one phenomenon but includes a shift in limits (both maxima and minima), average condition, and variance. Hence, multidisciplinary actions are required to be taken for solving the menace of climate change that has a direct or indirect effect on insect diversity.

Keywords Climate variance · Extinct · Global warming · Insect dynamics · Metabolism

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12.1 Introduction

Global climatic alteration has created chaos all over the world, threatening not only plants or animals but also entire life forms on this planet. From declining polar ice caps to dwindling biodiversity, everything on earth has started receding at an unimaginable rate. It has been estimated that the global average temperature will hit 1–4.5 °C hike in the coming 100 years (IPCC 2014) mainly due to increased surface temperature, variable precipitation, increase in carbon dioxide (CO_2) concentration, and their interactions among them (Nayak et al. 2020).

The change in climate due to several natural and anthropogenic factors (Fig. 12.1) has led to various discernible changes like floods and droughts all across the globe, and it has been estimated that the growing rate of climate change will have a very strong impact on agriculture mostly in agro-based countries, for instance, India where almost one-third of the population is reliant on agriculture. According to the Economic Survey of India (2018) report, a reduction in annual agricultural income by 15–18% due to change in agricultural productivity as a result of climate change is foreseen. In these changing climatic circumstances, knowledge about insect dynamics is cardinal to draw up effectual strategies to counter the impact of climate change. Insects belong to that particular group of organisms that most likely do not utilize their metabolism for the maintenance of body temperature but depend upon surrounding temperature conditions for their successful development, reproduction, and survival, i.e., poikilothermic (Bale et al. 2002). Insects are highly responsive to even slight changes in temperature conditions as it dominates certain life events like growth and development, physiology, behavior, and relationship with other species as well. These climatic changes may not always be harmful to insects, but in some

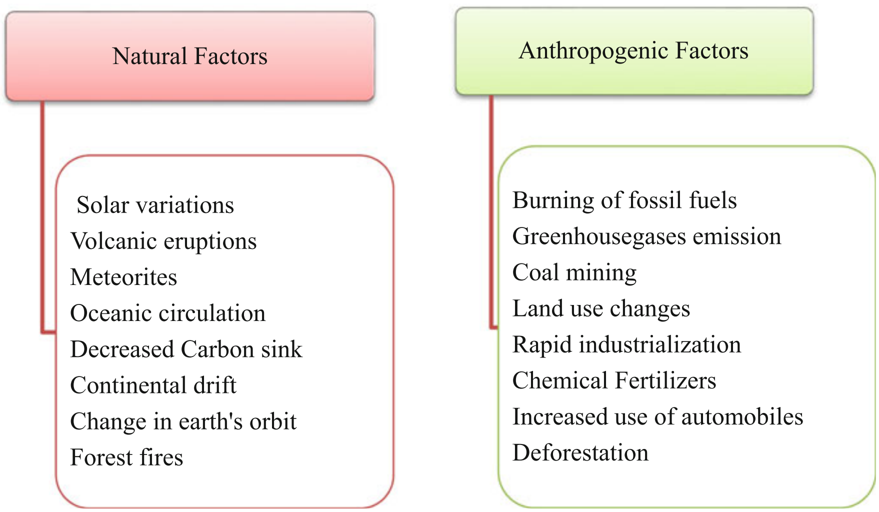

Fig. 12.1 Factors responsible for climate change

cases, these also prove beneficial for the insect populations depending upon their role in animal, plant, or human health (Sharma 2010; War et al. 2016).

Since insects have a variably shorter life span and high reproductive rate than other animals and plants, they show significant responses toward altering climate including contraction of geographical distribution besides all the developmental and behavioral changes. Climate change bears direct (Samways 2005; Parmesan 2007, Merrill et al. 2008; Nayak et al. 2020) as well as indirect (Harrington et al. 2001; Bale et al. 2002) effects on insect populations, and continuous monitoring of all the sensitive arthropod species gives the scientists an upper hand to understand the constant changes in biodiversity (Gregory et al. 2009). Climate change has been presumed to be the vital element for the wiping out of arthropod species (Butchart et al. 2005). Highly vulnerable are the species inhabiting cold regions (high altitude) because temperature warming has led to their forced shift uphill. Due to inhabitable conditions in high-altitude areas, eventually, many species have become extinct which is not easily detected until several hundred years (Sharma 2014). According to a report by Franco et al. (2006), climate change resulted in the extermination of four species of butterflies from lower reaches in the UK in over 25 years. In this global sixth extinction phase, driven largely due to anthropogenic activities, the current rate of extinction is 100–1000 times much more as compared to previous times. This climate change will soon devour the remaining species as nearly 45–275 species are vanishing each day (Sharma 2014). Habitat loss and the introduction of alien species, apart from extinction, are among the distinct drivers for the loss of species. The expected 80% pollination by insects (Pudasaini et al. 2015) considerably suffers from the hands-on climate change leading to poor yields and, ultimately, a threat to global food security. Global warming and climate alterations will highly dominate some important parameters in insect development and association (Fig. 12.2).

12.2 Insect Production Under Climatic Variability

Raising, breeding, and harvesting of insects as livestock are known as insect farming, microstock, or ministock. Insect farming is done to obtain various insect products. Honeybees belonging to the genus *Apis* are found across the globe even in different climatic conditions. There is an uneven distribution of these species. At present, the natural population of honeybees has shown a steep decline, and it has become a matter of great concern as this has led to a decrease in the production of various products that are obtained by the honeybees such as beeswax, honey, royal jelly, etc. Various factors as listed by Potts et al. (2010) such as the loss of habitat, use of pesticides, insecticides in agriculture, the introduction of invasive species, and climate change are responsible for the decline in the bee population. Changing climate poses a great risk even to the pollination services (Hegland et al. 2009; Schweiger et al. 2010). It is expected that because of the climatic change that occurs due to various anthropogenic activities, there will be an extinction of various insect

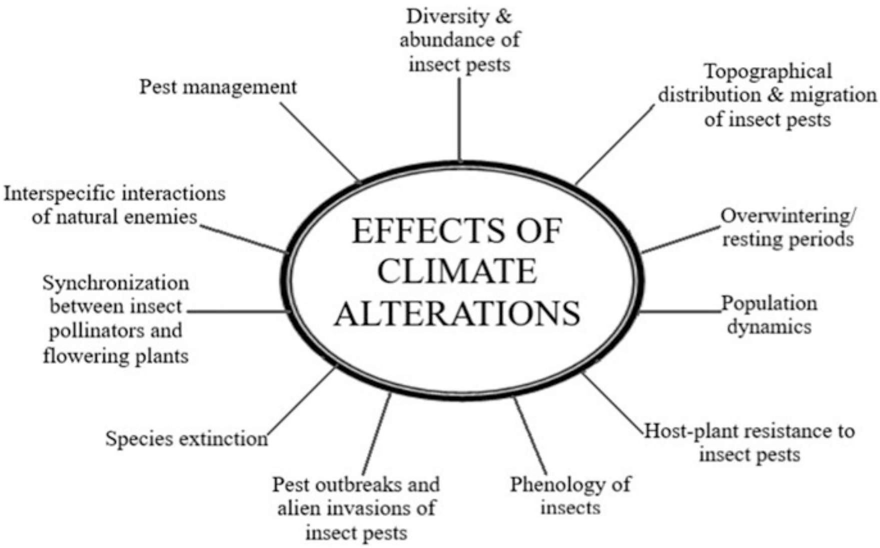

Fig. 12.2 Climate change and its impact on insects

species as both their survival and reproduction get hampered (Reddy et al. 2012). The most apt temperature for the rearing of the silkworm is about 24–28 °C. An increase in temperature and carbon dioxide concentration has a direct impact on the life cycle of the silkworm. To balance the declined levels of nutrition in the leaves of mulberry, silkworm feeds on a large number of such leaves, which may lead to an increase in its life cycle. Silkworm, being poikilotherms, is more sensitive to atmospheric temperature. Due to changes in climate and agricultural activities, insect pest scenario has also depicted huge changes (Neelaboina et al. 2018). Production of raw silk is more vulnerable to changing climate as it affects both the host plants and silkworm rearing technologies. It has been predicted that climate change will have a severe impact on the productivity of the silkworm host, rearing of a silkworm, and post-cocoon technology, which will further have a great influence on the country's economy. An increase of 20 °C or more mean temperature annually will have a severe impact on the sericulture practices in tropical regions. There will be a net revenue loss of 10–20% in sericulture across the temperate regions (Ram et al. 2016). Abiotic factors such as temperature, rainfall, and humidity have a great influence on the production of lac (Bhagat and Mishra 2002). Sharma (2007) and Thomas (2010) concluded that lac production is mainly affected by the change in temperature. In the years 2003–2004, 20,050 tonnes of lac was produced, but this production declined to 16,978 tonnes in 2014–2015 because of high temperature during summers (Pal 2009; Yogi et al. 2017). The occurrence of frequent droughts affects the lac sector equally. Changing climate creates a stressful environment, and it has been predicted to have a negative impact on the abundance and diversity of insect pests that will ultimately affect the extent of damage in crops that are economically important (Fand et al. 2012). Thus, across the world, the rate of biodiversity loss is increasing due to the negative effect of climate change.

12.3 Institutes Working on Insect Production Under Changing Climate

The International Platform of Insects for Food and Feed (IPIFF), which was created in 2012, has the main objective of promoting the broad use of insects as a protein-source alternative for consumption by humans and as animal feed. The organization actively supports the insect sector development. The main aim of IPIFF is to provide information regarding the benefits of eating insects by the general public. The Centre of Environment Sustainability through insect farming aims to achieve the goals of the growth of the insect industry. According to its leaders, insect farming provides an economical and sustainable path for the production of high-value protein. GREEiNSECT, a research project funded by Danida, Ministry of Foreign Affairs, works to investigate the use of selected species in insect farming which can play an important role in sustainable food security. They carry out research on mass rearing of insects and their contribution toward food security and generation of income. ICAR-National Bureau of Agricultural Insect Resources is a leading institution located in Bangalore that is involved in the collection, characterization, authentication, preservation, exchange, exploration, and application of insects that are important for the agricultural sector. The Institute of Entomology, Biology Centre, Czech Academy of Sciences (CAS), aims to work out the taxonomy, genetics, physiology, and ecology using a wide range of insects and model ecosystems. This institute aims to understand the effect of climate change on the composition and structure of arthropod species.

12.4 Quantification of Climate Change

Climate change is expected to bring about remarkable responses from various species of insects. In recent years, such responses have been detected already as reported by Hill et al. (2002), Battisti et al. (2005), and Netherer and Schopf (2010a, b). Any climatic change beyond the species tolerance leads to a shift in the life cycle events, individual density, and morphological forms, and some may even become extinct (Rosenzweig et al. 2007).

12.4.1 High Temperature

The biggest threat pounded by climate change is the rapid change in the relative abundance of insect species since they are unable to oppose harsh and stressful climatic conditions that may lead to their peril (Jump and Penuelas 2005). With the increase in temperature, the high-latitude or mountain resident insects are most likely to be coerced toward further high altitudes from their native places (Parmesan 2006; Menéndez 2007). Even after moving toward high altitude, they will eventually run out of the habitable area and may inescapably become extinct. Climate change has a significant impact in determining the geographical distribution of insect pests, and according to Hill (1987), low temperatures are more dominant than high temperatures in the distribution pattern. Increasing temperatures tend to impart greater ability in extending the geographical range of insect species that are inhibited by low temperatures at high latitudes to overwinter (Elphinstone and Toth 2008). Butterflies of North America and Europe have shown a range shift in their distribution as many species have shifted at high altitudes and toward the north due to climate change and global warming (Konvicka et al. 2003; Wilson et al. 2005). The same kind of northward and high-altitude distribution shift has been witnessed in the case of butterflies, beetles, aquatic bugs, dragonflies, and grasshoppers in the UK (Hickling et al. 2006) and corn earworm, *Helicoverpa zea*, in North America. Range expansion of pink bollworm, *Pectinophora gossypiella*, is sought due to warmer areas which will aid in its reach to colder areas which were otherwise intolerable to the pest (Gutiérrez et al. 2006). An expected movement of pod borers, *Helicoverpa armigera*, and *Maruca vitrata* from present tropical distribution in Asia, Africa, and Latin America to northern Europe and North America in the next 50 years is also predicted (Sharma 2010). Range expansion has more often been recorded than range contractions. Northward migration of *Nizara viridula* (green stinkbug) was studied by Musolin (2007), in Japan.

Insects going through winter diapause will be the ones that are likely to undergo major changes. Higher temperatures will lead to increased metabolism, consuming their reserved nutrient source much early, thereby leading to shortening of the duration of diapause or overwintering period. Delayed onset of diapause would be seen due to warming in winter periods, while early summer may lead to early cessation of diapause, thereby extending the life cycles of the insect pests. Every 2 °C rise in temperature is estimated to add one to five additional life cycles per season (Pandi et al. 2018) which will lead to agricultural damage and yield loss. With each degree of temperature rise, the yield loss would increase to another 10–25% (Shrestha 2019). This will ultimately lead to higher insect populations, thereby threatening food security to a wider extent. A study by Ouyang et al. (2016) deciphered up to 7 days earlier emergence in *Helicoverpa armigera* due to an increase in temperature. The rapid increase in the insect pest population may be attributed to the higher temperatures due to the considerable reduction of reproductive maturity in insects. The phenological changes in insects can be easily monitored since a slight climate change can lead to behavioral changes. For instance, high temperatures will lead to early adult emergence in insects, and the flight period will increase to significant levels (Menéndez 2007). Lepidopterans are known to exhibit the best examples of changes in phenology. A study by Roy and Sparks (2000) revealed that 26 species out of 35 species of butterflies in the UK showed early initial emergence. In Spain, 17 butterfly species proceeded their first appearance by

1–7 weeks in barely 15 years (Stefanescu et al. 2003). Similarly, 16 species of butterflies out of 23 (~70%) in California, USA, had advanced emergence by almost 8 days per 10 years (Forister and Shapiro 2003). Apart from butterflies, aphids were also reported to advance their emergence much prior to their actual period of emergence in the UK (Harrington et al. 2007). The increase in the temperature will aid in the early emergence of insects, leading to a higher number of life cycles per season and perhaps more damage to crops annually. Berg et al. (2006) reported that an increase in temperature has decreased the reproduction time by half in the spruce beetle, which has led to the damage of spruce forests.

12.4.2 Carbon Dioxide

Increased concentration of carbon dioxide has a marked influence on the plant phenotype (Curtis and Wang 1998). Elevated carbon dioxide concentration leads to an increase in photosynthesis rate, growth rate, and biomass (Norby et al. 1999; Owensby et al. 1999). This results in an increased ratio of carbon and nitrogen in the tissues as nitrogen concentration becomes diluted by 15–25% (Hughes and Bazzaz 1997). An increase in the concentration of carbon dioxide also lessens the water content of leaves and augments the rate of senescence in plants (Sicher and Bunce 1997), thus affecting the insects feeding on them. Insects having powerful and sharp mandibles such as crickets, grasshoppers, and larvae of the caterpillar are classified as leaf-chewing insects. It has been observed that such insects eat up more areas of the leaf when they feed on the plants that are cultivated under elevated carbon dioxide concentrations (Lindroth et al. 1995). On similar lines, the insects that feed within the leaf are called leaf miners, and they also damage more area of the leaf which is grown under elevated carbon dioxide concentration due to a decrease in nitrogen concentration (Salt et al. 1995). Thus in response to elevated concentration of carbon dioxide, the consumption level of insects rises. Coviella and Trumble (1999) reported that due to elevated atmospheric carbon dioxide levels, insects feeding on plants will tackle host plants that are less nutritious, and this will lead to an increase in the larval developmental period and may even surge the death rate in some cases. Moreover, it also lessens the efficiency of ingestion of food in insects as reported by Fajer (1989). Performance of herbivore insects as investigated by Zvereva and Kozlov (2010) shows a positive correlation with a nitrogen concentration of the leaf, and under elevated carbon dioxide, nitrogen, and water content, this decreases both in collard and mustard plants. Cabbage white butterfly causes more damage to the leaf structure of the plant grown under increased carbon dioxide concentration (Hamilton et al. 2005). Fewer herbivore insects were found on the plants that were not grown in ambient carbon dioxide concentration. Thus, it can be concluded that the plants grown under elevated carbon dioxide levels provide less nutrition to the insects, which has a direct effect on their performance and behavior. Elevation in CO_2 decreases the nutritional content of plant leaves by decreasing the concentration of proteins and amino acids (Johnson et al. 2020). The performance of

Helicoverpa armigera declines when exposed to elevated CO_2 concentration due to a decrease in the nutritional chemistry of the host plant. Tocco et al. (2021) found that the dung beetle, *Euoniticellus intermedius*, on exposure to elevated atmospheric carbon dioxide shows an increase in the developmental period and death rate of the beetle. The rise in CO_2 levels also reduces the size and mass of an adult beetle which affects its fitness. Elevated levels of carbon dioxide have an indirect effect on the leaf chemistry due to which the palatability of the leaves also decreases (Bezemer and Jones 1998). The meta-analysis of the effect of elevated carbon dioxide concentration on the insects was done by Stiling and Cornelissen (2007), and they found that under elevated carbon dioxide concentration, an abundance of insects declines by approximately 22.0%, the consumption rate of plants by insects increases by almost 17.0%, the development time increases by about 4.0%, the relative growth rate depicted a decline of 9.0%, and pupal weight decreased by 5.0%. Elevated carbon dioxide raise the mean annual temperature from 10.5 to 20.1 °C, and the damage to plant leaves increase the levels of leaf sugars by 31% which led to a significant rise in the density (DeLucia et al. 2008). At elevated carbon dioxide, the levels of leaf sugars increase by 31% that leads to a significant rise in the density of Japanese beetle. Hematophagous insects show a direct response to carbon dioxide (Guerenstein and Hildebrand 2008), whereas herbivore arthropods are affected by the altered leaf chemistry that occurs due to a rise in carbon dioxide levels (Cornelissen 2011). In addition to increasing temperatures and humidity, increased CO_2 levels also greatly influence the host-plant interaction. Gregory et al. (2009) deciphered that a high level of CO_2 will, no doubt, increase plant growth and productivity, but it may tend to increase the level of damage caused by herbivorous insects. However, in the case of enriched CO_2 environments, nitrogen-based defenses will tend to decrease, while carbon-based defense will increase slightly (Sharma 2014). This host-plant interaction is detrimental for insects practicing monophagy (single host plant) since depletion of a single host will lead to questionable sustenance of monophagous insects. For instance, the gypsy moth *Lymantria dispar* feeds on *Quercus rubra* (red oak) and *Quercus velutina* (black oak). If the eggs of gypsy moth hatch before budding in the oak plant, the larvae will end up starving, and if eggs hatch extremely late after budding, it will lead to reduced fecundity as the foliage quality will reduce sharply (Ward and Masters 2007).

12.4.3 Drought

Drought is one of the biggest challenges for the production of cereals under the current scenario of climate change, and this has a huge impact on the outbreaks of insect pests. Climate change not only includes the increases in temperature. The intensity and frequency of drought have raised, and it has been estimated that in the near future, this condition will increase which will have an alarming effect on the mortality of trees (Diffenbaugh et al. 2017; Lehner et al. 2017; Hartmann et al. 2018). Extreme alterations in rainfall patterns will inevitably pose a detrimental influence on the abundance and diversity of insects. Sardana and Bhat (2016) elucidated that deviating or fluctuating weather conditions cause an upsurge of various insect pests like heavy rains might lead to the emergence of red hairy caterpillar, while long dry conditions followed by severe rainfall will lead to the eruption of cutworms. Water stress in sorghum leads to great damage by *Chilo partellus* (spotted stem borer) and *Melanaphis sacchari* (sugarcane aphid) than the plants in well-irrigated regions. Hence, an increase or decrease in insect damage may be attributed to a change in the moisture content of the host plant. According to Sharma et al. (1999), humid conditions also meddle with the interactions between host plants and insects. The more humid the conditions, the more easy it would be for insects to detect odors to build a relationship with host plants. Lack of rainfall accompanied by swift growth of vegetation sets off significant changes in the brains of these insects that lead to the secretion of serotonin, which stimulates locusts to breed profusely, and they become densely populated. In recent years, change in environmental parameters such as drought has led to the outbreak of locusts.

Deficit rainfall for a prolonged time affects the growth and survival of trees which leads to a severe outbreak of insects in forest areas (Netherer and Schopf 2010a, b). It has been found by Dai et al. (2004) that drought-like conditions have tend to increase since the mid-1950s in the land areas of the Northern Hemisphere. Under the conditions of drought stress, more infections tend to develop. Drought provokes the outbreak of insects. Herms and Mattson (1992) proposed that drought-like conditions increase the fitness and abundance of herbivore insects due to an increase in the nutritional status of plants. Pests feeding on the plant sap depict a positive response to the drought condition. Drought increases the concentration of sugar and nitrogen in the leaves of plants, and the insects feeding on such leaves show increased fecundity rate, development, and abundance (Herms 2002). McClure (1980) demonstrated that the abundance, survival, and fecundity of *Fiorinia externa* got increased with an increase in the nitrogen content of eastern hemlock trees.

Drought has a deleterious effect on the insects feeding on the tree trunk; however, the leaf-eating, gall-making, and sap-feeding insects are benefited from the drought-like conditions. Under acute drought, outbreaks of the bark beetles occur as observed by Netherer et al. (2019). Recent investigations carried out by Ahmed et al. (2017) and Nguyen et al. (2018) revealed that the rate of parasitism is low in aphids that are fed on the water-stressed plants due to a reduction in the abundance and size of the host. Temperature, along with other variables such as humidity, rainfall, carbon dioxide (CO_2) concentration, and radiations, also aids in influencing pest status (Harrington et al. 2001).

12.4.4 Biotic Stress

Due to the complete sedentary lifestyle of the lac insect, they are more prone to the attack of predators, which results in considerable damage to the lac crop (Singh et al. 2011). Both vertebrate and invertebrate species act like the predators of the lac insect

(Mohanta et al. 2014; Shah et al. 2015). Among vertebrates, rats and squirrels are the most common enemies of the lac insect. Invertebrate enemies destroy 30–40% of the lac cells and thus have an adverse effect on the yield and fecundity of lac insects (Sarvade et al. 2018).

12.5 Modeling and Simulation

According to the production model as given by Valashedi and Pichaghchi (2019), the production of insect products is significantly related to temperature, and even a half-degree increase in temperature due to climate change will decrease the production of honey by approximately 40 tonnes per year. Trait-based models suggest that insect populations inhabiting the low-to-mid-latitude areas are at more risk due to climate change (Kellermann and Heerwaarden 2019). Experimental simulation of climate change due to elevated temperature and carbon dioxide concentration was carried out in laboratory conditions by Schneider et al. (2020). They found that increased temperature favors the survival and development of pests, from eggs to adult stages. The relationship between microclimate, ecophysiology, and vital rates can be determined by using the mechanistic models of the effects of climate change on insects. Such models depict responses specific to the developmental stages and carryover effects between the consecutive stages (Maino et al. 2016). Lobo (2016) suggested the use of species distribution models or SDMs for predicting the presence of insect species under different climatic conditions. This model relies on the information of the presence of species.

To determine the relationship among pests, plants, and their environment, crop and forestry population system models act as useful tools. Tang and Cheke (2008) proposed that optimal strategies to achieve the goals at the societal and individual level can be found using simulation models. With climatic variations determined by NASA-Goddard Institute of Space Studies (GISS) general circulation models, it has been estimated that European corn borer will shift up to 1220 km in a northward direction and the future generations will even continue to occur in that region (Porter et al. 1991). Using various models, it has been estimated that an increase in temperature by 2 °C could increase the life cycles per year. Various correlative models such as MaxEnt, Bioclim, and random forest are used to predict the possibly appropriate regions for a particular species (Kumar et al. 2014). According to Evans et al. (2015) and Gillson et al. (2013), correlative modeling is the most common method used for forecasting the climate change effects on the wide range of insect species, and it has become the basis of climate change policy. Correlative modeling serves as an important tool for assessing the alteration in species distribution and their rate of extinction. Results of these models are given in the form of maps that depict the regions that are adequate for the survival of any species. Another type of model, i.e., the mechanistic model, involves the understanding of environmental variables and the ability of an insect species to tolerate these environmental conditions (Kumar et al. 2014). Both correlative modeling and mechanistic modeling are categorized as ecological niche models (ENMs). Thus, the analysis of climate changes along with the development of various models facilitates the prediction of risks of pests.

12.6 Adaptation Options

Insects express different types of adaptability toward the changing climatic conditions. Insect communities respond to climate changes due to sensitiveness to temperature and the short time between the consecutive generations. In Europe, heritable changes in the dates of egg hatching have been reported by Asch et al. (2012) that occurred due to disturbance in the phenological rhythmicity between the winter moth and the oak tree because of increasing atmospheric temperature. Insects are retorting to the changing climatic conditions by the shift in the process of voltinism or by adaptation to the local environmental conditions. An alteration in the timing of the emergence of adults is another way of responding to the changing climate (Maurer et al. 2018). Buckley et al. (2015) have found that over the last few years, rocky mountain grasshoppers inhabiting the higher altitudes show setbacks in their development and those living in lower altitudes manifest early development. Certain insects respond to climatic changes by proliferating their number of generations in a year (Altermatt 2010). Alteration in the temperature and rainfall pattern decreases the availability of host plant which forces the insects to shift to the new host plant for feeding as reported by Bush (1969) in apple maggot that changed its host plant from hawthorn fruit to apple trees. Lehmann et al. (2020) assessed the 31 insect pests and observed that among them 29 species showed some kind of response to climate change by changing their geographic range, duration of life cycle stages, and food web interactions. According to Diamond (2018), insect pests depict an evolutionary response to global warming. Being cold-blooded, they are more responsive to climate warming and thus show response to climate change in various ways; some may undergo alteration in the periodic events of their life cycle, and some may even alter their distribution pattern. Climate crisis greatly influences the insect pests that use specified host plants in their life cycle and dwell in a narrow range of the habitat. Insects living in tropical regions are more sensitive to increasing temperature, and adaptation, dispersal, and phenotypic and genotypic plasticity can lessen the impact of this elevated temperature on these insect species (Deutsch et al. 2008). Atmospheric warming, particularly in high latitudes, increases the phenomenon of multivoltinism in organisms that rely on external sources for maintaining their body temperature. To cope up with water loss in insects, cockroaches depict aggregation (Dambach and Goehlen 1999). For the reduction of water loss, during summers, clumping behavior is seen in *Chironomus* larvae. In Finland, Pöyry et al. (2011) reported an increase in multi-voltinism in moths due to a temperature rise. Insects living in montane forests buffer against the rapidly changing climatic conditions by shifting to higher altitudes or toward the poleward aspect of the slope. They express different phenotypes in response to the environmental conditions including the alterations in the global climate. This phenotypic plasticity helps the insects in their survival and adaptability (Bonamour et al. 2019; Sgrò et al. 2016).

12.7 Conclusion

The worldwide climate change crisis has triggered crucial changes in the association of insect pest and their host. Climate change has led to change in the geographical reach of various insect species, thereby altering their diversity and abundance. This change in topography has resulted in more crop loss, thereby imposing a burden on agricultural output and food security. The phenomenon of insect evolution has been estimated to be as long as 500 million years ago which is still an ongoing process. Insects have managed to co-evolve along with the host and numerous abiotic factors to ensure sustainability, therefore making them a highly resilient group of animals in the entire animal kingdom. Climate change has vastly influenced extinction, synchronous pollination, pest outbreaks, phenology, host-plant resistance, and a series of uncountable and interrelated associations among insects and plants. Most of the implications of climate change are attributed to human activities so the solution also lies in curbing human activities. Therefore, proper inspection of anthropogenic activities is required to understand and address future and long-term implications of climate change.

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Chapter 13
Sustainable Solutions to Food Insecurity in Nigeria: Perspectives on Irrigation, Crop-Water Productivity, and Antecedents

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Abstract Improving living standards by enhancing agricultural productivity is mandatory to resolve Nigeria's socioeconomic problems as more than 50% of the country's population is dependent on agriculture for a living. Irrigation might offer huge potential in Nigerian agriculture, owing to the country's vast water resources. This review seeks to provide an overview of Nigeria's poverty and food insecurity situation and also proposes a long-term solution based on irrigated agriculture. This investigation utilized data from the past 20 years from more than 100 studies on food security, irrigation, and crop-water productivity between 2000 and 2020. The results elucidated that 92% of the evaluated studies opined that improvements in irrigation schemes enhanced the living standards of farming communities, reduced poverty, and improved food security status. Maintaining the current rise in the agriculture sector and its substantial contribution to poverty reduction seems to be indispensable in enhancing agricultural productivity. Therefore, agriculture equipped with better irrigation facilities is necessary for achieving the desired agricultural productivity. It is also crucial to increase the quality and efficacy of social services at all agrarian

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levels. In summary, enhancing food security, increasing irrigation efficiency, and crop-water productivity by improvement in social participation, facilitation of technical training, research and development promotion, intensification of governance, and public-sector management are of utmost importance for Nigeria. Appropriate access to high-quality marketing opportunities and the adoption of contemporary agricultural technologies would be key to the next level of success.

Keywords Food security · Livelihood · Irrigation · Nigeria · Poverty

13.1 Introduction

Agricultural productivity, especially in low-income nations, is critical to global food security and the battle against hunger and poverty (von Braun et al. 2008). Rapid population growth and lower per capita agricultural output in Sub-Saharan Africa have increased the demand for improvised irrigation facilities in the region (Oldeman 1997; Angelakıs et al. 2020b). Although the amount of freshwater available for agriculture in the world is rapidly diminishing (Cai and Rosegrant 2002), there is potential in Sub-Saharan Africa, particularly Nigeria, owing to the large surface as well as groundwater resources (Xu et al. 2019). Irrigated acreage and efficiency should be improved to meet the food and fiber demand of the ever-increasing African population (Gebrehiwot and Gebrewahid 2016). The global population in the next 30 years might be growing by additional two billion people. Feeding such a huge population and reducing hunger significantly could only be possible by boosting agricultural production. This, in turn, will be dependent on expanding irrigation acreage coupled with efficient water management, even though a rising number of countries are experiencing water scarcity. According to the FAO, the irrigated area in developing nations would increase by nearly 20% by 2030. FAO predicts that using irrigation water more efficiently and planting several crops each year on irrigated land can expand the effective irrigated area by 34% by just consuming 14% higher water (FAO 2018). The most remarkable growth rate of 44% is predicted in Sub-Saharan Africa, where only 4% of the cultivable area is now irrigated (Pavelic et al. 2013).

Nigeria is the most populous country in the African continent and the seventh most populated nation on the globe (Adekola 2016). The country's population in 2019 was 203 million of which the rural population constituted 51.4% of the total and a population density of 212 inhabitants per square kilometer (Oluwatayo et al. 2019). The country's population has grown from 41 million in 1963 to 140 million in 2006 and recently touched 213 million (Anaele 2014a, b; Statista 2022). Most of the policymakers often doubt that with a growth rate of 2.59% from 2019 (Nzediegwu and Chang 2020), the country's resources can maintain pace with the growing population. The agricultural sector which provided employment to 36.55% of nation's economically active people remains the country's largest employer in 2017 (Akoteyon 2018). Low-cost techniques and small landholdings of between 0.5 and 2.5 ha characterize the farming system of Nigeria, leading to lowland and labor productivity (FAO 2018; Jellason et al. 2020; Jellason et al. 2021b). In addition, Nigeria is also afflicted by extreme poverty and food scarcity (Otaha 2013; Adebayo and Ojo 2012).

Food access is one of the most critical aspects of food security. Nigeria's enormous rainfed agricultural industry has been unable to maintain pace with the country's rapid population increase (Byerlee et al. 2014). And the simplest method to gain such access is to raise food production, which can be accomplished by cropping intensification (Byerlee et al. 2014), land area expansion (Gibbs et al. 2010), productivity, or a combination of these factors (Chamberlin et al. 2014). Irrigation is critical for enhancing cropping intensity and production (Carruthers et al. 1997). However, there is less understanding of the relationship between food production, food security, irrigation agriculture, and environmental sustainability in most Sub-Saharan African countries (Qadir et al. 2010). Maximizing the productive potential of irrigation water is critical to achieving growth, sustainable development, poverty reduction, and maintaining food security (Grey and Sadoff 2007). Many low-income countries continue to prioritize water and water management (Grey et al. 2016). Nigeria has 71 million hectares of agricultural land, accounting for 77% of the country's total geographical area. Out of this, 40.5 million hectares are arable land with around one million hectares of internal water bodies. Despite these potentials, high food import bills continue to plague the country (Onuka 2017). Prevalence of malnutrition is a concern in all sections of the country, particularly with rural areas being more vulnerable. Food shortages, hunger, poor food quality, high food costs, and even a complete absence of food are all too common, particularly in north-central and northeast regions (Akinyele 2009; Matemilola and Elegbede 2017). Inequality, food insecurity, and poverty are persistent challenges which bedevil the country despite the strength of the economy (Grant et al. 2012). This study aims to overview the prevalence of poverty and food insecurity in Nigeria and provides long-term remedies based on irrigation agriculture.

13.1.1 Conceptual Framework for Effective Irrigation System

The authors developed a conceptual framework as illustrated in Fig. 13.1 to show the development pathway toward sustainable food security, poverty reduction, and economic growth in Nigeria.

Figure 13.1 shows how the availability of irrigation water, along with adequate water management and better agronomic techniques, can lead to increased productivity, poverty reduction, and long-term food security. Conceptually, increasing productivity translates to higher producer income, better work wages, more affordable food prices for consumers, and economic growth. This could lead to improved natural resource management and environmental protection, achieving the cardinal Millennium Development Goal of reducing poverty and food insecurity while protecting ecological health.

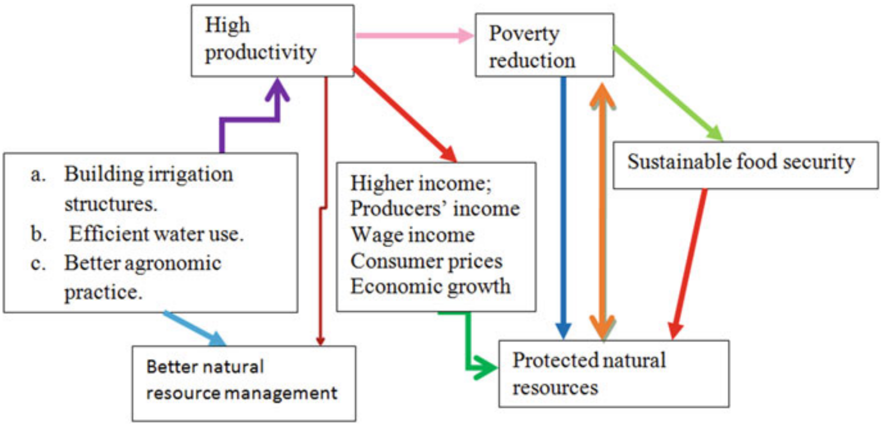

Fig. 13.1 The link between access to irrigation and poverty reduction: a conceptual framework

13.2 Methodology

The research collected secondary data from over 80 studies on food security, irrigation, water efficiency, and crop-water production. We used FAO statistics, Web of Science, and Google Scholar. The information gathered was evaluated in order to reach a reasonable conclusion about Nigeria's food insecurity issue, which has been a source of concern for stakeholders in the food subsector in recent years (Eme et al. 2014). In addition, the same databases were utilized to analyze the literature and empirical findings on irrigation agriculture's contribution to food security and poverty alleviation in developing nations, focusing on Sub-Saharan Africa. The keywords used in the search included irrigation water use efficiency, food security, water productivity, and irrigated agriculture.

13.3 Food Insecurity and Poverty in Nigeria

Food security prevails if people have access to safe, healthy, and ample food at all times to keep them active and healthy (McGuire 2015). Nigeria's food insecurity is worrying, with the situation worsening in the north (Adebayo and Ojo 2012; Babatunde et al. 2008) and nearly 62% of the total population living in extreme poverty (Astou 2015; Benatar 2016). In 2018, Sub-Saharan Africa had the highest percentage of undernourished persons (22.80%) in the world (Boliko 2019). Although global food insecurity declined from 14.8% in 2000 to 10.8% in 2018, hunger in Nigeria has increased since 2007, rising from 6.1% in 2007 to 13.4% in 2015 (Fawole and Adeoye 2015). Food insecurity in the country is alarming and shocking (Fawole and Özkan 2017). From 2009 to 2017, food insecurity continued to climb, with minor fluctuations in all three generally used metrics: the prevalence of undernourishment, food insecurity, and the number of undernourished persons (FAO 2019).

Nigeria was named the country with the most significant poverty rate globally by the World Poverty Clock in June 2018. According to data from the World Bank, 87 million people live in extreme poverty, accounting for 46.55% of the entire population (World Poverty Clock 2018). Nearly, four million Nigerians have fallen into poverty since June 2018, a trend hastened by unemployment, insecurity, low crop yield, and high food costs (World Poverty Clock 2018). Nigeria had the most significant stunting frequency in Africa, at 43.6% in 2018, while the prevalence of undernourishment increased from 9.3% to 11.5% between 2000 and 2018 (Otekunrin et al. 2019a).

Specifically, in Kwara State, Akinde et al. (2016) conducted a study on the food security determinants among rural families. According to the findings, over one-third of the rural farming households surveyed were food insecure. Another study on the determinants of poverty among crop farmers in Nigeria (Olawuyi 2012) found that only 69.2% of farm households were food secure. Similarly, Okunmadewa et al. (2007) investigated the food security condition among Nigerian urban families and discovered a 49% incidence of food insecurity in the study area. Food insecurity among women and children has been a severe and recurring problem (Sasson 2012). Food insecurity in Sub-Saharan Africa is caused by a mismatch between food production and population growth (Khan et al. 2014). The increase in agricultural production is 3.7%, but it is not keeping up pace with the 6.5% increase in food consumption (Ebele Mary et al. 2014). A map of Nigeria with the distribution of food insecurity by states and regions is given (Fig. 13.2).

13.3.1 Irrigation, Poverty, and Food Insecurity Nexus

Irrigated area must be doubled from 12 to 24 million hectares, and water productivity from irrigated and rainfed agriculture must rise by at least 60% to meet future food demand in Africa (Wright and Cafiero 2011; Shrestha 2017). Irrigation water investment is a tool for Africa's long-term development (Mwanza 2003; Adela et al. 2019). Access to irrigation water is critical for farmers to access modern farm inputs though an increase in efficiency and income, improving production and income while reducing poverty (Zewdie et al. 2019). Alternative water sources for home usage include irrigation water and crop yield growth (Usman et al. 2019). Farmers can use irrigation to get out of the "multi-scale poverty trap" (Burney and Naylor 2012; Porter et al. 2014; Lundqvist and Unver 2018). Irrigation enhances equality in the favor of resource-poor farmers (Prasad et al. 2006).

The Malabo Proclamation endorsed by the African Union's state chiefs and government in June 2014 states that "efficient and effective water management systems, particularly through irrigation," is the key to sustainable food production in Sub-Saharan Africa (Bjornlund et al. 2017). According to Wang et al. (2019), in 1900, the irrigated land area was 40 million hectares globally. However, by 1998, the figure had risen to 271 million hectares, with much of the growth occurring after the 1950s (Döll and Siebert 2000). The apparent influence on crop yield has been the

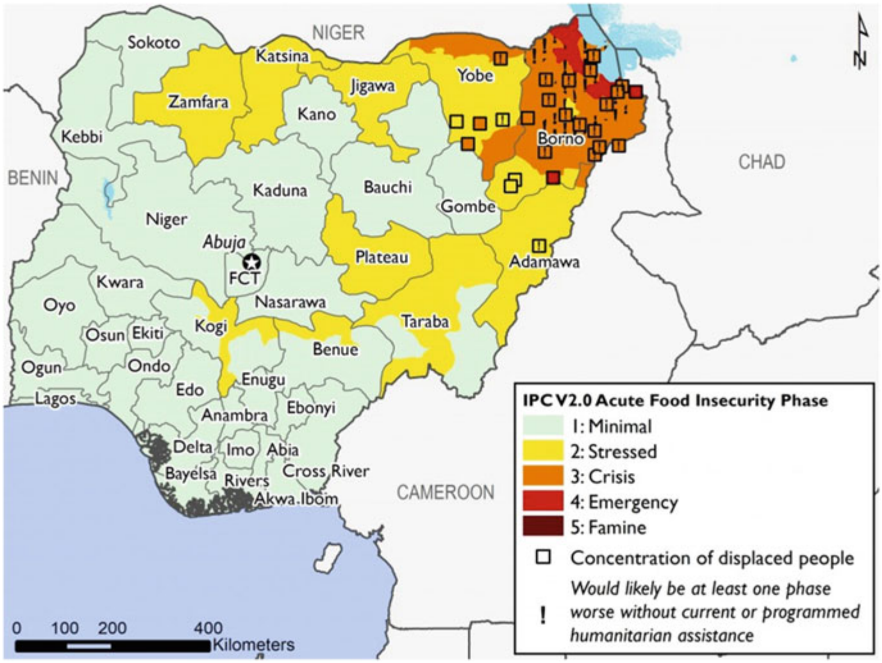

Fig. 13.2 Food insecurity status in Nigeria. (Source: https://fews.net/)

primary driver of this unprecedented intensification in irrigated agriculture (Angelakıs et al. 2020a). Rainfed agriculture covers around 80% of the world's farmed land and accounts for roughly 60% of crop production. In contrast, irrigated agriculture covers approximately 275 million hectares, or about 20% of cultivated land, and produces 40% of the world's food (Bjornlund et al. 2017; Angelakıs et al. 2020a).

Irrigation investments, poverty alleviation, and food security have a strong positive association (Chapagain 2006). In comparison to non-irrigated farmland, irrigated land provides 2–2.5 times the yield and 3 times the crop value per hectare, despite irrigation accounting for only one-sixth of the world's total production area, which includes cropland, rangeland, and pasture (Xie and Zhou 2014). According to Smith (2004), agricultural intensification through irrigation is a catalyst for poverty alleviation and food security, particularly in developing countries. Income, inequality, and poverty reduction are all influenced by irrigation (Bhattarai and Narayanamoorthy 2003). Another study found that non-irrigated households had a higher incidence and degree of poverty than irrigation households (Meliko and Oni 2011).

Furthermore, a study by Adebayo et al. (2018) discovered that irrigation agriculture is positively connected with enhanced crop productivity, income, and household food security, especially when combined with superior agronomic techniques.

13.3.2 Irrigation Development as the Cornerstone of Food Security in Nigeria

If Nigeria alleviates rural poverty and food insecurity while still meeting rising food demand, it would need to invest in irrigation or enhance current production systems. Insurgencies, adverse climatic conditions, and low production are significant causes of Nigeria's food insecurity, poverty, and hunger (Otekunrin et al. 2019a; Jellason et al. 2021a). Irrigation agriculture remains an important alternative to fulfil increasing food demand due to partial and temporal variations in rainfall (Otekunrin et al. 2019b). Nevertheless, any effort to expand agriculture must be complemented by the development of irrigation systems (Kadigi 2012; Akinde et al. 2016; Easter and Welsch 2019). In Sub-Saharan Africa, Nigeria has the most irrigation potential which is estimated to be more than 2.5 million hectares (Xie et al. 2014). Climate change, population increase, and other factors have necessitated making irrigation crucial for Nigeria's food security strategy. Sub-Saharan Africa has the smallest planted irrigation area and the lowest irrigation efficiency, resulting in the highest hunger levels (Smith 2004; Adebayo et al. 2018). Data presented in Fig. 13.3 supports this assertion by demonstrating a negative relationship between irrigation, irrigation efficiency, and malnourishment. Malnourishment is minimal in the region with high agricultural and irrigation efficiency. Irrigation-enhanced agriculture is a catalyst for poverty reduction, particularly in developing nations (Bhattarai and Narayanamoorthy 2003; Smith 2004).

Low staple food production and the continued effect of fuel oil on Nigeria's economy are two reasons contributing to the country's high degree of food insecurity (Osabohien et al. 2018). According to Omorogiuwa et al. (2014), just 40% of the country's agricultural land is farmed, despite being suitable for agriculture. However, there are 84 million hectares of arable land, besides the availability of 267 billion cubic meters of surface water (Davies et al. 2010) and three of Africa's eight major rivers in the country. Irrigated agriculture accounts for merely 2% of total

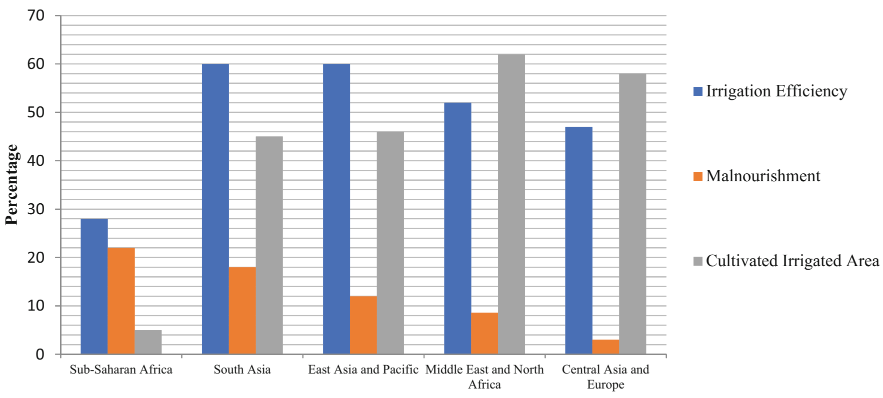

Fig. 13.3 Irrigation and malnourishment data from different regions. (Source: Domenech 2015)

cultivable land (Bahri et al., 2011). Irrigated farms in the country's dry savanna agroecological zones provide higher returns than non-irrigated farms in the exact location (Oni et al. 2009). Irrigated agricultural regions are 2.5 times more productive than rainfed agrarian areas (Stockle 2001). Furthermore, an estimate by FAO (2001) indicated that irrigation can increase the productivity of most crops by 100 to 400% compared to rainfed agriculture.

Several authors (Irz et al. 2001; Christiaensen 2007; Otsuka and Kijima 2010) argue that irrigation is critical for global productivity growth, poverty reduction, and food security. Rainfed rice yields have rarely exceeded 3 tons/ha, even in nations with better production systems such as China, Japan, Indonesia, and Sri Lanka, where irrigated rice yields have averaged 5–10 tons/ha (Seck et al. 2012). This elucidates that irrigation is a critical component in alleviating food scarcity and lowering poverty levels in many Sub-Saharan African countries (Mkavidanda and Kaswamila 2001; REPOA 2004; Sokoni and Shechambo 2005). Nigeria's water resources are abundant enough to support year-round rice production. As evidence, the ten plot states irrigation project produced an additional yearly production of one million metric tonnes in 2012 (Uduma et al. 2016).

In Sub-Saharan Africa (SSA), rapid population increase and shifting food consumption patterns necessitate doubling food output by 2050 (Leimbach et al. 2018). Due to the limited tendency of land expansion, around 85% of the increase in output would have to come from increased crop yields and greater crop intensity, both of which are the result of irrigation (Edgerton 2009). Furthermore, Yang and Zehnder (2001) demonstrate that water scarcity is a severe impediment to expanding agricultural production. Due to rising obstacles to the expansion of the farming output, insufficient or absence of water in some regions of the globe has slowed the poverty reduction strategy (Brown and Halweil 1998, Felloni et al. 1999, Liu et al. 2000, Yang and Zehnder 2001). If a country's internal renewable water resource is less than 1000 cubic meters per inhabitant per year, it is considered water-stressed. Nigeria's average internal renewable water resources per capita were 1158 cubic meters in 2017. Irrigation has many promises, especially if combined with solid agronomic methods that save water and are environmentally benign. Nigeria aims to produce more food sustainably which is a good initiative. However, there is enormous potential for changing production methods, agricultural water management, technologies, and practices. Before beginning new initiatives, it is critical to understand the restrictions, what can be fixed in the future, and what new models might be available to unlock various irrigation potentials of Nigeria. As Africa's most populous country, there is a surge in demand for water and food. Nigeria's predicament exemplifies the water and food situation broadly in Africa.

13.3.3 Irrigation Potential in Nigeria

Nigeria's usable surface water resources have been approximately 80% of the total natural flow (Frenken 2005) (Table 13.1). It has a volume of over 267 billion cubic

Table 13.1 Surface water irrigation potential in Nigeria

	Uplands (ha)	River Valleys (ha)	Inland swamp (ha)	Delta swamp (ha)	Total	%
North	343,000	578,000	154,100	–	1,075,600	68
Middle belt	82,000	28,000	28,000	–	138,000	9
South	180,000	11,000	93,400	78,000	362,400	23
Total (ha)	605,000	617,500	275,500	78,000	1,576,000	100
Percentage (%)	**38**	**39**	**18**	**5**	**100**	

Source: Aquastat (2005)

Table 13.2 Groundwater resources in Nigeria by region

Region	Basement type	Average yield per second
Sokoto Basin	Sedimentary rock	1–5 l/s
Chad Basin zone	Sedimentary rock	1.6–2 l/s
Middle Niger Basin	Sandstone aquifers	0.7–5 l/s
Niger Valley	Alluvium	7.5–37 l/s
Benue Basin	Sandstone aquifers	1.00–8 l/s
South west zone	Sedimentary rock	–
South central	Sedimentary rock	3–7 l/s
South-eastern	Cretaceous sediment	–
Basement complex	Cretaceous sediment	1–2 l/s

Source: Umara (2014)

meters (Bm^3). Surface water from Niger, Cameroon, and Benin provides 65.2 km^3 per year of external water resources (Umara 2014). The country's groundwater potential is around 57.9 km^3, with an average production of 3.5–10 l per second (Umara 2014). Irrigation is practiced on less than 7% of farmed land, and merely 12% of the irrigation capacity is only utilized (Bahri et al. 2010). In addition, there are 149 dams around the country. Among them, the states own 81, while 59 are owned by the federal government, and 9 by private companies. There are 107 major dams of which 59 are intended for irrigation and 20 for hydropower generation. Only 15 of the country's 34 small and medium dams are being used for irrigation (Adedeji 2008).

Nigeria's irrigation potential ranges from 1.5 to 3.2 million hectares. According to the most recent estimate, over 2.1 million hectares of land can be irrigated with around 1.6 million hectares via surface water and 0.5 million hectares via groundwater (Bashir and Kyung-Sook 2018).

Though available extractable water resources in Northern Nigeria are enough for at least 0.5 million ha, regions suitable for irrigation with groundwater are yet to be examined and identified. The region-specific basement aquifers and average groundwater removal yield per second are depicted in Table 13.2.

Low-lying land flooded by rainwater during the rainy season is known as "Fadama areas." They are found across the ecological zones of the Sahel, Sudan, and sections of the Guinea savanna. These wetlands are also crucial for agriculture's grazing and irrigation.

13.3.4 Role of Irrigation in Agricultural Production, Poverty Alleviation, Food Security, and Economy

The relationship between agricultural output increase, poverty reduction, and food security has been established (Mellor 1995; Thirtle et al. 2003; Koledoye and Deji 2015). Nigeria's irrigation potential demonstrates a great possibility, particularly in the north, where food insecurity and poverty are more acute. However, since irrigated land accounts for less than 1% of total cropland, its contribution to total crop production is negligible (Bashir and Kyung-Sook 2018). For example, only 2.8% of farm home plots were irrigated in the 2010–2011 cropping season, while the value in the following year was still low (1.6%) (Tashikalma et al. 2014). Irrigation is primarily being used in the northwest, with 6% irrigated plots compared to only 1.3% in the southwest (Thirtle et al. 2001). For each percentage increase in agricultural productivity, the headcount measure of poverty declined by nearly 1% in a sample of 40 nations (Thirtle et al. 2001). Agricultural productivity increase is more likely to favor the poor and consequently expand the economy (Thirtle et al. 2001).

Adugna et al. (2014) conducted a study in Ethiopia and found that based on a sample of 313 rainfed and irrigated farmers, poverty incidence was 37.3% higher on rainfed-only farms. Based on data collected from 200 farmers in Ethiopia's Ada Liben district, a related study examined the influence of small-scale irrigation on household food security (Tesfaye et al. 2008). Rice, maize, tomatoes, and other vegetables are cultivated under Nigeria's public irrigation programs. Rainfed (lowland and upland) rice accounted for 77% of the 3.2 million hectares of crop harvested in 2018/2019. Contrarily, irrigation systems account for only 17% of cultivated land and 27% of domestic production (Adekoyeni et al. 2018). Irrigated land in Nigeria can provide a significantly higher yield of 3.5–4 tons per hectare, as compared to rainfed land, which produces only 1.9 tons per hectare (Adekoyeni et al. 2018). However, there is a difference in yield between lowland cultivars that yield 2.2 tons per hectare and highland rainfed cultivars that produce 1.7 tons per hectare (Uduma et al. 2016) (Fig. 13.4). For instance, the Bakalori irrigation system is one of the country's operational irrigation projects, with yields of up to 4.6–5.2 tons per hectare, comparable to Asian rice yields of 5.5 tons per hectare in well-managed farmland (Breisinger et al. 2015) (Table 13.3).

Table 13.4 shows that the Sudan and Savanna zones have a higher yield potential than the Guinea savanna and forest zones. As a result, we may infer that the Savanna zone, which has the highest level of food insecurity, has more potential for rice production, though it is the cornerstone of poverty reduction and food security.

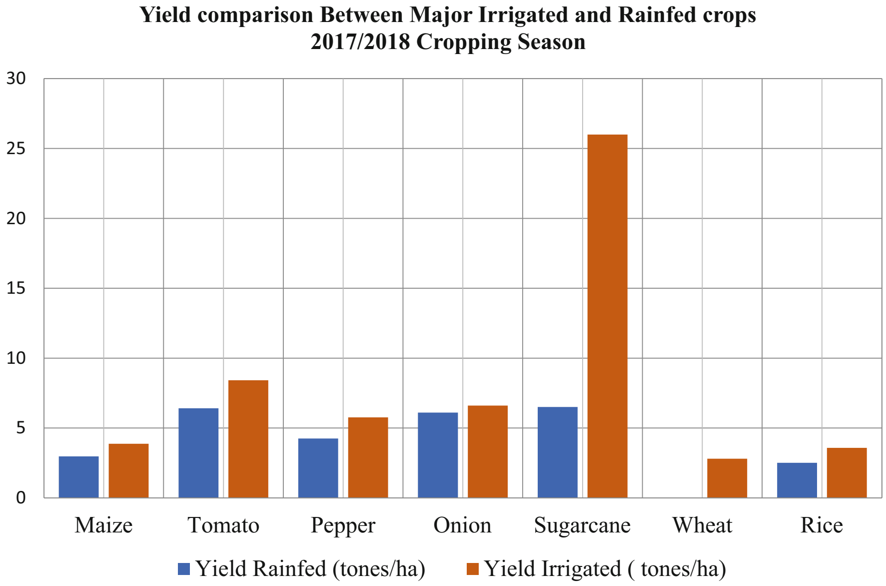

Fig. 13.4 Average yield of irrigated and rainfed agriculture in Nigeria. (Source: Tashikalma et al. 2014)

Table 13.3 Average yield per hectare of irrigated rice in some irrigation scheme in Nigeria

Location	Zone	Average yield (t/ha)	State located
Kadawa	Sudan	3.54	Kano
Watari	Sudan	8.03	Kano
Marte	Sahel	4.68	Borno
Bakalori	Sudan	4.50	Sokoto
Ngala	Sahel	5.00	Borno
Bedeggi	Guinea Savanna	2.78	Niger
Bende	Equatorial Forest	1.75	Abia

Source: Kebbeh et al. (2003)

13.4 Priorities for Sustainable Irrigation

Irrigation practices alone will not be enough to alleviate Nigeria's food insecurity and poverty.

Therefore specific priorities should be considered for it to be sustainable which can successfully improve the farming community's livelihood and also exert a multiplier effect on society as a whole. Several studies have been undertaken and published on the importance of infrastructure development, education, access to input, a sound marketing system, training, and research and development to increase productivity, reduce poverty, improve food security, and grow the economy. There

Table 13.4 Priorities for sustainable irrigation

Priorities	References
1. Road, pipe-borne water, and electricity are essential in improving agricultural productivity, hence accelerating the poverty reduction process and improving the food security of rural poor	Smith (2004), Fanadzo et al. (2010), Nadeem et al. (2011) and Llanto (2012)
2. Investments in agriculture and technology. Policies and institutional and economic reforms need to be redirected toward agricultural transformation	Hussain et al. (2004)
3. The technical skills of farmers should accompany irrigation as prioritized area	Fanadzo (2012), Beyene and Engida (2013) and Adekunle et al. (2015)
4. An increase in productivity of agricultural water use reduces the cost of production and helps conserve natural biomass	Turral et al. (2010)
5. Improving output marketing, postharvesting handling, value additions, and technologies	Namara et al. (2011), Shiferaw et al. (2011), Ali et al. (2015) and Gibbs et al. (2010)
6. For sustainability, application of critical inputs, seeds, fertilizers, herbicides, etc., in the correct quantity assurance of affordable cost and timeliness in their supply is essential for transformation	Namara et al. (2011), Ragasa et al. 2013, Ali et al. (2015), Gibbs et al. (2010) and Aloyce et al. (2019)
7. Encouragement of private-sector involvement	Arigor et al. (2015) and Ogundere (2007)
8. Research and development and favorable policies related to water management and social protection policies to protect shock and risk associated with agriculture	Rockström (2010), Ugalahi et al. (2016), Osabohien et al. (2018) and Tashikalma et al. (2014)

are a few studies which indicate priority areas in addition to irrigated agriculture investment.

13.5 Conclusion

In Nigeria, food insecurity and poverty are widespread, and the situation has worsened which demands urgent action. This poses a severe threat to Nigeria's long-term growth plan besides complexities in achieving food security. However, to reclaim the country's glory as a leading food producer in Sub-Saharan Africa, productivity must be increased, and opportunities must be created for the country's growing youth population. The simplest way to achieve this is to invest heavily in irrigation agriculture and its precursors. Improving irrigation projects will surely enhance the farming community's and customers' living conditions by lowering food prices resulting in high dividends. Irrigated agriculture would help to alleviate poverty and improve food security, national security, and economic progress.

Nigeria has enormous potential, particularly in locations with relatively abundant land and water resources for the expansion of irrigated agriculture. Nevertheless, a higher level of farmer participation in irrigation development programs is urgently required to promote accessible and sustainable irrigation production systems. This could improve the efficiency of water resource management. Farmers must be protected by policies that provide them with possibilities for better and assured produce pricing. Furthermore, farmers' access to subsidized inputs and a viable credit system which allows them to borrow money without putting up their assets at the disposal of funding agencies must be prioritized. The government should prioritize more research on the irrigation sector and also organize farmer training on better agronomic techniques to conserve the natural environment and fulfil the Millennium Development Goals (MDGs) of zero hunger.

Conflict of Interest Authors declare no conflict of interest.

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Chapter 14
Functions of Soil Microbes Under Stress Environment

Sana Zahra, Rifat Hayat, and Mukhtar Ahmed

Abstract All the functions carried out in an ecosystem are due to the action of several microbial species present in the earth. So, any kind of stress can alter their proper functioning and force them into stress conditions. However, microbes have the ability to reduce the intensity of stress by several acclimation mechanisms. In this review, the type of stressors like drought, temperature (freezing, high), soil type, heavy metals, nutrient status, etc., which affect the functions of microbes and the acclimation mechanisms to respond such stress conditions, was discussed. In addition, some techniques which were used by researchers to identify the population of microbes and their action toward stress were also discussed. Also, this review highlights how microbes play a role in reducing stress conditions from plants. This is because in a soil ecosystem, plants and microbes rely on each other, and any sort of stress that affects microbes will also influence physiology of plants as well. Among all the type of microbes, bacteria and fungi are discussed briefly because of their abundance in soil ecosystem and their beneficial role in enhancing plant growth under stress environments.

Keywords Soil microbes · Drought · Temperature · Moisture · Heavy metals

14.1 Introduction

Microbes are unicellular or multicellular, either prokaryotic or eukaryotic tiny organisms that can only be seen under microscope. However, they are present in a huge amount in the different ecosystems. In a soil ecosystem, they are almost present everywhere; specially their amount is considerable in the area of rhizosphere due to

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the presence of root exudates, as it will serve as food for them. Out of so many types discovered until now, five main types of microbes include bacteria, fungi, protozoa, algae, and viruses. Bacteria are unicellular organisms categorized into different types based on their shapes which are *cocci*, *bacilli*, *spirilla*, etc. Fungi are basically plants like unicellular or multicellular small organisms that do not contain chlorophyll; common types include *Agaricus*, *Rhizopus*, *Penicillium*, etc. Protozoa are unicellular organisms; common types include *Paramecium*, *Amoeba*, etc. Algae are plantlike organisms mainly green in color mostly found at wet ecosystems; its types include *Fucus*, *Laminaria*, and *Spirogyra.* Electron microscope is used for viruses because of its small size among all other types of microbes. *Bacteriophage* is a common type of virus. Microbes are widely studied because of their abundance and importance in soil ecosystem functioning. All the processes in a soil environment are due to the different functions of microbes (Kennedy and Gewin 1997).

Soil microbes take part in cycling of nutrients and waste and thus prevent the ecosystem. They fix atmospheric nitrogen for plants, thus improving soil nutrient status; they recycle the synthetic chemicals applied to soil. In this review functions of two types of microbes, i.e., bacteria and fungi, are discussed mainly because of their abundance in soil as compared to the other ones and due to the beneficial roles they play in stress environment (Aislabie et al. 2013).

14.1.1 Effect of Different Stress Environments on Microbes and Functions of Microbes in Mitigating That Stress

Stress is defined as something which can alter the functioning of organisms. It can be biotic and abiotic, both of which causes retardation in the functioning of microbes, which not only leads to the reduced agricultural productivity but also causes disturbance in the plant and microbial functioning. Importantly, a stress environment can be detrimental for microbes present in soil. Accordingly, in this review paper, I have discussed several stress environments and their effects on microbial functioning and the mechanisms adopted by microbes to cope with such conditions. The type of stress ranges from environmental to anthropogenic and from stress caused by chemical to physical modifications. Each type of the stress will affect them in several ways. A type of stress that is tolerable for one species will be detrimental for other, for example, a high temperature which is bearable or favorable for thermophilic bacteria can be detrimental for other species of bacteria or cause dormancy of some species. Consequently, there will be varying acclimation mechanisms based on varying stressors faced by different microbial species. Death of any of microbial species will add nutrients into the soil which is either used by plants or by microbes to perform their functions for survival under stress environments (Farrar and Reboli 2006; Schimel and Bennett 2004).

The adaptability to the stress conditions by microbes is a long-term achievement that can be achieved by genetic alterations after several years or even decades.

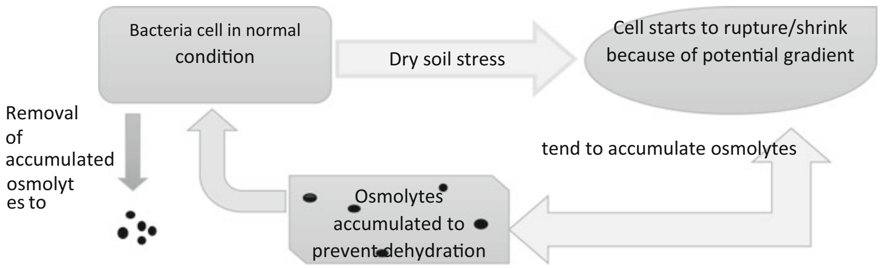

Fig. 14.1 Conceptual diagram of bacterial cell in drought and rewetting stress

Several direct and indirect mechanisms help microbes to overcome stress condition that come one after another like drought stress and rewetting of soil because in drought condition soil becomes drier and there is a chance of dehydration, while rewetting after it can cause cell rupture (Kieft 1987). In drought condition where the soil is dryer, solute concentration in surrounding environment rises and hence creates a potential gradient which causes cell rupture. So, bacteria tend to accumulate osmolytes like amino compounds to maintain an equilibrium with the surrounding to avoid dehydration. After getting rid of drought stress, it will face another stress in the form of rewetting of soil which again can cause cell rupture, so bacterial species tend to remove those accumulated osmolytes for their survival (Fig. 14.1) (Koujima et al. 1978).

Everything in excess and less both have beneficial and harmful effects; likewise increased temperature and a too cold or freezing temperature will be a stressor to microbes because in such condition, the microbial cell membrane will get rupture due to the formation of ice crystals in it. Acclimation mechanisms adopted by microorganisms under such conditions are modifying their membrane to avoid making crystals, stability in membrane fluidity, and adopting such proteins which resist freezing (Walker et al. 2006).

Heavy metals that are dumped or deposited in the soil either naturally or through anthropogenic activities create worst conditions by causing stress to the microbes. Several researches have been held to figure out the main sources of emission/discharge of heavy metals and to know their impact on microbial community within soil because in a soil ecosystem, the microbes drastically get affected by heavy metals and it causes a shift of microbial community from a particular ecosystem (Singh et al. 2014). Furthermore, different soil type and soil structure causes both a favorable and stress condition for microbes. The research studies based on experimentations revealed that the stable soil microaggregates provide a favorable environment for microbes and serve as best habitat for microbes. Clayey soil having smaller particles contains considerable amount of different species of microbes than the sandy soils having comparatively large soil particles. However, it may also cause a stress environment. For example, clayey soils have more pore volume than sandy soils, but the pores are smaller because of the smaller particle size of clay; it will retain more water for longer time which causes oxygen-deficient situation and causes stress environment for aerobic microbes. The nutrient are either provided through fertilizers or occurs naturally will define the population of microbes and microbial population in a soil is randomly distributed based on the type and amount of nutrient. However, microbes are present in a considerably huge amount at the place, where roots are present in soil (Burdman et al. 2000).

14.1.2 Functions of Microbes in Mitigating Stress for Plants

Soil-plant-microbe ecosystems are interlinked to one another, so any sort of stresses that influence the functions of microbes will also cause a negative impact on plants and physiological and metabolic mechanisms. Therefore, in this review, I have discussed the stresses faced by plants in an ecosystem along with microbes and the microbial functions in mitigating that stress. As mentioned above, stress may be biotic and abiotic. Biotic stress includes pathogens, weeds, and pest infestation, while abiotic stress includes salinity, drought, metal toxicity, temperature, etc. In salinity stress, an uprising concentration of ethylene is reported; however, reduced root activity and reduced chlorophyll content are witnessed under drought stress (Zapata et al. 2003).

14.1.3 Functions of Microbes Under Nutrient Deficiency Stress

A stress condition marked with oxygen deficiency and arid climate poses a great challenge to the macronutrient (P, S, and others) and micronutrient (Fe and others) cycling which can cause a stressful condition because of the crucial role of these nutrients in plant functioning and development, such as protein synthesis, root and shoot growth, and cell wall and organelle formation. So, fungi and bacteria are considered the main microbial communities that coexist in the soils with nutrients and expedite the process of nutrient fixing through redox reactions, for example, the *Thiobacillium* and *Metallogenium* species of bacteria are known for the dissolution of Fe through weathering processes, such as sorption, solubilization, chelation, accumulation, transformation, and precipitation. *Pseudomonas* species of bacteria was found to have performed well under aerobic conditions, whereas other microbes, such as *Desulfotomaculum*, under anaerobic conditions in degraded soils helped in the mobility of Fe nutrients. The fungi improve the availability and translocation of Fe by releasing siderophores (chelators). It helps in the mineralization and decomposition of Fe and enhancing soil fertility. Sulfur up to 95% is usually bound in organic form. Under stress environments, microbes can help to convert this crude form of sulfur to more utilizable inorganic form through microbial desulfurization. An experimental study identified several species of bacteria, such as *Pseudomonas* *brassicacearum*, *Stenotrophomonas rhizophila*, *and others from Arthrobacter* genus. All such varieties of microbes were proved to be able to coexist with organic sulfur for its transformation under such conditions.

Furthermore, in anaerobic conditions, acidophilic microbes (e.g., *Acidithiobacillus ferrooxidans*) enhanced Fe and S nutrient mineralization through being capable of performing aerobic respiration. Phosphorus in soil is present in organic and an inorganic form (Hayat et al. 2010). Many microorganisms undertake the responsibility of converting organic phosphate or P esters to inorganic P. The inorganic P is solubilized by microorganisms called PSM that released different acids in soil and lower soil pH. The solubility of P can be increased by the respiration of microbes as this will release CO_2 which reacts with the water available in soil pores thus forming carbonic acid, which in turn will solubilize P in the soil (Berg 2009).

Although microbial population also get affected by stress environment, they have adopted certain strategies as discussed above, to overcome these stress environments. However, they also take part in mitigating that stress from plants. Microbes like plant growth-promoting bacteria and mycorrhizal fungi seem beneficial in several research studies.

14.1.3.1 Bacteria

Bacteria are the unicellular prokaryotic organisms that are too small which are only seen under microscope. They are present almost everywhere. In the rhizosphere the bacterial species are in huge amount as compared to the other microbes present in soil (Kaymak 2010). A spoon of soil contains millions of bacteria. They may be beneficial or harmful. Some types of bacteria have been found to be effective for plants in stress environment. The activity of PGPR can result in better performance or survival of plants under stress environment, as they took part in several mechanisms to cope up with stress conditions. For example, plant growth-promoting bacteria are present in the root nodules which benefit the plants in their growth even under stress conditions by fixing the atmospheric nitrogen for them (Kloepper and Schroth 1978). In the saline condition when there is risk of reduced crop productivity, due to decrease in nitrogen fixation, the plant growth-promoting bacteria fix the atmospheric nitrogen and provide it to the plants by converting it into plants available form, thus reducing the risk under such environment. Many bacteria in the soil secrete enzymes which solubilize the phosphorus and make it available to plants also by various enzymatic secretions; they make a barrier to the stressor (Berg 2009; Hayat et al. 2010).

High Concentration of Na^+ and Functioning of PGPR in Minimizing Its Negative Impact

Na toxicity is thought to be an important factor which has drastic effect in plants because it causes retardation in nutrient uptake by plants, so microbes like PGPR seem effective in this regard. They have potential to cope with such stress environments by producing exopolysaccharides which not only reduce Na^+ uptake but also bind it, so that their concentration will be reduced thoroughly; this will create a maximum K^+/Na^+ condition which is effective in salinity stress conditions (Geddie and Sutherland 1993; Hamdia et al. 2004).

Water-Deficit Stress Condition and Functioning of PGPR in Minimizing Its Negative Impact

As discussed above, in a soil environment, there is close interaction between plant, soil, and microbes so a stress condition in soil affects both microbes and plants. We know that the plant body constitutes of more than 90% of water, so water serves as a building block for plants. From seedling to germination stages, all the processes like process of photosynthesis, etc. involve water molecule; hence, a low water content/supply to plants can cause reduced plant growth and plant yield, decreased photosynthetic process, membrane damage, etc. Similarly, a water-deficit condition can cause reduction in leaf area in plants and cause severe stress condition for plants. Such kind of stress may cause reduced physiological and biochemical characteristics. So, plant growth-promoting bacteria have the potential to cope with such conditions and minimize that stress condition from plants. In a water-deficit situation, the PGPR produces exopolysaccharides which gives protection to them from dehydration and making them survive under such condition (Sandhya et al. 2009).

Functions of PGPR in Minimizing Stress Caused by Pathogens

Plant pathogens are the organisms which cause several diseases in plants and cause alterations in their physiology because not all plants are vulnerable to pathogenic attacks. The effects caused by pathogens (like destruction of entire plant species) are not only related to plants, but it has severe impacts on the economy of country. In such situation, the plant growth-promoting bacteria seem beneficial in minimizing the stress from plants, by several mechanisms such as:

(a) Induced systematic resistance in plants: It is a mechanism which is triggered in plants when a pathogen is attacking; it is basically a physical or chemical barrier of the host plant.
(b) Reducing pathogens in plants by producing iron-chelating compounds: To minimize the pathogen population, they produce certain iron-chelating compounds to create iron-deficit condition for pathogens (Arora et al. 2001; Bhattacharyya and Jha 2012).

14.1.3.2 Arbuscular Mycorrhizal Fungi

A symbiotic association in which both partners get benefitted is accomplished by plant roots and fungi which are known as mycorrhizae. All types of the soils around the world have fungi; in fact, it is most abundantly present in soils after bacteria. From all the types of fungi discovered until now, the *arbuscular mycorrhizae* and *ectomycorrhizae* are abundantly found in symbiotic associations in a soil ecosystem.

It plays function such as in making plants able to absorb more water by increasing its root surface area, so that water can easily be accessible to plants in a deficient condition. In a symbiotic association, the mycorrhizae not only benefit the plant with supplying sufficient amount of nutrients and water by increasing its root surface area but also shield them from various other stresses (Evelin et al. 2009).

It involves several steps:

1. Penetration of fungi into the roots
2. The multiplication of fungal hyphae into soil
3. Absorption of nutrient and water

Functions of Arbuscular Mycorrhizal Fungi in Different Stress Environments

The functions of arbuscular mycorrhizal fungi are useful in minimizing stress environments faced by plants during their growth stages and also play a significant role in stress environment caused by water-deficit condition. Due to increase in root surface area and small projections, it is effective in absorbing more water in a scarce condition (Khalvati et al. 2005). It helps to overcome pathogenic attacks. It is not only involved in making water and nutrients available to the plants but also regulates the defense mechanism in plants against pathogenic attacks (Azcón-Aguilar and Barea 1997). The arbuscular mycorrhizal fungi provide tolerance to the plants in a drought stress condition; also it is found useful in making plants survive under salinity stress.

The maintenance of K^+/Na^+ ratio is accomplished by the mycorrhizal fungi as it seems effective in saline conditions because an increase K^+/Na^+ tells us about the tolerance level in most plants (Zhang et al. 2011). Arbuscular mycorrhizal fungi have potential to increase nodulation under salinity stress. VAM plays a major role in nitrogen fixation in a salinity stress condition.

14.2 Techniques to Study Microbial Functions

Because of the very small size of microbes, it is unable to witness their functions by naked eye, so there are several techniques invented to study their function in soil environment. To well understand the microbial population in a soil ecosystem and to know their functions, both in normal and under stress conditions flow cytometry or single cell analysis technique seems effective. In this technique different chemicals are used which indicates about the microbial activity. Methods based on rRNA and rDNA analyses seems effective in knowing the microbial population and the functions performed by microbes under stress and normal conditions (Torsvik and Øvreås 2002). Genomic methods such as metagenomics and microarrays are used to study the population and types of microbes. Bacterial artificial chromosomes seem beneficial in getting information regarding functions of several types of bacteria in a soil ecosystem. However, the changes that occurred in the microbial communities as a result of different stressors can also be detected. A changing environment can cause shifting of microbial community. However, functional analyses of environmental DNA tell about the processes that occur in soil and within different microbial communities (Xu 2006).

14.3 Conclusion

Different stress environments have a different range of negative effects on functions of microbes as well as on the plants in a soil-plant-microbe ecosystem. However, it can be mitigated by microorganisms for their survival using different strategies based on type and intensity of stress. Under drought and rewetting stress, the microbes survive first by accumulating osmolytes in drought stress while removing them in rewetting stress. After which they help in mitigating the stress environment faced by plants; mainly it can be mitigated by the action of PGPR and mycorrhizal fungi. So, their functions under stress environments were identified by using several techniques, which are highlighted in this review.

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Chapter 15
Modeling Impacts of Climate Change and Adaptation Strategies for Cereal Crops in Ethiopia

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Abstract Teff, maize, wheat, sorghum, and barley are the five major food crops in Ethiopia. This chapter provides a summary of the work investigating the effect of climate change and potential adaptation strategies to mitigate their effects for the abovementioned major field crops in Ethiopia. Climate change studies were carried out using an in silico approach via the utilization of crop growth [AquaCrop, Decision Support System for Agrotechnology Transfer (DSSAT), Agricultural Production Systems sIMulator (APSIM)] and global climate models. Maize varieties, Melkasa-1, BH-660, and BH-540, resulted in a significant change in yield during the midcentury by −13 to −8%, +3 to +13%, and −10 to +4%, respectively. For maize, the use of optimal planting date, nitrogen (N) fertilization, and irrigation contributed to improve yield under future climates. For wheat, cross-location average yield could slightly increase during the midcentury when simulated under RCP8.5 (elevated CO_2 scenario) when accompanied with optimal N fertilization management. In contrast, barley yield during the midcentury is projected to decline by 6 to 11% relative to baseline yield. Optimal planting date, tied ridging, rotation with legumes, and N fertilization along with elevated CO_2 could minimize the negative impacts of climate change on the productivity of barley. For sorghum, simulation studies showed that the crop is highly responsive to time of planting, with yields negatively impacted during the midcentury by up to 9.1% for March and 12.2% for April planting. Planting time could be considered as an effective adaptation strategy for

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sorghum in Ethiopia. For teff, yield during the midcentury could decline by up to 12% when sown after the top 10 cm soil is wet and no extended dry spells of more than 7 days occur afterward for over 25 days. This indicates the importance of precipitation quantity and seasonal distribution for sowing teff. In addition, optimal N fertilization (64 kg/ha) could increase productivity of teff while reducing the negative impacts of climate change. Higher N above this level (64 kg/ha) causes issues related to lodging. Thus, for teff crop, yield losses could be reduced due to the effect of climate change by planting early and providing optimal N fertilization.

Keywords Maize · Wheat · Teff · Sorghum · Ethiopia · DSSAT · AquaCrop · APSIM

15.1 Introduction

Teff (*Eragrostis tef*), wheat (*Triticum aestivum*), maize (*Zea mays*), sorghum (*Sorghum bicolor*), and barley (*Hordeum vulgare*) are the major cereal crops in Ethiopia (Taffesse et al. 2011). Enhancing cereal productivity under the increasing population growth is critically needed in order to reduce hunger and malnutrition. Elevated temperatures, rainfall variabilities, and occurrence of other extreme events (i.e., flood and drought stress) could pose critical threat to crop production (IPCC 2013, 2021). Many cereals are sensitive to temperature increase and water stress, especially if the stress occurs during the flowering period (Prasad et al. 2008a, 2015, 2017; Lizaso et al. 2018). Climate-related stress in Ethiopia is projected to reduce the yield of the cereal crops under future scenarios (Kassie et al. 2014a, b; Araya et al. 2015b, 2020b, 2021a; Gebrekiros et al. 2016; Abera et al. 2018). Climate change is a threat to food security, although the overall impacts are yet to be understood, and adaptation management strategies need to be identified in order to reduce the risk. In addition, as available resources are limited, the adaptation management strategies need to be quantified in order to address the threat timely and cost-effectively. Crop growth simulation models have been used to quantify the impacts of climate change and evaluate optimal adaptation management strategies at various spatial scales to support decisions (Araya et al. 2020a, b, 2021c; Silungwe et al. 2018). Individual quantitative information on components of climate change factors is available at various scales in scientific studies and reports. However, the quantitative information on the impact of climate change and adaptation strategies for the above major cereal crops in Ethiopia have not been adequately summarized. This synthesis can provide useful insights on future research investments and for guiding new policies at the regional and country scales. This study mainly focuses on midcentury period (2040–2069) to understand and quantify the yield deviation due to climate change and discusses the management strategies that can be used to reduce the risk. Therefore, the objective of this chapter is to present a summary of individual studies relevant to the impact of climate change and adaptation strategies for major cereal crops (teff, wheat, maize, sorghum, and barley) in Ethiopia.

15.2 Methods

15.2.1 Study Sites, Data Sources, and Scenarios

The analysis was carried out based on the information obtained from previous studies (Akinseye et al. 2020; Araya et al. 2015a, b, 2020a, b, 2021a, b, c; Gebrekiros et al. 2016; Thomas et al. 2019; Zewdu et al. 2020) that were focused on future climate change and adaptation for major cereal crops in Ethiopia (Table 15.1). However, some other studies that were focused on crop management data based on present or past climate were also included. These investigations were conducted at different scales and locations (from site specific to country scale), and many of the management scenarios evaluated differ among all the different field crops. Climate change studies were conducted using different crop growth models such as Decision Support System for Agrotechnology Transfer (DSSAT), Agricultural Production Systems sIMulator (APSIM), and AquaCrop along with global climate models (GCM). Most of the simulation studies on the selected five major crops were conducted for the midcentury (2040–2069) relative to the baseline (1980–2005/2009) period. Table 15.1 shows the locations, crops, and various scenarios and treatments used for assessing the impacts of climate change and adaptation strategies. Since the climate change studies differ in time and spatial scale as well as in terms of management treatment for each crop, the data is summarized and presented by crop type.

15.2.2 Maize

Climate change and adaptation management strategies presented and discussed by Araya et al. (2021a) are summarized. The climate data (daily maximum and minimum temperature and radiation data) based on the Coordinated Regional Downscaling Experiment (CORDEX) for midcentury (2040–2069) period (Endris et al. 2013; Mascaro et al. 2015) under high Representative Concentration Pathways (RCP8.5) was extracted for 21 Ethiopian locations and entered in DSSAT model. Maize was exposed to three worst case scenarios: (i) the climate extracted under high-emission scenario, (ii) maize grown in soils with low water-holding capacity (sandy loam soils), and (iii) under unchanged rainfall [(although future rainfall based on GCMs was expected to increase (Vizy and Cook 2012; Thomas et al. 2019)]. The baseline (1981–2010) rainfall was extracted from the Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) (Funk et al. 2014, 2015; Dinku et al. 2018). Three maize varieties (Melkasa-1, BH-660, and BH-540), three irrigation treatments (0, 60, and 150 mm), four N fertilizer treatments (64, 96, 128, and 160 kg N/ha), and three planting dates (April 25, May 25, and June 25) were evaluated for identifying adaptation options for the midcentury period (Araya et al. 2021a).

Table 15.1 The locations, crops, and various scenarios and treatments used for assessing the impacts of climate change and adaptation strategies

Country	No of locations	Crop model No. of varieties	Baseline period	Baseline rainfall	GCM	Period	RCP	CO_2 con. ppm	Soil type	Irrigation mm	Nitrogen kg/ha	Planting date/ density	References (source)
Ethiopia	22 locations	Maize (3 varieties) DSSAT	1980–2005	CHRIPS	CORDEX	2040–2069	8.5	571	Sandy loam	0, 60, and 150 mm	64, 96, 128, 160	April 25; May 25; June 25	Araya et al. (2021a)
Ethiopia	Bako	Maize DSSAT and APSIM	1980–2009	MS	20GCM (CMIP5)	2010–2039 2040–2069 2070–2099	4.5 and 8.5	380, 432, 571 801	Clay	–	Vary by farmers/ survey	May 25	Araya et al. (2015a)
Ethiopia	21 locations	Wheat DSSAT	1980–2005	CHRIPS	CORDEX	2040–2069	8.5	571, 380	Clay and sandy clay loam	0, 60, and 150 mm	64, 96, 128, 160	–	Araya et al. (2020a)
Ethiopia	Kulumsa	3 wheat varieties APSIM	1980–2009	MS	3GCM (CMIP5)	2040–2069	8.5	571	Clay	Rainfed	32, 64, 96, 128	July 10; Density: 100, 200, and 300 p/m^2	Araya et al. (2020b)
Ethiopia	Kulumsa	3 wheat varieties APSIM	1980–2009	+20% and −20% rain	1, 2, 4, 6 °C	–	–	360, 432, 571 801	Clay	Rainfed	32, 64, 96, 128	June 25–July 10; July 10–30; Aug 1–15	Araya et al. (2020b)
Ethiopia	Adigudom	Barley DSSAT	1980–2009	MS	3GCM (CMIP5)	2040–2069	8.5	571	Clay, loam, and sandy clay loam	Rainfed	32, 64, 96, 128	June 20–Aug 20	Araya et al. (2021b)

Ethiopia	Adigudom	Barley DSSAT	1980–2009	MS	1, 2, 4, 6 °C	–	–	360, 432, 571 801	Clay, loam, and sandy clay loam	Rainfed	32, 64, 96, 128	June 20–Aug 20	Araya et al. (2021b)
Ethiopia	Adigudom and Kulumsa	Barley DSSAT	1980–2019	MS	–	–	–	–	Clay, loam, and sandy clay loam	Rainfed and tied ridging	64 kg N/ha and rotation with chickpea	July 20, plt. density: 250 plants/m^2	Araya et al. (2021c)
Ethiopia	Srinka and Kobo	2 sorg. var. DSSAT	1980–2009	MS	20 CIMP5 GCMs	2040–2069 and 2070–2099	4.5 and 8.5	–	Silt loam and clay	Rainfed	–	–	Zewdu et al. (2020)
Ethiopia	Alamata	1 sorg. var. APSIM	1980–2009	MS	1 GCM HadGEM2-ES	2010–2039 2040–2069 and 2070–2099	4.5 and 8.5	–	–	Rainfed	64 kg N/ha	Mar, Apr, May, June	Gebrekiros et al. (2016)
Ethiopia	6 agro-ecologies	1 sorg. DSSAT	1960–1990		HadGEM2_ES	2035, 2055 and 2085	RCP8.5		Grid scale	Rainfed			Thomas et al. (2019)
W. Africa (Nigeria and Mali)	Bamako and Kano	2 sorg. var. APSIM	1980–2009	MERRA	5 CMIP5 GCMs	2010–2039 2040–2069	4.5 and 8.5	360 and 571	–	Rainfed	NPK 60: 30:30	June 14, July 9, and August 5	Akinseye et al. (2020)
Ethiopia	Debrezeit	1 teff var. AquaCrop	1980–2009	MS	5 CMIP5 GCMs	2010–2039 2040–2069	4.5 and 8.5	–		Rainfed	64 kg N/ha	July 18, July 28, Aug 19	Araya et al. (2015b)

CMIP5 coupled model intercomparison project phase 5, *CORDEX* coordinated regional downscaling experiment, *CHIRPS* climate hazards group infrared precipitation with station data, *GCM* global climate model, *MERRA* modern-era retrospective analysis for research and applications, *MS* measured, *Sorg*. sorghum, *var*. variety

15.2.3 Wheat

The impacts of climate change and adaptation strategies for wheat were conducted from site specific to national scale on various soils (clay and sandy clay loam soils) based on climate change scenarios described above for maize (Araya et al. 2020a, b). While only one wheat variety was used when conducting national-scale studies, three wheat varieties (early-, medium-, and late-maturing varieties) were evaluated at two selected locations (Araya et al. 2017, 2020b). Separate studies were conducted using either DSSAT or APSIM model. The future climate data for 21 locations was extracted based on methods described for maize. Climate change adaptation strategies that include three irrigation rates (0, 60, and 150 mm) and four N fertilizer rates (64, 96, 128, and 160 kg N/ha) under elevated and baseline carbon dioxide (CO_2) scenarios were evaluated as presented for maize (Table 15.1). Furthermore, responses of three wheat varieties to various combinations of elevated temperatures (1, 2, 3, 4, 5, and 6 °C), changed rainfall (−20% and +20%), N rates (32, 64, 96, and 128 kg N/ha), plant densities (100, 200, and 300 plants m^{-2}), and CO_2 levels (360, 432, 571, and 801 μmol mol^{-1}) were evaluated (Table 15.1). The results of the combination of these factors were extracted, discussed, and summarized.

15.2.4 Barley

Climate change impact assessment and adaptation strategies for barley were conducted in Northern Ethiopia for two selected locations (Araya et al. 2021b). The main study was conducted using DSSAT model. Climate data from three GCMs ensembles were extracted for the midcentury period (under elevated CO_2 (RCP8.5; 571 μmol mol^{-1})) and entered into the crop model (Table 15.1). In addition, sensitivity analysis was carried out to understand the response of barley to the combination of climatic factors such as elevated temperatures (baseline temperature +1, 2, 4, and 6 °C), CO_2 (360, 432, 571, and 801 μmol mol^{-1}), different N rates (32, 64, 96, and 128 kg N/ha), and soil types (clay, loam, and sandy clay loam). In a separate study, the impact of tied ridging and different crop rotations with wheat and chickpea (*Cicer arietinum*) (wheat-barley, wheat-chickpea-barley, chickpea-barley) in improving barley yield was evaluated as a climate change adaptation strategy in Northern Ethiopia (Araya et al. 2021c). Furthermore, information on optimal planting date for barley was also reviewed from Araya et al. (2012), Gessesse and Araya (2015), and Araya et al. (2021c). The results of the impacts of climate change and agronomic management practices for reducing the negative impacts of climate change on barley yield were reanalyzed, extracted, discussed, and summarized.

15.2.5 Sorghum

Climate change impact assessment reports were reviewed for Ethiopian sorghum from Gebrekiros et al. (2016), Thomas et al. (2019), and Zewdu et al. (2020). These authors used different GCMs and crop models such as APSIM and DSSAT to conduct the simulation studies at different temporal and spatial scales. Zewdu et al. (2020) used 20 GCMs under RCP4.5 and RCP8.5 for the periods 2040–2069 and 2070–2099. The climate data was entered in DSSAT, and climate change impact results were generated for two sorghum cultivars at two locations in Northern Ethiopia (Table 15.1). Gebrekiros et al. (2016) used APSIM model, and descriptions of treatments and scenarios are presented in Table 15.1. Similarly, information on the contribution of N fertilization, planting date, and irrigation in reducing climatic risk on sorghum yield was reviewed and summarized based on information presented in Hegano et al. (2016), Shamme et al. (2016), Mebrahtu and Tamiru (2019), Wale et al. (2019), Abera et al. (2020), Kotharia et al. (2020), Mehari et al. (2020), and Getachew et al. (2021).

15.2.6 Teff

The impact of climate change on teff productivity was assessed for major teff-growing area in Central Ethiopia (Debrezeit). The study was conducted using AquaCrop model based on five Coupled Model Intercomparison Project Phase 5 (CMIP5) GCMs under RCP4.5 and RCP8.5 scenarios (Araya et al. 2015b) (Table 15.1). Araya et al. (2015b) evaluated suitable sowing times to reduce drought risks under climate change for the near-term (2010–2039), midterm (2040–2069), and end-term (2070–2099) periods. In addition, information on the impact of management practices such as N fertilizer and irrigation on teff yield was discussed and summarized based on the information presented in Araya et al. (2011, 2019), Haileselassie et al. (2016), and Tsegay et al. (2015).

15.3 Results and Discussion

15.3.1 Maize

Short-maturing maize variety, Melkasa-1, yield decreased by 8.7 to 15% during the midcentury period (Table 15.2 and Fig. 15.1a, b and c). Under rainfed condition, Melkasa-1 yield increased by 168–207 kg/ha^{-1} for every additional 32 kg N above the 64 kg N/ha up to 160 kg N/ha (Fig. 15.1a). Similarly, under irrigated conditions (150 mm), Melkasa-1 produced additional yield gain over the 64 kg N/ha by 248, 213, and 301 kg/ha due to the application of 96, 128, and 160 kg N/ha,

Table 15.2 Comparison of baseline against the future (midcentury) yield for three maize varieties under different N and water management strategies for Ethiopia

		Nitrogen (kg/ha)			
		64	96	128	160
Crop variety	Irrigation treatment	Dev. (%)	Dev. (%)	Dev. (%)	Dev. (%)
Melkasa-1	Rainfed	−8.7	−8.9	−8.0	−11.2
	60 mm	−7.6	−9.9	−12.3	−11.0
	150 mm	−7.4	−7.5	−12.3	−14.9
	Rainfed	20.0	16.0	13.1	10.9
BH−660	60 mm	10.9	10.0	5.0	7.6
	150 mm	6.2	7.7	4.0	2.4
	Rainfed	8.0	1.3	−5.8	−5.8
BH−540	60 mm	−0.4	−3.9	−7.0	−9.7
	150 mm	0.0	−4.6	−7.4	−13.9

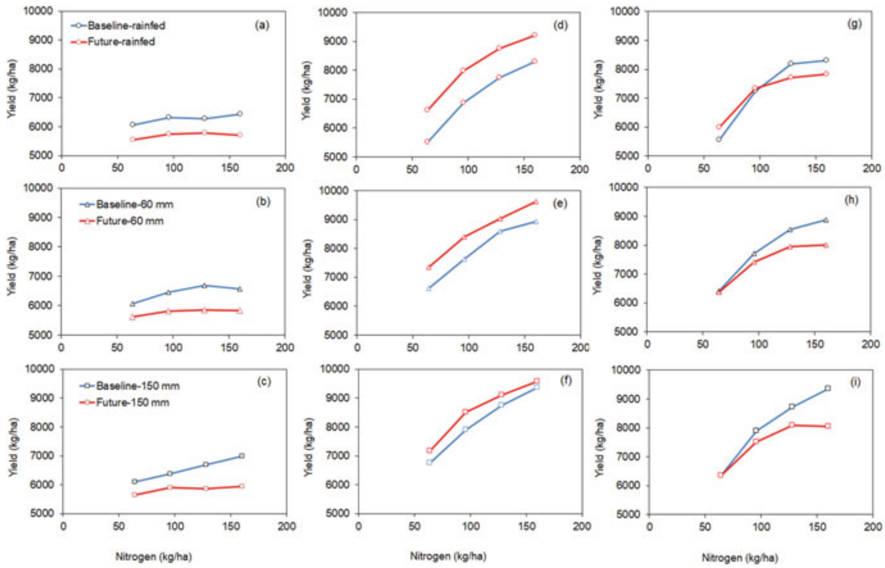

Fig. 15.1 The relationship between maize yield and N fertilizer and irrigation under baseline (1980–2005) and future (2040–2069) climate for (**a**–**c**) Melkasa-1, (**d**–**f**) BH-660, and (**g**–**i**) BH-540 for as averaged for 21 locations in Ethiopia

respectively (Fig. 15.1c). This shows that the increase beyond 64 kg N/ha did not improve maize yield substantially, which implies that Melkasa-1 yield could be optimized with the application of 64 kg N/ha. Araya et al. (2021a) reported the right amount of N rate for Melkasa-1 was 64 kg N/ha. Climate characteristics (Kassie et al. 2014a, b), yielding potential and N use efficiency (Tolessa et al. 2007; Abera et al. 2018), seeding rate (Zeleke et al. 2018), and soil characteristics (USDA, 2014a, b) could affect the N application rate (Araya et al. 2021a). For example, the recommended N fertilizer for dryland rift valley of Ethiopia was less than 64 kg N/ha (Kassie et al. 2014a).

Midcentury maize (variety BH-660) yield increased significantly with the increase in N fertilizer from 64 to 160 kg N/ha (Table 15.1). However, the rate of yield increase was decreasing up to 160 kg N/ha. The increase in maize yield during the midcentury due to the application of 96, 128, and 160 kg N/ha when compared to maize grown (under the rainfed) with 64 kg N/ha generated yield advantages of 1360, 2148, and 2588 kg/ha, respectively. This shows that there was an increase in maize yield by 1360, 788, and 440 kg/ha for each additional application of 32 kg N beyond 64 kg/ha up to 160 kg N/ha (Fig. 15.1d). Similarly, the yield gains with irrigated condition during the midcentury climate could range from 14 to 18.5% (1042–1329 kg/ha) at 92 kg N/ha, 22.8 to 26.8% (1682–1923 kg/ha) at 128 kg N/ha, and 30.8 to 33.4% (2269–2400 kg/ha) at 160 kg N/ha, respectively, relative to their corresponding 64 kg N/ha. The lowest and highest increase corresponded to 60 and 150 mm irrigation water application, respectively (Fig. 15.1e, f). Experimental studies in Ethiopia showed higher yield of maize BH-660 at the rate of 92–115 kg N/ha (Mandefro et al. 2001; Abebe and Feyisa 2017). Similarly, Araya et al. (2021a) reported the application of 128–160 kg N/ha could enhance midcentury maize yield. Considering all these management practices, BH-660 under midcentury climate change increased by up to 20%, compared to the corresponding baseline yield. This shows optimal application of N could be considered as a potential agronomic climate change adaptation strategy for maize in Ethiopia. Thomas et al. (2019) reported that climate change during the midcentury might not significantly decrease the yield of maize in Ethiopia due to the expected increased future rainfall along with improved agronomic practices (e.g., application of N at optimal level).

The yield of the maize variety BH-540 under climate change varied compared to the corresponding baseline. Under midcentury climate scenario, there was an additional increase in maize yield under rainfed condition by 1346, 373, and 117 kg/ha with the increase in N rate from 64 to 96, 96 to 128, and 128 to 160 kg N/ha, respectively (Fig. 15.1g). Similarly, the yield increases for irrigated midcentury maize due to each 32 kg increment in N rate from 64 to 96, 96 to 128, and 128 to 160 kg N/ha were 1168, 561, and −32 kg/ha, respectively. These results portrayed that increasing N beyond 128 kg N/ha has no positive contribution to yield enhancement. Araya et al. (2021a) reported the optimal N application for the variety BH-540 was 128 kg/ha.

Choice of planting time is one of the most important and less costly adaptation strategies for maize crop under climate change. Araya et al. (2021a) showed that the optimal planting date for Melkasa-1 for most part of Ethiopian locations was around May 25 with some exception in the eastern and southern parts such as Jijiga, Harar, A. Minch, and Dilla (Fig. 15.2a), whereas the optimal planting date for BH-660 and BH-540 was around April 25 to May 25 but still with some exception like Dilla, Asela, Jijiga, and A. Minch (Fig. 15.2b). As maize is sensitive to water stress, other reports from Ethiopia showed that planting time could significantly affect maize yield (Balem et al. 2020). This study showed that the choice of planting date could impact maize yield between −13% and 21% for Melkasa-1 and −32% and 21% for

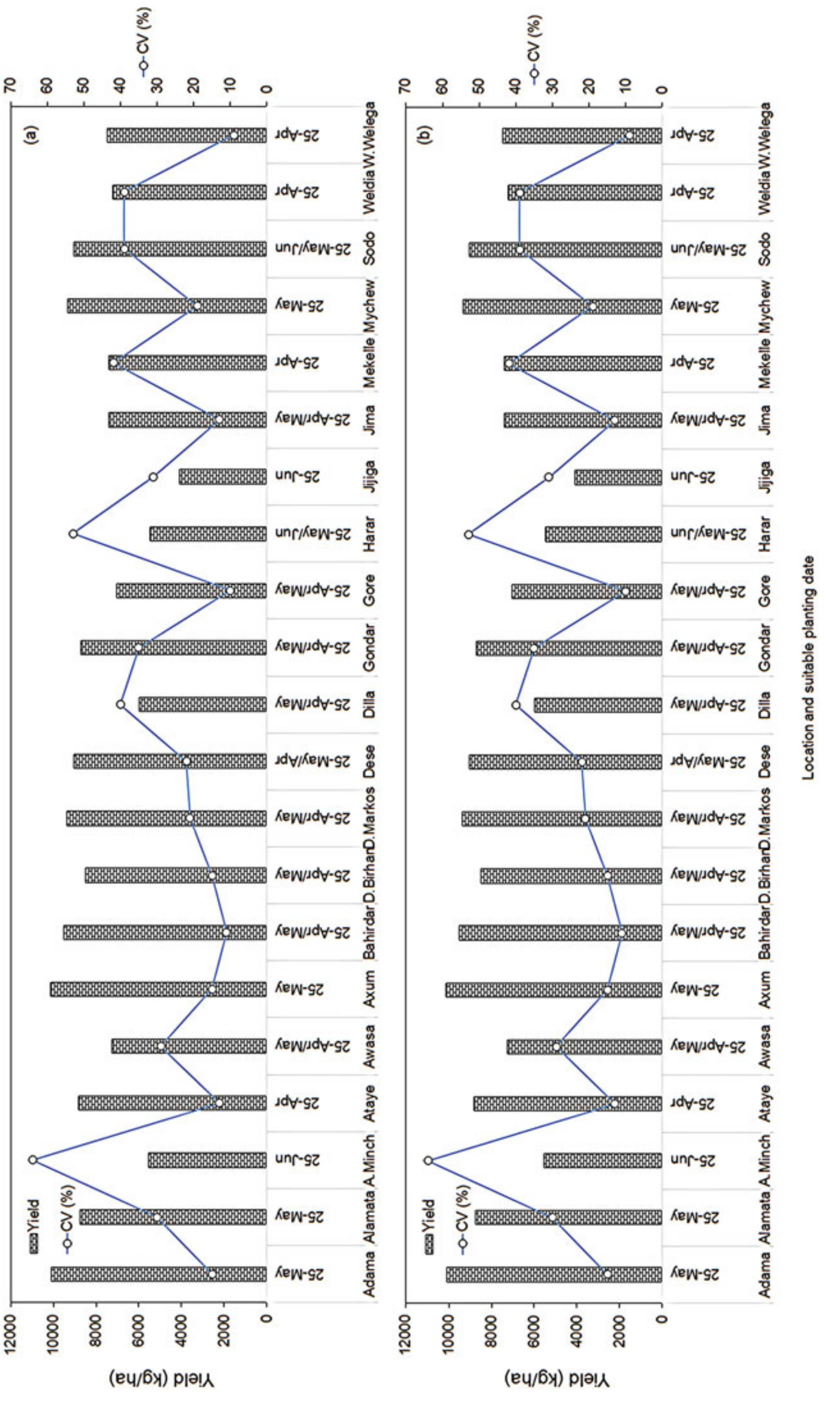

Fig. 15.2 Optimal planting dates selected based on inter-seasonal yield variabilities (CV %) and yield for Melkasa-1 (**a**) and BH-660 (**b**) maize varieties for different Ethiopian locations

BH-660. Dolapo et al. (2019) and Balem et al. (2020) reported the optimal interaction of planting date and fertilizer application could significantly contribute to maize yield improvement and economic benefit.

Irrigation slightly improved cross-location maize yield under both the baseline and climate change scenario. Melkasa-1 maize yield increased by 9 and 4% during the baseline and midcentury period when supplied with 150 mm, respectively. Yield of BH-660 increased by 8–23% and 4–8%, under the baseline and midcentury climate scenario, respectively, when 150 mm irrigation was applied, compared to the corresponding rainfed (Araya et al. 2021a) (Table 15.3). However, the baseline maize performs better under higher irrigation due to relatively longer growing period. Similarly, Araya et al. (2015a) projected a decrease by 9–13% in days to maturity for midcentury maize in southwestern Ethiopia. Days to maturity shortened due to increased temperature would mean grain filling could be shortened, which could have a substantial negative impact on yield especially for those short-maturing varieties like Melkasa-1. In the case of BH-660, yield did not seem to reduce under climate change among other factors because of its relative longer maturity period and increased rainfall. Other similar studies on maize indicated that median maize yield could slightly increase by 1.4–5.5% for the period 2035–2085 relative to 2013 (Thomas et al. 2019). For BH-540, yield increased by 6.6–14.5% due to the application of 150 mm irrigation water during the baseline when compared to the corresponding baseline management (rainfed and 64 kg N/ha), whereas the yield increase for the midcentury maize was between 2.8 and 6% with 150 mm irrigation water (Table 15.3 and Fig. 15.1i). Overall, BH-660 performed best under climate change scenario followed by BH-540 and least was for Melkasa-1. With the use of improved variety, N management, and irrigation practices, there is great potential for enhancing maize yield in Ethiopia during the midcentury period. Although future

Table 15.3 Comparison of rainfed against their corresponding irrigated scenario for the baseline and midcentury maize yield under different N management strategies

		Baseline (1980–2005)				Midcentury (2040–2069)			
		N kg/ha							
		64	96	128	160	64	96	128	160
Crop variety	Irrig. Trt.	Dev. (%)	Dev. (%)	Dev. (%)	Dev. (%)	Dev. (%)	Dev. (%)	Dev. (%)	Dev. (%)
	Rainfed								
Melkasa-1	60 mm	0.0	2.0	7.0	2.0	1.0	1.0	2.0	2.0
	150 mm	1.0	1.0	7.0	9.0	2.0	3.0	2.0	4.0
	Rainfed								
BH-660	60 mm	20.0	11.0	11.0	8.0	11.0	5.0	3.0	5.0
	150 mm	23.0	15.0	13.0	13.0	8.0	7.0	4.0	4.0
	Rainfed								
BH-540	60 mm	15.0	6.0	4.0	7.0	6.0	1.0	3.0	2.0
	150 mm	14.5	8.8	6.6	12.4	6.0	2.4	4.8	2.8

Dev. percent of deviation

rainfall distributions are uncertain, it is anticipated that rainfall in Ethiopia is expected to increase, which might maintain maize yield levels (Thomas et al. 2019).

15.3.2 Wheat

Wheat is sensitive to elevated temperature although most wheat-growing Ethiopian locations are within the optimal range (<21 °C) (Araya et al. 2020a). Some studies showed temperatures beyond 30 °C could reduce yield due to floret sterility (Farooq et al. 2011). Other reports indicated that the reproductive and grain-filling periods of crops are sensitive to high temperatures (Prasad et al. 2008a, 2017 Prasad and Djanaguiraman 2014). Araya et al. (2020b) conducted sensitivity analysis for wheat grown within optimal ranges of temperature and reported an increase in wheat yield by 37% at 432 μmol/mol CO_2 and by 49% at 571 μmol/mol CO_2, compared to baseline CO_2 scenario (360 μmol/mol). On the other hand, assuming baseline CO_2 (360/380 μmol/mol) and increased temperature by 2 °C, wheat yield decreased by 1.7 to 10%, while under elevated CO_2 scenario (571 μmol/mol), wheat yield increased between 3.8 and 7.0% (Araya et al. 2020b). Similarly, some studies showed that median wheat yield in Ethiopia could slightly decrease by 0.3 to 2.7% for the period 2035–2085 relative to 2013 (Thomas et al. 2019). Furthermore, considering an increase in temperature by 4 °C under baseline CO_2 scenario (unchanged CO_2), wheat yield was simulated to decrease by 10 to 28.5%, whereas wheat yield slightly improved (−6.9 to +4.5%) under elevated CO_2 (571 μmol/mol) when compared to baseline yield. The same authors reported an increase in wheat yield in Central Ethiopia during the midcentury by 0.3 to 9.1% under elevated CO_2 with N supply of 64 to 128 kg/ha. Elevated CO_2 might have positive impacts on yield because simulated temperatures are within the optimal range (the optimal temperature for grain-filling period is within the range of 15 to 25 °C; Nuttall et al. 2017), whereas, for locations that are beyond the optimal temperature limit, less beneficial effect of CO_2 was simulated (Araya et al. 2020a). Thus, climate change may not substantially decrease wheat yield during the midcentury period as long as temperatures are not beyond the requirement limit along with optimal management practices and elevated CO_2 scenarios. However, there could be some level of variation among wheat varieties in response to climate change (Sommer et al. 2013). Araya et al. (2020b) studied the response of three wheat varieties (early, medium, and late maturing) to climate change under elevated CO_2 scenario with improved N management (64 to 128 kg N/ha). They reported that the yield of all three varieties slightly varied. However, yield of the varieties remained unchanged or improved (−0.4 to +9%) under near-future, midcentury, and end-century period although the response of the varieties to CO_2 and N slightly differs. For example, under improved management, the yield of an early-, medium-, and late-maturing cultivar slightly increased by 3.4 to 4.3, 0.3 to 9.1, and 1.1 to 3.5% during the midcentury period, respectively (Araya et al. 2020b).

In Ethiopia, wheat-planting date could vary depending on the locations due to difference in climatic (onset of rain) and topographic factors. For example, 75% onset of rain for Adet (northwestern Ethiopia) occurs around mid-June (Abera et al. 2019). Similarly, Gari et al. (2019) reported that farmers in the central highland of Ethiopia plant wheat in early to late June. In contrast, in Northern Ethiopia, planting of wheat is conducted around early to end of July. Therefore, use of location-specific optimal planting date could increase resilience to climatic risks, reduce the impacts of climate change, and improve rainwater use efficiency and yield (Araya et al. 2010, 2011; Araya and Stroosnijder 2011). Adjusting planting date (by matching the water stress-sensitive growth stages with the main rainy season) could help to reduce drought stress, improve water use efficiency, and increase yield (Araya and Stroosnijder 2011).

The response of wheat to N fertilizer could differ by location, water availability, and CO_2 concentration or combinations of the three factors (Fig. 15.3). Araya et al. (2020a) reported most of the locations in Ethiopia showed an increase in yield with increase in N, while some dry locations did not respond well to the increase in N fertilizer. For example, Fig. 15.3 shows a strong linear relationship between yield and N rate. The same authors reported a yield increase of 4.7 kg/ha for every unit increase in N rate (kg/ha) considering rainfed yield at zero N of 2581 kg/ha during the midcentury period under elevated CO_2 scenario (Fig. 15.3). In contrast, for every unit of increase in N rate, there was a wheat yield increase by 5.5% under 60 mm and 6.1% under 150 mm irrigation level (Araya et al. 2020a). The simulated yield levels for zero N under 60 and 150 mm irrigation during the midcentury were 2481 and 2328 kg/ha, respectively (Araya et al. 2020a). Araya et al. (2020b) reported an increase in wheat yield by at least 36% due to increase in N from 64 to 128 kg/ha during the baseline period. Cross-location average yield increased by 16 to 21% due to increased N (160 kg/ha) when compared to 64 kg N/ha (Araya et al. 2020a). Thus, increase in N fertilizer could be considered as an effective and suitable climate change adaptation practice under climate change.

Irrigation did not substantially contribute to cross-location yield increment because of:

(i) Diversity of climate locations, which might have masked the contribution of irrigation. Wheat was responsive to irrigation only in drier locations.
(ii) Improved water use efficiency, photosynthesis, and yield under elevated CO_2 (Hsiao and Jackson 1999).

Figure 15.3 indicated the yield increase due to irrigation is negligible when averaging cross-location yield values although not all locations produced similar level of yield. Araya et al. (2020a) reported irrigation improves wheat yield for drier areas (locations), but the impacts of irrigation were limited when averaged across the locations because most of them receive adequate rainfall for growing wheat. Simulation studies in Central Ethiopia showed that a decrease in rainfall by 20% under elevated temperature (2 °C) and CO_2 (571 μmol/mol) did not reduce yield (Araya et al. 2020b). This could be due to the positive effect of CO_2 on enhancing water use efficiency during drought years (Leakey et al. 2006; Kimball 2016).

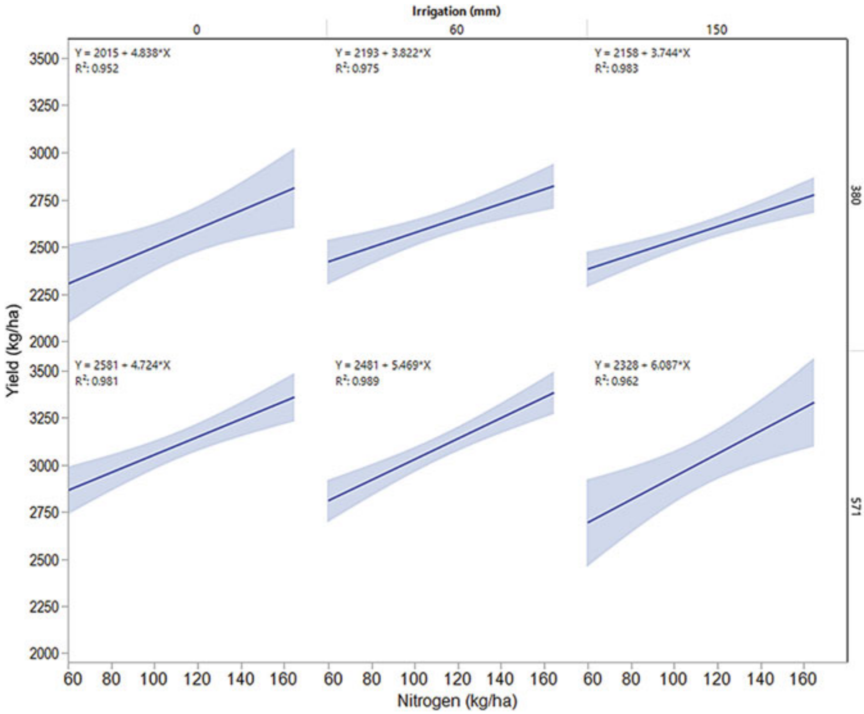

Fig. 15.3 Wheat yield as affected by N fertilizer, CO_2, and irrigation under future climate for elevated and baseline CO_2 in Ethiopia

15.3.3 Barley

Barley is sensitive to temperature changes. An increase in temperature by 2 and 4 °C with baseline CO_2 (360 μmol/mol) could decrease barley yield by 14 to 20% and 29 to 33%, respectively (Araya et al. 2021b). Projections for midcentury based on three global climate model (GCM) ensembles under RCP8.5 showed that barley yield could decrease by 6 to 11% during the midcentury (Araya et al. 2021b) (Table 15.4). Many studies showed that elevated CO_2 under future climate scenarios could benefit C3 crops (like wheat and barley) when temperatures are not beyond the optimal limit (Prasad et al. 2002, 2003, 2005, 2006, 2017; Ainsworth and Long 2021). In conditions where reproductive and grain-filling periods are not limited by high temperatures (heat), elevated CO_2 could increase wheat yield by enhancing N and water use efficiency and stimulating carbon assimilation (Leakey et al. 2006). Kimball (2016) reported that exposure of C3 crops to an elevated CO_2 of 550 μmol/mol could decrease evapotranspiration (10%) and increase yield (19%), compared to a baseline CO_2 scenario of 353 μmol/mol. Ainsworth and Long (2021) reported increased CO_2 by 200 μmol/mol under optimal condition (no stress) could increase yield of C3 crops by 18%, while the yield gain could be limited to 10% under N-deficient conditions or further increase in temperature.

Table 15.4 Summary of impacts of midcentury climate change and management practices on major cereals grown in Ethiopia

Crops	Changes from the baseline	Variety characteristics			Planting date			Irrigation (mm)			N fertilizer (kg/ha)				References
	Percent	Early	Medium	Late	Early	Normal	Late	0	60	150	64	96	128	160	
Maize	(−13 to −8%)	×				×	×	×	×	×	×				Araya et al. (2021a)
	(2.4 to 20%)			×	×	×		×	×	×				×	
	(−14 to +8%)		×			×		×	×	×			×		
Wheat	(4.3 to 6.2%)	×			×	×		×			×		×		Araya et al. (2020b)
	(0.3 to 5.2%)		×		×	×		×			×		×	×	
	(1.1 to 5.9%)			×	×	×		×			×		×		
Barley	(−11 to −6%)	×			×	×	×	×	×	×	×				Araya et al. (2021b)
Sorghum	(−9.1 to −3.4)		×		×			×			×				Gebrekiros et al. (2016)
	(−22 to −10%)		×			×		×			×				
	(−6 to 1.4%)	×	×	×		×									Thomas et al. (2019)
Sorghum	(−4 to 5%)	×			×			×			×				Zewdu et al. (2020)
	(−6 to 2%)	×			×			×			×				
Teff	(2 to 5%)		×		×			×			×				Araya et al. (2015b)
	(−8 to −6%)		×			×		×			×				

The dry planting (sowing in dry soil before the start of rain) practice of barley in Northern Ethiopia is one of the traditional practices used for coping with drought (Araya et al. 2012). However, dry planting (that occurs around June 20–25) technique increases the prevalence of weeds as weed seeds emerge faster than barley. Araya et al. (2012) reported early planting after the emergence of weeds would be the best strategy for farmers in the Northern Ethiopia in order to kill weeds, reduce risk of sowing failure (false start), and increase barley rainwater use efficiency and yield. Araya et al. (2021b) showed that the start of barley planting in northern semi-arid Ethiopia could slightly vary by soil type with earlier (July 1) and later (July 20) planting for coarse- and fine-textured soils, respectively. Similarly, Araya et al. (2010) reported planting of barley around July 4–12 in Northern Ethiopia improves water use efficiency and yield. Barley yield improved with early planting, although there are possibilities of sowing failure (false start) occurs by up to 20% (Araya et al. 2012). Similarly, Araya et al. (2021b) projected a decline in barley yield during the midcentury by 20 to 25% assuming unchanged (baseline) CO_2 scenario. Kebebe et al. (2019) studied the impact of midcentury climate change on barley yield (in Lemu Bilbilo district of Oromia region in Ethiopia) and reported a yield decline by at least by 13.8 and 5.8% under RCP4.5 and RCP8.5, respectively. Silungwe et al. (2018) highlighted that sowing date strategies and fertilizer application (micro-dose fertilization) are suitable practices for enhancing food security under rainfed condition.

The optimal N fertilizer for barley can vary with soil types. Araya et al. (2021b) reported that the optimal N fertilizer in Northern Ethiopia was 64 kg N/ha for coarse- and 32 kg N/ha for fine- and medium-textured soils. Nitrogen fertilizer management along with the inclusion of legumes in rotations could be considered as an adaptation crop management strategy for adding N to the system via N fixation in legumes and enhancing barley yield under climate change. For example, barley rotations after chickpea were reported to enhance barley yield due to N addition (Araya et al. 2021c).

Irrigation needs of crops depend on climate condition, crop type, growth stage, and soil factors (Doorenbos and Pruitt 1977; Doorenbos and Kassam 1979; Allen et al. 1998; Araya et al. 2011). Barley in Northern Ethiopia is moderately affected by irrigation. Araya et al. (2010) reported that full irrigation did not significantly change the barley yield when compared to the control. However, the irrigation needs depend on the distribution of the rainfall at the location during the season. Ararssa et al. (2019) reported a decrease in yield with increase in irrigation. They reported that some level of water stress of about 20% less than full irrigation might be beneficial for enhancing barley yield. In Northern Ethiopia, more irrigations are needed with delayed planting because of the short rainy season (Araya and Stroosnijder 2011). Similarly, other reports also showed that delayed planting could lead to increased relying of the crop on irrigation (Carter and Stoke 1985).

Tied ridging conserves the rainwater and improves soil water storage throughout the growing season (Wiyo et al. 2000; Araya and Stroosnijder 2010; Biazin and Stroosnijder 2012; Silungwe et al. 2018). Tied ridging improved soil water by more than 13 and 44%, respectively, when compared to the control (Araya and

Stroosnijder 2010). Tied ridge prolongs the retention of soil moisture, enhances nutrient uptake by crops, and provides suitable environment to crops especially in areas where there are agrometeorological challenges such as temporal and spatial rainfall variability (Silungwe et al. 2018). Okeyoa et al. (2014) evaluate the impact of mulching, tied ridging and minimum tillage on maize yield in Central Highlands of Kenya proved the importance of mulching and tied ridging for increasing yield and reducing runoff and improving soil water. The same authors reported that during short rains in 2011, tied ridging and mulching increased maize grain yields by 94 and 75%, respectively, compared with control. However, tied ridging might have negative impact in places where there is good supply of water and where soils are dominated by clay with shallow characteristics due to sensitivity of barley to water logging (aeration stress) (Araya et al. 2021c).

15.3.4 Sorghum

Sorghum as one of the major crops in Ethiopia is projected to be impacted by climate change. Zewdu et al. (2020) conducted simulation study on the impact of climate change on sorghum yield using CERES-sorghum for two sorghum varieties at two locations (Kobo and Srinka) in Northern Ethiopia. They reported a decrease by 4 to 6% for Kobo area whereas an increase by 2 to 5% for Srinka area during the midcentury under RCP8.5 (Zewdu et al. 2020). Under midcentury RCP4.5, sorghum yield decreases by 5 and 2% for Kobo and Srinka locations, respectively. The two varieties slightly varied in terms of yield performance under climate change (Zewdu et al. 2020) (Table 15.4). Similarly, Misganaw and Mohammed (2021) reported an increase in yield for early- and late-maturing sorghum varieties during the midcentury climate scenario. Summary of impacts of midcentury climate change and management practices on major cereals grown in Ethiopia is presented in Table 15.4. Akinseye et al. (2020) reported that sorghum yield declines by 4.8 and 6.2% at Bamako and Kano for early-maturing sorghum variety, respectively, and an increase by 12.3% at Bamako and 2% at Kano for medium-maturing varieties during the midcentury period. As described in sections above, increased temperatures might have contributed to the decrease in yield. Upper threshold temperature limit for crops might vary depending on crop type and crop growth stage. The optimal temperature for the time of flowering period is in the range of 25 to 28 °C (Prasad et al. 2006, 2008b, 2015, 2017). However, short time exposure to high temperature above 31 °C could significantly decrease pollen and floret fertility (Prasad et al. 2006, 2008b, 2015; Prasad and Djanaguiraman 2011). Negative effects of elevated temperatures could include decreased floret fertility, increased pollen sterility, decreased seed set, and reduced grain number (Prasad et al. 2008b, 2015; Djanaguiraman et al. 2014, 2018; Prasad and Djanaguiraman 2011). In addition, yield reduction could also be attributed to shortening growing period (Hasanuzzaman et al. 2013; Hatfield and Prueger 2015).

In Northern Ethiopia, use of optimal planting time and varietal choice are keys to successful sorghum production. Gebrekiros et al. (2016) studied the impact of climate change on sorghum yield at one of the locations (Alamata) in Northern Ethiopia. They reported that sorghum yield during the midcentury climate could decline more when planted late relative to the baseline scenario. Gebrekiros et al. (2016) concluded that April and March planting could be used to reduce the negative impact of climate change on sorghum yield during the midcentury period. Eggen et al. (2019) reported change in the onset of rain under future climate could decrease Ethiopian sorghum yield. Early planting and irrigation were found to increase sorghum yield under future climate in semi-arid regions of Ethiopia (Kobo and Meisso; Getachew et al. 2021). However, there might be some difference in planting date depending on cultivar/variety characteristics. For example, Akinseye et al. (2020) reported that use of optimal planting date could reduce yield loss although may vary by variety and location.

A study in Northern Ethiopia showed that sorghum gives the highest yield when 69 kg N/ha was applied in three split applications each receiving 1/3 at sowing, 1/3 at mid-vegetative, and 1/3 at booting (Abera et al. 2020). Shamme et al. (2016) conducted field experiments in Western Ethiopia and reported that N rate of 92 kg/ha was optimal for sorghum production. Simulation studies showed that sorghum responds well to N application of 69 kg N/ha in Senegal although the response differs by climate condition (Araya et al. under review). Other studies also showed that N rate of 46 kg/ha could result in high yield (Hegano et al. 2016).

In Northern Ethiopia, flood irrigation is used to reduce drought risk during vegetative and mid-growth stages in sorghum (Mebrahtu and Tamiru 2019; Wale et al. 2019; Mehari et al. 2020). These studies showed that irrigated sorghum produces higher yield compared to those in non-irrigated fields. Climate change adaptation strategies for sorghum might vary by agro-ecology and cultivar characteristics (Akinseye et al. 2020). In dryland Raya and Wag Hemra areas of Northern Ethiopia, supplementary irrigation has been used as an effective way for enhancing yield of sorghum (Mebrahtu and Tamiru 2019; Wale et al. 2019; Mehari et al. 2020). Kotharia et al. (2020) reported that irrigation requirement for sorghum decreases under climate change due to the shortening of the growing period. This decrease in growing period could contribute to reduce the assimilate gains due to the shortening of the grain-filling period. In semi-arid Cameron, sorghum yield could reduce by rainfall variability and drought (Abou et al. (2021). In addition, drought tolerance and heat tolerance and yield-enhancing traits were identified as the most important traits for climate change adaptation in sorghum (Singh et al. 2014; Kotharia et al. 2020). Low income, small farm size, poor access to yield-enhancing factors (e.g., irrigation and improved varieties), and other socioeconomic factors contributed to their vulnerability. Climate change adaptation strategies for sorghum should include the improvement of socioeconomic conditions (Abou et al. 2021).

15.3.5 Teff

Climate change could reduce teff yield during the midcentury if suitable adaptation measures are not implemented (Araya et al. 2015b). Suitability studies under climate change for teff were presented by Yumbya et al. (2014) and Zewudie et al. (2021). Studies showed that teff distribution under future climate is expected to increase in some areas while could decrease in other areas of Ethiopia (Zewudie et al. 2021). By the midcentury, teff area in Ethiopia is projected to decrease by 24% mainly due to climate change (Yumbya, et al. 2014). Many of the warmer areas in Ethiopia are projected to be lost as unsuitable for teff (Zewudie et al. 2021). Zewudie et al. (2021) reported that temperature, precipitation, and slope are land suitability determining factors for teff under future climate. For example, in Northern Ethiopia, teff production has been limited by climate variability (Araya and Stroosnijder 2011). Studies on other grain crops showed that increased temperatures and water stress are expected to affect crop development and yield under current and future climates (Prasad et al. 2008a, 2017; Prasad and Djanaguiraman 2014; Hatfield and Prueger 2015).

Studies showed that teff is sensitive to sowing date strategies under the present and climate change scenarios (Araya et al. 2015b). Teff responded well to early sowing mainly due to the matching of the critical stages of teff with the length of rainy period (Araya et al. 2015b) (Table 15.4). According to Araya et al. (2015b), teff yield during the midcentury could decline by up to 9% when normal sowing time is used, while no yield decline was simulated for teff sown early in the season (Table 15.4). Similarly, Haileselassie et al. (2016) reported early sowing was found to reduce irrigation application, enhance water use efficiency, and improve yield. Early sowing of teff without irrigation could yield as high as late sown teff that received four irrigations (from flowering to maturity period). If normal planting has to be used, one irrigation at the time of flowering could yield as high as that which received four irrigations for late sown teff (Haileselassie et al. 2016). Overall, this indicates that use of optimal sowing time in teff could be considered as an adaptation management strategy under future climate.

Similarly, use of optimal plant density is key for enhancing yield. Mengie et al. (2021) reported optimal plant density could contribute to yield enhancement. The same authors reported seed rate of 5 kg/ha in row and broadcasting sowing method yielded 2300 and 2160 kg/ha, respectively, which is higher than the other seeding rates tested in their experiment (Mengie et al. 2021). This shows use of optimal seeding rate could be considered as a yield-enhancing strategy for teff under climate change.

Araya et al. (2011) presented teff crop coefficient and irrigation water requirement. Teff studies in semi-arid Ethiopia suggested that (i) teff's early seedling establishment requires moist/wet topsoil, (ii) teff is likely to give significantly higher grain yield when a nearly optimal water supply is provided, and (iii) teff can tolerate moderate water stress, but yield and biomass could reduce under severe water stress (Araya et al. 2011). Tsegay et al. (2015) reported optimal sowing of teff with one irrigation at flowering along with optimal N fertilizer could help to achieve stable yield in Northern Ethiopia. Applied irrigation should match with N fertilizer supply. For example, applying irrigation without adequate supply of N or vice versa may not enhance yield (Araya et al. 2019).

Nitrogen fertilizer application of up to 64 and 32 kg N/ha improved teff yield by up to 91 and 42%, respectively, compared to teff without N fertilizer (Haileselassie et al. 2016). Teff yield could improve by up to 119% with optimal N fertilizer application rate and irrigation management compared to that without irrigation and N fertilizer (Haileselassie et al. 2016). Araya et al. (2019) reported N fertilizer application rate of 64 kg/ha could be optimal under adequate water supply; however, increasing N fertilizer beyond this level may cause lodging. In addition, increasing N fertilizer application rate without adequate water supply has little yield benefit (Araya et al. 2019).

15.4 Conclusions

Under climate change, maize yield could reduce due to the shortening of the grain-filling period. Although temperature has increased during the midcentury relative to the baseline, it is not beyond the optimal limit of the required for the growth and development of maize for most highlands of Ethiopia. Use of optimal planting date, application of N fertilizer, and irrigation contributed to yield increment under future climate. Different varieties of maize in Ethiopia responded differently to climate change. Melkasa-1, BH-660, and BH-540 yield changed by −13 to -8%, +3 to +13%, and −10 to +4%, respectively, compared to their corresponding baseline yield with the same management.

Wheat yield in highlands of Ethiopia is expected to slightly increase by up to 6% during the midcentury. Optimal N management is an effective climate adaptation practice. However, drier locations were less responsive to N but were more responsive to irrigation. There was an increase in wheat yield by 4.7 kg/ha for every unit increase in N rate (kg/ha) considering rainfed yield at zero N of 2581 kg/ha during the midcentury period (under elevated CO_2 scenario). The rate of increase did not change substantially when irrigation of 150 mm was applied. This indicates that N substantially improved wheat yield when average cross-location was considered, while irrigation did not substantially improve wheat yield. Only drier locations were responsive to irrigation.

Some of the major sources of barley yield losses in Northern Ethiopia during the baseline scenario were associated with use of inappropriate planting date and N rates. Barley yield during the midcentury could decline by 6 to 11% when compared to the corresponding baseline yield. Use of optimal planting date, N, crop rotation, and tied ridging along with elevated CO_2 scenario were beneficial for growing barley under the midcentury climate. Tied ridging could minimize drought risks under the present and future climate change through improving soil water availability in the root zone, enhanced barley yields, and increased rainwater use efficiency. In addition, the inclusion of legumes like chickpea could enhance the biological fixation of N, which could be beneficial for resource-poor farmers in Ethiopia under future climate.

The use of optimal planting date and N fertilizer management are among the best management strategies for reducing the impact of climate change on sorghum yield. Many studies showed N rate of 46 to 92 kg/ha was suitable for enhancing sorghum yield depending on water availability. Studies showed sorghum yield in Northern Ethiopia could reduce due to midcentury climate change by up to 9.1% for March, up to 12.2% for April, or up to 22.2% for May planting. Thus, use of optimal planting time and N fertilizer could be considered as an adaptation strategy for sorghum in Ethiopia.

Teff yield could decline due to climate change during the midcentury period by up to 12%. Rainfall distribution and amount play substantial role on yield performance of teff during the midcentury period. Studies showed that teff yield losses could be minimized by using early planting strategies. Elevated CO_2 also improved teff yield probably due to improved water use efficiency, resulting from reduced transpiration (limited stomatal conductance under elevated CO_2).

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Chapter 16
Strategies for Mitigating Greenhouse Gas Emissions from Agricultural Ecosystems

H. Singh, P. V. V. Prasad, B. K. Northup, I. A. Ciampitti, and C. W. Rice

Abstract Climate change, driven by rising greenhouse gas (GHG) concentrations in the atmosphere, poses serious and wide-ranging threats to human societies and natural ecosystems all over the world. Agriculture and forestry account for roughly one-third of global emissions, including 9 to 14% of GHGs from crop and livestock activities. Due to increasing demand based on human population and income growth and dietary change, GHG emissions are likely to increase by about 76% by 2050 relative to the levels in 1995. Nitrous oxide (N_2O) and methane (CH_4) are the major GHGs contributed from the agricultural sector, contributing 50 and 70%, respectively, to the total levels. However, carbon dioxide (CO_2) emissions are mainly contributed by a change in land use patterns and decomposition of organic materials. Global emission pathways that would limit warming to 1.5 °C or less, in line with the Paris Agreement's temperature goal, depend on significant reductions in agricultural GHGs (N_2O and CH_4) as well as net zero CO_2 emissions from fossil fuels. As the agricultural sector mainly contributes to N_2O and CH_4, 4.8 Gt CO_2-eq reduction in direct global agricultural non-CO_2 emissions below baseline by 2050 is needed. These ambitious targets of mitigation pathways present an enormous challenge, and accomplishment of these goals is only possible by the implementation of effective GHG mitigation strategies to the agricultural sector. Mitigation measures in the agricultural sector include increasing C sequestration as well as reduction in the GHGs from livestock and agricultural processes. In this chapter, we discussed mitigation strategies for GHG emissions from the agricultural sector at the global scale.

Keywords Agricultural systems · Carbon sequestration · Climate change · Ecosystems · Greenhouse gas · Livestock

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16.1 Introduction

Over the last several decades, an increase in agricultural GHG emissions has been reported, along with the growing global agricultural production. Agriculture and forestry, which together account for roughly one-third of global emissions, have received much attention in recent years. According to the Intergovernmental Panel on Climate Change (IPCC 2014), the agricultural sector is the second highest GHG contributor after electricity and heat production sector, with this last sector contributing about 24% of the global GHG emissions. However, crop and livestock production are expected to increase by 48% and 80% by 2050, respectively, as the human population grows and shifts toward a more animal-based diet (Bennetzen et al. 2016). Thereby, this scenario for increasing crop and livestock production poses the risk to increase by 76% in agricultural GHG emissions by 2050 relative to 1995 (Popp et al. 2010). The global trends in total GHG emissions from agriculture, forestry, and other land use activities between 1970 and 2010 are presented in Fig. 16.1 (Smith et al. 2014). According to GlobAgri-WRR model, it is projected that GHG from the agricultural sector alone would fill about 70% of the allowable "emissions budget" in 2050 (15 of 21 Gt), leaving almost no space for emissions from other economic sectors and making the achievement of even the 2 °C target

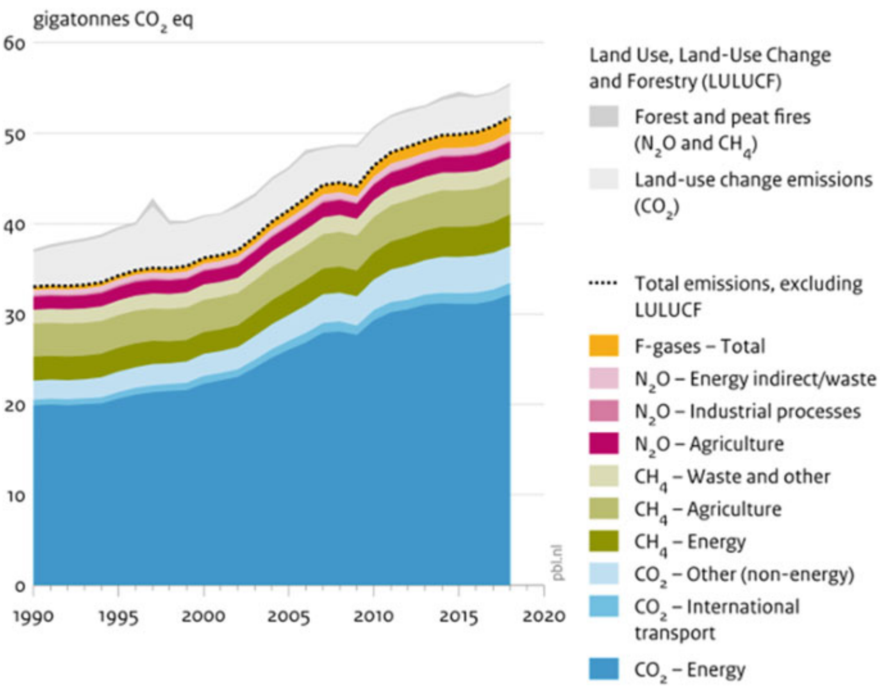

Fig. 16.1 Global trends in total GHG emissions from agriculture, forestry, and other land use activities between 1990 and 2018. (Adapted from Olivier and Peters 2020)

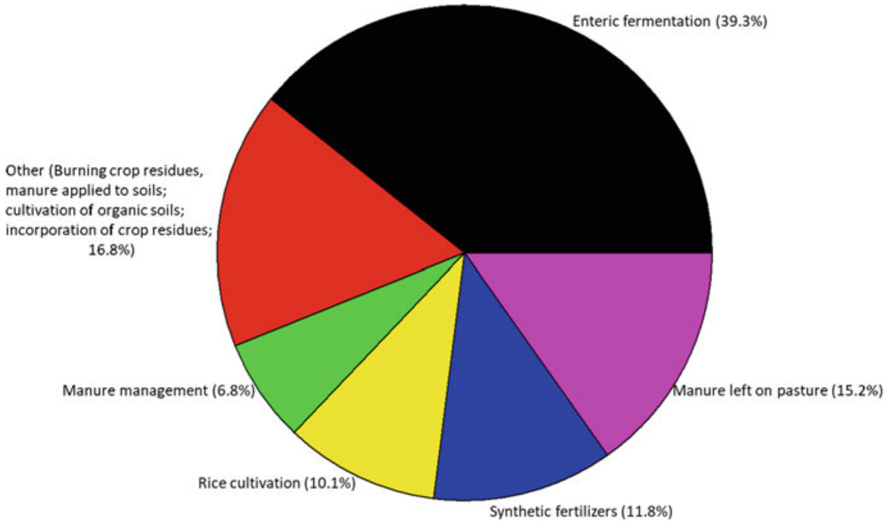

Fig. 16.2 Different sources responsible for these agricultural GHG emissions and their percent contribution. (Source: Data adapted from FAO)

impossible (Searchinger et al. 2018). Agricultural lands have a significant impact on the earth's C and nitrogen (N) cycles due to their large size and intensive management, and agricultural activities result in releases of all three GHGs. The land use changes mainly result in the emission of CO_2, while agricultural management practices are the major contributor to N_2O (50%) and CH_4 (70%) emissions of the total anthropogenic emissions of these gases. Both are potent GHGs: N_2O has a global warming potential 296 times that of CO_2, and CH_4 has a global warming potential 23 times that of CO_2. The different sources responsible for these agricultural GHG emissions and their percent contribution are listed in Fig. 16.2 (FAO 2010).

These agricultural GHG emissions can be divided into two categories based on their production: (i) crops and (ii) livestock. The sectors are interlinked as some crops are grown for animal feed, while at the same time, the animal manure can be used as fertilizer for crops. Thereby, the allocation of the emissions to these categories is complicated and depends on accounting methodologies. Agricultural activities are the main source of the global N_2O emissions, with the share of almost 65%. For the livestock category, animal dung and urine on pastures, rangeland, and paddocks are the largest global source of N_2O emissions, accounting for 23% of the total N_2O and 4% of the total N_2O from manure management. For the crop category, synthetic N fertilizer use is the largest source, accounting for 13% of the total N_2O emissions, followed by the 11% share from decomposition of crop residues. Additionally, manure management accounts for 9% of the total N_2O emissions. Therefore, all these sources account for 74% of global N_2O emissions, with 32% share from livestock, 24% share from the crop, and 18% share from fossil fuel combustion (Fig. 16.3). Additionally, indirect N_2O emissions from agricultural activities account for another 9% of the total N_2O emissions (Fig. 16.3) (Olivier and

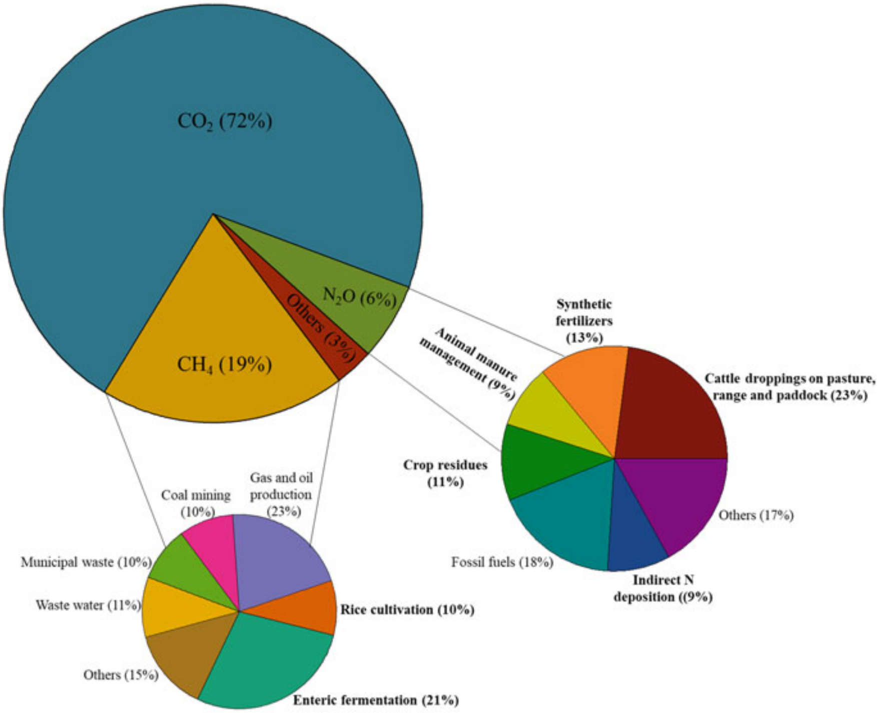

Fig. 16.3 Key drivers of nitrous oxide (N_2O) and methane (CH_4) emissions from the agricultural sector. Sections with bold letters represent agricultural sources. (Data adapted from Olivier and Peters 2020)

Peters 2020). Similarly, enteric fermentation from ruminants and rice production in flooded conditions contributes to CH_4 emissions for the livestock and crop, respectively. Cattle alone are responsible for 21% of current global CH_4 emissions, accounting for 75% of all ruminant-related CH_4 emissions (31%), followed by buffalo, sheep, and goats that have contributions of about 10%, 7%, and 5%, respectively. Rice cultivation on flooded rice fields accounts for 10% of CH_4 emissions due to the anaerobic decomposition of organic material resulting in the production of CH_4 (Fig. 16.3) (Olivier and Peters 2020). However, the CO_2 emissions are mainly derived from land use changes such as clearing of forests for agricultural development. The conversion of soil carbon (C) to CO_2 by soil microbes is accelerated in response to cultivation and growing annual crops (Verge et al. 2007). However, after few decades of soil cultivation, the soil C content is stabilized at low levels and loss as CO_2 decrease (Hutchinson et al. 2007). In addition, the use of fossil fuels for farming operations is also a source of CO_2 emissions in agriculture (Dyer and Desjardins 2003). Other sources of CO_2 emissions from agricultural lands include (a) transformations between croplands and pasture; (b) peat drainage and burning; (c) wood harvesting; (d) regrowth of forest and other natural vegetation after agricultural abandonment and harvest; and (e) soil CO_2 flux due to grassland and cropland management (Hansis et al. 2015; Houghton and Nassikas 2017; Gasser et al. 2020).

Global N_2O emissions were reported to increase to 1.1% in 2019 to a total of 2.8 $GtCO_2$-eq, similar to the annual average reported since 2014, when growth rates ranged between 0.8 and 1.3%. The different sources that were the main role players for the increase in N_2O emissions in 2019 were application of synthetic N fertilizers (+2.7%); manure deposited in pastures, rangeland, and paddocks (+1.3%); indirect N_2O from agriculture (+2.1%); and other agricultural sources (+1.1%), accounting for more than 75% of the total net increase in N_2O emissions. The countries with the largest increase in N_2O emissions in 2019 were Brazil (+2.9%), Australia (+5.9%), China (+0.9%), India (+1.6%), and the Russian Federation (+2.1%), whereas the countries with decreased N_2O emissions in 2019 were Sudan, Zaire, the Central African Republic, and the United States. Similarly, global CH_4 emissions were reported to increase at 1.3% to a total of 9.8 $GtCO_2$-eq, which was lower than the 1.8% increase in 2018. This was significantly greater than years 2015 and 2016, with an overall increase of 0.3% and 0.1%, respectively, but similar to the increase reported in years 2012, 2014, and 2017 of around 1.4%, which is also the average annual increase since 2010. Among the different sources of CH_4 emissions, livestock farming (particularly non-dairy cattle) was the second largest contributor after coal production. Among different countries that contributed most to the 1.3% growth were notably China (+2.2%) and the United States (+2.5%), with increases also seen in (in decreasing order of absolute changes) Indonesia, Brazil, the Russian Federation, Pakistan, and India. Notably, decreases were seen in Turkey, Sudan, Canada, Venezuela, Germany, and Zaire.

Global emission pathways that would limit warming to 1.5 °C or less, in line with the Paris Agreement's temperature goal, depend on significant reductions in agricultural GHGs (N_2O and CH_4) as well as net zero CO_2 emissions from fossil fuels (Leahy et al. 2020). Similarly, Wollenberg et al. (2016) also suggested a global target of reducing non-CO_2 emissions from agriculture by 1 Gt CO_2-eq below baseline by 2030 to restrict warming to about 2 °C above pre-industrial levels in 2100. The most magnificent scenarios evaluated by the IPCC (2018), which limit warming to 1.5 °C with limited or no overshoot, reduce global agricultural emissions by 16–41% (interquartile range) in 2050 compared to 2010, whereas baseline emissions increase by 24–54% over the same period. This % reduction equates to 4.8 Gt CO_2-eq in direct global agricultural non-CO_2 emissions below baseline by 2050 (Huppmann et al. 2018; Frank et al. 2019). These ambitious targets of mitigation pathways represent a large challenge, and accomplishing these targets is only possible by the implementation of effective GHG mitigation strategies from the agricultural sector.

As a major source of global emissions, the agricultural sector may also provide relatively low-cost opportunities for GHG mitigation. Agricultural GHG fluxes are complex due to interaction with other factors and variation in fluxes on spatial (varied fluxes at different places on piece of land) and temporal (variation based on time of the day) basis. However, the active management of agricultural systems offers possibilities for GHG mitigation (Smith et al. 2008). Mitigation measures in the agricultural sector include increasing C sequestration and reducing the emissions from both livestock and agricultural processes. There are two ways to achieve mitigation in the agricultural sector, i.e., through supply-side measures and demand-side measures. Supply-side measures include reducing emissions via livestock management, land management, and land use change and increasing C sequestration from afforestation. Demand-side measures include changes in eating habits and reducing food wastes; however, quantitative measures for demand-side measures are more uncertain (Smith et al. 2014). In this chapter, we will discuss mitigation strategies for GHG emissions from the agricultural sector at a global scale.

16.2 Mitigation Opportunities: Increased Sinks and Reduced Emissions

16.2.1 Increasing Carbon Sequestration

According to the recent IPCC reports, even if we can substantially reduce anthropogenic C emissions in the near future, it is necessary to make efforts to sequestering previously emitted C to ensure atmospheric C to safe levels and mitigate climate change (Smith et al. 2014). Carbon sequestration can be defined as a sustained increase in C storage (in soil or plant material or in the sea). Among these sources of C sequestration, the soil's usefulness as a C sink and drawdown solution are essential, based on global estimates of historic C stocks and projections of rising emissions (Lal 2004, 2008). Since more than one-third of the world's arable land is under agriculture (World Bank 2015) and soil C pool (2500 Gt) being 3.3 times the size of the atmospheric pool (760 Gt) and 4.5 times the size of the biotic pool (560 Gt) (Lal 2004), increasing soil C in agricultural systems will be a key component of using soils as a C sink. The C sequestration potential of global soil is estimated between 0.4 and 1.2 Gt C year^{-1} or 5–15% (1 Pg = 1 × 10^{5} g) (Lal 2004). Various crop management techniques have been suggested for increasing C sequestration in soils (Janzen et al. 1998). However, large uncertainties have been reported with quantifying the impact of different crop management techniques on C sequestration and GHG mitigation. Increasing soil C sequestration could potentially remove between 0.79 and 1.54 Gt C year^{-1} from the atmosphere in a feasible manner, recognizing the large potential of soils mitigating CO_2 emissions (Laborde et al. 2021).

Due to the historical expansion of agriculture and pastoralism (Sanderman et al. 2017) and subsequent land use conversion from native ecosystems (e.g., peatlands, forests, grasslands) to arable land, 33% of the soils around the globe have been degraded and have lost much of their soil C (FAO 2019). The average amount of soil organic carbon (SOC) in the top 30 cm of native soil worldwide is about 15 Mg ha^{-1}

(Hutchinson et al. 2007). However, within the first 20 years of cultivation, about 20–30% and 50–75% of this C are lost to the atmosphere as CO_2 in temperate and tropical regions, respectively (Dumanski 2004). However, Lal (2013) reported that prolonged intensive cultivation decreases the soil C stock at the rate of 0.1–1.0% year^{-1}. The extent of C loss ranges from 10 to 30 Mg C ha^{-1}, depending on the soil type and historic land use, which is higher in soils prone to erosion, salinization, and nutrient mining than the C loss from least or undegraded soils (Lal 2013). The historical C losses from global soils are estimated to be 78 ± 12 Pg (Lal 2004; Buragohain et al. 2017). Globally, the soils of Africa are relatively low in soil organic C content with about 58% of soils containing less than 0.5% organic C and only 4% containing more than 2% organic C (Du Preez et al. 2011).

Different management practices reported to increase C sequestration include (i) reduced and zero tillage, (ii) perennial and deep-rooting crops, (iii) more efficient use of organic amendments (animal manure, sewage sludge, cereal straw, compost), (iv) improved rotations, (v) irrigation, (vi) bioenergy crops, (vii) intensification, (viii) including cover crops, and (ix) conversion of arable land to grassland or woodland (Smith 2004). The potential of these management practices for sequestering C is presented in Table 16.1. It has been estimated that implementation of appropriate management practices could help to sequester approximately 0.4–0.8 Pg C year^{-1} (Watson et al. 1996). Similarly, Lal (2010) reported that adopting suitable management practices for C sequestration at agricultural soils and restoring of degraded soils can help in sequestering about 0.6–1.2 Pg C year^{-1} for about 50 years with a cumulative sink capacity of 30–60 Pg. The potential of different management practices in sequestering C and mitigating CO_2 emissions is described below; however, prudent combination of these management practices would result in enhanced C sequestration.

Table 16.1 Carbon sequestration potential by different management practices

Management practice	Soil carbon sequestration potential (t C ha^{-1} year^{-1})
No tillage	0.38
Reduced tillage	<0.38
Set-aside	<0.38
Permanent crops	0.62
Deep-rooting crops	0.62
Animal manure application	0.38
Cereal straw application	0.69
Sewage sludge	0.26
Composting	0.38
Bioenergy crops	0.62
Organic farming	0–0.54
Extensification	0.54

All estimates are adapted from the figures in Smith et al. (2000)

16.2.1.1 Tillage Methods and Residue Management

Conventional tillage can be defined as a plow-based method which includes successive operations of plowing or turning over of soil, whereas conservation tillage is a generic term indicating at tillage methods that reduce runoff and loss of soil by erosion as compared to conventional tillage practices. Conservation tillage practices reported to increase C sequestration by reducing tillage-induced breakdown of soil aggregates resulting in the slowdown of organic matter decomposition relative to the conventional tillage and adding organic matter as residues to the surface soil (Hati et al. 2020). Different tillage practices impact both soil-aggrading and soil-degrading processes, thereby affecting soil C storage (Lal and Kimble 1997) (Fig. 16.4). Soil-aggrading processes have a positive impact on SOC and include the humification of crop residue, increase in resistant or non-labile fraction of SOC, sequestration of SOC in the formation of organo-mineral complexes, and increase in stable aggregation and deep placement of SOC in sub-soil horizons, while soil-degrading processes have a negative impact on SOC and include erosion, leaching, and mineralization. The effect of tillage on soil processes that affect C dynamic and reserves in soils can be observed in Fig. 16.4.

Several studies have reported that conservation tillage practices help in sequestering soil C in both temperate and tropical regions. Conservation tillage increased SOC by about 8% as compared to conventional tillage on an Ultisol in eastern Nigeria (Ohiri and Ezumah 1990). Several studies emphasize that conservation tillage practices have already increased soil C contents relative to levels that would have existed under conventional farming (e.g., moldboard plowing); they have estimated C sequestration rates of 0.31–0.82 Mg C ha^{-1} year^{-1} in the United States and across the world (West and Post 2002; Spargo et al. 2008; Franzluebbers 2010). However, the capability of no tillage for increasing C sequestration is still debatable. Several authors in recent years found that no-till was capable only of increasing the

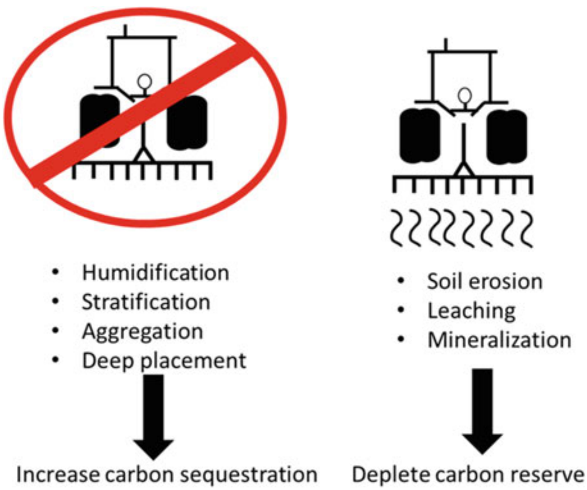

Fig. 16.4 Tillage effects on soil processes that affect C dynamics and reserves in soil

soil C in the top layer of soil, while it was compensated with the greater decrease observed in deeper layers, thereby resulting in no difference among different tillage treatments for the total C in the soil profile. However, long-term experiment results show that switching from plow-till to no-till farming is the most effective factor in crop management for SOC sequestration (Table 16.2). In a recent meta-analysis, Nicoloso and Rice (2021) found that soil C can be increased to a depth of 1 m by the intensification of no-tillage cropping systems which included double cropping, leguminous cover crops.

Crop residue management impacts the SOC dynamics as crop residues are a direct source to SOC pool. Crop residues contain approximately 45% C by dry weight (Lal 1997). Assuming that crop residues contain an average of 45% C and that approximately 15% of residue-derived C is stored as passive C in the soil, aboveground crop residues have a large potential to store SOC in the passive form on a global scale (Lal 1997). The total amount of SOC storage is determined by the quantity and quality of crop residue, plant roots, and other organic material returned to the soil, as well as the rate of their decomposition. Residue retention in combination with reduced-tillage and no-tillage practices is a viable option for increasing SOC storage in soil. In surface soil layers, under no-tillage practices, some of the residue-derived SOC gets converted into passive pool and forms organo-mineral complexes, which takes between 100 and thousands of years for decomposition. SOC accumulates when residue C inputs exceed residue C outputs and soil disturbance is kept to a minimum, while under intensive or conventional tillage practices, the decomposition of crop residues is accelerated due to good aeration, thereby resulting in reduced residue-derived C sequestration. Therefore, no-tillage practices in combination with residue retention help in the formation of the passive SOC pool and are important for long-term C sequestration.

16.2.1.2 Crop Selection and Rotation

Crop rotation refers to a planned sequence of crops grown in a regularly recurring succession on the same area, in contrast to continuous monoculture or growing a variable sequence of crops. Carbon sequestration on agricultural lands can be affected by crop rotations, climates, soils, and management practices. The use of balanced fertilization, application of organic amendments, and similarly application of crop residues in addition to intensive crop rotations can increase C sequestration levels to 5–10 Mg ha^{-1} year^{-1} since those amendments contain 10.7–18% C, which can also be helpful in the sequestration of C (Mandal et al. 2007). Different legume crops, such as peas (*Pisum sativum*), lentils (*Lens culinaris*), alfalfa (*Medicago sativa*), chickpea (*Cicer arietinum*), and sesbania (*Sesbania grandiflora*), can serve as substitute sources for N. Soil structure improvement and increased SOC content in sub-soil horizons are possible by growing deep-rooted plants. Similarly, improvement in SOC content of the sub-soil could improve in response to growing improved pastures in acid savanna soils in South America (Fisher et al. 1994). In West Africa, Lal et al. (1978, 1979) also observed significant positive effects of growing cover

Table 16.2 Impact of adopting no-tillage practices on soil carbon sequestration in different parts of the world

Location	Rotations/soils	Increase in SOC sequestration (kg ha^{-1} $year^{-1}$)	Depth (cm)	Duration (years)	Reference
Brazil (South)	Various rotations	611	30	9	Bayer et al. (2000)
Canada	Average for groups: Gleysolic, brown, dark brown, and black (Century Model prediction)	200	–	10	Desjardins et al. (2005)
Europe	Assessment based on long-term experiments: Europe	387	25	–	Smith et al. (2000)
	United Kingdom	613	25	–	
Spain	Various rotations on Calcic Luvisol	100	30	11	López-Fando and Pardo (2001)
United States:	Various crop rotations on:				
(1) Kansas	Grundy silty clay loam	20	30	15	Havlin et al. (1990)
	Muir silt loam	62	30	15	
(2) Nebraska	Spring wheat-fallow spring	−225	30.4	12	Halvorson et al. (2002)
	Wheat-winter wheat-sunflower	542	30.4	12	
(3) Ohio	Various rotations on clay loam	566	30	30	Dick et al. (1998)
(4) Oregon	Various crops on coarse-silty mixed mesic	94	22.5	44	Rasmussen and Rhode (1988)
	Winter wheat-lentil (*Lens culinaris* Medik.)	587	20	3	Bezdicek et al. (2002)
	Winter wheat-barley with no-till management	166	20	25	
(6) Texas	Continuous corn (4y) followed by continuous cotton (4y) on sandy clay loam	15-20	20	26	Salinas-Garcia et al. (1997)
(7) Miscellaneous regions	39 paired tillage experiments	220	Various depths	5–20	Paustian et al. (1997)
World	Till to no-till 276 paired treatments excluding wheat-fallow treatments	570 ± 140	Various depths	Various time	West and Post (2002)

crops on increase in SOC content. Cover crops help in increasing soil C content only in surface layers; utilizing agroforestry (AF) systems could help in depositing C to deeper layers of soil (Meena et al. 2020; Sarto et al. 2020). The AF consists of mixture of trees, agricultural crops, and livestock to exploit the economic and ecological benefits of agroecosystem. It is a crucial leader of terrestrial C sequestration containing about 12% of the global terrestrial C (Dixon 1995). The roots of forest tress and perennial crops penetrate deeper subsurface horizons, thus placing SOC at deeper horizons far away from the range of tillage implements (Lorenz and Lal 2014). Estimating the C sequestration potential of agroforestry systems under varied ecological and management environments ranged from 0.29 to 15.21 Mg ha^{-1} $year^{-1}$ in aboveground plant biomass and 30 to 300 Mg ha^{-1} $year^{-1}$ in belowground plant parts up to a depth of 1.0 m (Nair et al. 2010). Thereby, the implementation of appropriate crop rotation and utilizing AF can help in sequestering soil C at a rate of 0.15–0.17 Mg C ha^{-1} $year^{-1}$ (Meena et al. 2020).

Bare soil is prone to erosion and nutrient leaching and contains less C than the same field under vegetation. One of the solutions for increasing C sequestration is to plant cover and catch crops that cover the soil between the main crop or in fallow periods. It is estimated that eliminating summer fallow and replacing it with some cover crop would help in sequestering soil C at a rate of approximately 0.05–0.20 Mg C ha^{-1} $year^{-1}$ (Meena et al. 2020). The basic concept of increasing C sequestration on eliminating summer fallow is that it increases soil biomass addition, resulting in increased C deposition. Also, if the soil is left bare (fallow), it is more prone to erosion by wind or water, and as most of the C is deposited in surface layers in croplands, it is more prone to wind and water erosion and decomposition. Soil erosion alone is responsible for the loss of 1.1 Pg C $year^{-1}$ (Meena et al. 2020). Legumes enhance biological diversity, increase N input (via N fixation), and improve crop residue quality and overall soil C flux (Lal 2004). The greater the biodiversity of an ecosystem, the more will be the sequestration capacity. The unique advantage of cover crops over the other management options is that they not only enhance the SOC stock but also reduce the C loss, unlike organic manures. Hence, replacing the fallow period with cover cropping improves the soil quality by enriching SOC through their biomass and promoting soil aggregation and protecting the surface soil from runoff and erosion.

16.2.2 Reducing Nitrous Oxide Emissions

In recent years, there has been a growing interest in the possibility of mitigating climate change by reducing emissions of non-CO_2 GHGs. Agriculture is the largest anthropogenic source of N_2O, one of the most important non-CO_2 GHGs because it is a long-lived GHG (about 114 years) and a major source of NO in the stratosphere (Reay et al. 2012). For the past few decades, the amount of N_2O in the atmosphere has increased almost linearly at approximately 0.7 ppb or 0.26% $year^{-1}$ (Smith 2010). The IPCC (2001) reported that the increased microbial production of N_2O in expanding and fertilized agricultural lands is the main driver of this increase. With a growing human population and the resulting need for more food production, agricultural land area and N_2O emissions are expected to increase in the coming decades. We assume that changes in N cycling in soil systems have influenced increases in atmospheric N_2O over the past century and will help dictate future changes since roughly 70% of the N_2O emitted is derived from soils (Bouwman 1990; Braker and Conrad 2011). Among different continents, Asia is the continent with the largest N_2O emissions, reflecting its large population and agricultural area (Oenema et al. 2014). On a per capita basis, Asia has the lowest estimated N_2O emissions, followed by Africa and Europe. Expressed per surface area of agricultural land, emissions are highest in Asia and Europe and least in Oceania and Africa. The largest source of N_2O emissions in Asia, Europe, and North America is fertilizer N, while manure N from grazing animals is the largest source in Africa, Latin America, and Oceania. Therefore, the main source for N_2O emissions from the agricultural land includes lower efficiency of synthetic N fertilizers applied to croplands and urine and dung excreted by the animals, either in pastures or in confinements (stables, barns, sheds, corrals). In general, management practices that optimize the natural ability of the crop to compete with processes where plant available N is lost from the soil-plant system (i.e., NH_3 volatilization, denitrification, and leaching) and directly lowering the rate and duration of the loss processes can reduce N_2O emissions from synthetic N fertilizers and organic N sources such as crop residue and animal excreta (Doerge et al. 1991). In this section, we have described different management strategies which have the potential for mitigating N_2O emissions from croplands and grazing lands around the world.

16.2.2.1 4R of Fertilizer Management

The major source of N_2O emissions from croplands is the application of N fertilizers. In addition, increasing demands for food around the world would not allow reductions in the usage of N fertilizers to decrease N_2O emissions. Moreover, crop improvement in major crops such as corn (*Zea mays* L.) increases the dependency on N fertilization as yields increase over time (Ciampitti and Vyn 2012). Therefore, the only solution to reduce N_2O emissions from croplands without jeopardizing global food production is to enhance nitrogen use efficiency (NUE) (Ciampitti and Vyn 2014; Singh et al. 2019). The uptake of N fertilizer by crops varies widely across the world, and global cereal NUE is reported to be only 33% (Raun and Johnson 1999). Additionally, the insignificant trend of increase in global cereal NUE from 2002 to 2015 reported by Omara et al. (2019) is a cause of concern. It is estimated that each year, approximately 1.5 Tg of N is lost as N_2O to the atmosphere because of the application of synthetic N fertilizers to agricultural ecosystems (Mosier et al. 1996). This accounted for about 44% of the anthropogenic input and 13% of the total annual N_2O input into the atmosphere. However, the contribution of synthetic N fertilizers to N_2O emissions is still thought to be underestimated. Additionally, N_2O production from other major N sources such as animal manures and biological N fixation has not been included in the abovementioned estimates. To meet the needs of rapidly expanding population, the use of N fertilizers is also projected to increase in the coming years for increasing global food production. Thereby, it is very important to reduce the loss of N fertilizers as N_2O emissions and increase the N use efficiency. This will result in mitigating GHG emissions from different N fertilizers and will be economically beneficial for the producers. The "4R" approach of using the right source, right rate, right timing, and right placement is an accepted framework for reducing loss of N fertilizers as N_2O and increasing crop N use efficiency. Modifying just one of the 4R components may not be enough to reduce N_2O emissions (Decock 2014). Different studies demonstrated that the use of right time alone (delayed and/or split application) (Phillips et al. 2009; Zebarth et al. 2012) or right source (e.g., urea-containing microbial inhibitors) (Parkin and Hatfield 2013; Sistani et al. 2011) has been not very successful in mitigating N_2O emissions. The 4R technique is effective when you have site-, soil-, and crop-specific knowledge and information, accompanied with appropriate technologies and best management practices. It has been reported that implementation of 4R strategy could help in achieving N uptake more than 70% for many cereals (Snyder and Fixen 2012).

While choosing the best fertilizer source may appear to be a simple task, there are several factors that ultimately influence this decision. Selecting an appropriate fertilizer source starts with an assessment of which nutrients are necessary, and this information comes from some form of site diagnostics such as soil testing. The responses of different N fertilizers (nitrate-, ammonium-, or urea-based) to N_2O emissions are very dynamic depending on soil conditions (well-drained or moist conditions), air temperatures, and other climatic conditions. Therefore, there is possibility of decreasing N_2O emissions from N fertilizers and increasing N use efficiency by choosing specific fertilizers for a particular location. Another option for choosing the right source of N fertilizer is the use of "enhanced efficiency fertilizers" instead of conventional fertilizers. Enhanced efficiency fertilizers have been reported to improve N fertilizer use efficiency by increasing the availability of N to crops while reducing N loss to the environment (Snyder 2017; Zhang et al. 2015) including N_2O emissions (Akiyama et al. 2010; Ju et al. 2011). Experiments have shown that these types of fertilizer can decrease N_2O emissions by 35–38% relative to conventional N fertilizer (Akiyama et al. 2010). Bastos et al. (2021) and Arango and Rice (2021) found a 66% reduction in N_2O emissions with a combination of placement and a nitrification inhibitor.

Nitrous oxide emission from N fertilizer application can be reduced by synchronizing with plant N demand. The N uptake during the beginning of the growing season of the crop is lower, increases exponentially during vegetative growth, and drops sharply at crop maturity. Therefore, applying N fertilizer a few weeks after planting rather than at or before planting increases the likelihood that the N will end up in the crop rather than be lost to the atmosphere as N_2O emissions. Soil moisture is the major driver of the N_2O emissions from soil as it regulates the availability of oxygen to microbes. Impacted by different soil types, the maximum N_2O emissions are emitted when soil water-filled pore space ranges from 60 to 90% (Wang et al.

2021; Bastos et al. 2021). Therefore, application of N fertilizer during high soil moisture levels may also help in reducing N_2O emissions. Split N applications to crops result in reduced concentrations of soil mineral N in the early growth stage of crops. Application of the second portion of N during the active growth phase, when N uptake is at maximum, also reduces the potential for N_2O emissions to occur (Van Groenigen et al. 2010). Split application of N was reported as an effective strategy to reduce N_2O emissions from potato cultivation (Burton et al. 2008). In corn production, a single application of N was reported to emit 35% more N_2O compared to split applications (Fernández et al. 2016).

In addition to the right timing, applying N more than the crop requirement increases soil ammonium and nitrate concentrations in soils (Andraski et al. 2000). As a consequence, relatively higher N_2O emissions can occur when compared with applications at the required rate (McSwiney and Robertson 2005; Ma et al. 2010). To know the amount of N fertilizer application, the proper information about the site soil and crop need is required. Stehfest and Bouwman (2006) also reported the rate of N fertilizer application to be the strongest predictor of N_2O emissions in their extensive review of published articles all over the world. Although the reported mean N_2O emission factor is 1.2%, which means for every 100 kg of N input, 1.2 kg of N is lost as N_2O emissions (Albanito et al. 2017), results from a growing number of field experiments indicate that the fraction of applied N emitted as direct N_2O increases with increasing rate of N application (McSwiney and Robertson 2005; Ma et al. 2010; Hoben et al. 2011; Shcherbak et al. 2014; Millar et al. 2018). Therefore, using the single emission factor across the fertilizer rates may result in an underestimation of fertilizer-induced N_2O emissions when fertilizer addition exceeds crop demand.

Right placement of N fertilizer in the soil also helps to reduce N_2O emissions. For example, the application of urea in a narrow band close to plant roots instead of its application by broadcast helps to reduce N_2O emissions. Also, different crops have exhibited different root growing habits and require specific N fertilizer placement method for the enhancement of N use efficiency. For corn, shallow instead of deep placement of N fertilizers is reported to decrease N_2O emissions and increase N use efficiency (Breitenbeck and Bremner 1986). The precision fertilizer application tools are also reported to help reduce N_2O emissions and increase N use efficiency. This is because precision fertilizer application helps to access the spatial variability in the field, recommending less N fertilizer application in areas of the field with low yield potential, thereby helping to avoid N fertilizer wastage on locations in the field that are not likely to respond to N fertilizer application. Precision fertilizer application reduced the average N fertilizer rate by 25 kg N ha^{-1} in one study, resulting in significant reductions in N_2O emissions (Sehy et al. 2003).

16.2.2.2 Grazing and Manure Management

The relative importance of microbial processes that lead to N_2O emissions from animal manures will be determined by the manure environment, which is influenced by local management practices and climate, both of which vary between regions. A large portion of N_2O emissions resulting from manure are produced in manure-amended soils by microbial nitrification under aerobic conditions and partial denitrification under anaerobic conditions, with denitrification producing more N_2O (Hockstad and Hanel 2018). This manure can be deposited by the grazing animals in grassland-based systems or applied manually after collection and storage from confined-animal feeding systems. Under continuous stocking, specific hotspots of mineral N, or higher overall amounts of mineral N, are expected to appear in soils within grazed paddocks or portions of grazed paddocks. This premise is based on the fact that cattle have more opportunity (more time) to congregate in local areas (e.g., water sources, near to borders, shady areas) of paddocks, resulting in less-even N distributions (Singh et al. 2019). It is reported that animals spend 27% of their time and deposit around 49% of all N in consumed biomass to these areas (Augustine et al. 2013). Additionally, N_2O emissions from the pen surfaces of open-lot dairy or beef feedlot facilities can also be significant due to improper handling and storage of the manure (Montes et al. 2013).

For grassland-based systems, changing the form of grazing management and intensity of grazing pressure are among the strategies available to reduce N_2O emissions. Due to the effects on soil compaction and other physical, chemical, and biological properties of soils, higher stocking rates applied to pastures result in higher N_2O emissions from grazing lands. Also, stocking at high rates may result in the consumption of more low-quality forage by animals, which has an impact on both animal performance and greater N_2O emissions (Wang et al. 2015). Thus, the management of stocking density (animal numbers ha^{-1} $year^{-1}$) applied to graze paddocks is an essential practice for mitigating N_2O emissions. Increased N_2O emissions due to increased deposition of manure and urine could be caused by intensive forms of stocking. Further, the anaerobic conditions caused by increased soil compaction in grazing paddocks help to support N_2O emissions from these deposits. Reduced dietary N and increased mineral content of biomass available for grazing are two other ways to reduce N_2O emissions from grazing lands. N excretion in urine is reduced when dietary N is reduced. Additionally, inhibiting nitrification from N hotspots in grazing lands could be a useful strategy for reducing N_2O emissions. Approximately 55% of the total daily N_2O emissions from grazing paddocks is contributed by N hotspots which include urine patches, dung pats, shaded areas, and areas near water troughs (Cowan et al. 2015). The primary source of significant emissions from these hotspots is cow urine and dung, which enriches the soil with nutrients, particularly N, and moisture, creating ideal conditions for N_2O emissions. Different mitigation strategies for reducing N_2O emissions from these areas have been recommended, including restricted grazing during wet periods that favor denitrification, feeding cattle low-N diets, using stand-off pads, application of soil amendments (i.e., lime) to increase soil pH to shift the balance between N_2O and non-greenhouse N_2, or use of zeolite to capture soil NH_4. The blanket application of nitrification inhibitors like dicyandiamide in combination with urease inhibitors like nBTPT has been recommended as the best approach to reduce N losses from grazing lands among all the abovementioned strategies (Zaman and Nguyen 2012). However, there is a need of research for investigating timing, type, rate, and cost associated with nitrification inhibitor application in different regions for mitigating N_2O emissions from grazing lands.

In confined-animal feeding systems, manure is typically collected and must be managed from the point of excretion through storage, treatment, and finally applying to land. To reduce the N_2O emissions from animal manures during its storage, it is suggested that solid manures need to be kept covered. However, there are some studies with contradicting results reporting increased N_2O emissions of manure covering (Table 16.3) (Petersen et al. 2013). Additionally, the application of nitrification inhibitors to the manures while storage has the potential to reduce N_2O emissions (Petersen 2018). According to one meta-analysis, the reduction in N_2O emissions due to nitrification inhibitor application to stored manures can range from 40 to 50% (Qiao et al. 2015). Likewise for N fertilizer application, different factors such as method, rate, placement, and timing of application according to crop nutrient requirements are crucial for mitigating N_2O emissions from manures.

16.2.3 Reducing Methane Emissions

Methane is a GHG currently contributing to about 15 % of global anthropogenic GHGs emitted every year when assuming a greenhouse warming potential of 25 times CO_2 over 100 year and 50.6% of anthropogenic CH_4 emissions are released as a result of agricultural activities. China followed by India, Brazil, the United States, Indonesia, Australia, Russia, Argentina, Thailand, and Nigeria are ten major contributors of the CH_4 emissions from the agricultural sector, constituting about 54.6% of the global emissions. Among different agricultural activities, 59.8% of CH_4 emissions are contributed by the enteric fermentation followed by emissions from rice cultivation, other agricultural activities, and manure management (Karakurt et al. 2012). Enteric fermentation refers to the process of foods being fermented by microbes in an animal's digestive system. As a byproduct of this process, CH_4 is released by animals exhaling (Karakurt et al. 2012). The majority of CH_4 emissions in this sector is contributed by domesticated ruminants like cattle, buffalo, sheep, goats, and camels. However, other domesticated non-ruminants such as swine and horses also contribute to CH_4 emissions through enteric fermentation, but emissions per animal species vary significantly. Another major contributor to CH_4 emissions from the agricultural sector includes rice cultivation which contributes approximately 11% of global anthropogenic CH_4 emissions (IPCC 2013). In a flooded rice field, the decomposition of organic materials in an environment without oxygen results in the release of CH_4. The breakdown of organic components under flooded rice conditions consumes available oxygen in soil and water rapidly, and methanogenic bacteria produce CH_4 when the oxygen in the environment is depleted. Additionally, manure storage from confined-animal feeding systems in liquid form can contribute to CH_4 emissions. Storing manures in liquid systems such as lagoons, ponds, or pits results in anaerobic conditions, resulting in CH_4 emissions (Steed and Hashimoto 1994). However, the amount of CH_4 from manure varies with

Table 16.3 Effects of different management options on CH_4, N_2O, and combined CH_4+ N_2O emissions from manure storage

Type of storage	Management option	Nitrous oxide	Methane	$N_2O + CH_4$	References
Solid manure	Forced v. passive composting	−35	−90	−78	Amon et al. (2001)
		−41	+32	−7	Amon et al. (2001)
		+44	−81	−34	Pattey et al. (2005)
			−28		Hao et al. (2001)
	Straw cover	−42	−45	−42	Yamulki (2006)
		−11	−50	−14	Yamulki (2006)
	Plastic cover	−70	−6	−36	Chadwick (2005)
		+2000	−81	−17	Chadwick (2005)
		−54	+120	+111	Chadwick (2005)
		−99	−87	−98	Hansen et al. (2006)
		−32			Thorman et al. (2006)
		+304			Thorman et al. (2006)
Liquid manure	Straw cover	+57	−25		VanderZaag et al. (2009)
		+100	−27	−23	VanderZaag et al. (2009)
			+37	−24	Guarino et al. (2006)
			+3		Guarino et al. (2006)
			+7		Guarino et al. (2006)
			−28		Guarino et al. (2006)
	Solid cover	+432	+22	+238	Berg et al. (2006)
		+30	−32	+1	Amon et al. (2007)
		−4	−70	−52	Amon et al. (2007)
		−50	−37	−48	Amon et al. (2007)
		−13	−14	−13	Clemens et al. (2006)
		+20	−16	−11	Clemens et al. (2006)
		+2	−29	−4	Clemens et al. (2006)
		−19	−14	−16	Clemens et al. (2006)

"+" represents higher emissions (%) and "–" lower emissions (%) compared with the reference (untreated) manure. The comparison of systems is based on CO_2 equivalents. Data is adapted from Peterson et al. (2013)

respect to the storage type, ambient temperature for storage, and manure composition. Open biomass burning, savanna burning, agricultural residue burning, and open forest clearing burning are other agricultural sources of CH_4 emissions. In this section, we will be discussing strategies to mitigate CH_4 emissions from different agricultural sources.

16.2.3.1 Improving Rumen Fermentation Efficiency and Productivity of Animals

Due to their unique digestive system, which includes a rumen, ruminant animals such as cattle, buffalo, sheep, and goats produce a lot of CH_4. The methanogenic archaebacterium responsible for CH_4 production is located mainly in the rumen, and its growth is affected by diet and other nutritionally related characteristics such as level of intake, feeding strategies, quality of fodder, and fodder concentrate ratios (Karakurt et al. 2012). Therefore, numerous nutritional technologies have been evaluated to increase rumen fermentation efficiency and reduce CH_4 production, such as direct inhibitors, feed additives, propionate enhancers, CH_4 oxidizers, probiotics, defaunation, diet manipulation, and hormones. Up to 40% reduction in CH_4 emissions is reported as a result of dietary manipulation depending on the degree of change and nature of the intervention (Benchaar et al. 2001). Dietary manipulation includes improving forage quality or changing the proportion of diet and dietary supplementation of feed additives that directly either inhibit methanogens or alter the metabolic pathways leading to a reduction of the substrate for methanogenesis. Forage quality can be improved by providing high-quality forage as it contains higher amounts of easily fermentable carbohydrates and less neutral detergent fiber, leading to a higher digestibility and passage rate, thereby resulting in lower CH_4 production, while more mature forage has a higher C:N ratio, which results in decreased digestibility and higher CH_4 production (Beever et al. 1986). Feeding legume forage results in lower CH_4 emissions as it contains condensed tannins, a low fiber content, high dry matter intake, and fast passage rate (Beauchemin et al. 2008). In general, feeding C_3 plant yields less CH_4 emissions than that from C_4 plants (Archimède et al. 2011). Similarly, replacing grass silage with maize silage helps in reducing CH_4 emissions from enteric fermentation. The reason is the same that grass silage is usually harvested at a later stage of maturity and contains lower content of digestible organic matter, lower sugar, and N contents, whereas maize silage provides higher contents of dry matter with readily digestible carbohydrates, e.g., starch, increasing the dry matter intake and animal performance (Beauchemin et al. 2008). Additionally, concentrates, fat supplementation, organic acids, essential oils, ionophores, and probiotics as feed additives reduce CH_4 emissions from enteric fermentation. Another method suggested for increasing rumen fermentation is the possibility of breeding animals with low CH_4 emissions. However, Eckard et al. (2010) suggested that breeding for reduced CH_4 production is unlikely compatible with other breeding objectives. Another way to reduce enteric CH_4 emissions is to increase the milk yield of dairy animals. However, increasing productivity will only reduce the total enteric CH_4 emissions if the amount of milk produced is kept constant by reducing the number of animals (Sirohi et al. 2007). Diet not only has a direct impact on CH_4 emissions from intestinal fermentation, but it also has an indirect impact on CH_4 emissions during storage by influencing manure composition (Hindrichsen et al. 2005).

16.2.3.2 Manure Management

Methane production is significantly decreased under dry and aerobic conditions; thereby, switching from liquid to dry manure management systems would help minimize CH_4 emissions from manure storage and handling. Methanogenesis is dependent on temperature, being lower under cooler temperatures. Therefore, storing slurry at cooler temperatures (10 °C) could result in 30% to 46% reduction in CH_4 emissions (Table 16.4). In cold and temperate climates, the temperature difference between animal housing and outside manure storage is significant. Therefore, by frequent removal of manure from housing to outside storage could help mitigate CH_4 from manure (Table 16.5). While storage, aeration of the solid manure left for composting also helps reduce CH_4 emissions from manure as it helps maintain aerobic conditions. Similar to N_2O emissions, covering both liquid and solid manures using straw or plastic sheets is also a mitigation strategy for CH_4 emissions from manure. However, some studies also reported contradicting results showing increased CH_4 emissions on manure covering (Chadwick 2005; Berg et al. 2006). Another method reported to mitigate CH_4 emissions from manure is its separation, herein defined as a process whereby a fraction of slurry particles is isolated by one of the several mechanical separation processes. Separate storage of the liquid and solid fractions after manure separation has, in most cases, but not always, resulted in lower CH_4 emissions (Table 16.4). Anaerobic digestion of manure is another strategy for mitigating CH_4 emissions where methanogenesis is optimized for breaking down degradable organic matter in manure and transforming it into biogas. As CH_4 is collected and used as fossil fuel, it reduces CH_4 emissions during storage. The potential of anaerobic digestion for reducing CH_4 emissions from manure reported under different studies can be found in Table 16.4. Additionally, treatment of slurry/manure using sulfuric acid is reported to reduce CH_4 emissions by 67% to 99% during 3-month storage period (Table 16.4). Manure aeration is an efficient way for mitigating CH_4 emissions because aerobic conditions are maintained. Amon et al. (2006) reported a reduction in CH_4 emissions (by 57%), with aeration of cattle slurry, while Martinez et al. (2003) reported reductions in CH_4 emissions of 70% to 99% after aeration of pig slurry. Therefore, using these mitigation strategies alone or in combination with others could help reduce CH_4 emissions during manure storage and handling.

Table 16.4 Effects of different management options on CH_4, N_2O, and combined $CH_4 + N_2O$ emissions from manure treatment

Management option	Type of manure	Nitrous oxide	Methane	$CH_4 + N_2O$	References
Manure separation	Pig slurry (5 °C)	0	−8	−8	Dinuccio et al. (2008)
	Pig slurry (25 °C)		+3	+41	Dinuccio et al. (2008)
	Cattle slurry (5 °C)	0	+4	+4	Dinuccio et al. (2008)
	Cattle slurry (25 °C)	0	−9	−9	Dinuccio et al. (2008)
	Cattle slurry	+1133	−34	−23	Fangueiro et al. (2008)
	Cattle slurry + wooden lid	+10	−42	−39	Amon et al. (2006)
	Pig slurry		−93	−29	López-Mosquera et al. (2011)
	Cattle slurry		−42	+25	López-Mosquera et al. (2011)
	Pig slurry		−18		Martinez et al. (2003)
	Cattle slurry		−40		Martinez et al. (2003)
Anaerobic digestion	Cattle slurry	−9	−32	−14	Clemens et al. (2006)
	Cattle slurry	+49	−68	−48	Clemens et al. (2006)
	Cattle slurry + wooden lid	+41	−67	−59	Amon et al. (2006)
Aeration	Cattle slurry	+144	−57	−43	Amon et al. (2006)
	Pig slurry		−99		Martinez et al. (2003)
	Pig slurry		−70		Martinez et al. (2003)
Dilution	Pig slurry		−35		Martinez et al. (2003)
	Cattle slurry		−57		Martinez et al. (2003)
Additives					
NX_{23}	Pig slurry		−47		Martinez et al. (2003)
Stalosan	Pig slurry		−54		Martinez et al. (2003)
Biosuper	Pig slurry		−64		Martinez et al. (2003)
Sulfuric acid (pH 6)	Cattle slurry		−87		Petersen et al. (2012)
	Pig slurry		−99		Petersen et al. (2012)
	Pig slurry		−94		Petersen et al. (2012)

"+" represents higher emissions (%) and "–" lower emissions (%) compared with the reference (untreated) manure. The comparison of systems is based on CO_2 equivalents

16.2.3.3 Reducing CH_4 Emissions from Flooded Rice Cultivation

Rice is grown on over 140 million hectares around the world and is the world's most widely consumed staple food. About 90% of the world's rice is produced and consumed in Asia, and 90% of rice land is flooded, at least temporarily (Wassmann et al. 2009). During the growing season, the soil redox potential decreases significantly due to flooded and anaerobic conditions, creating an environment conducive to methanogenesis, thereby resulting in CH_4 emissions. Estimates of global CH_4 emissions from paddy soils range from 31 to 112 Tg year^{-1}, accounting for up to 19% of the total emissions, while 11% of global agricultural N_2O emissions come from rice fields (US-EPA 2006; IPCC 2007). Rice production may need to increase to keep pace with the growing demand; efficient and sustainable management is needed to mitigate CH_4 emissions from rice paddy fields while maintaining high rice yields. Water regime and organic inputs determine most CH_4 emissions from rice fields, but soil type, weather, tillage management, residues, fertilizers, and rice cultivar also play a role. Therefore, changing the water management with soil submergence to a limited period seems to be the most promising option for mitigating CH_4 emissions from flooded rice fields. Midseason drainage (a common irrigation practice adopted in major rice-growing regions of China and Japan) and intermittent irrigation (common in northwest India) reduce CH_4 emissions by over 40%. Under midseason drainage, the time under anaerobic conditions is reduced, and most of the CH_4 in the soil is oxidized when exposed to air, which raises the soil redox potential to levels that prevent methanogenesis (Souza et al. 2021). However, the field needs to be reflooded before the soil moisture level falls a critical plant water stress level and prevents yield loss. Also, practicing early-season drainage in combination with midseason drainage is reported to be more effective than only midseason drainage as it helps reduce about 80–90% of CH_4 emissions. As the main solution for reducing CH_4 emissions for flooded rice is to limit soil submergence to a limited period, switching flooded rice cultivation to upland rice cultivation also reduces CH_4 emissions. However, the adoption of upland rice cultivation is not preferred because its production potential is much lower (Neue 1993). Another option for minimizing CH_4 emissions from flooded rice is by the adoption of direct seeding instead of transplanting. However, there are debates about the profitability of direct seeds rice due to the weed problem.

In addition to water management, fertilization management is relevant for mitigating CH_4 emissions from rice cultivation. Soil fertilization using fresh organic matter amendments, such as rice straw and green manures, significantly increases CH_4 production and emissions. Therefore, organic amendments may need to be minimized to reduce CH_4 emissions from wetland rice fields. However, sometimes, use of green manures and crop residues is the only source of soil nutrition for resource-limited farmers. In general, due to the availability of chemical fertilizers and responsive rice cultivars, organic amendments have declined in recent years. Among different chemical fertilizers, sulfate-containing fertilizers mitigate CH_4 emissions (Ro et al. 2011). This is because sulfate-reducing bacteria compete with methanogens for limited hydrogen. Use of urea-encapsulated calcium carbide as an N fertilizer if flooded rice is reported to mitigate CH_4 emissions due to slow release of acetylene (Bronson and Mosier 1991).

16.2.4 Quantifying and Modeling GHG Fluxes

The improvement in accuracy and robustness of the estimates of the GHG implications of the abovementioned practices is necessary as the agricultural sector plays an important role in addressing climate change. Particularly, the capacity to estimate

Table 16.5 Effects of different management options on CH_4, N_2O, and combined CH_4 + N_2O emissions from animal housing

Management option	Animal category	Nitrous oxide	Methane	N_2O + CH_4	References
Straw bedding	Fatteners	+106	−2	+29	Philippe et al. (2007)
	Gestating sows	+383	−9	+131	Philippe et al. (2007)
	Weaned pigs		−18	+22	Cabaraux et al. (2009)
	Dairy cattle	+85	+33	+48	Edouard et al. (2012)
Sawdust v. straw	Weaned pigs	+286	−51	+195	Nicks et al. (2003)
	Fatteners	+6867	−33	+286	Nicks et al. (2004)
	Fatteners	+7600	+100	+667	Kaiser (1999)
Wood shavings v. straw	Laying hens	+259	+319	+275	Mennicken (1998)
Cooling	Pigs		−31		Sommer et al. (2004)
	Fatteners		−43		Groenestein et al. (2012)
	Nursing sows		−46		Groenestein et al. (2012)
	Gestating sows		−33		Groenestein et al. (2012)
	Weaned pigs		−30		Groenestein et al. (2012)
Frequent manure removal	Pigs	−39	−56	−51	Amon et al. (2007)
	Pigs		−40		Haeussermann et al. (2006)
	Weaned pigs	0	−50	−50	Groenestein et al. (2012)
	Fatteners	0	−86	−86	Groenestein et al. (2012)

"+" represents higher emissions (%) and "–" lower emissions (%) compared with the reference (untreated) manure. The comparison of systems is based on CO_2 equivalents

CH_4 and N_2O emissions and changes in emissions needs to be strengthened, and a global monitoring system to provide measurements of soil C stocks over time should be established. Making informed decisions about the most appropriate mitigation strategies requires a thorough understanding of how much C can be sequestered or how various practices can reduce much GHG emissions. However, significant gaps remain, particularly in developing countries, where there are still many questions about the sources of agricultural emissions, as well as a lack of methods and methodologies for monitoring emissions through supply chains and evaluating the GHG impacts of investments. Additionally, the mathematical models can articulate the factors that control GHG fluxes and soil C stock changes. Therefore, a combination of field measurements and models considering farming systems is the most effective method for estimating global-scale agricultural emissions and sinks, as well as forecasting changes in emissions due to changes in management practices, environmental and economic conditions, or government policies (Table 16.5).

The rate of GHG emissions from soils and/or uptake can be measured directly using the chamber method and micrometeorological techniques. However, because emission rates are highly variable in both space and time, measuring flows of these gases over areas and time periods of interest poses significant challenges. For example, following a rainstorm or fertilization, N_2O emission rates can change 100-fold or more (Smith et al. 2000), and similar changes in CO_2 emission rates occur after tillage (Reicosky et al. 1997). Therefore, calculating annual flux rates demands frequent sampling to adequately represent large, short-term fluxes and avoid under- or over-estimation of fluxes. Due to the high spatial variability of flux rates, either several small areas within a field must be sampled and averaged, or the measurement technique must integrate fluxes over a relatively large area. In addition, automated chamber systems can be utilized for overcoming the error due to temporal variability.

Mathematical models can be used for articulating the factors that control GHG fluxes and soil C stock changes. There are two basic types of models: (i) empirical and (ii) "process-oriented" models. Empirical models use field measurements to determine statistical relationships between soil C stocks and environmental and management factors (e.g., IPCC 1997; Ogle et al. 2003), whereas more dynamic, "process-oriented" models attempt to simulate the biological, chemical, and physical processes that control GHG dynamics. Process-oriented models are useful to portray the effect of combinations of management practices as well as soil and climate conditions. Several dynamic, process-based models have been developed to simulate soil C stock changes and N_2O and CH_4 fluxes from soil.

16.3 Conclusions

Global agriculture has significant potential to reduce GHG emissions and sequester C in soils using currently available technology. However, because there are so many variables that influence emission and sequestration processes, some practices that reduce one gas emissions may increase emissions of another. Promoting practices that maintain or increase C stocks while also increasing the efficiency of agricultural inputs (e.g., fertilizer, irrigation, pesticides, animal feed, and animal waste) is the key to reducing net GHG emissions from agriculture. To achieve the best overall mitigation results, GHG mitigation practices should address both C stocks and N_2O and CH_4 emissions. The largest potentials for soil C sequestration are associated with adoption of no-till practices, reduced fallow, use of cover crops, and conservation set-asides with perennial grasses and trees on highly erodible cropland. Nitrous oxide emissions from soils constitute the single largest agricultural GHG source. More efficient use of N fertilizer and manure, increasing the overall efficiency of N use for crop improvement, as well as additives that inhibit the formation of N_2O in soils could help in the reduction of N_2O emissions. Methane emissions are mainly contributed through enteric fermentation and emissions from stored manure from livestock production or from flooded rice cultivation. Manure management systems that capture and combust CH_4 can provide a renewable energy source that both is helpful in reducing CH_4 emissions and can displace fossil fuels. Improved production technologies (e.g., improved feed quality, CH_4-suppressing feed additives, and animal breeding) can reduce enteric CH_4 emissions, increase livestock production, and perhaps improve profitability. For rice cultivation, avoiding the use of organic inputs, fertilizer management, using nitrification inhibitors and irrigation management techniques such as midseason drainage or intermittent drainage can help in mitigating CH_4 emissions.

With respect to quantification, this report finds that direct field measurement is viable, although at times expensive, for assessing C sequestration; field measurement of CH_4 and N_2O is not yet ready for wide implementation. Direct measurement appears best suited for programs focused on innovative new practices for which research is lacking. In contrast, modeling will likely be most efficient for scaling up known management practices well supported by research and modeling capacity. Important data gaps remain for program or project implementation particularly management data for establishing baseline conditions. Additional work is needed to assess potential reversal rates for the subset of management practices for which this could be a problem.

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Chapter 17
Environmental and Economic Benefits of Sustainable Sugarcane Initiative and Production Constraints in Pakistan: A Review

Hafiz Ali Raza, Muhammad Usman Hameed, Mohammad Sohidul Islam, Naveed Ahmad Lone, Muhammad Ammar Raza, and Ayman E. L. Sabagh

Abstract Sugarcane crop has a vital role to play in the economy of developing countries. The crop requires a high amount of water during its development. Therefore, it becomes necessary to adopt innovative, ecofriendly, and water-efficient methods for its cultivation. In this chapter, sugarcane production constraints have been discussed to promote sustainable sugarcane production with special reference to Sustainable Sugarcane Initiative (SSI) techniques. The constraints include high input costs, poor production practices, water scarcity, lack of implementation of modern technologies, less incentives, climate change, and delay in payment to the farmers. Sugarcane production can significantly be increased by using SSI with less input costs, efficient water utilization, reduction of weed losses, and controlling the infestation of pests and diseases. There is a need to take proper steps for increasing the production and profitability of sugarcane by timely irrigation, cost-effective inputs, better-quality seeds, and preventive measures against post-harvest losses. The capacity building of sugarcane farmers is also recommended.

Keywords Sugarcane production · Traditional methods · Input cost · Sustainable Sugarcane Initiative · Economic stability

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17.1 Introduction

Sugarcane is an important economic and commercial crop in the world (Grivet and Arruda 2002). It has a significant role in socioeconomic developments as it improves the income of the growers and creates employment opportunities for masses; It create employment opportunities to more than half a million people globally (Raza et al. 2019a, b). Due to its economic and medicinal value, it is cultivated worldwide and gives high-yielding products. Sugarcane belongs to the family Poaceae; the crop has fibrous, stout, and jointed stalks; it is about 3 m height and rich in sugar (Maloa 2001). The decreasing trend of sugarcane production has been observed from the last couple of years globally. Unfavorable climatic conditions, agricultural transformation, and low returns from the market, as well as decline in planting area, have been expected to lead to the lower production of sugarcane in the upcoming years. The most noticeable decline in production has been recorded in Brazil the leading country in sugarcane production and contributing more than one third of the overall sugarcane production in the world (James 2008). Sugarcane is considered one of the important cash crops, grown all over the world. Among the sugarcane producers, Brazil is the leading sugarcane-producing country with an annual production of 739,300 thousand metric tons (TMTs) and contributes about 39% of the world's total sugarcane production (Walton 2020). India ranks the second-largest producer and contributes almost 19% of the overall sugarcane production in the world with an annual production of 341,200 TMTs (Masuku 2011). China is the third- and Thailand is the fourth-largest sugarcane producers in the world with an annual production of 125,500 and 100,100 TMTs, respectively. Pakistan stands at the fifth position among other sugarcane-producing countries with an annual production of 63,800 TMTs (Aman and Khan 2021). Sugarcane is considered an essential raw material for sugar production in Pakistan, and it is expected to produce 5.9 million metric tons in 2021–2022. Non-availability of minimum support prices, delays in payment dues and water scarcity are prompting some farmers to switch to other crops such as cotton and corn instead of sugarcane.

Sugarcane contributes approximately 60% of foreign exchange earnings and almost 18.9% of the national gross domestic product (GDP) in Pakistan (Chandio et al. 2016). Agriculture provides the basic necessities of life to almost 68% of the total population living in rural areas, and unfortunately, 62% of which is living below the poverty line (Aslam 2016). The total area cultivated in Pakistan is approximately 22 million hectares (Mha) and includes rice 13.14% (2.89 Mha), wheat 41.73% (9.18 Mha), maize 5.14% (1.13 Mha), sugarcane 5.18% (1.14 Mha), and cotton 13.45% (2.96 Mha). These major five crop covers almost 78.64% (17.30 Mha) of the overall cropped area and reflect that these five crops represent a large area of cultivated land (Mari et al. 2011). In Pakistan, among the five major crops, sugarcane occupies the second-largest among the cash crops. It has industrial importance in the sugar industry and other byproducts that are produced from sugarcane.

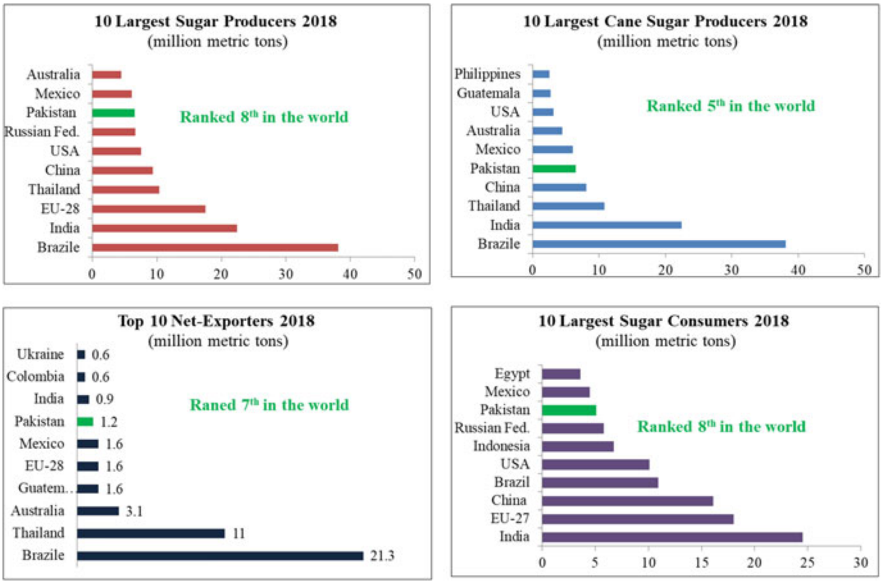


Fig. 17.1 Pakistan sugar in the global perspective. (Adapted from PSMA annual report, 2018)

The total cultivated land area of sugarcane around the world is 27 Mha with a total production of 1333 million tons (Natrajin 2005). In the world ranking, Pakistan is the eighth-largest consumer of white sugar, seventh-largest net sugar exporter, seventh-largest cane sugar producer, and fifth in sugarcane production with an annual production of 83.3 million tons. Figure 17.1 shows the status of the Pakistan sugar industry with reference to the global sugar industry. The total area, production, and yield for sugarcane crops in Pakistan have been shown in Figs. 17.2, 17.3 and 17.4. During 2016–2017, its total cultivated area was 1.217 million hectares with a production of about 73.6 million tons, and its role in GDP and the value addition of agriculture are 0.7% and 3.6%, respectively (Azam and Shafique 2017). In Pakistan, sugarcane is grown in three climatic zones, tropical Sindh, subtropical Punjab, and temperate Peshawar valley. Punjab is the major contributor with almost 62% share in sugarcane production, while Sindh and the North-West Frontier Province (NWFP) also contribute about 26% and 16%, respectively. Sugarcane is the second major provider of sweetness after honey in Pakistan (Qureshi and Afghan 2005), and it provides the raw material for the second agro-based industry after textiles. However, in recent times, sugarcane is recognized for its role in sustainable energy production (Gheewala et al. 2011). Moreover, unprocessed sugarcane is consumed as food and feed for animals in leading producing countries such as Brazil, India, and Cuba (Girei and Giroh 2012). Furthermore, sugarcane juice is used as a raw material and also used for wax (Lamberton and Redcliffe 1960). Wax is a vital part of the cosmetic and pharmaceutical industries, and it is considered as a better substitute for expensive carnauba wax (Singh et al. 2015). However, some

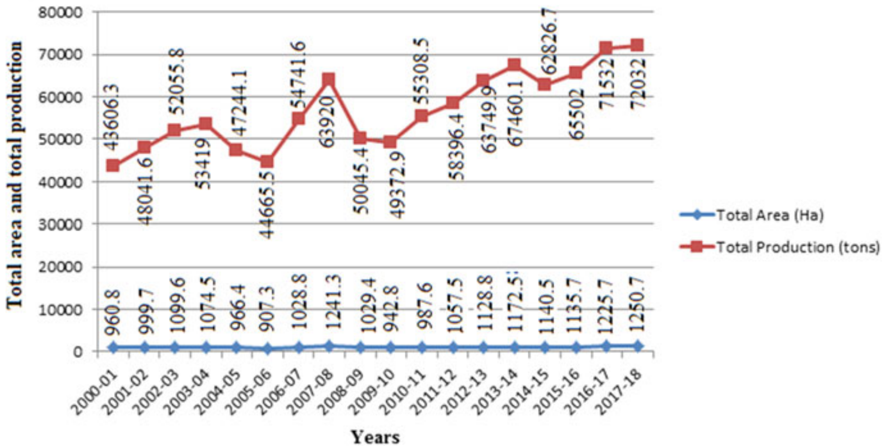


Fig. 17.2 Total area (Ha) and total production (tons) of sugarcane crop in Pakistan

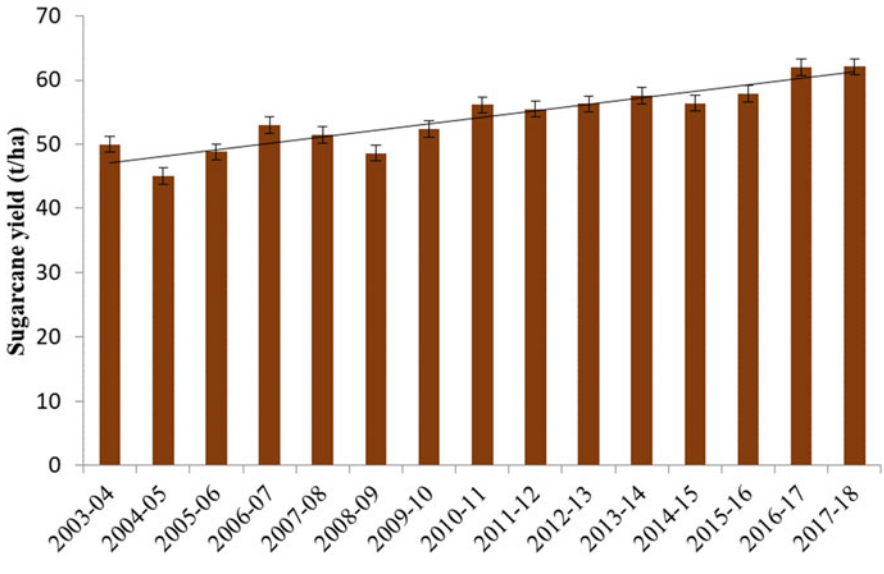


Fig. 17.3 Total yield of sugarcane in Pakistan from 2003 to 2018

important byproducts of sugarcane are refined sugar, molasses, brown sugar, jaggery, biogas production, pulp, biofertilizer, ethanol (Xu et al. 2005), and paper making (Prasara-A and Gheewala 2016). In India, sugarcane is commonly used in the treatment of anuria, hemorrhage, jaundice, dysuria, and other urinary diseases, respectively.

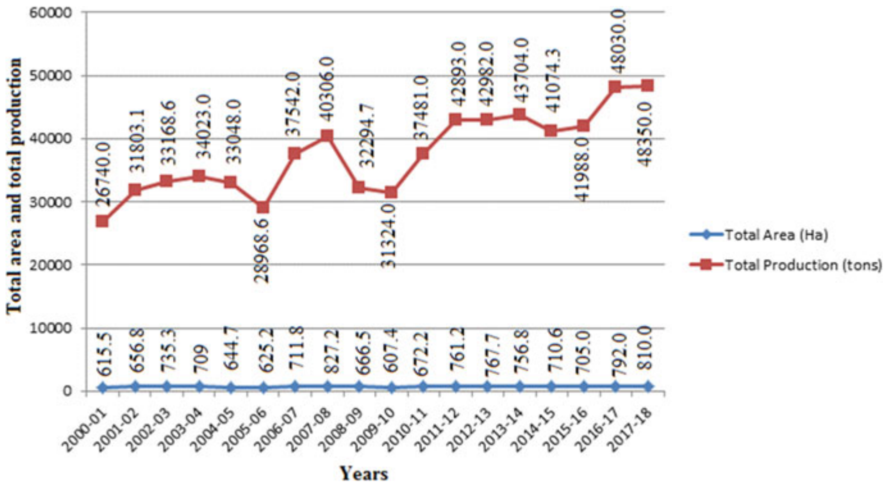


Fig. 17.4 Total area, production, and yield of sugarcane crop in the Punjab province of Pakistan

17.2 Sugarcane as an Energy Source

Pakistan is facing a challenge to energy crises in recent times (Knox et al. 2010). Sugarcane can be used as a reasonable source to overcome the energy crisis in Pakistan (Solangi et al. 2019). Bioenergy has gained better attention as a substitute for fossil fuels. Bioethanol obtained from sugarcane can offer advantages to the environment, human health, and economy of Pakistan (Pereira and Ortega 2010). In the residential region of São Paulo, ethanol replaced gasoline in Brazil resulting in major improvements in air quality. On the basis of lifecycle, it decreases the emissions of greenhouse gases if proper agricultural practices and suitable feedstock are used (Macedo et al. 2008). Ethanol is produced mostly in Brazil from sugarcane and in the USA from corn. In 2008, Brazil produced 22.5 billion liters of ethanol, the European Union 2.7 billion liters, and the USA 34 billion liters mainly from sugar 106 beet (Low and Isserman 2009). For the production of ethanol in 2008, Brazil used 3.4 million hectares of land, while the USA used 8.13 million hectares (Goldemberg and Guardabassi 2010).

17.3 Overview of Sugarcane Production in Pakistan

In Pakistan, ethanol is produced at a very small scale in sugar industries, and it is being used for its own sustainability. Figures 17.5 and 17.6 show the total yield and average recovery of sugarcane in the Punjab province of Pakistan. The average per hectare production of sugarcane is ranging from 620 to 700 maund per acre which is very low in Pakistan as compared to other sugarcane-producing countries (Rai and

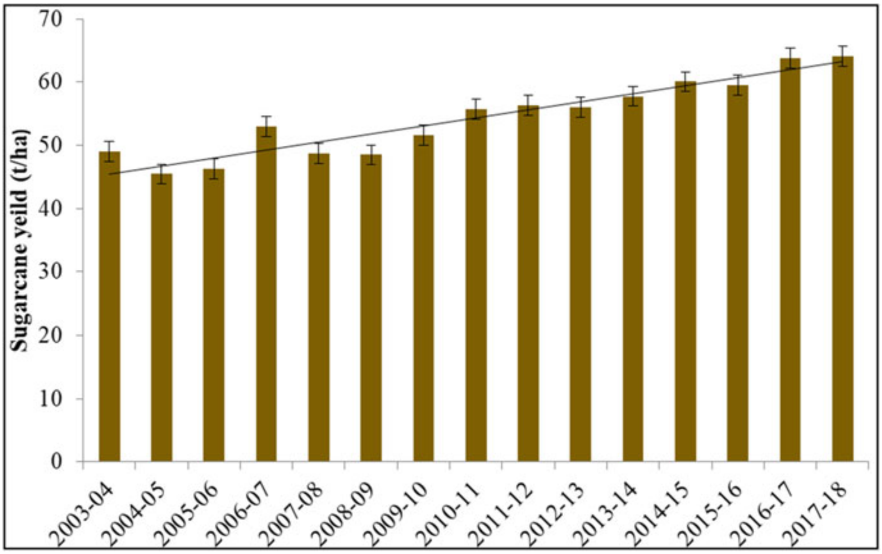


Fig. 17.5 Total yield of sugarcane in the Punjab province of Pakistan for the periods 2003–2018

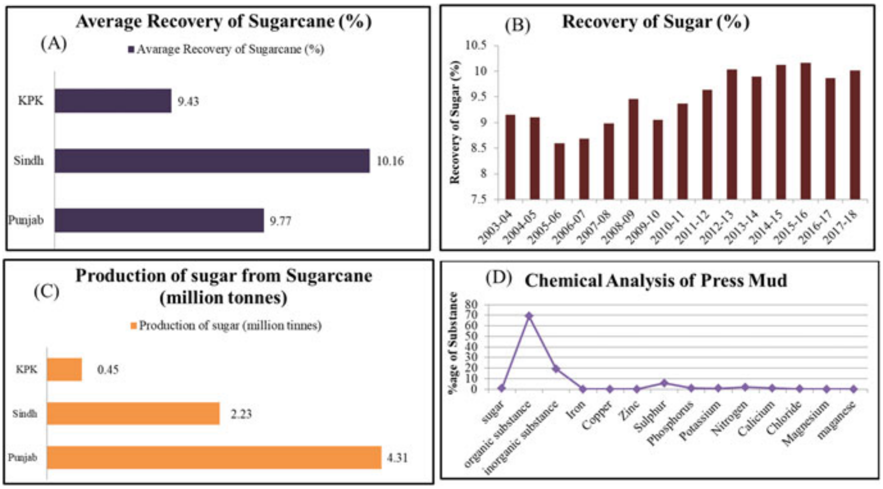


Fig. 17.6 (**a**) Average recovery of sugarcane, (**b**) recovery of sugar, (**c**) production of sugar from sugarcane, and (**d**) chemical analysis of press mud in Pakistan. (Adapted from PSMA annual report, 2018)

Shekhawat 2014). Similarly, its per acre yield is very low in Punjab as compared to other country provinces due to various factors. Among these factors, soil type, soil erosion (Iqbal and Ahmad 2005), cultural practices, plant material, climatic conditions, fertilizer, labor component, pest and disease management, lack of technology, and irrigation water have a considerable impact on sugarcane production (Lahoti

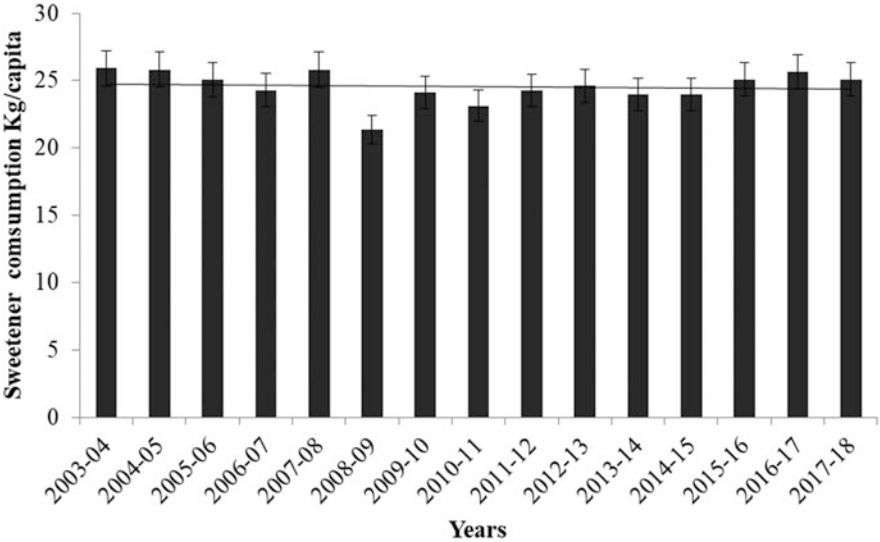


Fig. 17.7 Pakistan Sugar Mills Association (PSMA) sweetener consumption kg/capita. (Adapted from PSMA annual report, 2018)

et al. 2010). Similarly, high input costs like urea, DAP, FYM, irrigation, seed, pesticides, water shortage, and weedicides were also considered important factors in this regard (Sawaengsak and Gheewala 2017). Therefore, high input price directly affects the production of sugarcane. Similarly, distance to sugar mills, the operation of poor management, and post-harvest losses are the gap between potential and actual yield ultimately hampering sugarcane production (Fischer 2015). Sugarcane varieties are also the major factor of low production because these varieties perform effectively in the first year but not performing subsequently ultimately records low yield (Perera et al. 2003). Weeds compete with the crop for the available nutrients, sunlight, and water, which reduces the yield drastically and results in low-quality sugarcane (Girei and Giroh 2012). Hence, farmers are unable to get high sugarcane production due to many causes such as late planting, lack of financial resources, primitive or post-harvest measures, and environmental resistance (Rabelo et al. 2011). Pakistan Sugar Mills Association (PSMA) mentioned that the sweet consumption kg/capita, provincial shares in Pakistan, and area under cultivation are shown in Figs. 17.7, 17.8 and 17.9.

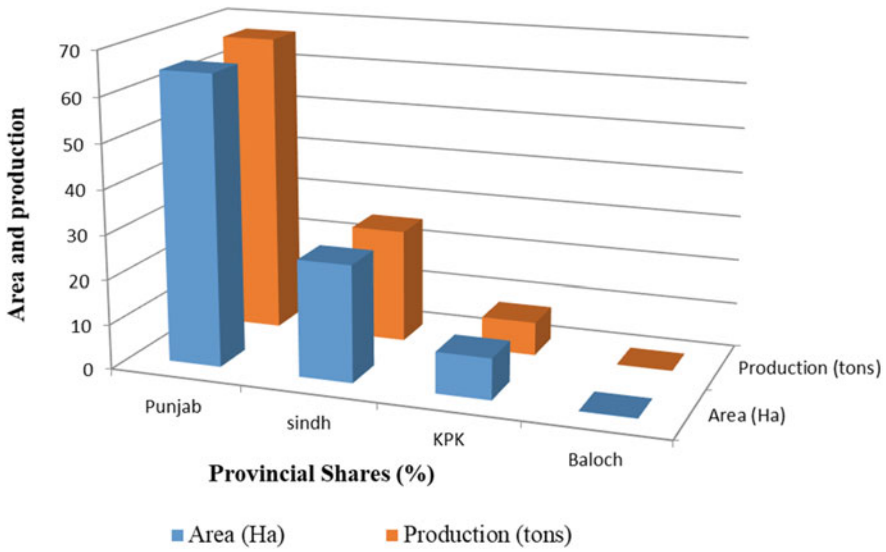
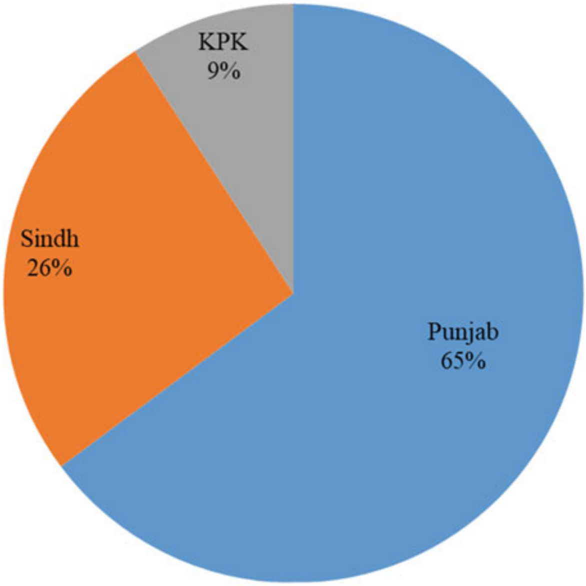


Fig. 17.8 Provincial shares for sugarcane crops in Pakistan

Fig. 17.9 Total area under cultivation for sugarcane in different provinces of Pakistan. (Adapted from Pakistan Sugar Mills Association (PSMA) annual report, 2018)



17.4 The Current System of Sugarcane Production in Pakistan

17.4.1 Climate

Sugarcane is grown in tropical or subtropical climates with a minimum of 600 mm rainfall annually. Sugarcane in Pakistan is harvested in the southern, central, and northwestern zones. The range of minimum temperature during December to January is about 4 °C, and the maximum temperature is 38 °C from June to July. During the winter seasons, the minimum temperature hinders or stops the growth of sugarcane. The climate throughout the year normally favors crop productivity. But extreme conditions of weather especially a limited amount of rainfall are a serious concern to produce sugarcane crop interference in Pakistan.

17.4.2 Climate Change and Sugarcane Response

Among many other factors, climate change is one of the emerging issues in the world. It is anticipated that it has a negative impact on sugarcane production, particularly in developing countries due to lack of awareness, ineffectual forecasting, unsuitable vindication strategies on the effects of climate change, and more exposure to natural hazards. It poses a significant threat to farmers due to the lack of proper infrastructure, inappropriate strategies, and the adoption of traditional agronomic practices (Käyhkö 2019). In Pakistan, farmers' livelihoods and agricultural productivity are affected due to the climate change. Therefore, a precise understanding of climate change and adoption of appropriate mitigation strategies can reduce the economic losses of sugarcane. Thus, environmental awareness is an important step as it is responsible for the reduction in cane yield (Abid et al. 2019).

Cane production may have been negatively affected and will continue to be significantly affected by the increased frequency and intensity of extreme environmental conditions due to climate change. Similarly, changes in the environment lead to global warming having increased greenhouse gas emissions. Global warming is believed to be caused by increasing concentrations of CO_2 and other greenhouse gases (GHGs) in the atmosphere (Zhao and Li 2015). Cane is sensitive to rainfall, temperature, sunlight, and soil (Trenberth 2012). Global temperatures are thought to increase by 3–5 °C by the end of the twenty-first century (Chohan 2019). Different climatic conditions can lead to changes in the sea level, precipitation, floods, droughts, abiotic pressures, and above all a rise in temperature. Rising temperatures could be favorable for some crops such as C_3 plants and sugarcane in some parts of the present world.

Cane production in Pakistan is negatively affected by abiotic and biotic factors diseases and pests are important biotic factors. There are many reasons for rising temperatures in the ecosystem, and change in human activities and deforestation, burning of fossil fuels, and industrialization of the ecosystem are the main causes (Chohan 2019). These are the reasons for low or high rainfall, high temperatures, high pest pressure, more favorable environment for pest growth, disease infestation, higher water requirements, reduced soil fertility, and pollination services. According to the previous studies (Nazir et al. 2013; Hussain et al. 2018; Raza et al. 2019a, b; Moitinho et al. 2021; Triques et al. 2021; Singh et al. 2018; Marin et al. 2019; Farooq and Gheewala 2020), several factors are responsible for the lower production of cane, viz., harvesting cost, transportation, high prices of inputs, a number of harvests, burring of the sugarcane residues, increased greenhouse gases, carbon monoxide, global, abnormal rainfall, and drought stresses, and excess use of pesticides and fertilizers which affects the soil organisms, environment, and soil fertility. However, lack of awareness and adoption rate of the latest technologies were identified as the major reasons of these constraints during farm surveys.

Extreme weather conditions, floods, salinity, drought, and frost have been shown to be the major causes for the deterioration of cane production in Pakistan (Chohan 2019). Punjab, especially in southern Punjab has the highest sugarcane production mainly due to suitable ecology in the area for its production. Rahim Yar Khan is the largest sugarcane-growing area in South Punjab. Over the past decade, due to the failure of other crops such as cotton, farmers have been growing sugarcane as they have more availability in sugar mills, sugarcane logistic support, and more profitable products. But in recent years, the trend of growing the cane community has changed due to the effect of climate change, and they have switched to other crops. However, this situation is very worrying and alarming, and Pakistan has no other alternative for sugar production other than the cultivation of cane.

It is, therefore, very important to inform farmers about the negative effects of climate change and the necessity to adopt appropriate mitigation strategies against it. Hence, the level of awareness and adoption of agronomic measures, including resistant varieties; sowing time and planting methods; soil and land preparation; weed, pest, and disease management; water; and nutrient management, appear to be promising measures to increase sugarcane production and boost farmers' income levels and living standards. It has been hypothesized that climate change is causing a decline in the production of sugarcane.

17.4.3 Preparation of Land

Sugarcane rigger, cultivator, chisel, and subsoiler are used to get proper germination and better crop growth. The simple plow is significant for the good preparation of seedbed in the sugarcane field. For achieving optimal crop growth, the land is prepared in such a way because the crop of sugarcane is deep-rooted, and proper land preparation plays a vital role in the growth of the root system of cane. Sugarcane rigger, cultivator, chisel, and subsoiler are used to prepare the land which enhances proper germination and better crop growth. Deep plowing with subsoiler should be used to prepare the soil properly one time after every 5 years in order to pulverize and increase the rate of water infiltration in the soil (Memon et al. 2010).

17.4.4 Time of Planting and Seed Rates

Two planting seasons are usually practiced in Pakistan: spring sowing in February to March and September to November sowing for rabi or fall. From the first week of September, planting starts in the fall and continues to mid-October in Sindh and Punjab. In other provinces like Khyber Pakhtunkhwa, planting is done in October and November. Planted crop in September commonly produces 25–35% higher yield. In Pakistan, the planting time of sugarcane is generally carried out in the autumn and spring seasons. Planting of high yield and high sugar recovery is done in autumn compared to planting in spring (Nazir et al. 2013). Sets should be selected merely from the young, cultivated crop as a completed matured crop will have a large of dry scale buds. In the dry scale buds' case, it should be treated with a lime solution. By two to three buds, all the sets should be equal in size and should be cut with a sharp tool.

17.4.5 Methods of Planting

The most commonly planting method of sugarcane are the double-set, end-to-end, and overlapping methods (Nazir et al. 2013). In conventional methods, 3 budded sets of 16,000 or 48,000 buds are directly implanted in the soil to attain 44,000 canes per acre for the normal population, but unluckily, merely 15,000 mill-able canes are attained at the end, and the row space is maintained at 1.5–2.5 ft which is 45–74 cm. For the better improvement of sugarcane yield, healthy seeds are used which increases the cane yield by 20–25%. These varieties contain high sugar content and are mostly planted in Punjab (Table 17.1).

17.4.6 Fertilizers

Fertilizers are the vital component for getting the optimum yield of sugarcane. In Pakistan, most of the farmers are using fertilizers in inadequate, imbalanced, and improper ways in a sugarcane field. In developed countries, only nitrogenous fertilizers are used for sugarcane production, but developing countries, like Pakistan, are utilizing a combination of different fertilizers such as potassium, nitrogen, and phosphate. The appropriate doses of balanced fertilizers are important to achieve the maximum yield of the sugarcane crops. Moreover, the use of

Table 17.1 Recommended varieties of sugarcane for the Punjab province

Varieties	Sugar (%)	Production capacity (maund)	Immunity
CPF-247	12.5	1400	Very good
SPF-245	11	1300	Medium
HSF-242	12.5	1500	Medium
CPF 243	12.55	1300	Medium
CP-77 400	11.90	1300	More
CPF 237	12.50	1400	Less
SPF-213	10.50	1300	Less
CP-72 2086	12.36	1065	More
HSF-240	11.70	1355	Less
SPF-234	11.60	1450	Less

Table 17.2 Duration of irrigation for sugarcane crops

Month	Number of irrigations	Duration of irrigation (days)
March, April	2–3	18–20
May, June	5	10–15
July, August	3–4	13–15
September, October	3	15–22
November–February	2	40–50

potassium is almost neglected in crops of cane. Table 17.1 exhibits fertilizer recommendations with respect to sugarcane crops for the Punjab zone (Nazir et al. 2013).

17.4.7 Irrigation

One of the aspects which are mostly neglected in this region is the application of irrigation methods. Lysimeter studies have exposed that the crop of sugarcane needs 88 to 118 kg water per kg cane and 884 to 1157 kg water per kg sugar produced, respectively (Shrivastava et al. 2011). It is difficult for some farmers to manage the enormous amount of water in fields due to financial weakness. Sugarcane crop gets into flooded conditions, and zones of the root remain merged in water (Giordano et al. 2019). It not only decreases the yield of sugarcane by decreasing sugarcane production but also causes waterlogging (Malik and Gurmani 1999). Furthermore, some areas are water-wracked, which leads to salinity (Watto and Mugera 2015). The mentioned number of irrigation and duration of irrigation for sugarcane crops is shown in Table 17.2.

17.4.8 Harvesting and Transportation

Most of the farmers cultivate sugarcane crops without soil analysis and seed treatment, which results in low yield and high production costs due to the absence of technology and modernization. Sugarcane is harvested when the crop attains the age of 12–14 months. The harvesting of sugarcane is done manually, hand-harvesting of sugarcane requires labor intensively, and one person can harvest on average 10,000 kg of sugarcane per day. When the crop of cane is 12–14 months old, it's the right time for harvesting.

Using a special type of tool, sugarcane is cut at ground level in the form of sticks. When sugarcane is harvested, it has a sugar content of almost 10%. The roots are left in the ground as they will ultimately grow and sprout to form the next crop. For loading, sugarcane is bound, topped, and stripped in bundles of 10 to 15 kg after cutting. Within 24–48 h of cutting, the harvested cane should be sent to the mill because late transportation will result in loss of sugar (Nazir et al. 2013). Figure 17.10 shows the flow sheet diagram of the conventional sugarcane cultivation method.

17.5 Sugarcane Crop: The Highest Consumer of Water

Pakistan has become a water-scarce country due to different reasons which ultimately has affected sugarcane production due to its high water demand. To complete one growth cycle, sugarcane requires 1500 to 2500 mm of rainfall/water. So, the crop needs 1500 to 3000 L of water to make a kilogram of sugarcane. Therefore, there is a need to conserve water for future usage for humans as well as for crop plants through the introduction of the Sustainable Sugarcane Initiative (SSI) for enhancing the production of sugarcane with minimum water requirement (Liu et al. 2018). The idea stands on the base of "more with less."

17.6 Sustainable Sugarcane Initiative (SSI)

The SSI is a method of sugarcane production with less water, fewer seeds, and optimum fertilization. The SSI technology has a definite economic advantage over the conventional method of cultivation. Through this method, the average yield of 118.14 tons per hectare can be obtained, whereas the yield from the conventional method was 64.74 tons per hectare. Farmers can achieve about 20% more productivity while reducing 30% of water and 25% chemical inputs using SSI technology (Gujja et al. 2009). The conventional method of sugarcane cultivation is one of the major issues in Pakistan because it requires more seed rate, less intercropping, high weeds infestation, a smaller number of tillers, and more water requirement throughout the cropping season. So, it is time to change the conventional method of

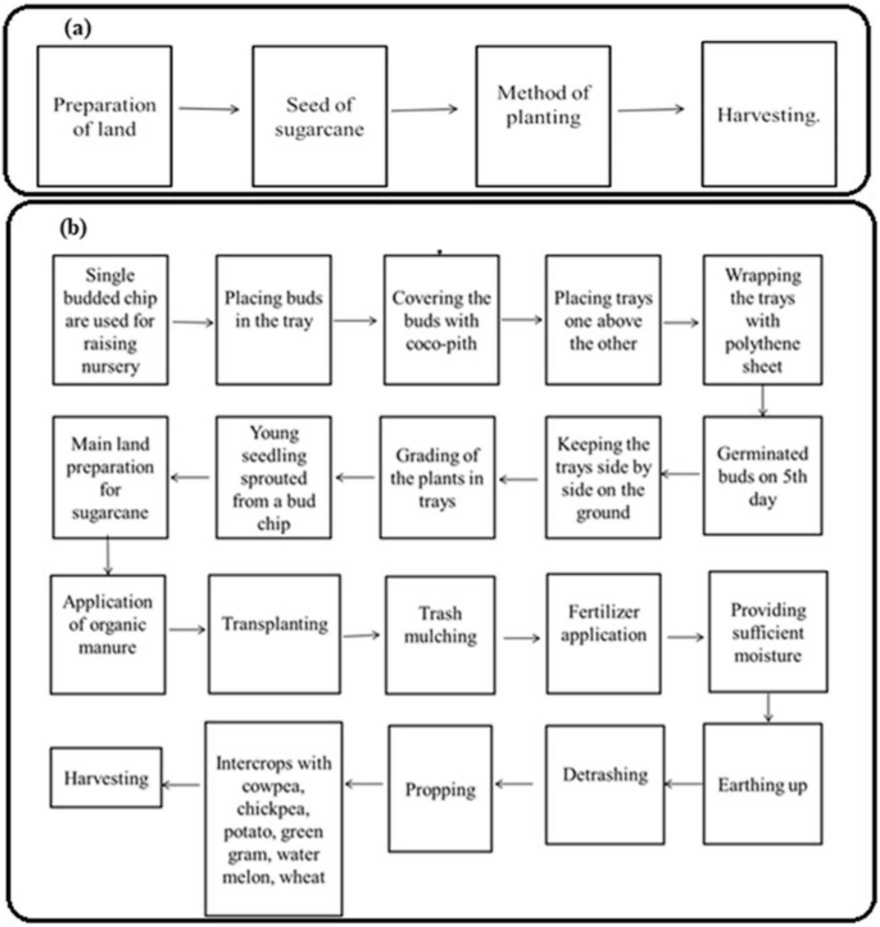


Fig. 17.10 Flow sheet diagram of (**a**) conventional sugarcane cultivation method and (**b**) SSI method for sugarcane cultivation

cultivation to a Sustainable Sugarcane Initiative method because SSI uses less seed, less water, more production, number of tillers, more accessibility to the air and light and optimal land use for higher yields. The major principles of the SSI method are single-budded chips raising nursery; young seedling transplanting (25–35 days old); 5×2 ft wide space-maintaining in the field; avoiding the accumulation of water and providing sufficient moisture; promoting plants protection method and organic measure; effective utilization of land by intercropping practice.

17.6.1 Nursery Planting

In this technique, single-budded chips (5000 buds/acre) are used for raising the nursery. Certain buds are placed in a tray filled with coco pith, and then placed with one another and wrapped with polythene sheets to keep air, water, and sunlight from entering the trays. Chlorpyrifos 50 EC is used as a measure by drenching the soil around the trays to avoid termites of sugarcane. Single-budded seed gives surely a 70% germination percentage when treated with chemicals (Jain et al. 2009).

17.6.2 Transplanting

Then the seedlings are transplanted into the already prepared field after 25–35 days at larger spaces of about 5 ft between rows. It is important to note that in the SSI method, the shot growth rate is much faster than the conventional method.

17.6.3 Wider Spacing

A wider spacing of 5 $\times$ 2 ft as recommended in the SSI system allows better yield as more sunlight is penetrating in the crop canopy and intercultural operations become easier. The use of intercultural operations to get rid of weeds is recommended as it reduces the damage caused by weeds by up to 60% (Babu 2015). It was observed that this wider space also enhances the weight and height of individual cane. Conventional methods have the efficiency to produce 10–15 tillers, whereas by using SSI, more than 20–25 tillers/plant can be obtained. The cultural practices made it easier and effectively control weeds without using agrochemicals. This technique allows the movement of farm machinery for multiple operations (Shanthy and Ramanjaneyulu 2016). Therefore, the SSI technique is the best strategy to save water and provide soil moisture by using irrigation-efficient techniques such as drip irrigation (Arthi et al. 2016).

17.6.4 Water-Efficient Utilization

Low production of sugarcane is the major challenge among sugarcane farmers in Pakistan. The low average yield of sugarcane is due to a shortage of water during its production period. However, this problem can be overwhelmed through the adoption of SSI. In Pakistan, the water table is depleting continuously. Therefore, it cannot sustain the traditional methods of sugarcane production, as they need more water (Panghal 2010).

17.6.5 An Organic Method of Cultivation

In the SSI method, farmers should add more biofertilizers and organic manures and follow measures of biocontrol, and this method discourages high uses of weedicides, pesticides, and chemical fertilizers. Sudden shifting to organic farming is not suitable; instead, a steady decrease of the inorganic method and implementation of the organic method can be tried by farmers for long-period profits.

17.6.6 Intercropping with Other Crops

In SSI method intercropping of cane with watermelon, French bean, wheat, chickpea, brinjal, potato and cowpea and in adding to effective use of land, this practice will decrease the growth of the weed up to 60% and give extra income to farmers (Loganandhan et al. 2013).

17.6.7 Overall Benefits of the SSI Method

In SSI method, the seed cost can be decreased up to 75% drastically, the rate of plant mortality decrease, weight, and length of individual sugarcane increase, easily transport the seedling to longer distance due to wider space intercultural with other crops. Table 17.3 displays a comparison between SSI and conventional method of sugarcane cultivation (Arthi et al. 2016).

17.7 Model Application of Sugarcane Crop

Accurate crop simulation models are valuable tools for a wide range of applications, including the evaluation of various crop management strategies and the understanding of potential climate change impacts (Thorburn et al. 2014). Crop models are useful tools for increasing sugarcane productivity since they help with knowledge synthesis and application, as well as yield forecasting (Andrade et al. 2016). Field-scale models, such as ALMANAC (Kiniry et al. 1992), EPIC (Williams et al. 1983), Canegro (Marin et al. 2019; Inman-Bamber 1991), and APSIM (Marin et al. 2019; Keating, et al. 1999), as well as regional-scale ones, such as Agro-IBIS (Kucharik 2003) and LPJmL (Bondea et al. 2007), have been applied to energy crops under a wide range of environments. These models differ in the degree of parameterization needed and in their ability to simulate different cultivars and different stress conditions (Marin and Jones 2014; O'Leary 2000). These complexities can be a barrier to the application of sugarcane crop models, possibly because of the lack of

Table 17.3 Comparison between Sustainable Sugarcane Initiative and conventional method of sugarcane cultivation

Comparison	Sustainable Sugarcane Initiative method	Conventional sugarcane cultivation method
Number of sets for sugarcane cultivation	5000	20,000–30,000
Spacing between two rows	5 ft	2–3.5 ft
Planting	After 20–25 days, transplanting nursery is grown in the main sugarcane field	No need of transplanting
Water requirement	Less water required	More water required
Mortality rate of cane plant	Low rate	High rate
No. of tillers per plant	25–30	10–15
Ease for intercropping	More	Less
Accessibility of light and air	More	Less
No. of plants per clump	9–10	4–5
No. of weeds	Less	More
Uniformity	Grading can be done through nursery	No grading

understanding of their capabilities and limitations and because of the difficulties in using them. Another problem seems to be the general lack of model credibility (Marin and Jones 2014). For crop simulations to be reliable, high-quality field data is required for model development, and more effort is needed in the parameterization and validation of models (Surendran et al. 2012; Andrade et al. 2016). Some of the physiological development and growth parameters that appear in model functions vary among sugarcane cultivars and therefore need to be estimated from data in order to predict growth and yield (Marin and Jones 2014). Region-specific calibrations of models are also essential (Andrade et al. 2016). Model calibration is a fundamental step in achieving high accuracy in crop development and yield estimation. Among the several models available in the literature, the Canegro model (Singels et al. 2008), included in the software DSSAT (Hoogenboom et al. 2018), can be applied to help in the interpretation of experimental results and in long-term simulations, to estimate the internal variability of yield, and thus to recommend management practices for sugarcane (Nassif et al. 2012; Hoffman et al. 2018). Since there are differences in growth among sugarcane cultivars, the accuracy of the model depends on its adequate parameterization, being performed according to each genotype.

17.8 SSI Method of Cultivation

17.8.1 Selection of Bud

For raising a healthy nursery, young mother canes are used in the SSI method, which have a good length of 7–8 in and are 7–9 months old. Canes with spots, fungus, and growth disease can be noticed and spotted. The required quantity of canes is cut, and buds are removed from the certain selected cane by a tool called a bud chipper. Bud chipper contains a fixed blade on the wood plank for cutting and a handle. Adjust a cane on a plank in such a way that cutting blade is over the cane and once the handle is pressed, a single bud chip comes off the canes. In this way, about 150/h can be easily cut off. The chipped buds will be treated through a chemical or organic solution. Per acre, 450–500 canes are required (Jain et al. 2009).

17.8.2 Treatment of Buds

Before planting, it is vital to treat the chipped buds with different chemical and organic solutions to avoid infestation. The buds are taken in a tube made of plastic or aluminum. Pour 10 L of water into the tube, and add 20 mL malathion or 5 g carbendazim and 500 g *Pseudomonas* or *Trichoderma*, 1 to 2 L cow urine, and 100 g lime. Put the bud chip in gunny or plastic bag, and dip the bag for 10 to 15 min in the prepared solution. For 2 to 3 h, the bud chip has to be dried in a shady place and then used for the plantation of the nursery (Jain et al. 2010).

17.8.3 Nursery

Young saplings are raised up in the nursery under the shady net. It is an entirely covered structure meant to make favorable conditions like wind-free, warm environment and provide shades. Well-decomposed coco pith is taken for raising nursery, and in the tray, partly fill each cone with coco pith. In the cone of the tray, put the buds in a slightly oblique or flat site, and don't push/press it too hard. Confirm that the faces of bud side up. In trays, the bud chip is entirely covered with coco pith. After filling all the trays, place them all over each other, and have a vacant tray down and top. Roughly, 100 trays are to be positioned together and covered. To create humidity and high temperature, keep the bundles for 5–8 days in the same position, and put a small weight on them. By soaking the soil with chlorpyrifos 50 EC (5 mL/L), take actions to control the termites near the trays. The nursery area must be free from weeds. Bundles can be kept preferably inside a room or in a shade net and tightly covered. If the climate is too cold, then the electric bulb creates artificial warmth. For nursery management, this is the most critical phase. Within

3 to 5 days, under proper conditions (especially warm temperature), primordia (white roots) will come out, and in the next 2–3 days, shoots appear. Either on the fifth or eighth day, based on the climatic condition, the trays must be removed from the polythene sheet and placed on the ground to facilitate watering. The irrigating trays must be started in the evening on the basis of the moisture content of the coco pith for the next 15 days. Leaves will start sprouting, and shoots will start growing strong. After the appearance of two leaves, the use of water should be gradually increased depending on the moisture level in trays. The grading of plants must be done at about 20-day-old seedlings (during the six-leaf stage). For a day, water should not be given to lose the coco pith that allows the easy lift-up of young seedlings. Plants that have a similar height/age can be lifted and placed in one tray. According to their height, grading of plants is attained, and the dead or damaged plant can be detached (Jain 2011).

17.8.4 Preparation of the Main Field

The preparation of the main field is the same as the conventional method. The following step should be followed for better mainland preparation (Gujja et al. 2009).

17.8.5 Removal of Residues

It is very important to prepare the land for sugarcane crop and it needs to be addressed from the planting of the entire crop up to the harvesting. Stalks are to be docile and detached from the arena, and all the remains can be fused into the soil through a rotavator (Nagendran 2009).

17.8.6 Tillage

Tillage operations by a tractor are quick and effective, and it is advisable that one plow for good and already aerated soil conditions and two plows for rough and hard soil are being applied. After plowing, the soil must be kept for an interval of time under good climate for a week or two before going for more tillage operations (Panghal 2010). By using a rotavator or harrows, tillage operation can be carried out. The operations are to be repeated to make the soil bed free from crop residues, weeds, and clods. By using a tractor, the land should be deeply cultivated after tillage operation. If the land is rough, flattening must be done using a leveler. After leveling, to facilitate the easy movement of irrigation water, a gentle slope can be maintained.

17.8.7 Application of Organic Fertilizers

The SSI method boosts the use of organic fertilizer. It increases the content of macro- and micro-nutrients in the soil in an ecofriendly way. It supports the ideal use of some chemical manure that can protect the soil from hazardous effects and degradation. Organic fertilizer like well-rotten press mud/compost/FYM should be utilized (almost 8–10 tons/acre). The amount of organic fertilizer should be adjusted to supply 112 kg of nitrogen/acre with one or more sources. For every 1 kg/acre of *Pseudomonas* and *Trichoderma*, decaying cultures can be combined with the organic fertilizers. Organic matter provides energy and a food source for biological activity. Many nutrients are held in organic matter until soil microorganisms decompose the materials and release them for plant use. This will increase the fertility of soil to realize higher yields.

17.8.8 Construction of Furrows, Ridges, and Transplanting

The distance between rows must be 5 ft to make the furrows. The soil should be aerated by running a subsoiler installed on the plow. This will sustain in deep plantation, a good combination of the fertilizer and prevention of lodging (Galal 2016). From nursery to the mainland, the ideal age of the young seedlings for transplanting is 25–35 days. It is recommended to stop giving water at least 1 day before transplanting. This will loosen the coco pith in cones and aid in the easy lifting of seedlings for transplantation. The planting method is zigzag which can be followed to attain maximum tillers and use more spaces. For easy penetration of sunlight and profuse tilling, the plant-to-plant distance of 2 ft must be maintained. One or 2 days before transplanting, moisten the soil by irrigating the field. Similarly, after planting, instantly apply appropriate irrigation as required according to the type of soil. If the soil is not properly compacted, water will run and air spaces will fill up adjacent to the plant. If the compaction of soil is not good. It is significant to water the field with a small quantity of water instead of swamping (Gujja et al. 2009). The expected outcomes of the Sustainable Sugarcane Initiative are given in Table 17.4.

17.8.9 Reduction in Weed Loss and Mulching

Generally, weed infestation is high during the initial growth stages when the crop is not well established. Weeds suppress the main crop leading to the loss in the production of sugarcane. In SSI, a nursery of sugarcane is grown which reduces competition at initial stages with weeds, and the incident of weeds is reduced by up to 60%. Seedlings are grown in a controlled environment and provided with optimum nutrients until fully established. SSI supports wider spacing which allows the mechanical destruction of weeds in an organic way. In sugarcane cultivation, trash

Table 17.4 Different points of view for the expected outcomes of the Sustainable Sugarcane Initiative

Farmers	Factory	Government
Saving in seed (sets)	Higher cane recovery	Employment generation in rural area
Higher cane yield with net return	Increase in crushing day	Electricity saved can be used for some other purposes
Bringing additional area under cane	Reduction in production cost	Groundwater exploitation can be reduced
More crops in unit area and time	Potential for cogeneration	Higher returns to the government through tax collection from sugarcane industries
Saving on water, labor, and electricity	Additional ethanol production	
Raising cane crop with poor-quality water		
Cultivation cane in marginal and problem soils		
Timely and need-based fertilizer application		

mulching is vital as it aids in developing a competition-free environment in the absence of weeds. Mulching will grow earthworms which in turn will increase the water infiltration and aeration of the soil. Within 3 days of planting, cane trash can be applied at 1.5 tons/acre (Galal 2016).

17.8.10 Fertilizer Application Doses

In cane cultivation, nutrient management is very necessary for the growth of good crop. It is always better to know the quantity of the needed nutrients by testing soil and improving the soil accordingly. If it is not convenient, then phosphorus, potassium, and nitrogen can be applied at the rate of 25 kg, 48 kg, and 112 kg, respectively, by the organic or inorganic method. Muriate of potash, superphosphate, urea, and ammonium sulfate is applied to attain the requirement of nutrients. Under the presence of mulching, a plant can get efficient NPK amount from the soil and due to having a healthy environment during early sprouting, sugarcane becomes resistant against an attack of certain fungus. The mentioned quantity of manures can be applied in two to three split doses for efficient use. At the time of preparation of land, apply organic fertilizers and incorporate green fertilizers into the soil. Moreover, biofertilizers such as rhizobacteria and *Azospirillum* are used, 2 kg each on the 30th and 60th days after planting by mixing it with FYM (200 kg/acre).

17.8.11 Water Management

Flooding in the field is not preferred compared to providing enough water on the required time. In the conventional methods, flooding is done, which supplies more water than the biological demand of the crop resulting in water excessibility, which may affect the growth of the crop. After transplantation, the irrigation frequency may differ depending on crop age, availability of moisture, rainfall, and type of soil. The frequency will be less for clay, and for sandy soil, it will be more. Irrigation is recommended, during the grand growth period (101–270 days) once in 7 days, during the tilling stage (36–100 days) once in 10 days, and during the maturity period (from 271 days till harvest) once in 15 days. Furrow irrigations help in water conservation hence increase water use efficiency. Alternate furrow irrigation means after 7–15 days as per the age of the crop and the moisture content, irrigating the odd numbers of furrows of initially followed through irrigating the even numbers of furrows. This will ensure up to 50% saving of water. Due to the raising of single seedlings and wider spacing in the SSI method, drip irrigation can be practiced efficiently (Gujja et al. 2009).

17.8.12 Earthing Up, De-trashing, and Propping

Earthing up means strengthening the crop stand using soil at the root zone. Generally during a crop period, full and partial two earthing up followed. Fractional earthing up is prepared after the application of the first fertilization, top dressing basically to cover the manure and to provide waterfront to the newly established roots. In this case, a small amount of soil from each furrow side is taken and placed over the manure band. This can also be prepared by the application of a country plow or bullock-drawn tool. Full earthing up is planned after coinciding with peak tilling the second top dressing. For irrigation, the freshly made furrows will be later used (Shanthy and Ramanjaneyulu 2016).

De-trashing means the elimination of additional and unfruitful leaves from the plants. Many leaves are produced by cane, and on average, a normal stalk bears 30–35 leaves in good condition. But only eight to ten leaves are sufficient for effective photosynthesis and the basal leaves do not participate in the method and finally they get dry. However, they would contest for the nutrients or could be utilized for the growth of stalk. The removal of dry leaves is important in the fifth and seventh months and mulch should be applied in interspaces for proper growth.

Propping means supporting the cane to avoid falling. It is generally done by attaching the cane to the leaves. At SSI, on one side of the field, it is suggested to provide a border such as a wooden structure to support housing products. In this way, it is possible to prevent the attachment of the middle leaves around, and thus the creation of its leaves will help in the growth of the crop and save work.

17.8.13 Protection of Plant

Light earthing up, with better water management besides trash mulching, is done on the 35th day. When the age of the crop is 45–60 days, 50 fertilized *Sturmiopsis* parasites/acre are released. When the age of crop is 4–11 months old, at 20 m' distance, the cards pasted with eggs of *Trichogramma chilonis* at 10 cards/acre should be distributed. Sugarcane can be prevented from moths through a variety of ways such as moth destruction by parasite *Isotima jevensis* Rohn, destruction and picking with hand, and selection of bud chips with resistant and disease-free varieties. Male moths can be trapped and destroyed against the third or fourth broods of the pest, release of parasite *Isotima javensis* Rohn, destruction and picking with hand, and selection of bud chips with resistant varieties and disease-free. Similarly, higher yield can be realized by the destruction of affected clumps, optimization of soil moisture, healthy buds, and crop rotation.

17.8.14 Intercropping and Harvesting

In the SSI method of sugarcane with wide spaces between the rows, intercropping in sugarcane with watermelon, cowpea, wheat, brinjal, chickpea, French bean, green gram, potato, and various other crops can be tried. Intercropping may be tried depending on location-specific factors. In the initial stage, intercropping controls up to 60% of weeds and increases the income of the farmer. They act as active mulch and preserve moisture and decrease the attack of the pest by being substitute hosts in several cases. The addition of green manures results in incresed the soil fertility when intercropping is incorporated. In most cases, the harvesting of sugarcane is done with collaboration in the industry. The desired level of sucrose content in the plants will be reached on the tenth month of 1-year crop duration, and they will be prepared for cutting within the next 2 months (Gujja et al. 2009).

17.9 Benefits of the SSI Method

In the tropics and subtropical part of India, this method of cultivation gives higher yield of almost 20–25%. As compared with the traditional method, maturity will be earlier, and crop growth will be healthy. Between the rows and clumps, equal and sufficient spacing allows air circulation and sufficient light improving the growth of the crop. This method permits a farmer to pay individual attention to the crop's pits or crops. It has been found useful under saline water and saline soil irrigated conditions, and it gives better ratoon crops. Age of all shoots will be the same; therefore, there are uniform accumulation of sugar in cane and growth of cane. An important factor is that the seedlings are placed at depth, which will be always moist;

therefore, the yields will not get affected in drought cases or cases of water non-availability (Loganandhan et al. 2013).

In this method, the cost of seed is reduced up to 75%, by using of optimum inputs, controlling weeds up to 60%, reduces delta of water and increasing revenue by efficient use of land. Sugarcane growers are facing the challenges of the high cost of production due to the conventional methods. There is a dire need to replace the conventional method of production with SSI to ensure high productivity by the sustainable use of resources. It leads to the substantial increase in sugarcane productivity, reduces the cost of production, and increases the farmer's income with cumulative effects of sustainable development (Rao 2014). Thus, the focus should be on increasing the production and proper utilization of agriculture practices for the wellbeing of farmers (Loganandhan et al. 2013). This is applicable by the adoption of new innovative methods such as SSI and the involvement of newly developed biotechnological tools (cultivars, gene enhancement) in sugarcane cultivation. The conceptual framework for sugarcane production is to enhance the income level of sugarcane farmers by utilizing available land resources in a more profitable manner. Alongside the need to improve yield and productivity of sugarcane along with disease resistance, the current scenario demands the resistant varieties to mitigate climate change which induced direct effects on the growth and development of sugarcane (Sundara 2011).

17.10 Conclusions

The focus on sustainable development is increasing worldwide. Certified schemes for SSI have become very popular in developed countries. Different countries are using different methods for sugarcane cultivation like the Roundtable on Sustainable Biomaterials (RSB), Better Sugarcane Initiative (BSI), Renewable Energy Directive (RED), Global Bioenergy Partnership (GBEP), and Sustainability Assessment of Food and Agriculture systems (SAFA). In Pakistan, there is no strategy for the cultivation of sugarcanes. There are different factors which are responsible for the low average production of sugarcane. Presently, Pakistan ranks as the third-largest groundwater consumer, accounting for almost 9% of the global groundwater withdrawals. For competitive water users and policymakers, water scarcity has become an increasingly social and economic concern. Almost 50–70% of water is lost due to surface evaporation, transpiration by weeds, and run-off leaching beyond the root zone. At any time, water becomes a limiting factor; when growth is decreased, it ultimately results in decrease in yield. Climate change and excessive use of pesticides are the main reasons for higher input costs, destroying natural biodiversity and causing threat to human health in developing countries. Sugarcane farmers are facing a myriad of challenges that directly or indirectly impact sugarcane production. So, there is a need to introduce sustainable agricultural techniques using the government to enhance the productivity of sugarcane. For this purpose, SSI should be initiated in Pakistan with the special regard to minimize the input costs by reducing the usage of chemical pesticides on sugarcane crops to make them environmental friendly. Therefore, the possible ways to increase sugarcane production to meet the demand of the increasing population are enhancing the capacity building of farmers regarding the proper utilization of resources, proper awareness regarding production practices, and motivating them to adopt new resistant varieties which are more resistant against sugarcane pests and diseases and to adopt innovative technologies such as SSI.

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Chapter 18
Modeling Photoperiod Response of Canola Under Changing Climate Conditions

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Abstract Disturbance in the photoperiod urged cultivars to show variant behavior regarding their phenology. There is evidence of variability in the sensitivity of cultivars to photoperiod causing pre-anthesis phases to respond to the photoperiod differently among them. A field experiment was conducted with eight canola cultivars (i.e., NARC Sarsoon, Punjab Canola, Faisal Canola, ROHI Sarsoon, Super Canola, Cyclone, Crusher and LG-3295) at two variable sites of rain-fed Pothwar. The study sites included the National Agricultural Research Center (NARC) in Islamabad (latitude 38.78 °N, 73.57 °E and 1632 ft. elevation) and URF-Koont in Chakwal (latitude 32.93 °N, 72.86 °E and 1634 ft. elevation). NARC Sarsoon showed significant results during both years of 2019–2020 and 2020–2021 with a mean photoperiod of 9.95 h^{-1} at NARC-Islamabad. Likewise, ROHI Sarsoon responded significantly during both years of 2019–2020 and 2020–2021 with a mean photoperiod of 10.44 and 10.07 h^{-1} at URF-Koont. Because of genetic characteristics (e.g., better yield potentials, early maturity and optimum usage of environmental conditions), these two varieties show excellence over other varieties. The DSSAT CSM-CROPGRO-Canola model confirmed the field results and accurately reproduced the photoperiodic response of canola cultivars. Based on this work it can be recommended that ideotype designing could be an option to mitigate the impact of climate variability, crop simulation modelling and

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effective and sustained implementation of a road map to understand the agricultural environment and climate change. To reduce oilseed imports, governments should offer incentives to farmers for enhancing the production of canola.

Keywords Photoperiod · Climate change · DSSAT CSM-CROPGRO-Canola · Ideotype

18.1 Introduction

The Global Climate Index 2021 survey states that, in a condition of a high susceptibility to climate change, Pakistan is a very low greenhouse gas (GHG) emitting country; however, the vulnerability is because of geographic and diverse climatic conditions, the threat of climatic changes related to water security and food owing to the intrinsic arid climate's association with the high dependency on water from melting glaciers. Climate variability is accepted as a worldwide phenomenon with long-term effects such as growth and change (Ahmed et al. 2022). Therefore, Pakistan is vulnerable to the effects of climate change because of its rapid industrialization.

According to German Watch, Pakistan has been ranked in the top 10 of the countries most affected by climate change during the past 20 years (Economic Survey of Pakistan 2020–2021). The rate of receiving energy from the Sun and its loss into the atmosphere regulates the balance of the world's temperature and climate. This energy is dispersed around the world by the wind and other means that affect the climate of various regions. Variation and increasing temperature throughout the twenty-first century will not be the same, which will cause draught in some countries and floods in other regions that will bring disasters (IPCC 2014). Change in climate is assumed to be troubling for agricultural communities that try to establish a quality yield (Erbs et al. 2015).

Climate change has a damaging effect on canola phenology, resulting in a low seed yield (average 950 kg ha^{-1}) in Punjab, Pakistan. Temperature change has been revealed to be a serious threat to agricultural production systems in developing countries as global studies have shown (Mal et al., 2018). Climate variability results in frequent changes in temperature events. Short-term change in temperature is solid evidence of variations in the flowering of plants, which has been observed by Moss et al. (2022).

Photoperiod refers to the length of the day, which varies with latitude and seasons. It is controlled by the rotation of the earth around the Sun and its tilt. With continuous rotation, the hemisphere is exposed to various amounts of sunlight, thus forming distinct seasons characterized by numerous lengths of day and temperatures. There is no significant difference in day length between years. Therefore, it is a reliable clue for plants to drive their nutritional, metabolic and reproductive behaviors, ultimately leading to regular seasonal rhythms. It is known that climate change has no direct impact on the photoperiod; however, photoperiod can predict environmental factors that directly affect plants' phenology. During evolution, the accuracy of physiological and behavioral photoperiod regulation related to environmental conditions has been selected (Walker et al. 2019).

Environmental conditions that change day and night are essential for the growth and development of plants. The seasonal changes in photoperiod and temperature are segments of the regular rotation of plant growth and reproduction (Shalom et al. 2015). The main factors that influence the flowering of plants are photoperiod and temperature. Long-day plants flower more rapidly as the photoperiod increases. The approach to describing the photoperiod's response of crop species helps breeders accelerate the development of genotypes with the desired responses.

In *Brassica* species, phenological development is altered by photoperiod, temperature and vernalization (Robertson et al. 2002). Photoperiod and temperature are the main abiotic environmental factors that determine the growth and development of crops (Chaturvedi et al. 2018). In view of the observed environmental change trends, it is important to conduct an analysis aimed at describing and selecting plant species that not only have the best performance characteristics but also have the best adaptability to environmental changes (Tchorzewska et al. 2017). In long-day plants, flowering occurs more rapidly because of increases in photoperiod—that is, there is a direct relationship between time to flowering and photoperiod (Torabi et al. 2020).

There is evidence of variability in the sensitivity of cultivars to photoperiod, causing pre-anthesis phases to respond to photoperiod in a different way among them (Pérez et al. 2020). For selecting a suitable environment for a genotype or specie in which it can grow successfully, it is important to determine the photoperiodic parameters of the flowering stage and also for crop growth and yield predictive models' development (Torabi et al. 2020). It is also crucial to estimate the uncertainty, which is related to the results; only considering the crop model results is not enough (Wallach and Thorburns 2017).

Crop simulators have been developed to evaluate the procedures of agronomic management strategies and to help analysts to understand the bridge between ecosystem, production variation, and crop management. To recognize the crop responses, a crop phenological model is a useful tool for accessing plant growth processes that can take years to calculate in the field (Fourcaud et al. 2008). Crop models have been used by many research sponsorships and groups for decision making in the agricultural system (Bannayan and Hoogenboom 2009; Hoogenboom 2000).

To assess the explanation of problems observed in the handling of crops, especially in developing countries where changing climatic conditions prevail, a crop model—that is, a Decision Support System for Agricultural Technology (DSSAT) model—is the best tool to apply in such a situation (Hoogenboom 2000). The crop simulation modeling approach can help quantify the yield of field crops under various climate scenarios. The adoption of the DSSAT model for canola is important to verify crop opportunities in varied climatic conditions. Satisfactory simulated results were observed for the growth parameters of the culture compared to the observed values. Furthermore, it was concluded that the CROPGRO model is an efficient tool for predicting and simulating phenology, growth and crop yield under semi-arid conditions (Boote et al. 1998).

In Pakistan, there are very few studies for assessing the impact of climate change and the adaptability of canola cultivation, which is one of the most important topics in the world. As time goes by, it poses a great threat to food security, so it is necessary to focus on this subject and carry out necessary research work according to the country's climatic conditions. This research was being carried out to simulate the potential impact of climate change on rapeseed in diverse environments, taking into account the importance of it in Pakistan and the topics with the following goals: (1) evaluate of photoperiodic response of canola cultivars, (2) assess the potential impact of climate variability on the growth and yield of canola, (3) apply the DSSAT model in canola evaluation and (4) validate and recommend adaptation strategies using the crop DSSAT model.

18.2 Role of Models in Canola Production

Dreccer et al. (2018) recorded the effects of temperature and water stress on the yield of wheat, barley, canola, chickpea and peas where they were analyzed in four major Australian production areas. In general, canola is the most sensitive to water stress. High temperature in the non-stress range reduces yield because of the specific effects on crops. Jing et al. (2016) reported that the CSM-CROPGRO-Canola model was calculated determining plant and soil data collected from field trials. The model can forecast the attended crop growth and simulate the light-absorption and utilization characteristics of rapeseed.

George and Kaffka (2017) recorded on a *rom,* a multi-environmental Canola variety, experiment to test the ability of the Agricultural Production System Simulator model (APSIM) to simulate canola production in California; it can accurately simulate canola production in various regions. With proper management and variety selection, canola ought to have a higher average yield throughout California. Without other improvements in variety adaptability or management changes, these simulations indicate that California canola production will decline moderately, but that it is still economically viable.

Hoisaini et al. (2012) evaluated that the Lebig–Sprengel (LS) and Mitscherlich–Baule (MB) models were suggested only to clarify the reaction of plants to nutrients and to evaluate the comprehensive response of canola to B and salinity pressure. Water salinity treatment consists of non-saline water—3, 6, 9 and 12 dS m^{-1}. Treatment B is used to add 0, 10, 20 and 30 mg kg^{-1} as H_3BO_3 to the soil. The results show that the improved LS model can satisfactorily predict the dry matter yield of canola. The improved LS model estimates the relative dry matter of the soil B concentration and salinity level; it is near to the consistent relative yield.

Therefore, use of the improved LS model is recommended to estimate the relative yield of canola under salinity and B stress. The threshold of salinity rises with the hike of B consolidation, and the maximum dry-matter yield decreases with the increase of B merging. It was found that excessive B reduced the dry-matter yield of canola. When plants are under both B and salt stress, this effect is inhibited. Irrigation water salinity and B consolidation both impact plant water use efficiency (WUE), but only B concentration affects rapeseed production in the same way.

Qian et al. (2018) recorded that the CSM-CROPGRO-Canola model was used to accept the response of canola to the predicted climate variation of Brandon on the prairies and Sinipishin and Normandine in eastern Canada. Based on the climate variation simulation of the regional climate model, CanRCM4, two representative concentration paths (i.e., RCP4.5 and RCP8.5) were developed for the near (2041–2070) and distant (2071–2100) future climate scenarios. Estimates of the planting dates based on air temperature, precipitation and soil moisture considers the potential of early planting as an adaptation measure.

Compared with the baseline climate, under RCP4.5 the simulated seed production decreases of Brandon, Sinipishin and Normandine are 42%, 21% and 24%, respectively, and in the distant future, respectively, 37%, 27% and 23%. A greater reduction was simulated under RCP8.5, especially with Brandon and Sini Pissin in the distant future. Under the current nitrogen fertilizer application rate, the simulated seed yield reduction is related to the increase of heat and water stress under rain-fed conditions. Barthet et al. (2020) recorded that the Canadian canola samples were harvested in 2016 and 2017 to develop a near infrared (NIR) model of canola quality.

All calibration models were tested for the first time on an external verification sample set in 2017. The handheld NIR spectrometer used in this study had a limited wavelength range of 908.1–1676.2 nm. Yet, the verification results showed that it can be used to predict several important parameters that define the quality of canola. The final test was performed using the calibration model with the fewest number of factors on the second external canola validation sample set (i.e., harvested in 2018). The prediction model of total glucosinolates is not very good, but it still can be used to classify tests into low- or high-glucosinolate samples.

Yordanova et al. (2018) evaluated that the effective analysis carried out by applying accurate models was based on plant growth and yield processes—for example, the feasibility model of canola as a biofuel such as the simulation model of the "Almanac for Agricultural Land Management with Numerical Evaluation Standards." Farre et al. (2007) stated that (1) the canola production history was introduced in the context of long-term climate records; (2) the impact of planting location, rainfall, soil type and soil moisture on yield and oil content was assessed; and (3) a critical sowing date for canola production was determined. He et al. (2015) evaluated that a modeling method was used to assess the canola crop's yield potential and yield gap, that how they are affected by inter-annual climate change and that water requirements using the APSIM-Canola model can narrow the yield gap. Improving water conditions can increase yield and water efficiency.

18.3 Materials and Methods

18.3.1 Study Locations

A field experiment was conducted with eight Canola cultivars (i.e., NARC Sarsoon, Punjab Canola, Faisal Canola, ROHI Sarsoon, Super Canola, Cyclone, Crusher and LG-3295) at two sites of rain-fed Pothwar. The study sites were the National Agricultural Research Center (NARC), Islamabad (latitude 38.78 °N, 73.57 °E and 1632 ft. elevation) and URF-Koont, Chakwal (latitude 32.93 °N, 72.86 °E and 1634 ft. elevation) (Fig. 18.1).

18.3.2 Climatic Conditions During the Canola Growing Seasons

Means of metrological parameters were calculated at NARC-Islamabad during both years, 2019–2020 and 2020–2021. The seasonal rainfall was 555.16 mm during 2019–2020 and 244.86 mm during 2020–2021. Respectively, sunshine hours during 2019–2020 and 2020–2021 were 6.37 h and 6.98 h. Mean maximum temperature was 21.76 °C, whereas mean minimum temperature was 9.31 °C during season 2019–2020. Similarly, during season 2020–2021 mean maximum temperature was 24.28 °C, whereas mean minimum temperature was 8.97 °C. Metrological parameter means were calculated at URF-Koont during both seasons, 2019–2020 and 2020–2021. The seasonal rainfall was 386.4 mm during 2019–2020, whereas seasonal rainfall was 161.4 mm during 2020–2021. Mean hours of sunshine during the growing seasons of 2019–2020 and 2020–2021 was 5.59 h and 5.34 h. Mean maximum temperature was 22.48 °C, whereas mean minimum temperature was 7.7 °C during season 2019–2020. Similarly, during season 2020–2021, mean maximum temperature was 23.85 °C, whereas mean minimum temperature was 7.6 °C.

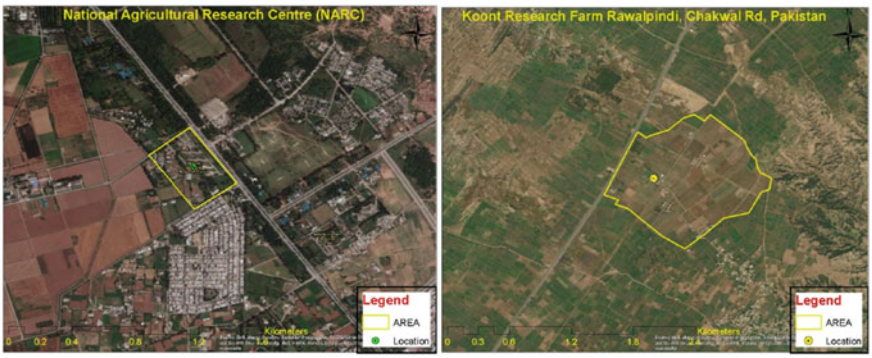

Fig. 18.1 Study sites

18.3.3 Experimental Design and Management Practices

Land preparation was done a week before sowing with some necessary tillage (i.e., 1–2 ploughings). The recommended dose of N-P-K was applied as 90–60–50 kg/hac. The Randomized Complete Block Design (RCBD) with three replications was selected for the experiment. Each plot was consistent on an area of 6 m^2. Seeds were sown with a hand drill at the depth of 1.5 inch with plant-to-plant distance of 10 cm and row-to-row distance of 30 cm. In total, each experimental plot had six lines. The crop was sown in between 16–20 October in years 2019–2020 and 2020–2021 at NARC-Islamabad after preparing the land well with necessary tillage practices. Whereas at URF-Koont, Chakwal, crop was sown in October during both years, 2019–2020 and 2020–2021.

18.3.4 Crop Measurements

During crop data collection, all the phonological stages including days to emergence, DFF, days of flowering, days to maturity, and the harvest index (H.I) were recorded.

18.3.5 Soil Measurements

The soil analysis at a depth of 0–30 cm showed a silt loam texture with organic carbon of 0.80% and PH of 7.60 in NARC-Islamabad. Whereas for URF-Koont, Chakwal, the soil analysis at the depth of 0–30 cm showed a sandy clay loam texture with organic carbon of 0.65% and PH of 8.1 (Tables 18.1 and 18.2).

Table 18.1 Soil physiochemical variables at NARC-Islamabad

Depth (cm)	Sand %	Silt %	Clay %	O.C	B.D	PH	SLL	SDUL	SSAT	Texture
0–30	34	33	33	0.80	1.30	7.60	0.195	0.360	0.450	Silt loam
30–60	32	33	35	0.60	1.35	8.20	0.195	0.350	0.440	Silt loam
60–90	32	33	35	0.41	1.35	8.40	0.200	0.340	0.430	Silt loam

Table 18.2 Soil physiochemical variables at URF-Koont

Depth (cm)	Sand %	Silt %	Clay %	O.C	B.D	PH	SLL	SDUL	SSAT	Texture
0–30	56	22	22	0.65	1.45	8.1	0.151	0.245	0.417	Sandy clay loam
30–60	56	20	24	0.45	1.45	8.8	0.151	0.245	0.417	Sandy clay loam
60–90	54	20	26	0.31	1.50	8.5	0.145	0.245	0.417	Sandy clay loam

Where *O.C* organic carbon, *B.D* bulk density, *SLL* soil lower limit, *SDUL* soil density upper limit, *SSAT* soil saturation

18.3.6 Modeling Flowering Phase

During the modeling phase, various modifier functions were used to predict flowering. Some of the temperature and photoperiod tasks were used to access the temperature and photoperiod effects on flowering as developed by Torabi et al. (2020). Diverse functions of temperature and photoperiod are described in the following sections.

18.3.6.1 Temperature Function

Segmented Function (S)

$$f\ (T) = \frac{(T - T_{\mathrm{b}})}{(T_{\mathrm{o}} - T_{\mathrm{b}})}\ (\text{if } T_{\mathrm{b}} < T < = T_{\mathrm{o}})$$

$$f\ (T) = \frac{(T_{\mathrm{c}} - T)}{(T_{\mathrm{c}} - T_{\mathrm{o}})}\ (\text{if } T_{\mathrm{o}} < T < = T_{\mathrm{c}})$$

$$f(T) = 0\ \ (\text{if } T < = T_{\mathrm{b}} \text{ or T} = > T_{\mathrm{c}})$$

where T is the average temperature from emergence to flowering; T_b is the base temperature, which was 5 °C; T_o denotes the optimum temperature, 26 °C; and T_c stands for ceiling temperature, which was 40 °C.

18.3.6.2 Photoperiod Function

$$f(\mathrm{PP}) = 1 - (P_{\mathrm{c}} - \mathrm{PP}) \times P_{\mathrm{S}}$$

Negative Exponential Function

$$f(\mathrm{PP}) = \exp\left[-P_{\mathrm{S}} \times (P_{\mathrm{c}} - \mathrm{PP})\right]$$

In the negative exponential (NE) function, PP denotes photoperiod (hd^{-1}); critical photoperiod is denoted by P_c below which the rate of development decreases because of the short photoperiod. P_S stands for photoperiod sensitivity.

18.3.7 Model Description

The CSM-CROPGRO-Canola model can predict growth and other crop parameters. It also provides templates for species, ecotypes, and cultivar traits. This model has a generic approach that facilitates simulations for the crop and its phonological responses. The model needs input files (e.g., soil, weather, coefficients, eco, and cultivar) to simulate results accurately. The simulated values were compared with observed values. A CSM-CROPGRO-Canola model can predict the phenology and other aspects of a crop (e.g., growth and yield).

18.3.8 Model Calibration

I. *Manual genetic parameter estimations*. Genetic parameters were generated manually based on observed data for each location (i.e., NARC-Islamabad and URF-Koont) during both growing seasons of 2019–2020 and 2020–2021. First, coefficients were generated by GEN for each cultivar then they were manually adjusted for each cultivar according to their respective responses.

II. *Genetic parameter estimations with the DSSAT-GLUE package*. To minimize the error between observed and simulated, data calibration is required. Two tools of the DSSAT model—Generalized Likelihood Uncertainty Estimation (GLUE) and Genetic Coefficient Calculator (GENCALC)—were used for calibration. In the CROPGRO-Canola model, by running these tools, genetic parameters were calibrated and then repeated adjustments were made manually until simulated parameters close to the observed data were reached. Accuracy of the model then was checked with statistical measurers—that is, root mean square error (RMSE), R^2 and d-index.

18.3.8.1 Upscaling Strategies for Cultivar Parameters in Regional Simulation of Canola Growth

On the basis of the two experimental sites, two upscaling strategies for the estimations of cultivar genetic parameters of canola were established and evaluated. To understand these, strategies could be split into two distinct solutions. Based on two different locations' 2 years of crop data (i.e., days to anthesis, days of flowering, days to maturity, leaf area index, biological yield, grain yield, and harvest index) genetic parameters were established directly for the first kind of solution. The second solution mainly focused on the distribution of genetic parameters across the experimental sites—NARC-Islamabad and URF-Koont—in both growing seasons of 2019–2020 and 2020–2021. In simulation of days to anthesis, days of flowering, days to maturity, leaf area index, biological yield, grain yield, and harvest index, these strategies were compared.

18.3.8.2 Strategy 1: Single-Site Parameter

For the single-site parameter (SSP) strategy, the authors used all eight cultivars that were sown at the two different locations of NARC-Islamabad and URF-Koont during two growing seasons, 2019–2020 and 2020–2021. Each cultivar was parameterized to determine simulation uncertainty caused by the eight cultivars. For each site based on 2 years, 2019–2020 and 2020–2021, of observed days to anthesis, days of flowering, days to maturity, leaf area index, biological yield, grain yield, and harvest index, cultivar genetic parameters were estimated with DSSAT-GLUE.

18.3.8.3 Strategy 2: Virtual Cultivar Parameters Generated from Posterior Parameter Distributions

From posterior parameter distributions, virtual cultivar parameters (VCPs) were generated for various scenarios under several climatic condition and for two locations for both growing seasons.

18.3.9 Model Performance Evaluation

In the current study, the DSSAT's CSM-CROPGRO module was tested for canola phenology, days to first flower (DFF), days to anthesis (DTA), days to end of flowering (EOF), days to maturity (DTM), biological yield, grain yield, and harvest index (H.I), which were the main components for optimum crop productivity. These stages were thoroughly scattered around the 1:1 line. The comparison of model performance was measured by using validation skill scores (i.e., R^2, RMSE, d-index).

18.3.10 Statistical Analysis

An analysis of variance (ANOVA) was performed to check the significant differences between means of various parameters for eight cultivar treatments, and two locations for the year 2020–2021 canola growing season. The ANOVA also was performed to find the significance of the effects of Y, L, Cv and all possible interactions on yield and other parameters. Multiple regression analysis and correlation analysis were performed to show the relationship of various parameters with yield and the direct and indirect effects of these parameters on yield.

18.4 Results and Discussion

18.4.1 Climatic Parameters

18.4.1.1 Metrological Characteristics of NARC-Islamabad

Weather conditions prevailing during study seasons were shown earlier in Figs. 18.1 and 18.2. Means of metrological parameters were calculated at NARC-Islamabad during both years 2019–2020 and 2020–2021. The seasonal rainfall was 555.16 mm during 2019–2020, whereas seasonal rainfall was 244.86 mm during 2020–2021. Mean maximum temperature was 21.76 °C, whereas mean minimum temperature was 9.31 °C during season 2019–2020. Similarly, during season 2020–2021 mean maximum temperature was 24.28 °C, whereas mean minimum temperature was 8.97 °C.

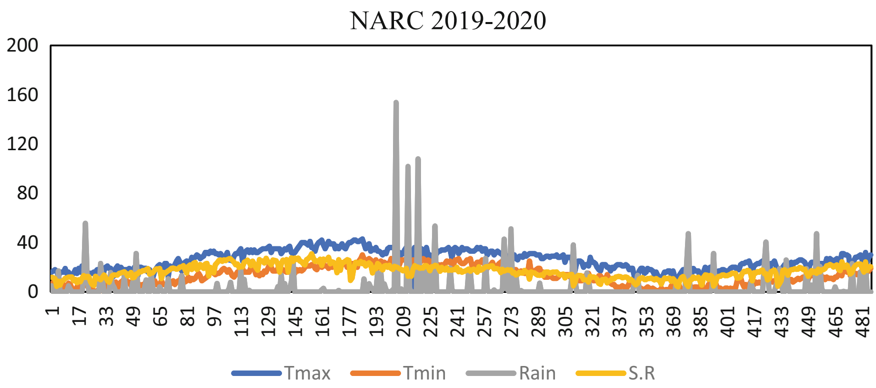

Fig. 18.2 Metrological characteristics of NARC-Islamabad during growing season 2019–2020

18.4.1.2 Metrological Characteristics of URF-Koont

Weather conditions prevailing during the study seasons are shown in Figs. 18.3 and 18.4. Means of metrological parameters were calculated at URF-Koont during both seasons, 2019–2020 and 2020–2021. The seasonal rainfall was 386.4 mm during 2019–2020, whereas seasonal rainfall was 161.4 mm during 2020–2021. Mean

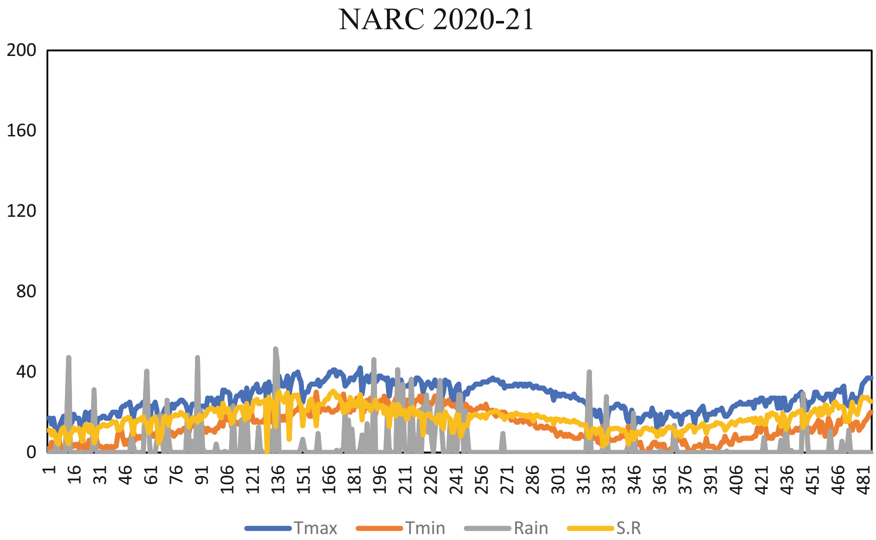

Fig. 18.3 Metrological characteristics of NARC-Islamabad during growing season 2020–2021

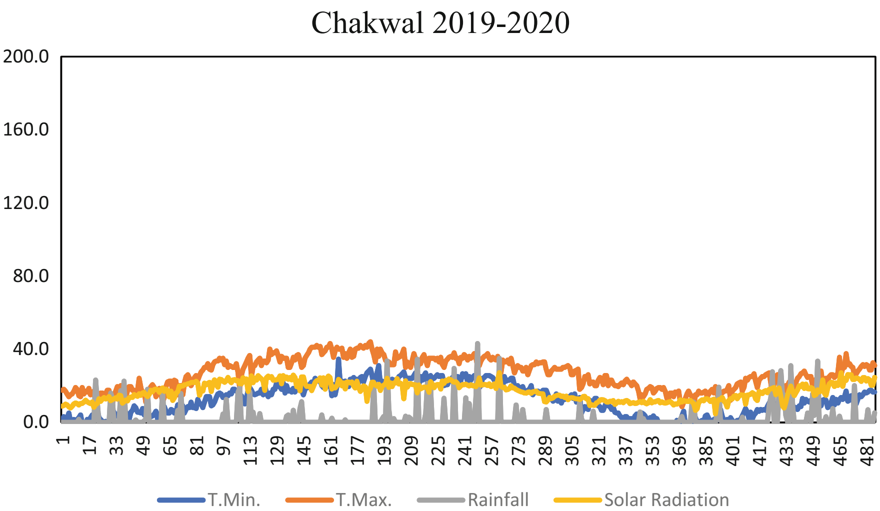

Fig. 18.4 Metrological characteristics of URF-Koont during growing season 2020–2021

maximum temperature was 22.48 °C, whereas mean minimum temperature was 7.7 °C during season 2019–2020. Similarly, during season 2020–2021 mean maximum temperature was 23.85 °C, whereas mean minimum temperature was 7.6 °C.

18.4.2 Agronomic Parameters

18.4.2.1 Days to Emergence

During the 2019–2020 growing season at NARC-Islamabad, seedlings emerged after 4–5 days from sowing; whereas during season 2020–2021 at NARC-Islamabad, seedlings emerged after 5 days from sowing. Similarly, during growing season 2019–2020 at URF-Koont, seedlings emerged above ground level after 7 days from sowing; whereas during growing season 2020–2021 at URF-Koont, seedlings emerged after 6–7 days from sowing.

18.4.2.2 Days to Anthesis

A significant difference was observed in DTAof all cultivars over the locations shown in Table 18.3. Days to anthesis of all eight cultivars had significant differences around the two locations of NARC-Islamabad and URF-Koont. Statistical analysis showed a highly significant difference among L, Y, Cv, L × Cv, whereas all the other interactive effects—namely, L × Y, Y × Cv, L × Y × Cv—were not significant at $p \leq 0.05$. During 2019–2020 and 2020–2021 at NARC-Islamabad, maximum number of DTAwere observed for Cyclone (103 days) and Cyclone (102 days), whereas minimum number of DTAduring both seasons were observed for the cultivars Faisal Canola (78 days) and Faisal Canola (75 days), respectively.

Similarly, during 2019–2020 and 2020–2021 at URF-Koont, minimum number of DFF were recorded for ROHI Sarsoon (57 days) and ROHI Sarsoon (54 days), whereas maximum number of days for the first season were recorded for Faisal Canola (77 days) and Super Canola (77 days); and for the second season, maximum DTAwas for Super Canola (75 days). The photoperiodic response plays an important role in controlling circadian cycles, increasing the expression of *CONSTANS* (*CO*) proteins under long days. In light of these results, there is evidence of variability in the sensitivity of cultivars to photoperiod (Slafer and Rawson 1994; Miralles and Richards 2000; González et al. 2003; Whitechurch et al. 2007), causing pre-anthesis phases to respond to current photoperiod in a different way among them. For visual comparison between cultivars at two different locations over two growing seasons, see Figs. 18.5, 18.6, 18.7 and 18.8.

Table 18.3 Three dependent variables, ANOVA table with DOF, F values and significant levels of fixed effects

	F values and significant levels of fixed effects							
Source	DF	DFF	DOF	DTM	LAI	B.Y	G.Y	H.I
R	2							
L	1	6989.03***	3216.7***	2192.3***	3313.22***	361.1***	5054.5***	199.9***
Y	1	153.1***	975.9***	189.6***	17823.4***	3509.0***	34196.8***	792.5***
Cv	7	449.8***	530.9***	246.0***	2111.03***	299.4***	4350.6***	184.4***
L × Y	1	2.28NS	20.7***	27.0***	735.64***	74.3***	462.5***	6.6**
L × Cv	7	273.1***	267.0***	224.01***	544.96***	86.7***	1011.5***	56.5***
Y × Cv	7	1.76NS	37.1***	10.90***	131.96***	28.3***	97.5***	17.0***
L × Y × Cv	7	1.65NS	32.2***	13.58***	194.72***	26.92***	92.3***	5.0**
Error	62							

**Significant level at 0.05 level, ***Significant level at 0.01 level, *R* replication, *L* locations, *Y* years, *Cv* cultivars, *L* × Y interaction of locations and years, *L* × *Cv* interaction of locations and cultivars, *Y* × *Cv* interaction of years and cultivars, *L* × *Y* × *Cv* interaction of locations, years and cultivars

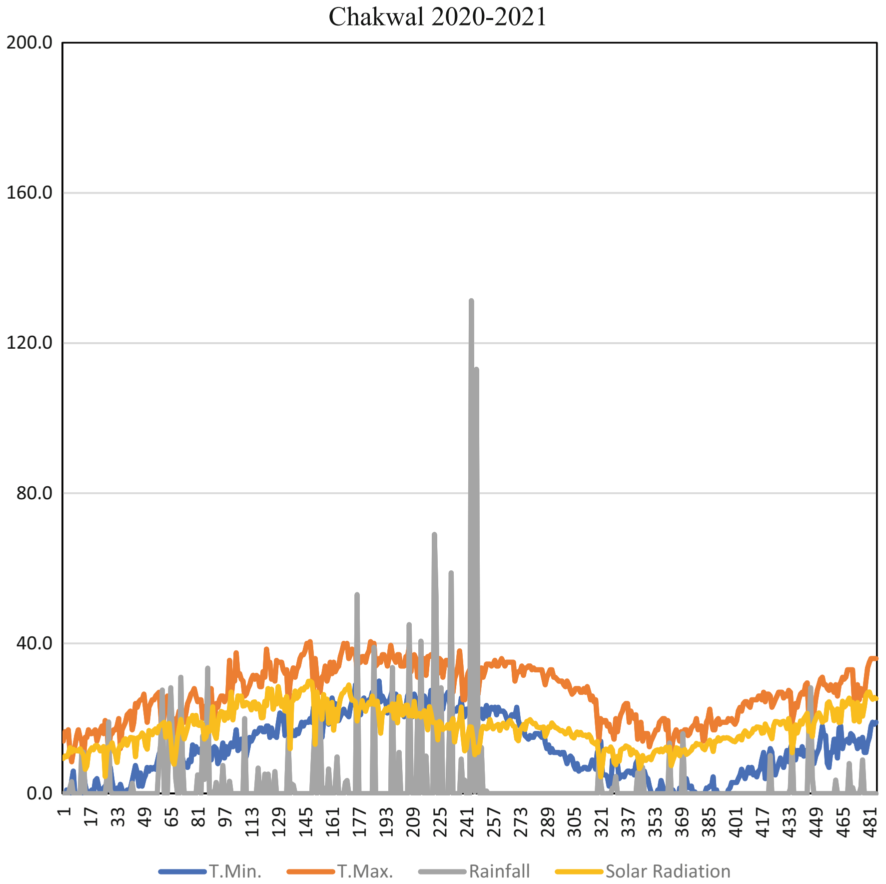

Fig. 18.5 Metrological characteristics of URF-Koont during growing season 2020–2021

18.4.2.3 Days to End of Flowering

Days to EOFvaried significantly at two different climatic locations, NARC-Islambad and URF-Koont, over the 2 years shown in Table 18.3. The ANOVA table shows that Y, L, Cv and all the interactions—L × Y, L × Cv, Y × Cv, L × Y × Cv—were significantly different at $P \leq 0.05$, maximum number of days. During the growing seasons 2019–2020 and 2020–2021 at NARC-Islamabad, maximum number of days were observed for LG-32 (126 days) and Cyclone (123 days), whereas minimum number of days was recorded for Faisal Canola (115 days) and ROHI Sarsoon (100 days).

Likewise, during the growing seasons 2019–2020 and 2020–2021 at URF-Koont, maximum number of days to EOFwere recorded for Faisal Canola (118 days) and Super Canola (114 days), whereas minimum number of days was

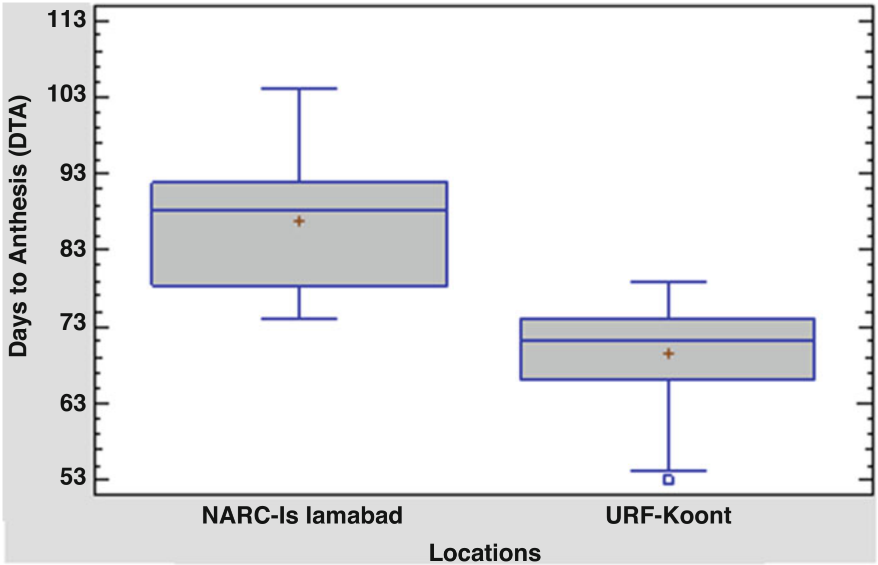

Fig. 18.6 DTA at different locations of NARC-Islamabad and URF-Koont

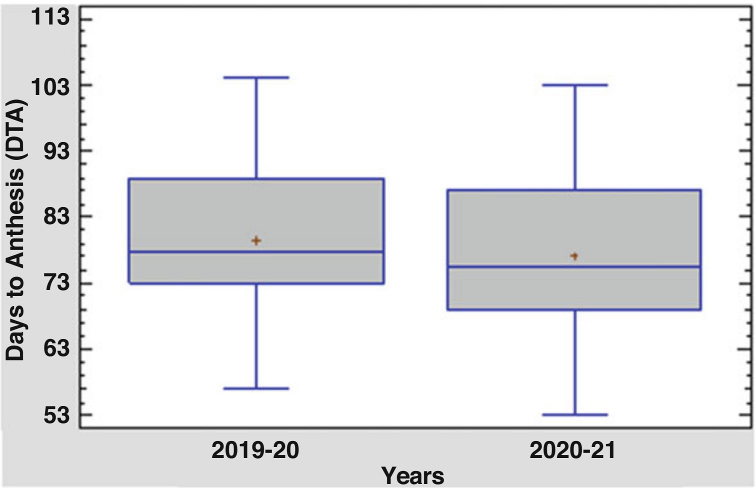

Fig. 18.7 DTA during both growing seasons of 2019–2020 and 2020–2021

observed for ROHI Sarsoon (88 days) and Sarsoon (81 days). Length of the flowering stage and growth period are key grain yield determinants for canola (Diepenbrock 2000). Comparison of two growing seasons at two separate locations are shown in Figs. 18.9, 18.10 and 18.11.

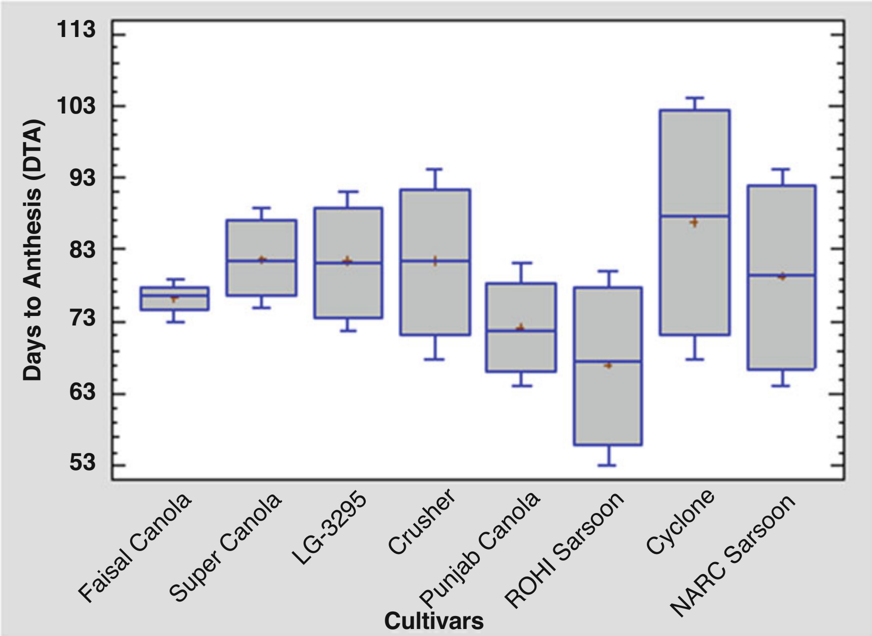

Fig. 18.8 DTA for all the cultivars

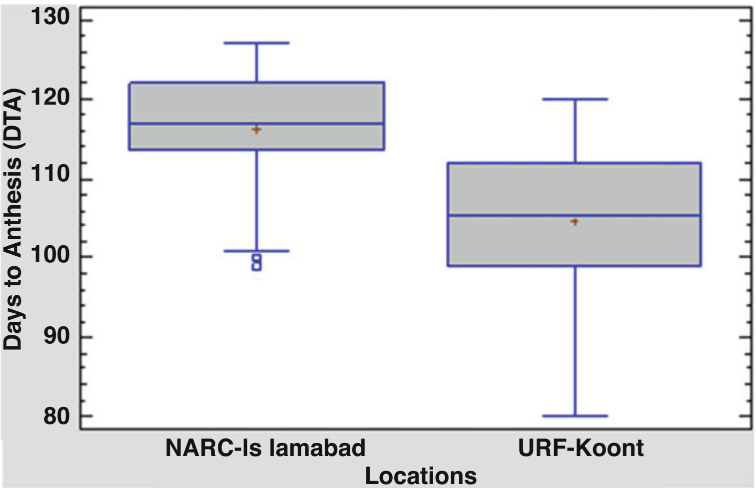

Fig. 18.9 DOF at the two locations of NARC-Islamabad and URF-Koont

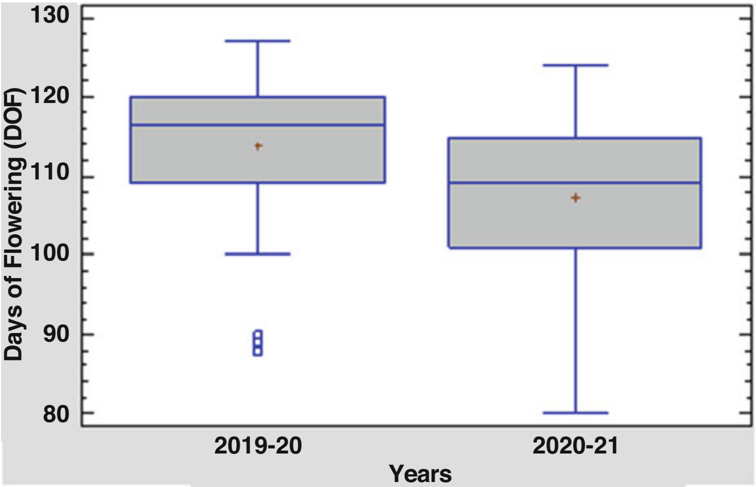

Fig. 18.10 DOF during both growing seasons of 2019–2020 and 2020–2021

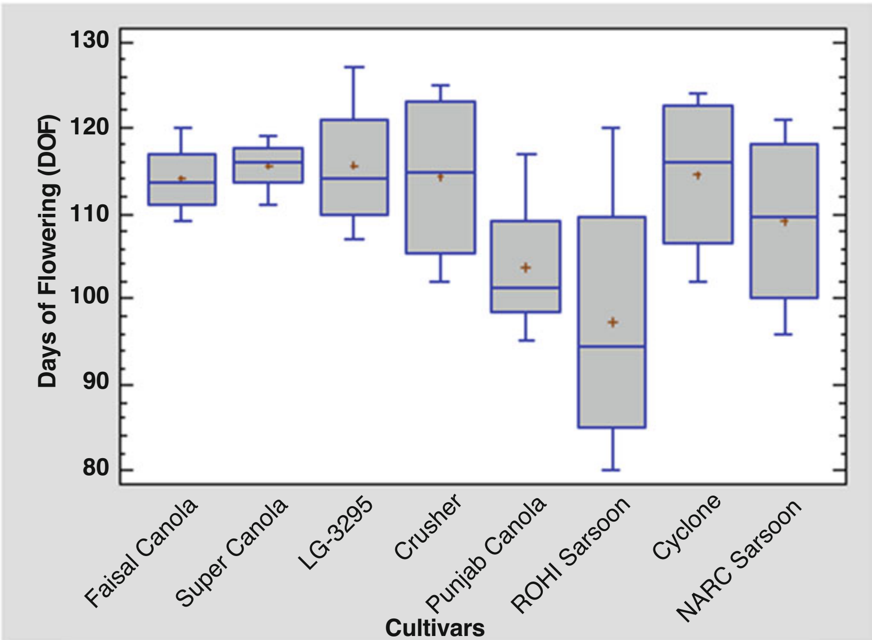

Fig. 18.11 DOF for all the cultivars

18.4.2.4 Days to Maturity

Days to maturity (DTM) was significantly influenced by the treatments. Statistical analysis showed that all treatments, L, Y, Cv and their interactions—L × Y, L × Cv, Y × Cv, L × Y × Cv—were highly significant at $P < 0.05$, as shown in Table 18.3. During 2019–2020 and 2020–2021 at NARC-Islamabad, maximum DTM were observed for cultivars Crusher (186 days) and Cyclone (186 days), whereas minimum DTM were observed for Faisal Canola (172 days) and ROHI Sarsoon (170 days). Similarly, during 2019–2020 and 2020–2021 at URF-Koont, maximum number of DTM were observed for Super Canola (180 days) and two cultivars for the second season, Super Canola (172 days) and Faisal Canola (173 days); whereas minimum number of DTM were observed for cultivars ROHI Sarsoon (156 days) and ROHI Sarsoon (152 days), respectively (see Figs. 18.12, 18.13 and 18.14).

18.4.2.5 Leaf Area Index

An ANOVA table shows that all the treatments, L, Y, Cv and their interactions—L × Y, L × Cv, Y × Cv, L × Y × Cv—were highly significant at $P < 0.05$, as shown in Table 18.3. During both growing seasons 2019–2020 and 2020–2021, maximum leaf area index (LAI) was observed for cultivars NARC-Sarsoon (4.89) and NARC-Sarsoon (4.65), whereas minimum LAI was observed for Faisal Canola (4.04) and Faisal Canola (3.28) for both seasons. In addition, during 2019–2020 and 2020–2021 at URF-Koont, maximum LAI was witnessed for cultivars ROHI Sarsoon (4.75) and ROHI Sarsoon (4.17), whereas minimum LAI for both seasons was observed for Faisal Canola (3.64) and Faisal Canola (3.21) (see Figs. 18.15, 18.16 and 18.17).

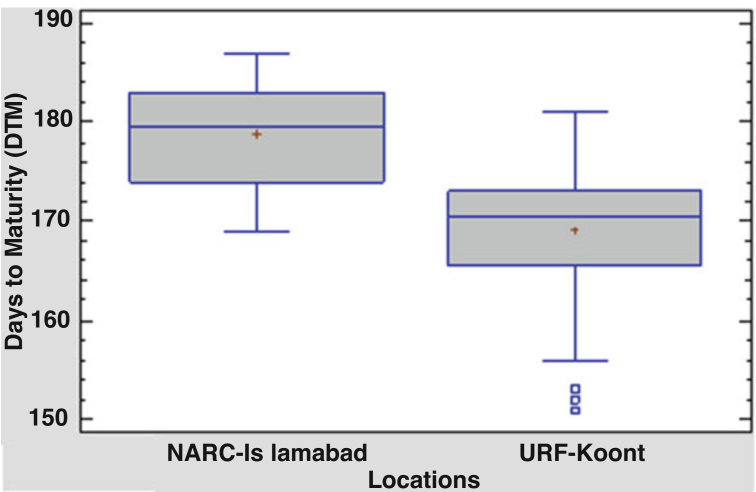

Fig. 18.12 DTM at the two locations of NARC-Islamabad and URF-Koont

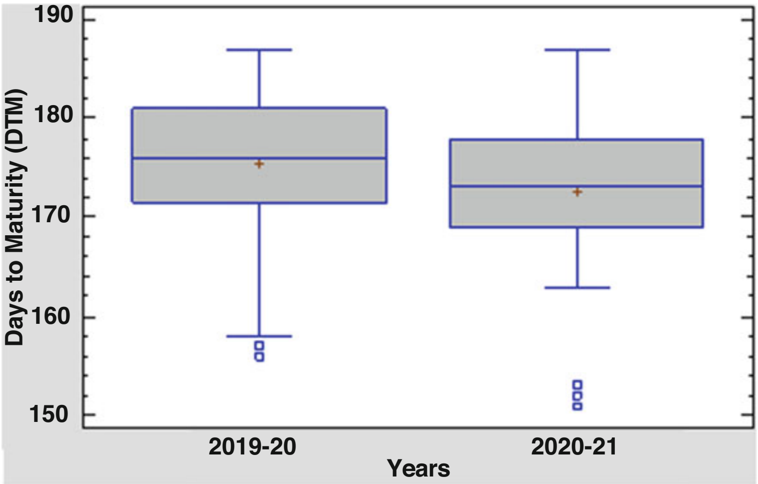

Fig. 18.13 DTM during both growing seasons of 2019–2020 and 2020–2021

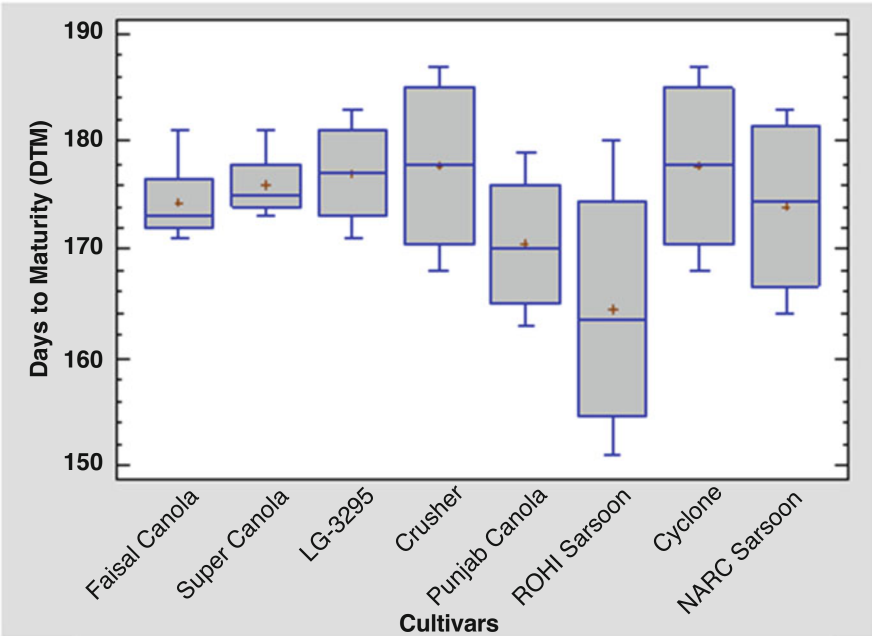

Fig. 18.14 DTM for all cultivars

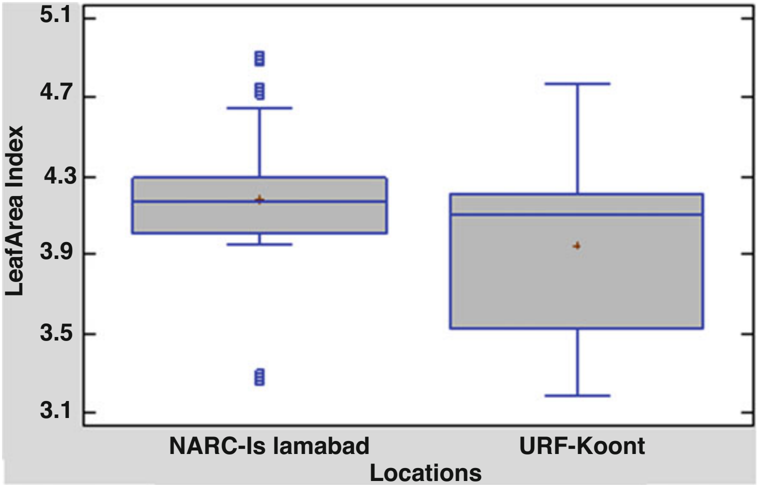

Fig. 18.15 LAI at the two locations of NARC-Islamabad and URF-Koont

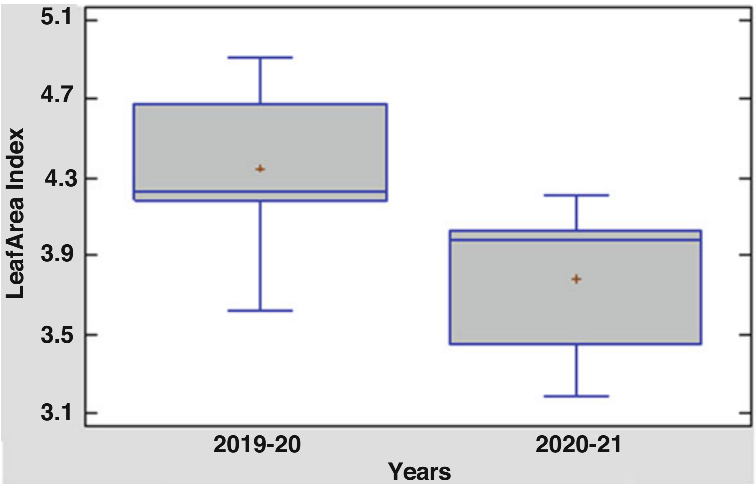

Fig. 18.16 LAI during both growing seasons of 2019–2020 and 2020–2021

18.4.2.6 Biological Yield

Results from data analysis show that all the treatments, L, Y, Cv and their interactions—L × Y, L × Cv, Y × Cv, L × Y × Cv—were highly significant at $P < 0.05$, as shown in Table 18.3. During both growing seasons 2019–2020 and 2020–2021 at NARC-Islamabad, highest biological yield was observed for Super Canola (13,854 kg/hac) and NARC Sarsoon (13,094 kg/hac), whereas lowest

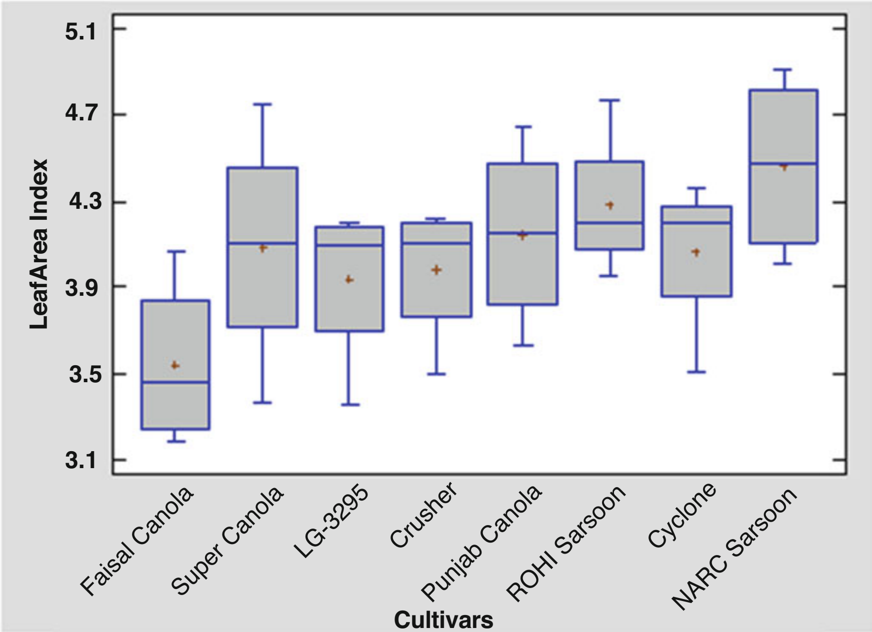

Fig. 18.17 LAI for all cultivars during both seasons 2019–2020 and 2020–2021

biological yield was observed for LG-3295 (12,770 kg/hac) and Faisal Canola (11,034 kg/hac). In the same way, during seasons 2019–2020 and 2020–2021 at URF-Koont, highest biological yield was observed for ROHI Sarsoon (13,768 kg/hac) and NARC-Sarsoon (12,165 kg/hac); whereas lowest biological yield was tracked for Faisal Canola (11,545 kg/hac) and LG-3295 (10,911 kg/hac). Increasing temperature adversely affected crop biomass. Among locations at NARC-Islamabad, there were relatively lower temperatures than in URF-Koont, which accelerated the life cycle. So, biomass production was not good at URF-Koont as compared to NARC-Islamabad (see Figs. 18.18, 18.19 and 18.20).

18.4.2.7 Grain Yield

Grain yield varied considerably among the eight cultivars at varying locations (i.e., NARC-Islamabad and URF-Koont) during both the 2019–2020 and 2020–2021 seasons. An ANOVA table shows that the treatments, L, Y, Cv and their interactions—L × Y, L × Cv, Y × Cv, L × Y × Cv—were significantly different at $p \leq 0.05$ (see Table 18.3). Throughout 2019–2020 and 2020–2021 at NARC-Islamabad, high-yielding cultivars were NARC Sarsoon (2930 kg/hac) and NARC Sarsoon (2670 kg/hac), whereas low-yielding cultivars were Faisal Canola (2230 kg/hac) and Faisal Canola (1860 kg/hac). Correspondingly, during 2019–2020 and

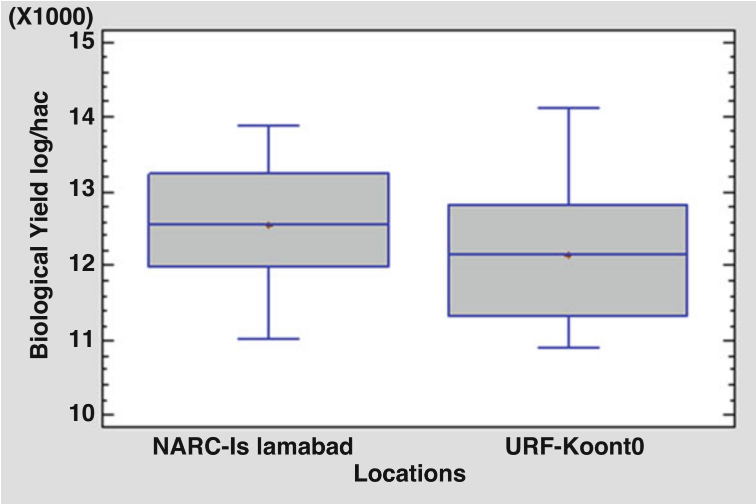

Fig. 18.18 Biological yield at the two locations of NARC-Islamabad and URF-Koont

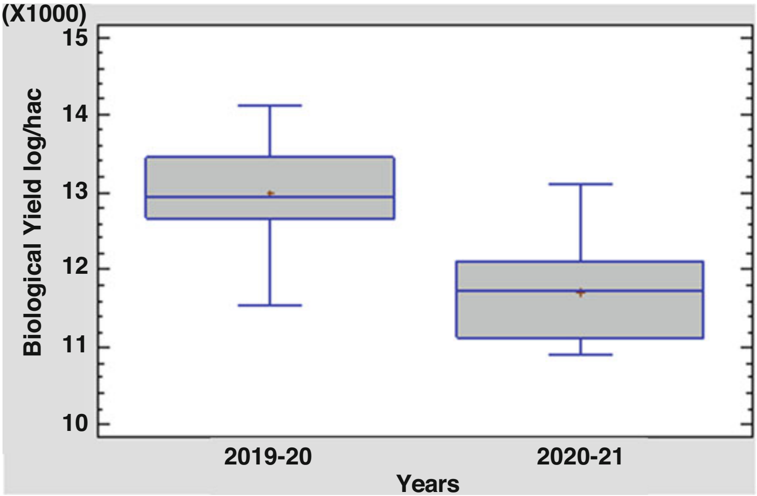

Fig. 18.19 Biological yield during both growing seasons of 2019–2020 and 2020–2021

2020–2021 at URF-Koont, high-yielding cultivars were NARC Sarsoon (2737 kg/hac) and ROHI Sarsoon (2331 kg/hac), whereas low-yielding cultivars were Faisal Canola (2115 kg/hac) and Faisal Canola (1762 kg/hac) (see Figs. 18.21, 18.22 and 18.23). High temperatures significantly reduced the grain yield of canola because of the shortening of the reproductive growth stage (Chaudhary et al. 2020). The length of the flowering stage and growth period are key grain yield determinants for canola (Diepenbrock 2000).

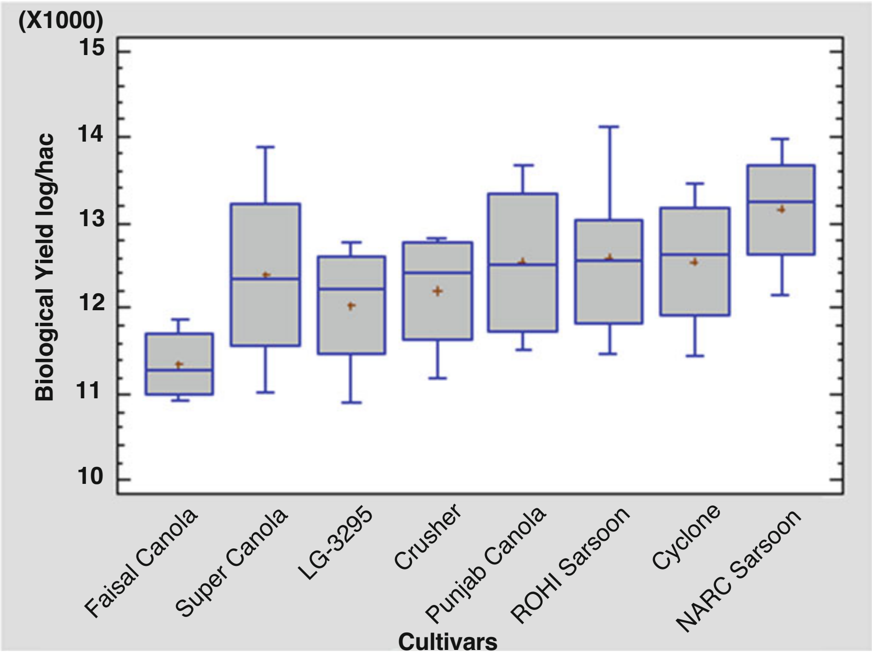

Fig. 18.20 Biological yield for all the cultivars

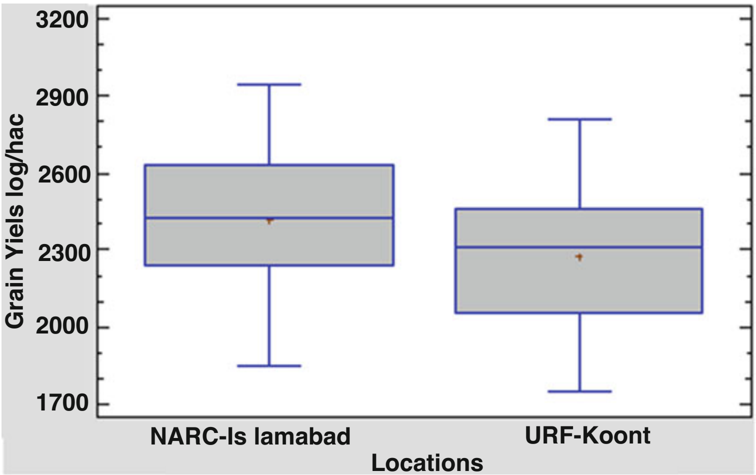

Fig. 18.21 Grain yield at the two locations of NARC-Islamabad and URF-Koont

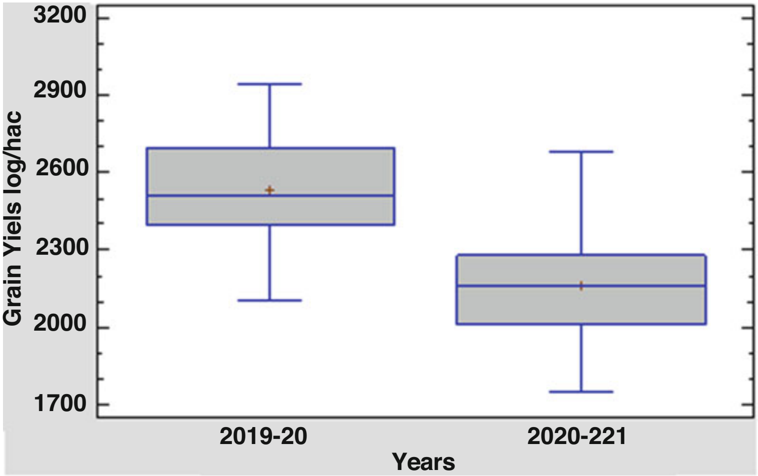

Fig. 18.22 Grain yield during both growing seasons of 2019–2020 and 2020–2021

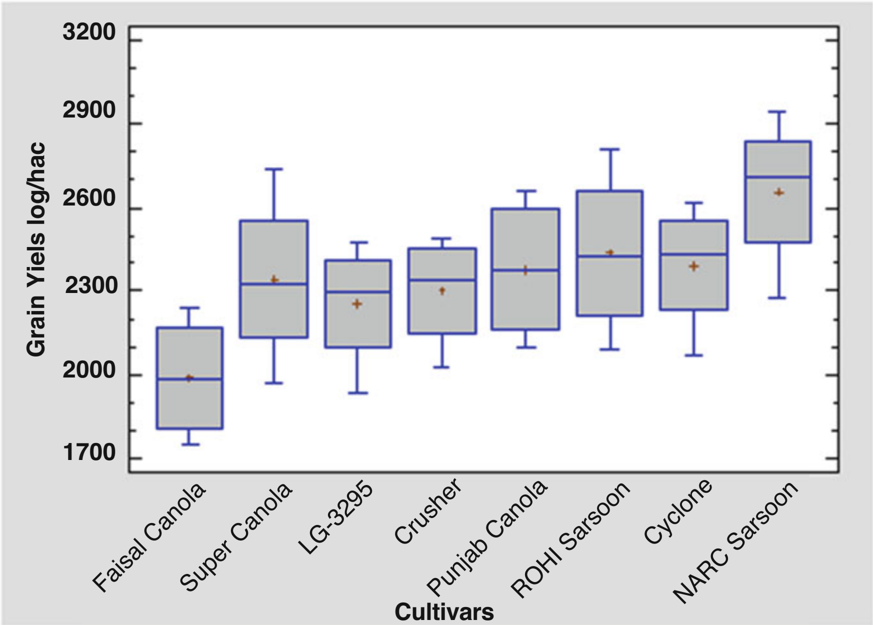

Fig. 18.23 Grain yield of all cultivars

18.4.2.8 Harvest Index

Harvest index (H.I) significantly differs for all the eight cultivars at varying locations (i.e., NARC-Islamabad and URF-Koont) during both seasons (2019–2020 and 2020–2021). An ANOVA table explains that all the treatments, L, Y, Cv and their

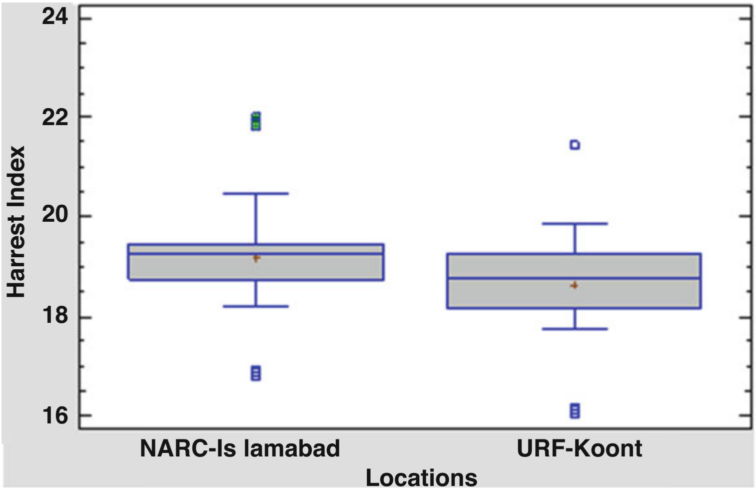

Fig. 18.24 H.I at the two locations of NARC-Islamabad and URF-Koont

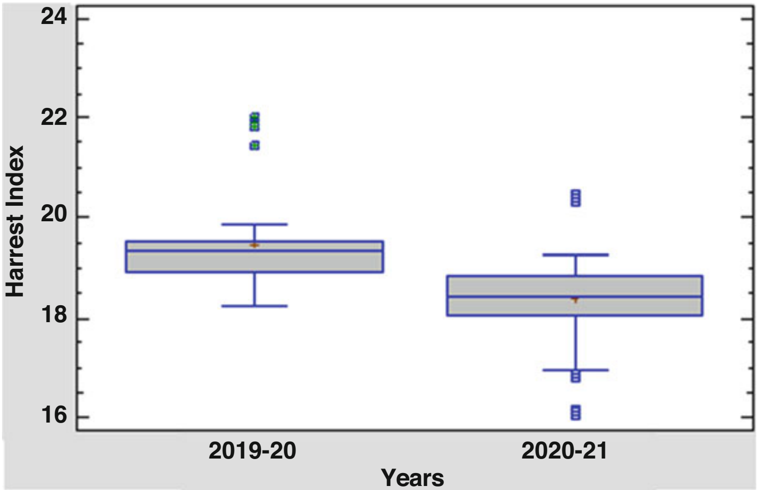

Fig. 18.25 H.I during both growing seasons of 2019–2020 and 2020–2021

interactions—L × Y, L × Cv, Y × Cv, L × Y × Cv—were significantly different at $p < 0.05$ (see Table 18.3). During 2019–2020 and 2020–2021 at NARC-Islamabad, cultivars with maximum H.I were NARC Sarsoon (21.9) and NARC Sarsoon (20.39), whereas cultivars with minimum H.I were Faisal Canola (18.80) and Faisal Canola (16.11).

On the contrary, during 2019–2020 and 2020–2021 at URF-Koont, maximum H.I was observed for ROHI Sarsoon (20.84) and ROHI Sarsoon (19.17), whereas cultivars with minimum H.I were Faisal Canola (18.31) and Faisal Canola (16.11) (see Figs. 18.24, 18.25 and 18.26). Grain size is reduced by increases in temperature.

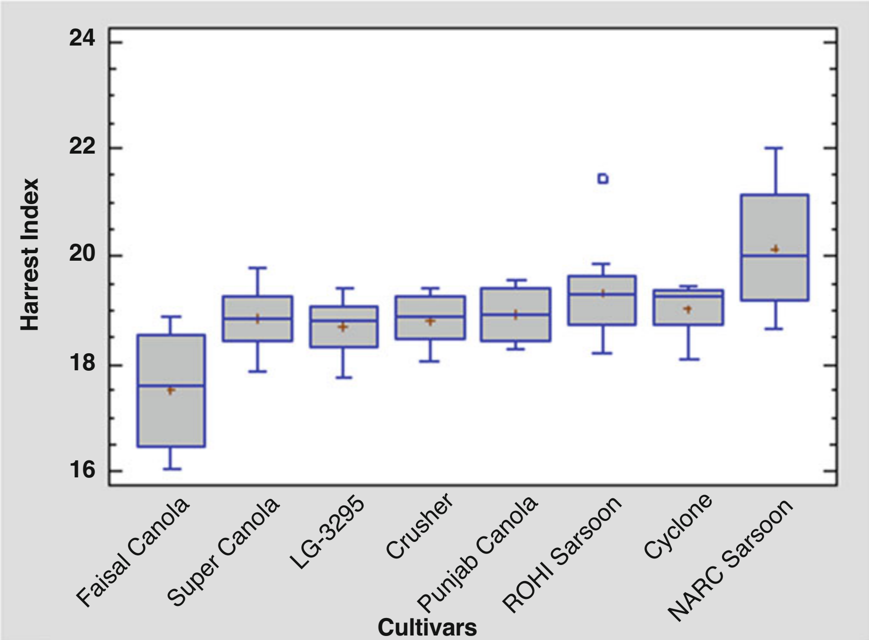

Fig. 18.26 H.I index of all cultivars

By reduction in grain size and weight, H.I decreases. Among the locations, URF-Koont had a higher temperature than NARC-Islamabad. Increases in temperature were observed over the years, resulting in reduction of grain size and weight (i.e., harvest index).

18.4.3 Simulation Outcomes

18.4.3.1 Phenology

Results showed that predicted days to anthesis at Islamabad during the growing season of 2019–2020 were a comparatively close correlation to observed days. At NARC-Islamabad, maximum DTAwere observed for Cyclone (103) and minimum number of DTAwere for ROHI Sarsoon (79). Meanwhile, maximum and minimum simulated days were recorded for Cyclone (103 days) and Faisal Canola (77 days), whereas the average number of stimulated days was 87.8 and observed days was 88. The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 0.61 and 0.99.

During 2019–2020 at URF-Koont, maximum simulated days for anthesis were counted for two cultivars, Faisal Canola (77 days) and Super Canola (77 days), and maximum observed days were the same as model simulated Faisal Canola (77 days) and Super Canola (77 days). Minimum simulated number of DTAwere for ROHI Sarsoon (57), which is exactly as observed for ROHI Sarsoon (57). The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.98, 0.57 and 0.99, whereas the average simulated and observed number of days were 70.625 and 70.625. For the growing season 2020–2021 at NARC-Islamabad, maximum and minimum simulated DTAwere for Cyclone (100 days) and Faisal Canola (77 days), whereas maximum and minimum observed DTAwere for Cyclone (102 days) and Faisal Canola (75 days).

The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 1.19 and 0.99. The average simulated and observed days were 87.25 and 85.625, whereas during the 2020–2021 growing season at URF-Koont, maximum and minimum simulated DTAwere for Super Canola (75 days) and ROHI Sarsoon (56 days); whereas maximum and minimum observed days were for Super Canola (75 days) and ROHI Sarsoon (54 days). The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.98, 0.93 and 0.99. The average simulated and observed days were 68.5 and 65.75.

Simulated days to EOFwere close to observed days. During 2019–2020 at NARC-Islamabad, maximum and minimum simulated days were for LG-3295 (125 days) and Faisal Canola (114 days), whereas maximum and minimum observed days were for LG-3295 (126 days) and Faisal Canola (115 days). The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 0.59 and 0.99. Similarly, during 2019–2020 at URF-Koont, maximum and minimum simulated days to EOFwere for Faisal Canola (77 days), Super Canola (77 days) and ROHI Sarsoon (57 days); whereas maximum and minimum observed days to EOFwere the same as the model predicted—Faisal Canola (77 days), Super Canola (77 days) and ROHI Sarsoon (57 days).

The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.98, 0.57 and 0.99. For the second season, 2020–2021 at NARC-Islamabad, maximum and minimum simulated DOF were for LG-3295 (125 days) and Faisal Canola (114 days); whereas maximum and minimum observed days to EOF were for LG-3295 (126 days) and Faisal Canola (115 days). The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 0.59 and 0.99. Similarly, during 2020–2021 at URF-Koont, maximum and minimum simulated days to EOFwere for Super Canola (129 days) and ROHI Sarsoon (88 days); whereas maximum and minimum observed days were for Super Canola (130 days) and ROHI Sarsoon (88 days). The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 0.62 and 0.99. Average simulated and observed values were very close to each other: 108.25 days and 108.62 days.

Comparison between simulated and observed data for DTM showed that there was a close link between the simulated and observed values. During the 2019–2020 growing season at NARC-Islamabad, maximum and minimum simulated days were for Crusher (186 days) and Faisal Canola (169 days), whereas maximum and minimum observed DTM were for Crusher (186 days) and Faisal Canola (172 days). The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.97, 0.70 and 0.99. Average simulated and observed days were 177.25 and 172.62.

Similarly, during the 2019–2020 growing season at URF-Koont, maximum and minimum simulated number of DTM were for Faisal Canola (174 days), Super Canola (174 days) and ROHI Sarsoon (154 days); whereas maximum and minimum observed DTM were for Super Canola (180 days) and ROHI Sarsoon (154 days). The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.92, 1.91 and 0.97. Average simulated and observed DTM were 168 and 170.75. During growing season 2020–2021 at NARC-Islamabad, maximum and minimum simulated number of DTM were for Crusher (186 Days) and Faisal Canola (169 days), whereas maximum and minimum observed number of DTM were for Crusher (186 days) and Faisal Canola (172 days). The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.97, 1.70 and 0.99. Average simulated and observed days were 177.2 and 179.6.

Likewise, at URF-Koont for growing season 2020–2021, maximum and minimum simulated DTM were for Faisal Canola and Super Canola (177 days) and ROHI Sarsoon (156 days); whereas maximum and minimum observed DTM were for Super Canola (180 days) and ROHI Sarsoon (156 days). The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.92, 1.91 and 0.97. Average simulated and observed DTM were 168 and 170.75 (see Figs. 18.27, 18.28, 18.29, 18.30, 18.31, 18.32, 18.33, 18.34, 18.35, 18.36, 18.37 and 18.38).

18.4.3.2 Leaf Area Index, Biomass and Grain Yield

Simulated leaf area index (LAI) values were exactly as observed for all cultivars during both years; this showed high model accuracy. During 2019–2020 at NARC-Islamabad, maximum and minimum simulated biological yield were for Super Canola (13,828 kg/hac) and Faisal Canola (11,852 kg/hac); whereas observed maximum and minimum biological yield were for Super Canola (13,854 kg/hac) and Faisal Canola (11,861 kg/hac). Average simulated and observed was 13020.1 kg/hac and 13094.7 kg/hac. The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 74.43 and 0.99.

Similarly, during 2019–2021 at URF-Koont, maximum and minimum simulated biological yield were for NARC Sarsoon (13,971 kg/hac) and Faisal Canola

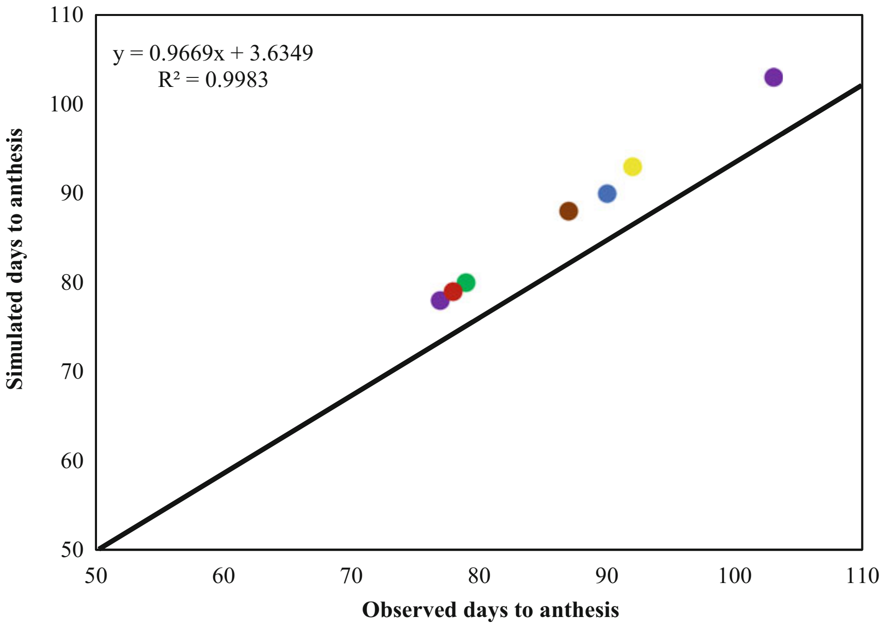

Fig. 18.27 Simulated and observed DTA for NARC-Islamabad during 2019–2020 growing season

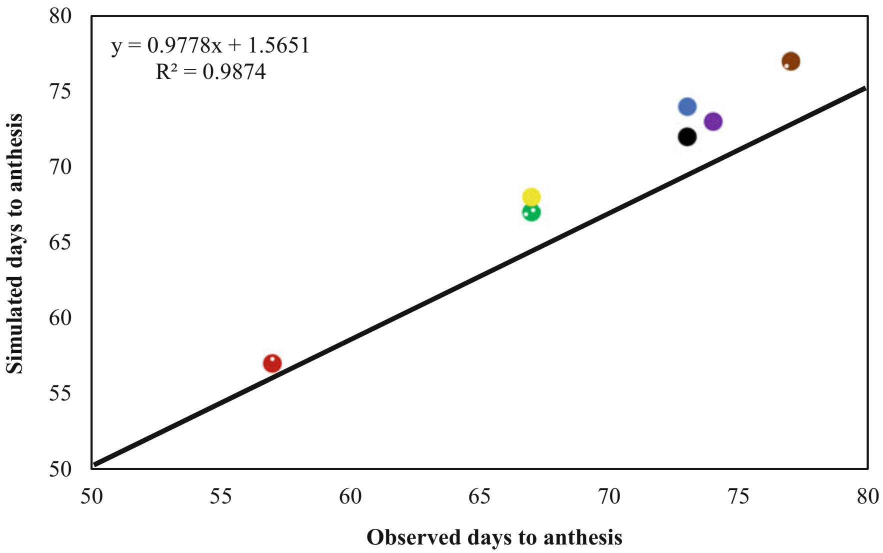

Fig. 18.28 Simulated and observed DTA for URF-Koont during 2019–2020 growing season

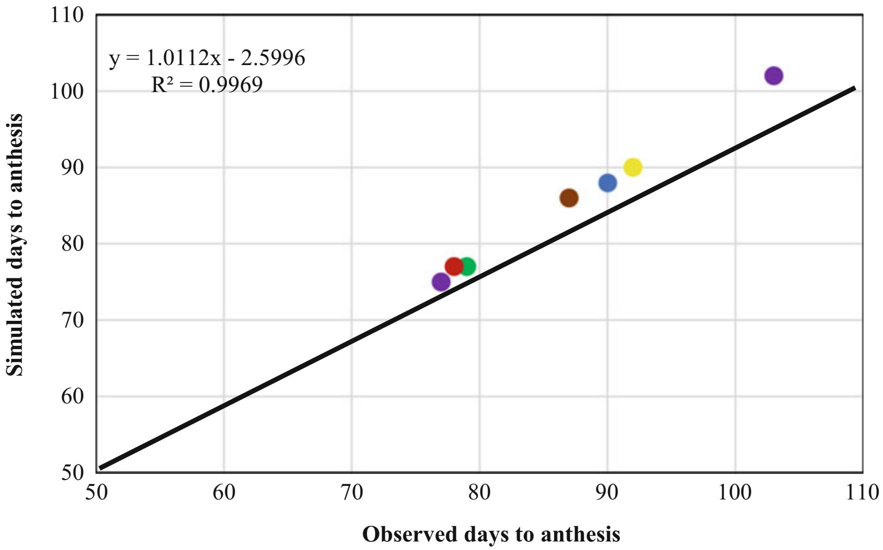

Fig. 18.29 Simulated and observed DTA for NARC-Islamabad during 2020–2021 growing season

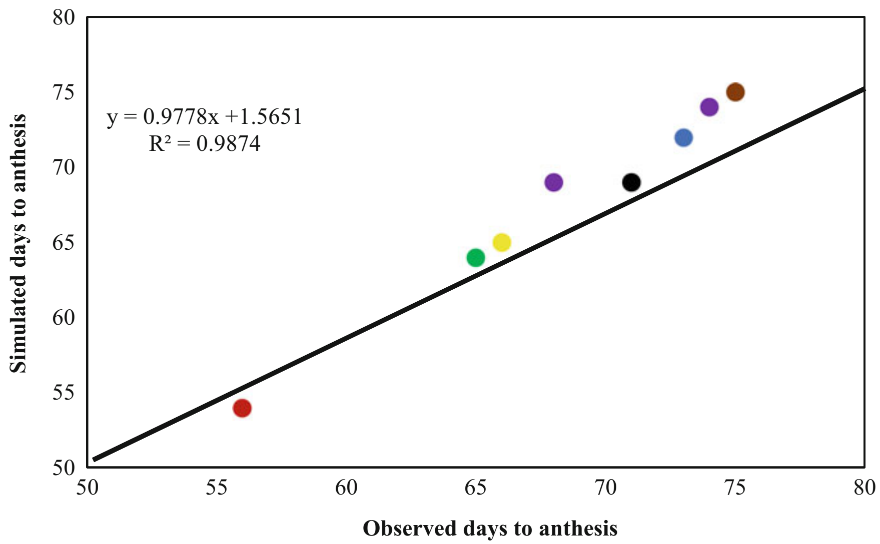

Fig. 18.30 Simulated and observed DTA for URF-Koont during 2020–2021 growing season

(11,500 kg/hac); whereas maximum and minimum observed biological yield were for NARC Sarsoon (13,982 kg/hac) and Faisal Canola (11,545 kg/hac). Average simulated and observed biological yield were 12811.3 kg/hac and 12872.1 kg/hac. The comparison of model performance was measured by using validation skill

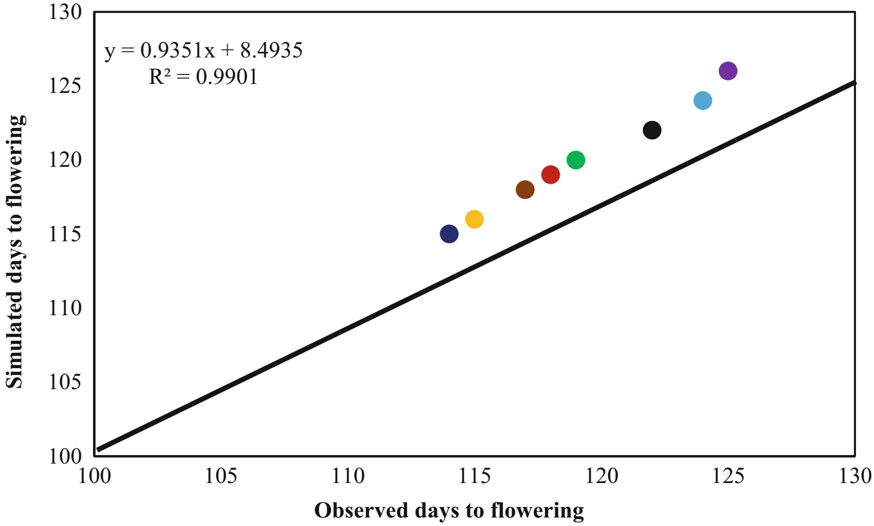

Fig. 18.31 Simulated and observed DOF for NARC-Islamabad during 2019–2020 growing season

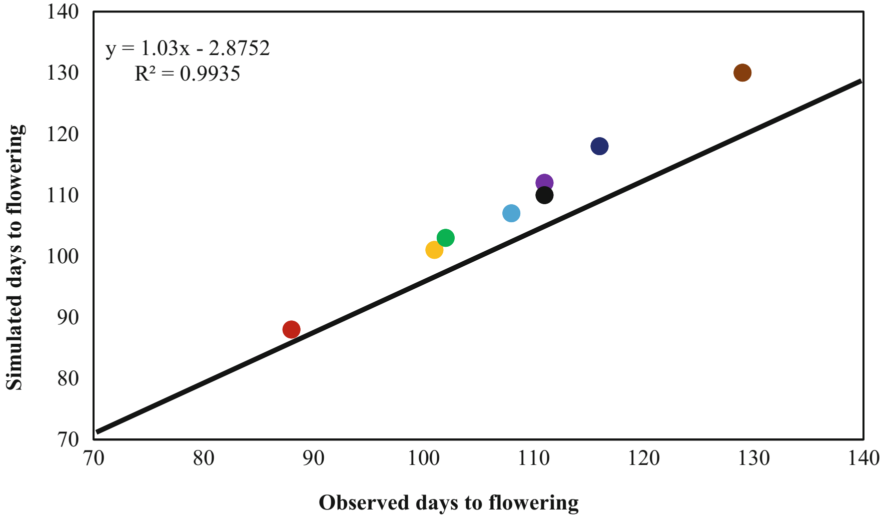

Fig. 18.32 Simulated and observed DOF for URF-Koont during 2019–2020 growing season

scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.97, 107.1 and 0.99.

During growing season 2020–2021 at NARC-Islamabad, maximum and minimum simulated biological yield were for NARC Sarsoon (13,095 kg/hac) and Faisal Canola (11,040 kg/hac); whereas maximum and minimum observed biological yield were for NARC Sarsoon (13,094 kg/hac) and Faisal Canola (11,034 kg/hac).

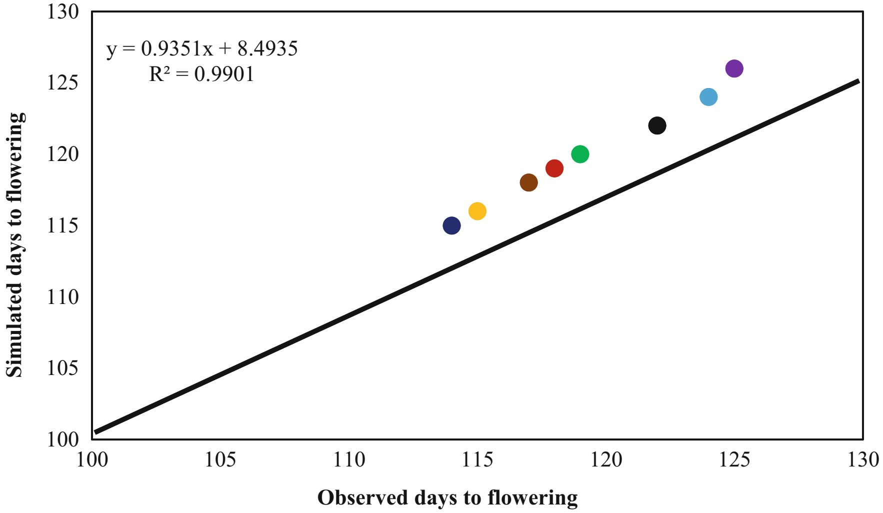

Fig. 18.33 Simulated and observed DOF for NARC-Islamabad during 2020–2021 growing season

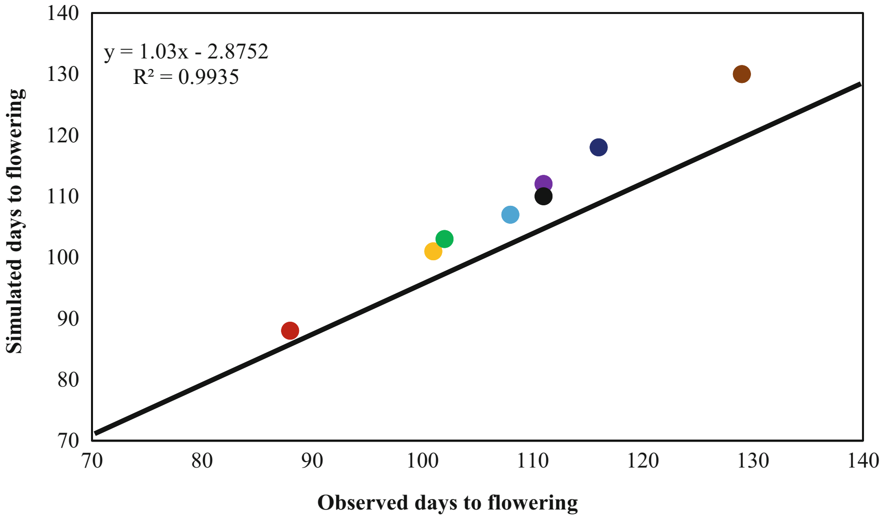

Fig. 18.34 Simulated and observed DOF for URF-Koont during 2020–2021 growing season

Average simulated and observed biological yield were 12019.1 kg/hac and 12,013 kg/hac. The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 6.73 and 0.99.

Similarly, during 2020–2021 at URF-Koont, maximum and minimum simulated biological yield were for ROHI Sarsoon (12,145 kg/hac) and Faisal Canola

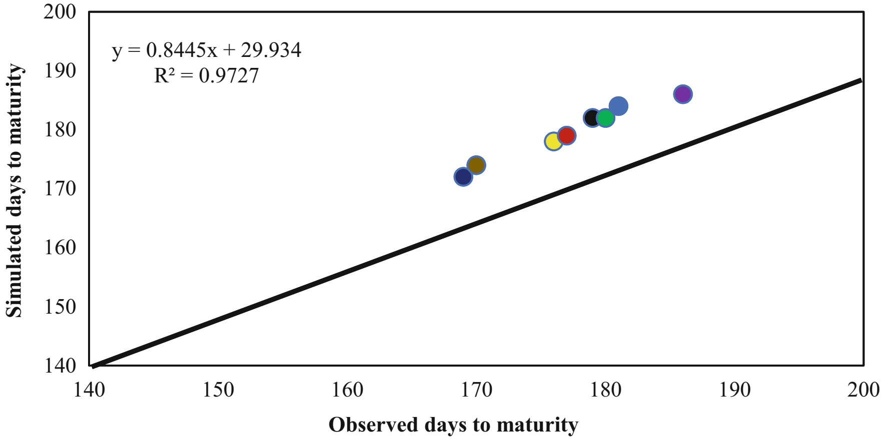

Fig. 18.35 Simulated and observed DTM for NARC-Islamabad during 2019–2020 growing season

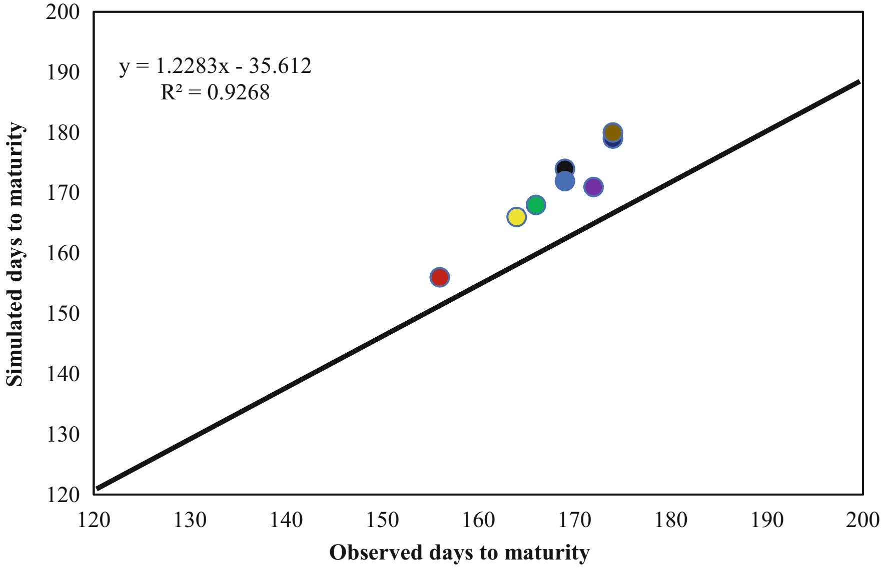

Fig. 18.36 Simulated and observed DOF for URF-Koont during 2019–2020 growing season

(10,932 kg/hac); whereas maximum and minimum observed biological yield were for NARC Sarsoon (12,165 kg/hac) and Faisal Canola (10,936 kg/hac). Average simulated and observed days were 11420.8 kg/hac and 11,423 kg/hac. The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 20.8 and 0.99.

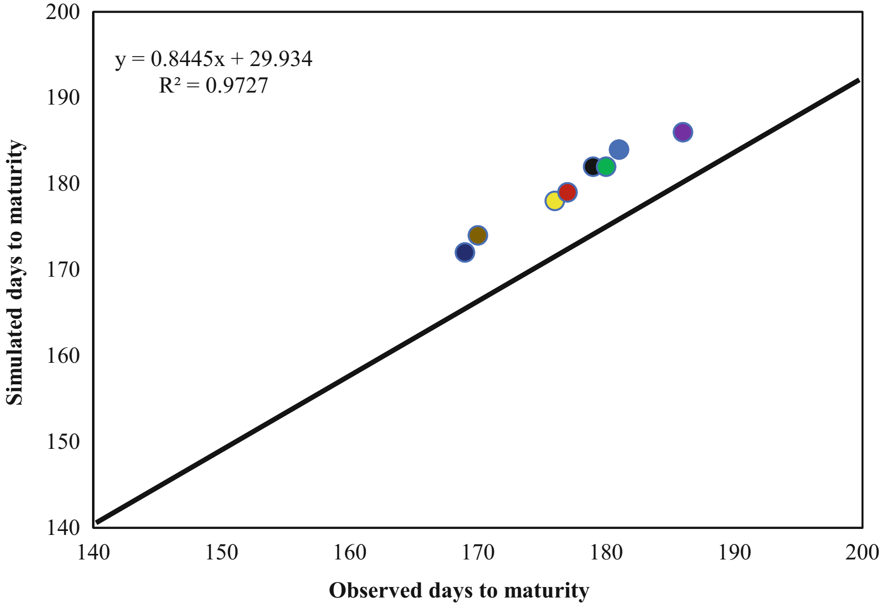

Fig. 18.37 Simulated and observed DTM for NARC-Islamabad during 2020–2021 growing season

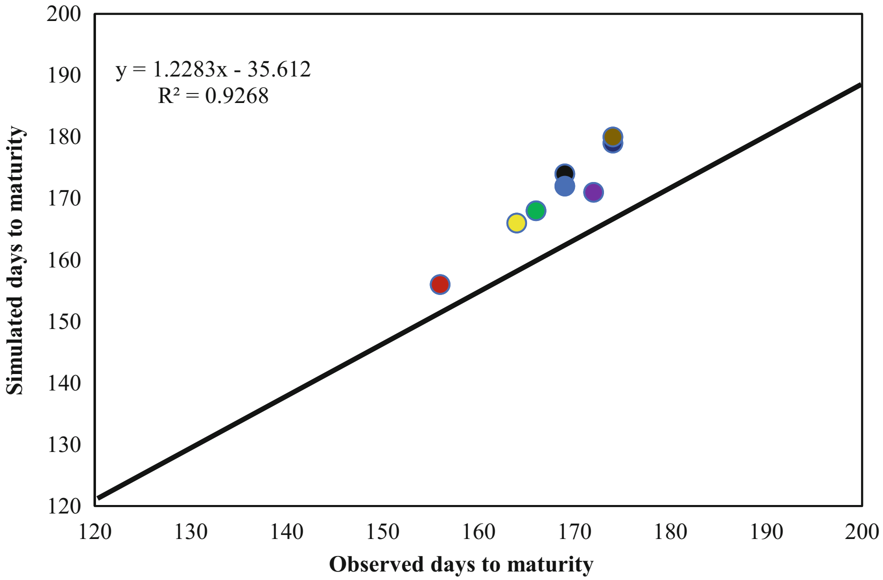

Fig. 18.38 Simulated and observed DOF for URF-Koont during 2020–2021 growing season

Grain yield predicted by the model was close to observed yield. During growing season 2019–2020 at NARC-Islamabad, maximum and minimum grain yield were for NARC Sarsoon (2889 kg/hac) and Faisal Canola (2234 kg/hac); whereas maximum and minimum observed grain yield were for NARC Sarsoon (2930 kg/hac) and Faisal Canola (2230 kg/hac). Average maximum and minimum grain yield were 2564.1 kg/hac and 2577.5 kg/hac. The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 20.07 and 0.99.

Similarly, at URF-Koont during 2019–2020, maximum and minimum grain yield were for ROHI Sarsoon (2753 kg/hac) and Faisal Canola (2115 kg/hac); whereas maximum and minimum observed grain yield were for ROHI Sarsoon (2798 kg/hac) and Faisal Canola (2115 kg/hac). Average maximum and minimum grain yield were 2458.7 kg/hac and 2478.8 kg/hac. The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 23.88 and 0.99. During growing season 2020–2021 at NARC-Islamabad, maximum and minimum grain yield were for NARC Sarsoon (2689 kg/hac) and Faisal Canola (1847 kg/hac); whereas maximum and minimum observed days were for NARC Sarsoon (2670 kg/hac) and Faisal Canola (1860 kg/hac). Average maximum and minimum grain yield were 2252 kg/hac and 2251.2 kg/hac. The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 8.19 and 0.99.

Likewise, at URF-Koont during 2020–2021, maximum and minimum simulated grain yield were for ROHI Sarsoon (2332 kg/hac) and Faisal Canola (1765 kg/hac); whereas maximum and minimum observed grain yield were for ROHI Sarsoon (2331 kg/hac) and Faisal Canola (1762 kg/hac) Average maximum and minimum grain yield were 2067.6 kg/hac and 2066.3 kg/hac. The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 2.49 and 0.99.

Simulated harvest index was very close to the observed one. During 2019–2020 at NARC-Islamabad, maximum and minimum H.I were for NARC Sarsoon (21.71) and Faisal Canola (18.84); whereas observed maximum and minimum H.I recorded were for NARC Sarsoon (21.9) and Faisal Canola (18.8). Average simulated and observed harvest index were 19.57 and 19.66. The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.97, 0.13 and 0.99.

Similarly, during 2019–2020 at URF-Koont, maximum and minimum simulated H.I were for ROHI Sarsoon (19.77) and Faisal Canola (18.39); whereas maximum and minimum observed days were recorded for ROHI Sarsoon (20.84) and Faisal Canola (18.31). Average simulated and observed harvest index were 19.15 and 19.28. The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.84,

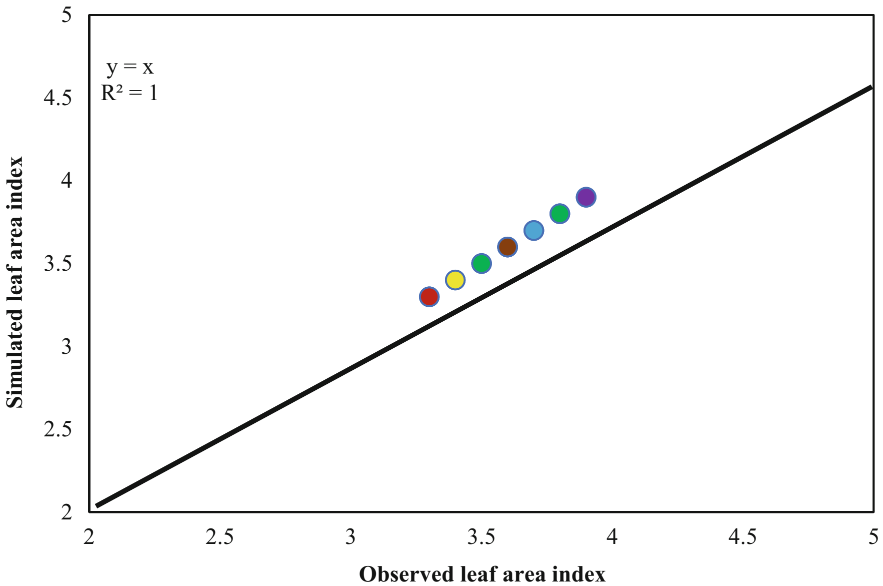

Fig. 18.39 Simulated and observed LAI for NARC-Islamabad during 2019–2020 growing season

0.28 and 0.99. During 2020–2021 at NARC-Islamabad, maximum and minimum H.I were for NARC Sarsoon (20.53) and Faisal Canola (16.73); whereas observed maximum and minimum harvest index recorded were for NARC Sarsoon (20.39) and Faisal Canola (16.85). Average simulated and observed H.I were 18.68 and 18.69. The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 0.63 and 0.99.

Likewise, during 2020–2021 at URF-Koont, maximum and minimum simulated H.I were for ROHI Sarsoon (19.21) and Faisal Canola (16.14); whereas maximum and minimum observed days were recorded for ROHI Sarsoon (19.17) and Faisal Canola (16.11). Average simulated and observed H.I were 18.07 and 18.05. The comparison of model performance was measured by using validation skill scores (R^2, RMSE, d-index). The values for R^2, RMSE and d-index were 0.99, 0.05 and 0.99 (see Figs. 18.39, 18.40, 18.41, 18.42, 18.43, 18.44, 18.45, 18.46, 18.47, 18.48, 18.49, 18.50, 18.51, 18.52, 18.53 and 18.54).

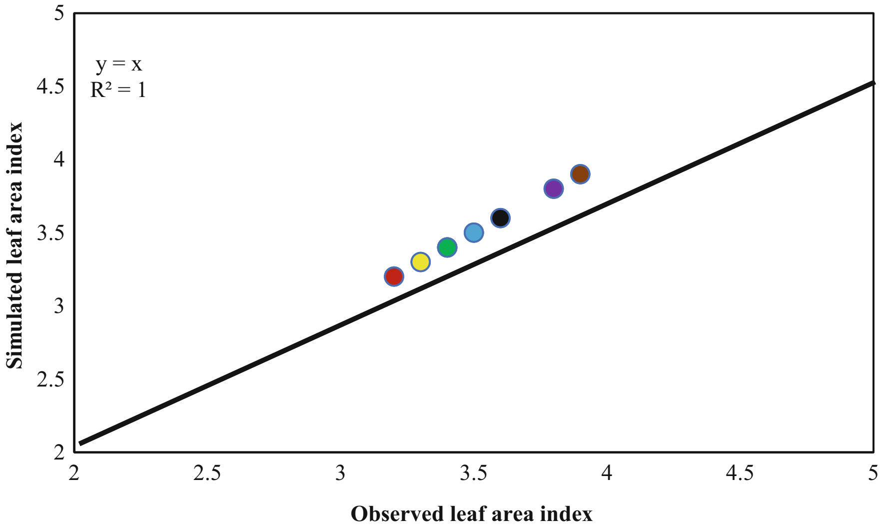

Fig. 18.40 Simulated and observed LAI for URF-Koont during 2019–2020 growing season

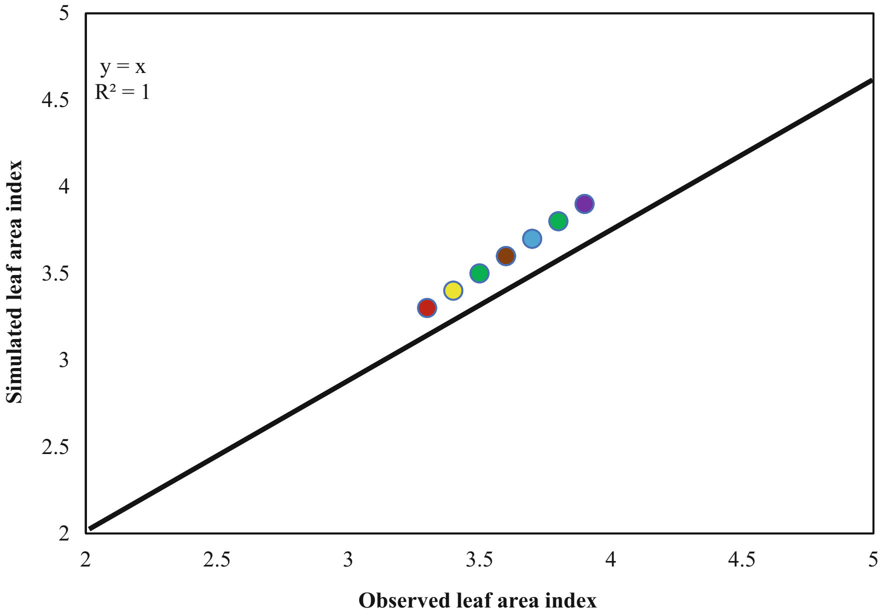

Fig. 18.41 Simulated and observed LAI for NARC-Islamabad during 2020–2021 growing season

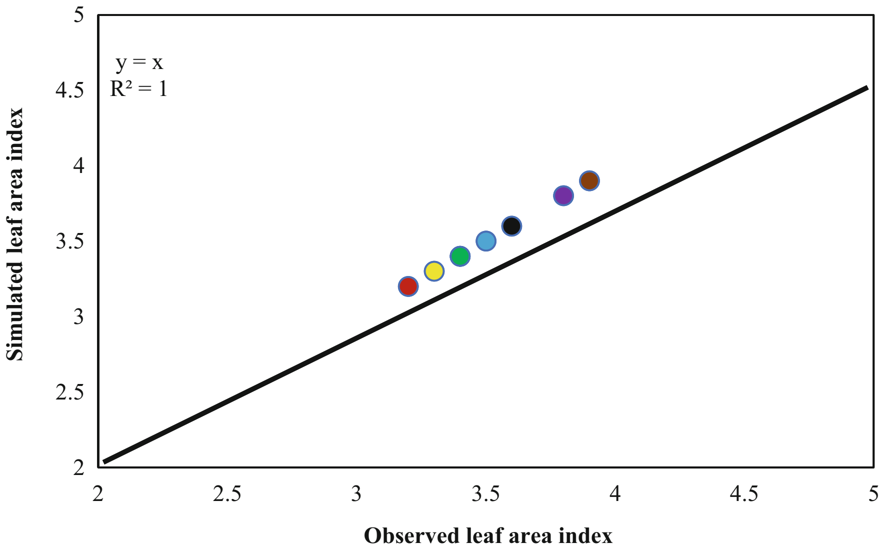

Fig. 18.42 Simulated and observed LAI for URF-Koont during 2020–2021 growing season

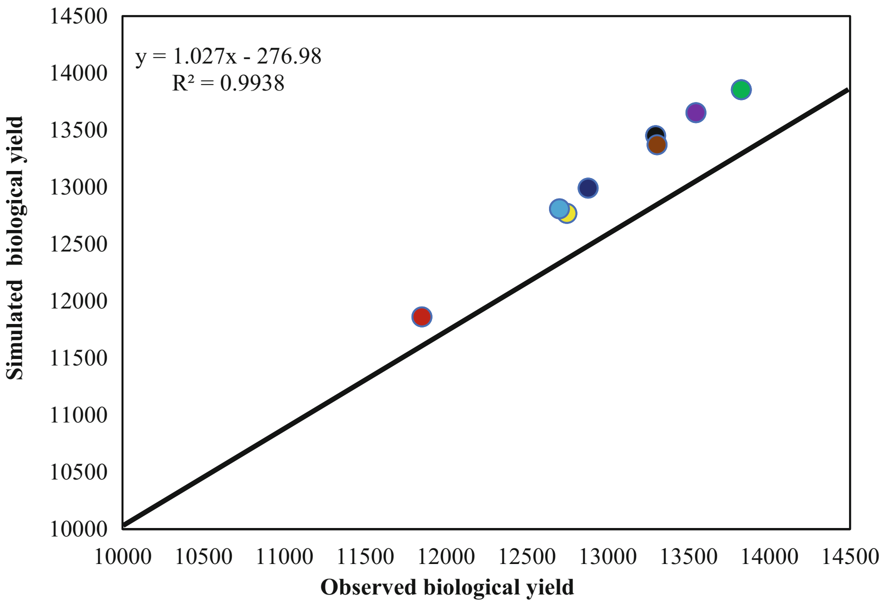

Fig. 18.43 Simulated and observed biological yield for NARC-Islamabad during 2019–2020 growing season

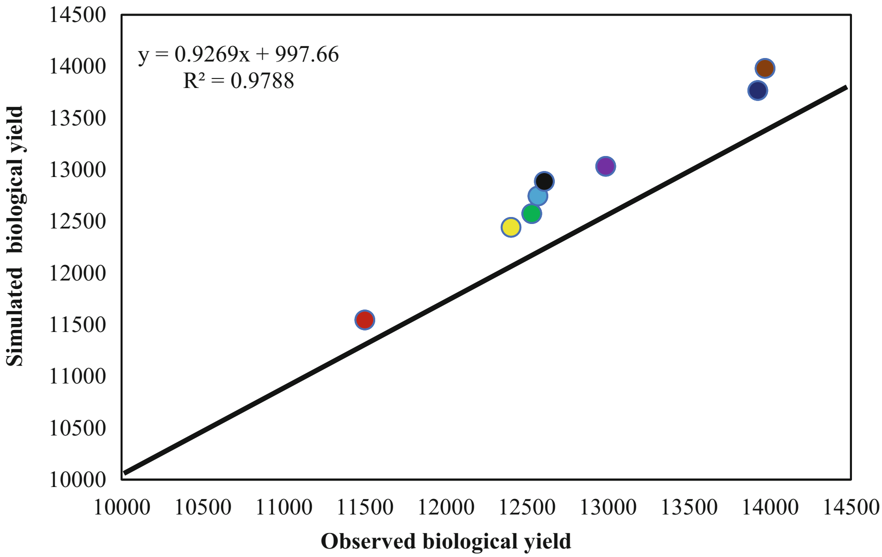

Fig. 18.44 Simulated and observed biological yield for URF-Koont during 2019–2020 growing season

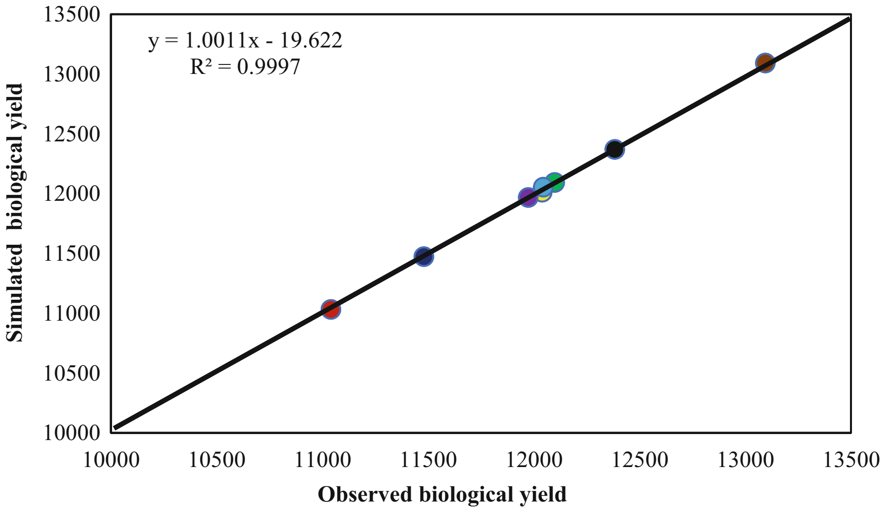

Fig. 18.45 Simulated and observed biological yield for NARC-Islamabad during 2020–2021 growing season

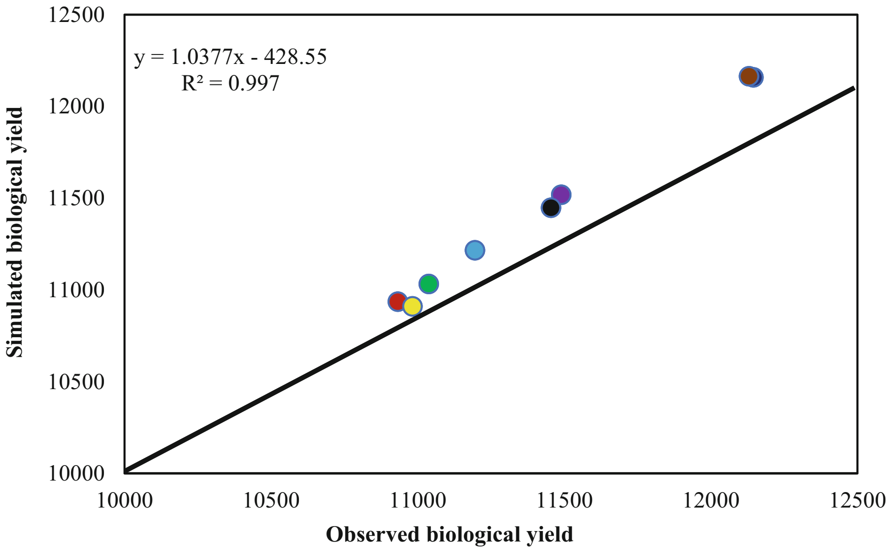

Fig. 18.46 Simulated and observed biological yield for URF-Koont during 2020–2021 growing season

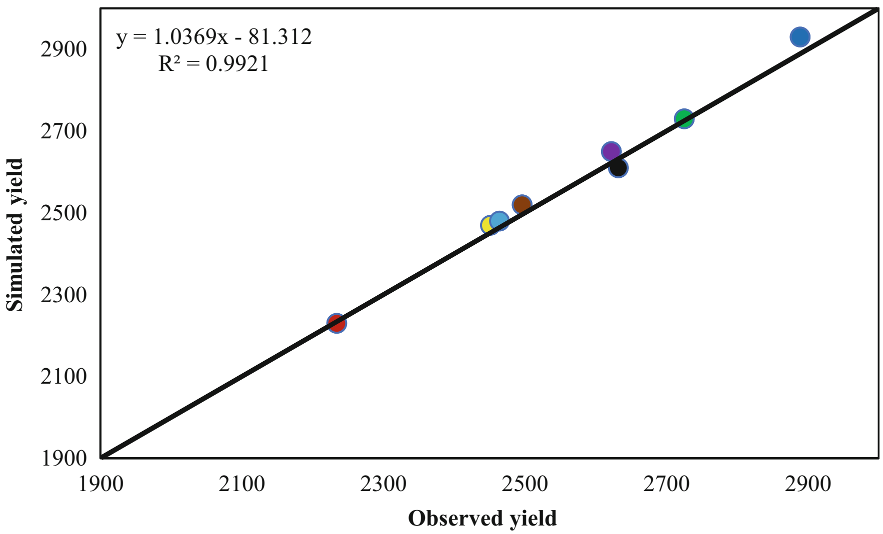

Fig. 18.47 Simulated and observed grain yield for NARC-Islamabad during 2019–2020 growing season

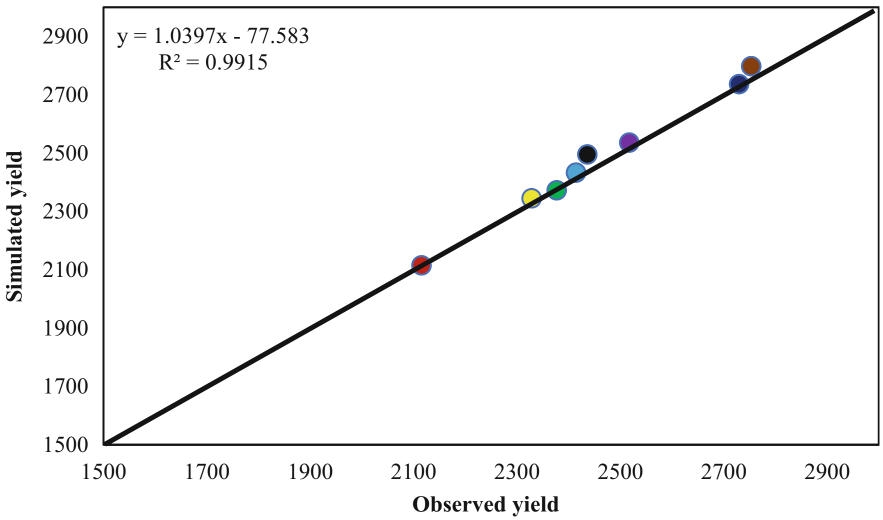

Fig. 18.48 Simulated and observed grain yield for URF-Koont during 2019–2020 growing season

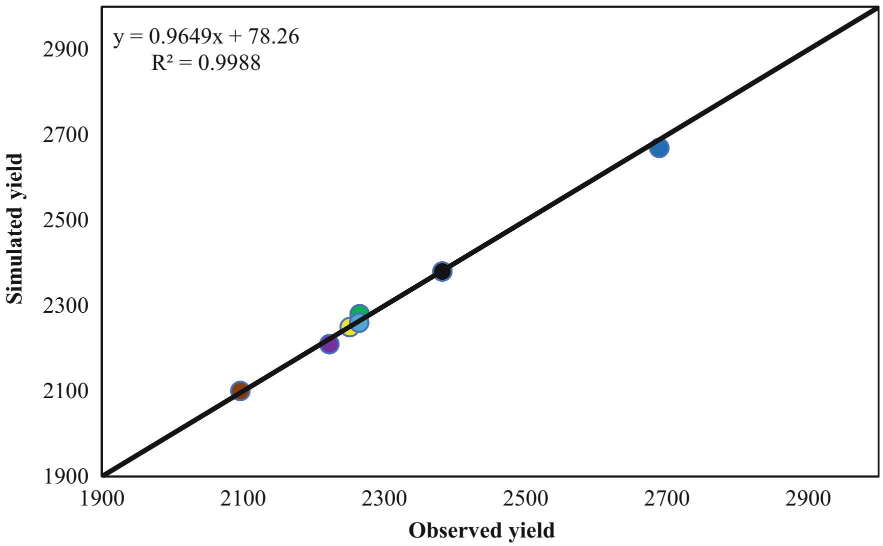

Fig. 18.49 Simulated and observed grain yield for NARC-Islamabad during 2020–2021 growing season

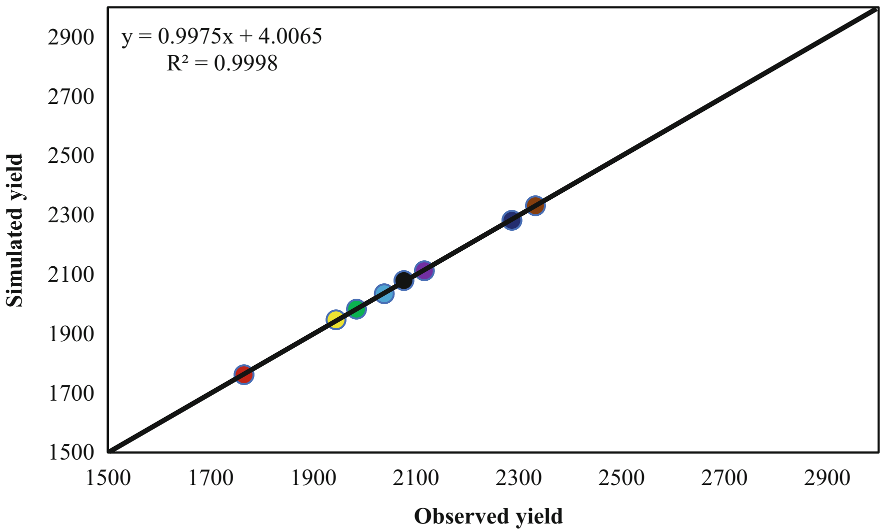

Fig. 18.50 Simulated and observed grain yield for URF-Koont during 2020–2021 growing season

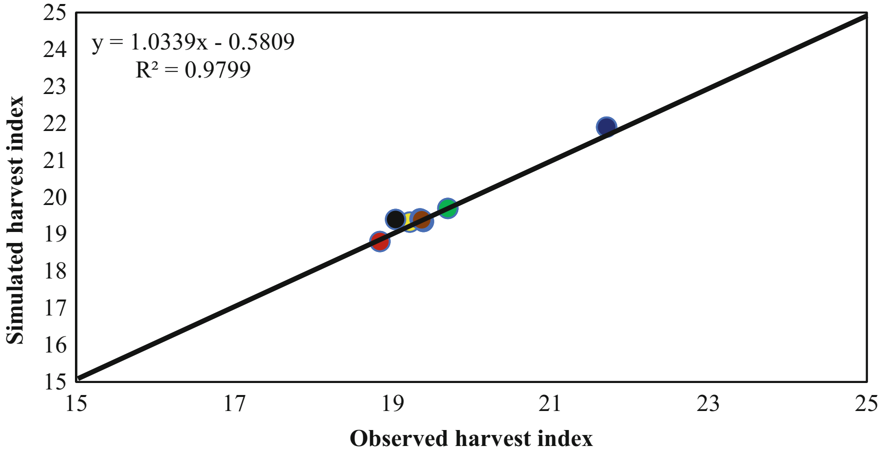

Fig. 18.51 Simulated and observed H.I for NARC-Islamabad during 2019–2020 growing season

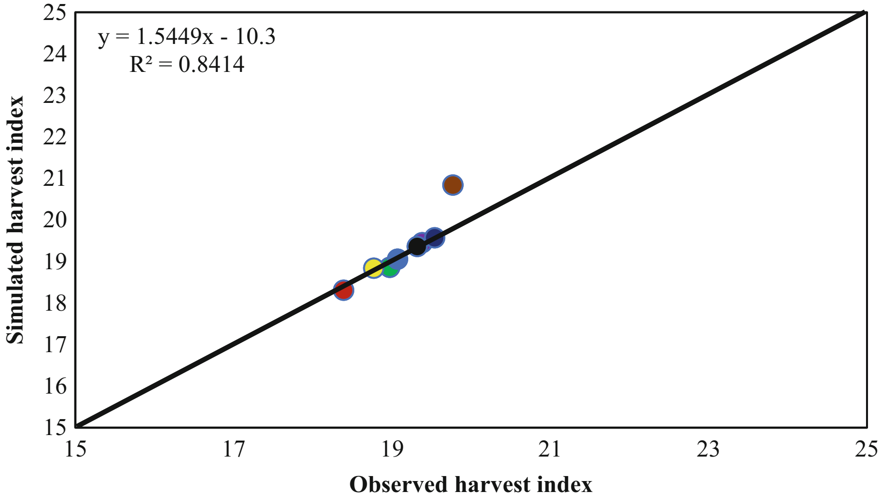

Fig. 18.52 Simulated and observed H.I for URF-Koont during 2019–2020 growing season

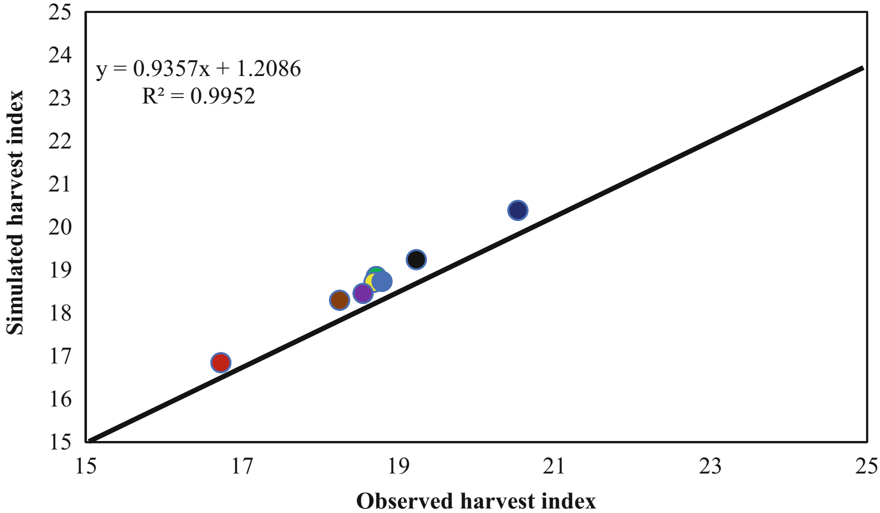

Fig. 18.53 Simulated and observed H.I for NARC-Islamabad during 2020–2021 growing season

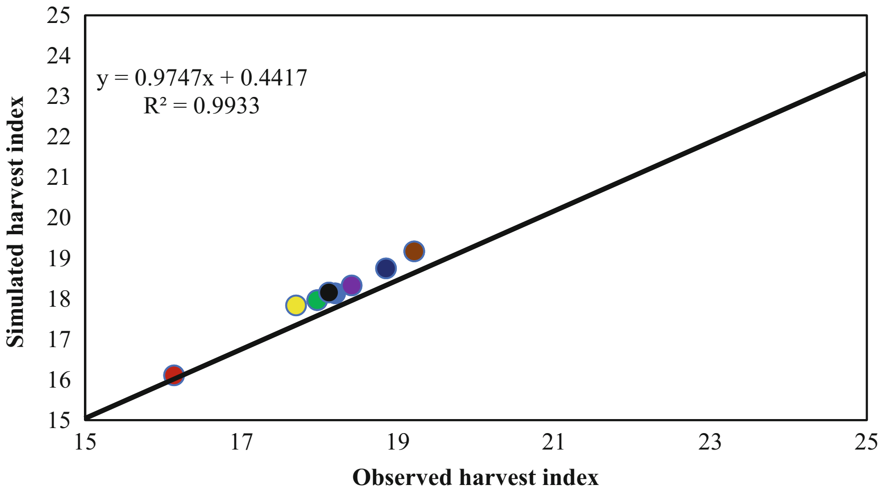

Fig. 18.54 Simulated and observed H.I for URF-Koont during 2020–2021 growing season

18.5 Conclusions

Photoperiod refers to the length of the day, which varies with latitude and seasons. It is controlled by the rotation of the earth around the Sun and its tilt. With the continuous rotation, the hemisphere is exposed to various amounts of sunlight, thus forming distinct seasons characterized by various day lengths and temperatures. There is no significant difference in day length between years. Therefore, it is a reliable clue for plants to drive their nutritional, metabolic and reproductive behaviors, ultimately leading to regular seasonal rhythms; although climate change has no direct impact on photoperiod. Nevertheless, photoperiod can predict environmental factors that directly affect the phenology of plants.

The main factors that influence flowering of plants are photoperiod and temperature. Long day plants flower more rapidly as the photoperiod increases. The approach to describing the photoperiod response of crop species will help breeders accelerate the development of genotypes with the desired photoperiod responses. For selecting a suitable environment for a genotype or specie where it can grow successfully, it is important to determine photoperiodic parameters of the flowering stage and for crop growth and yield predictive model development. The DSSAT CSM-CROPGRO-Canola model has confirmed field results and accurately reproduced the photoperiodic response of canola cultivars.

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Chapter 19
Modelling and Field-Based Evaluation of Vernalisation Requirement of Canola for Higher Yield Potential

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Abstract The climate is getting changed around the world, and it is influencing the agricultural production and agronomic practices. The agriculture sector is highly vulnerable to the phenomena of climate change. In Pakistan, the phenomena of climate change have been witnessed from decades and affecting the agriculture production and management practices, but no serious steps have been taken to minimise the problems of climate change and to reduce the effects of climate change on agriculture production and agronomic practices. Hence, the current study was carried out during canola growing seasons of 2019–2020 and 2020–2021 at both sites under rainfed conditions of Pothwar by keeping in view the circumstances of climate change aided with simulation modelling. The experiment was conducted with eight cultivars of canola arranging with the randomised complete block design with three replications at both sites with different sowing dates to form variable conditions of climate change during different phenological stages of crop specifically at flowering stage and grain filling stage. The Decision Support System for Agrotechnology Transfer (DSSAT) was used to simulate crop phenology, leaf area index (LAI), biomass, and yield. Days to the end of flowering was predicted by DSSAT with close association with observed days. The model predicted the days to

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maturity with close association with our observed days to maturity with R^2, RMSE and d-index of 0.99, 0.55 and 0.99, respectively. The model simulated LAI with good accuracy with R^2, RMSE and d-index value of 1, 0 and 1, respectively. The simulation outcomes for the biological yield depicted good performance of model with R^2, RMSE and d-index values of 0.99, 67.46 kg ha^{-1} and 0.99, respectively. Furthermore, grain yield simulation was close to observed data with R^2, RMSE and d-index of 0.98, 29.39 kg ha^{-1} and 0.99, respectively. The findings of our studies confirm that DSSAT is a good research tool that can be used to evaluate different managements and cultivars under multiple environments and furthermore can be used to design crop ideotypes as per changing requirements of the climate.

Keywords Climate changeDSSAT · Crop phenology · Leaf area index · Biomass · Yield · Ideotypes

19.1 Introduction

Climate change has harmed agricultural production and ecological systems in both developed and developing countries (Ahmed 2020; IPCC 2018), as the mean temperature is expected to increase by 0.3–4.8 °C at the end of the twenty-first century across the globe (IPCC 2013). It is expected that the crop growth, phenology and particularly yield are altered due to the increase in temperature and uncertainty in extreme events such as dry days, wet days, floods and droughts (Fatima et al. 2020; Babel et al. 2019; Kheir et al. 2022; Rahman et al. 2018). Since the Industrial Revolution, the global mean temperature has risen by 0.85 °C, and Pakistan ranked in the top ten countries globally which is effected due to climate change in the last 20 years, according to Germanwatch. Pakistan witnessed 152 extreme weather events and lost 0.53% per unit GDP (Global Climate Risk Index 2020). Extreme event in the form of flood (e.g. 2022 flood) resulted to almost $10 billion damage to the economy of Pakistan. The agriculture industry of Pakistan is considered to be vulnerable to climate change (Tariq et al. 2018; Ahmed et al. 2019). The impact of climate change on the agricultural production in Pakistan will vary across agricultural regions, based on direct/abiotic (climate warming) and indirect/biotic (augmented by pest and pathogen pressure) effects on crop production. Climate change in Pakistan is resulting in the shortage of food, and it is directly impacting the crop production (Abbas et al. 2017; Rasul and Sharma 2016). In Punjab, Pakistan, climate change has had a negative impact on canola phenology, leading to a little seed output (Zahoor et al. 2022). Many recent global climate change studies have found that climate change poses a severe danger to agricultural production systems in poor countries (IPCC 2019). This temperature trend has been documented in Punjab, Pakistan, for three decades, the start of the 1980s and primarily in the 2000s (Wang et al. 2011). The average temperature in Punjab, Pakistan, has risen by 0.78–1.5 °C over the last three decades and is anticipated to rise from 2 to 4 °C by the termination of the era, potentially affecting agricultural production (Naz et al. 2022; Ahmad et al. 2015). The average annual increase in surface temperature has had an impact on Pakistan's socio-economic sector (Akram and Hamid 2015).

Climate and agronomic managing strategies, such as sowing dates and cultivar selection, influence the phenology of all crops (Afzal et al. 2021; Ahmad et al. 2016). The long-term response of crop phenology to heating drifts has been difficult to quantify due to constant changes in sowing dates and the introduction of new cultivars (Ahmad et al. 2017). Crop improvement rates are boosted in most environments as temperatures rise (Ahmad et al. 2016), and increase in temperature has a direct impact on the length of phenological phases and, as a result, on seed output (Sommer et al. 2013). To develop improved adaptation techniques, like enhanced agronomic practices and better cultivars, which can lessen the potential harmful influence of climate change, it is essential to understand the phenological reactions of a crop as a result of variations in local temperature (Ahmad et al. 2016; Ahmed et al. 2022; Ali et al. 2022). An increase in temperature may be causing the duration of the phenological phases to shorten and the phenological phases of crop cycles to advancement. Later sowing dates and the introduction of new cultivars with a longer thermal time need could lessen these effects (Li et al. 2016). Vernalisation is the process in which flowering of a fully hydrated seed or a growing plant is developing by the cold treatment. The vegetative period of the plant is short, leading to an early flowering because of vernalisation. Plants requiring vernalisation show a delayed flowering or a vegetative flora without cold treatment. Often, these plants become rosettes with no elongation of the stem. Vernalisation involves the production of a hormone called vernalin; Melcher (1939) discovered it. Vernalisation is a process of aerobics which requires metabolic energy. Since all genotypes of canola appear to be commonly vernalised, it has been considered in many phenological models to affect phenological development (Wang et al. 2012). Vernalisation of germinated seeds or seedlings, just above freezing, is affected by the phenological development of canola. Seedlings exposed to these conditions are more responsive to the temperature and photoperiod effects than to those not vernalised seedlings. Vernalisation is process by which plants use a prolonged cold period (winter) to promote flowering. Many plants are vernalised and actively repress flora until after a prolonged cold exposure. This synchronises seed production with the favourable spring environment. It is equally important to have certain photoperiods and ambient temperatures following vernalisation. The growing degree days (GDD) approach was the first approach of assessing the influence of temperature on phenological development. A base temperature is assumed in this system, and the rate of development is a linear function of temperature above this temperature. GDDs are computed by taking the average of the day's maximum and minimum temperatures and deducting the base temperature. Growing degree days are accumulated during the growing season, usually starting from planting date, and a GDD need for each stage of development is determined using field observations (Aslam et al. 2017).

Crop simulation models were developed to evaluate agronomic management options and to help analysts understand the relationship between ecosystem, production variance and management. Crop phenological modelling is effective for simulating plant growth processes that could take years in the field to quantify (Fourcaud et al. 2008). These models have been utilised by several research organisations to make judgments in the agricultural system (Hoogenboom et al. 2019;

Bannayan et al. 2003). Crop models use high and low temperature, average rainfall and solar radiation per day as inputs to estimate daily growth and development. Crop models, such as the Decision Support System for Agrotechnology Transfer (DSSAT), are a useful tool for assessing and determining the causes of crop management issues, mostly in developing nations where climatic circumstances are changing (Hoogenboom et al. 2015). The objectives of this study were to evaluate the vernalisation requirement of canola cultivars under the specific regions of the University Research Farm Koont (URF-Koont) and National Agricultural Research Centre Islamabad (NARC-Islamabad) and to identify the ideotypes to inform breeders which varieties have less vernalisation requirement for the selected regions. We used the DSSAT-CROPGRO simulation model as a tool to predict the likely performance of selected canola cultivars under the range of selected locations and its environments. We hypothesised that the vernalisation requirement of canola cultivars will be less, and we will find out the short-duration varieties with high yield potential. However, in Pakistan, the evaluation of vernalisation requirement of canola has not been reported yet. Therefore, in Pakistan, it was needed to conduct an experiment on the evaluation of vernalisation requirement of canola to increase its yield potential.

19.2 Crop Modelling and Canola Production Under Changing Climate

Cristy et al. (2019) concluded that field experimentation and crop simulation studies were used over the potential cropping zone of Southern Australia to determine the yield potential of winter-spring canola crosses compared to currently available spring-type and winter-type cultivars. According to analyses, the four evaluated winter-spring crosses had a variety of vernalisation requirements, ranging from minor spring-type requirements to high winter-type requirements. The Catchment Analysis Tool (CAT) spatial modelling framework was used in this study to evaluate the expected canola yields of four cultivars across the entire cropping region of Southern Australia. Whish et al. (2020) performed a thorough phenological study of Australian canola cultivars at three locations with different vernal temperatures and photoperiods combined with a synthetic light system to extend the light system to 16 h. Only a few commercial Australian cultivars demonstrated substantial photoperiod responses, but the majority showed large vernal responses. Furthermore, the method for calculating vernal time (using the average daily temperature determined from the maximum and minimum temperatures or the sub-daily temperature estimate) altered the conclusions of how vernal exposure shortened flowering time. Waalen et al. (2014) performed an experiment to examine if there was a relation between the maintenance of cultivar-specific freezing tolerance levels and vernalisation saturation in winter rapeseed (*Brassica napus* L.) under field circumstances. Two cultivars, 'Banjo' and 'Californium', with varying vernalisation requirements, were chosen after a controlled screening of 18 cultivars. The vernalisation response and freezing tolerance of the two cultivars under field conditions were evaluated on five different dates throughout the winter of 2010/2011. Californium reached vernalisation saturation on October 11, but ‘Banjo’ took 13 days longer. The maximum freezing tolerance of the two cultivars was reached in early December, and it was sustained for 31 days in ‘Californium’ and 67 days in ‘Banjo’. The results of the experiment suggested that freezing tolerance and vernalisation saturation do not have a straightforward relationship. Matar et al. (2021) investigated the effect of photoperiod and developmental age on flowering time and vernalisation responsiveness in winter rapeseed, as well as the timing of vernalisation-driven floral transition. Floral transition is initiated within a few weeks of vernalisation, according to microscopy and whole transcriptome investigations of shoot apical meristems of plants maintained under controlled conditions. The presence of some Bna.SOC1 and Bna.SPL5 homoeologs among the induced genes suggests that they are involved in the timing of cold-induced floral transition. Furthermore, the blooming response of plants with a shorter pre-vernalisation time was linked to Bna.SOC1 and Bna.SPL5 gene expression delays. Nikoubin et al. (2009) conducted an experiment to see how vernalisation affects the phenology and development rates of canola types in a split plot; the experiment was set up as a randomised complete block design with four replications. The results revealed that increasing the vernalisation time from 0 to 50 days resulted in a reduction in the number of days spent at each stage of development (the commencement of green and yellow buds, as well as the beginning and end of flowering) and an increase in growth rate. The response of all cultivars to vernalisation was quantitative, showing that no-vernalisation treatment did not prevent flowering. The cultivars could flower if they developed at 85–94% of their maximum development rate. In Hyola308, the demand for vernalisation was 30 days, whereas in other varieties, it was 50 days. A basic vernalisation model was developed as a result of this research, which might be utilised in canola phenological development simulation models.

Schiessl et al. (2015) concluded that climate and day length adaptation influence flowering period, plant height and seed yield in crop plants. To evaluate these features under widely different field circumstances in the essential oilseed crop *Brassica napus*, they undertook a genome-wide association research using data from multiple agro-ecological environments spanning three continents. The Brass genome project genotyped 158 European winter-type *B. napus* inbred lines with 21,623 distinct single-locus single-nucleotide polymorphism (SNP) markers. Over the years 2010–2012, the panel calculated phenotypic relationships for blooming time, plant height and seed yield in 5 highly diverse locales in Germany, China and Chile, a total of 11 distinct environments. Rapacz and Markowski (1999) reported that there was a strong link between winter hardiness and frost resistance in both rape groups. In oilseed rapes grown in the late 1970s, cultivars with low erucic acid, particularly double zero, were less winter hardy than cultivars with high erucic acid. Double-zero cultivars have lesser frost resistance and reduced vernalisation requirements. There’s also a relationship between the need for vernalisation and frost tolerance and field survival. Frost resistance of double-zero cultivars in the 1990s was higher than double-low cultivars in the late 1970s. The decline in glucosinolate concentration in the 1970s was found to be associated with a decrease in the requirement for winter hardiness and vernalisation of cultivars. Over the next 20 years, the winter hardiness of double-low cultivars improved, but the vernalisation requirements remained the same. As a result, there was no link found between winter hardiness and the need for vernalisation in modern canola cultivars. Wang et al. (2012) reported that the APSIM-Canola model was calibrated and tested from the data of three field trial locations. In these tests, several cultivars and planting dates were used, and the main phenological phases, biomass and grain production were recorded. The model was able to simulate the commencement of phenological phases with varied sowing dates after the calibration of phenological parameters and explain the difference in biomass and yield induced by late sowing. The model, on the other hand, overestimated canola production under late sowing dates. Canola production dropped linearly with later sowing time, owing to reduced vegetative growth stages, and fluctuated greatly due to inter-annual climate variability, according to the data. On average, the yield potential in the studied region is 3 tonnes/ha. He et al. (2015) concluded that by using the APSIM-Canola model, we can estimate canola crop yield potential and yield gap. Similarly, APSIM can help to quantify the impact of inter-annual climate variability and irrigation water requirement to close the yield gap. The future canola production was totally irrigated, according to the results of a single hybrid cultivar simulation (3452 kg ha^{-1}). Irrigation boosts production and water productivity, especially in dry seasons. Raman et al. (2019) conducted an experiment to improve the resilience of canola to climate change; an integrated approach for breeding climate-smart varieties is required. Although the majority of the current breeding targets for canola improvement programs remain largely unchanged, emerging climate uncertainties reinforced the development of high-yielding resilient varieties for tolerance to excessive drought, frost, heat and waterlogging. Ecological and evolutionary adaptation and selective breeding processes have provided a range of natural variation in 'climate-smart traits' in canola and its closely related species.

19.3 Materials and Methods

Field experiment was conducted at two variable study sites, i.e. NARC-Islamabad (33.6701° N and 73.1261° E) and URF-Koont (32.9328° N and longitude 72.8630° E) (Figs. 19.1 and 19.2). Eight cultivars of canola were used as a plant material. This includes Punjab Canola, Faisal Canola, Super Canola, NARC Sarsoon, LG-3295, Rohi Sarsoon, Cyclone and Crusher during 2019–2020 and 2020–2021. The total area of the field selected was 325 m^2 for each site, and the size of each plot was 2×3 m. Daily weather data of study sites were collected from the Pakistan Meteorological Department (PMD) for the years 2019–2020 and 2020–2021. At both sites (NARC-Islamabad and URF-Koont) during years 2019–2020 and 2020–2021, the seasonal mean maximum temperature was 21.17 °C and 23 °C and 22.3 °C and 23.7 °C, respectively, and the seasonal minimum temperature was 8.7 °C and 8 °C

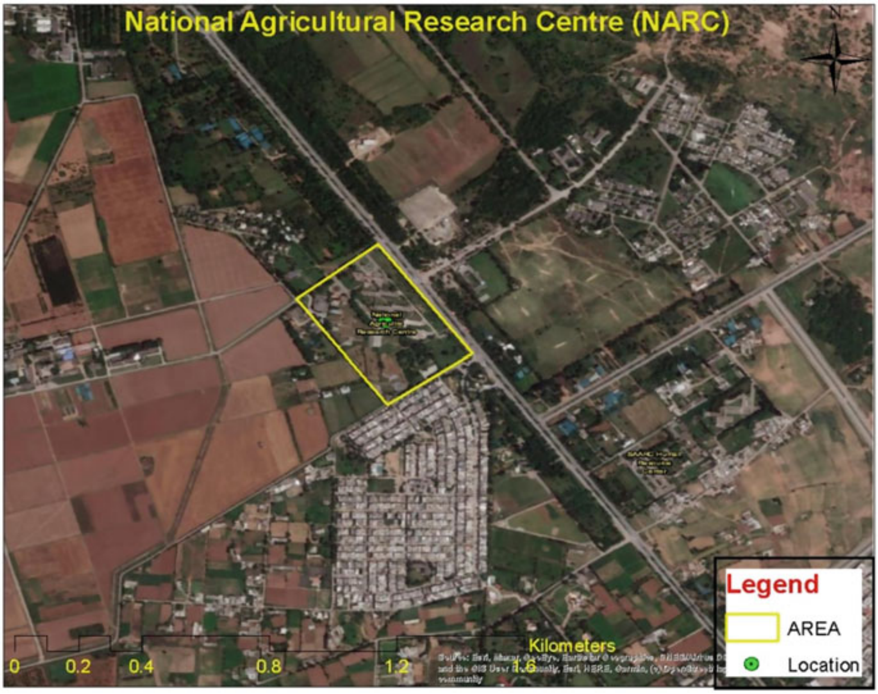

Fig. 19.1 Study site 1, i.e. the National Agricultural Research Centre (NARC) Islamabad

and 7.43 °C and 7.4 °C, respectively. The seasonal rainfall was 555.16 mm and 244.86 mm and 386.4 mm and 161.4 mm, respectively. The seasonal solar radiation was 13.55 and 14.98 and 14.54 and 15.74 MJ/m^2/d, respectively. On the basis of the collected weather data, we observed that the seasonal mean maximum temperature was high at URF-Koont than NARC-Islamabad and the temperature increase ranged between 0.7 and 1.83 °C during both growing seasons at both sites.

Growing degree days (GDD) were calculated as given by McMaster and Wilhelm (1997) using daily *T*min and *T*max and a base temperature of 5 °C as:

$$\text{Accumulative GDD} = \Sigma\left[(T\max + T\min)/2 - Tb\right]$$

where *T*max was the maximum daily temperature; *T*min, the minimum daily temperature; and Tb, the base temperature, which was taken as 5 °C.

The land was prepared with disc plough, and tillage practices at both sites were done to make the selected area well prepared. Crop was sown with the hand drill at a depth of 1.5 inch with plant-to-plant and row-to-row distance of 10 cm and 30 cm, respectively. The total area of the field selected was 325 m^2 for each site, and the size of each plot was 2×3 m. The recommended doses of fertilisers N-P-K were added at the time of sowing 90-60-50 kg h^{-1}, respectively. The experiment was designed with the randomised complete block design (RCBD) with three replications. Six

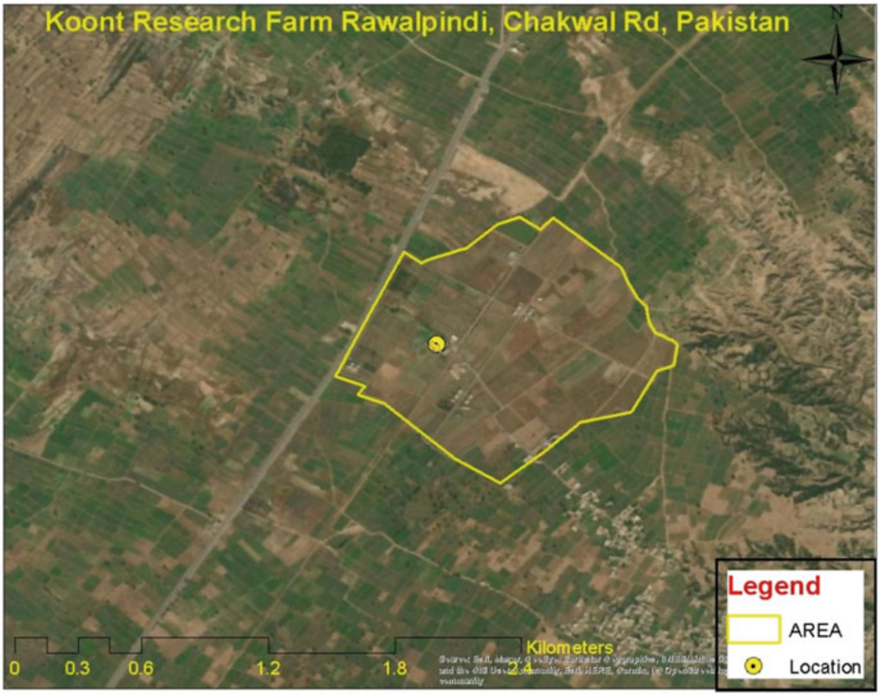

Fig. 19.2 Study site 2, i.e. the University Research Farm (URF) Koont

lines for each cultivar were maintained within each experimental plot at both locations during both growing seasons. The sowing of canola crop was done in between October 16 and 20 at NARC-Islamabad for years 2019–2020 and 2020–2021, while at URF-Koont, the sowing was done in between October 10 and 20 for both years. Different crop parameters were measured at different crop growth stages; crop measurement parameters were days to emergence, days to anthesis, days to end of flowering, leaf area index (LAI), days to maturity, biological yield and grain yield. We measured and observed all the crop parameters for both sites during both growing seasons. To check the soil physio-chemical properties, soil samples were collected from different layers of the experimental fields from 0 to 90 cm at every 30 cm depth intervals at both sites. The soil physio-chemical properties such as texture, sand%, silt%, clay%, organic carbon (OC), bulk density (BD), pH, SNH_4 mg kg^{-1}, SNO_3 mg kg^{-1}, soil lower limit (SLL), soil density upper limit (SDUL) and soil saturation (SSAT) were determined at each depth. The soil samples' analysis results showed that the soil texture was silt loam at NARC-Islamabad and sandy clay loam at URF-Koont. The soil profile at 30 cm depth contained 34% sand, 33% silt, 33% clay, 0.8% OC, 1.3% BD, 7.6 pH, 0.6 SNH4 mg kg^{-1}, 5.2 SNO_3 mg kg^{-1}, 0.195 SLL cm cm^{-1}, 0.36 SDUL cm cm^{-1} and 0.45 SSAT cm cm^{-1} at NARC and 56% sand, 22% silt, 22% clay, 0.65% OC, 1.45% BD, 8.1 pH, 0.5 SNH_4 mg kg^{-1}, 4.2 SNO_3 mg kg^{-1}, 0.1512 SLL cm cm^{-1}, 0.245 SDUL

Table 19.1 Soil physio-chemical variables at NARC-Islamabad

Depth	Sand %	Silt %	Clay %	O.C	B.D	PH	SLL	SDUL	SSAT	Texture
0–30 cm	34	33	33	0.80	1.30	7.60	0.195	0.360	0.450	Silt loam
30–60 cm	32	33	35	0.60	1.35	8.20	0.195	0.350	0.440	Silt loam
60–90 cm	32	33	35	0.41	1.35	8.40	0.200	0.340	0.430	Silt loam

Table 19.2 Soil physio-chemical variables at URF-Koont

Depth	Sand %	Silt %	Clay %	O.C	B.D	PH	SLL	SDUL	SSAT	Texture
0–30 cm	56	22	22	0.65	1.45	8.1	0.151	0.245	0.417	Sandy clay loam
30–60 cm	56	20	24	0.45	1.45	8.8	0.151	0.245	0.417	Sandy clay loam
60–90 cm	54	20	26	0.31	1.50	8.5	0.145	0.245	0.417	Sandy clay loam

cm cm^{-1} and 0.417 SSAT cm cm^{-1} at URF-Koont. All physio-chemical properties of soil for both locations have been shown in Tables 19.1 and 19.2.

19.3.1 Phenological Modelling

The phenological growth of canola cultivars from emergence to maturity was measured at two different sites in response to different sowing dates for research studies. A phenological model with distinct sensitivities to vernalisation was applied to the measured phenological data for canola cultivars in these crop experiments at two different locations. The phenological model was updated using optimisation to minimise the least square difference between the measured and predicted dates for canola phenological stages (generalised reduced gradient nonlinear method). Day length, temperature and vernalisation are used to determine the time it takes for two developmental stages in the phenological model, being emergence-start of flowering (SOF) and from start of flowering-end of flowering (EOF). To calculate the daily phenological growth rate (TT_{PP}), the accumulated photo-thermal sum including base temperature (PTT_B), photoperiod (F_{PP}) and vernalisation (F_{vern}) criteria is used, as follows:

$$TT_{PP} = \sum (PTT_B \times F_{PP} \times F_{vern})$$

Temperature growth rate is dependent on the daily average temperature (TT) ranging from 5 °C to an ideal temperature of 26 °C, where development occurs at a rapid rate. The effect of photoperiod (PP_{hr}) on the duration of thermal time was considered through a calculation of day length using the site-specific latitudes for each day.

$$\mathrm{PTT_B} = \sum \left(\mathrm{TT_{BO}} \times \mathrm{PP_{hr}} \times 24^{-1}\right)$$

The effect of photoperiod among cultivars was calculated by using day length and photoperiod sensitivity (PP_{sen}). A daily photoperiod factor was calculated as:

$$F_{\mathrm{PP}} = 1 - (0.01 \times \mathrm{PP_{sen}}) \times (20 - \mathrm{PP}_h)^2$$

The effect of vernalisation was integrated into the model by using a daily vernalisation factor (F_{vern}). Using the technique described by White et al. (2008), the total number of vernalisation days ($\mathrm{Vern_{sen}}$, d) needed to achieve full vernalisation was estimated to be between −4 and 18 °C, where average daily temperatures between 2 and 12 °C allocated a vernalisation unit (VD) of 1. VD decreases linearly from 9 to 18 °C for temperatures greater than 12 °C, where it reaches zero. VD decreases linearly from 2 to −4 °C, where its value is zero, for temperatures less than 2 °C.

$$V\nabla = \sum \mathrm{VD} - \mathrm{Devern}$$

According to the work of Ritchie and Nesmith (1991), if the daily maximum temperature exceeds 25 °C, devernalisation (Devern) was assumed to occur. Using this $V\Delta$ (d) and $\mathrm{Vern_{sen}}$ (d), a daily vernalisation factor (F_{vern}, dd^{-1}) is calculated.

$$F_{\mathrm{vern}} = \frac{V\nabla}{\mathrm{Vernsen}}$$

The phenological phases of emergence-SOF and SOF-EOF were achieved by using the specific parameters of $\mathrm{Vern_{sen}}$ when the cultivar-specific $\mathrm{TT_{PP}}$ was reached for that phase.

19.3.2 Model Description

For DSSAT model simulation, the inputs required were comprehensive physical and hydraulic properties of soil. The model was not set with autovalidation and calibration. To validate the model for conditions of any locality, changes are made in its parameters. Different new files are created for different management zones to precise agriculture using DSSAT. Assessment of simulations with observed results evaluates the model's value and suitability for accurate prediction and area (Porter et al. 2010). The inputs required under different situations for the application of model are soil properties, genotype information, weather data and experimental condition. These application software aid to prepare these databases and to compare simulated results with observed values and to improve the model's efficiency and accuracy. Proper crop management for risk valuation can be simulated with DSSAT model.

19.3.3 Model Calibration

19.3.3.1 Genetic Parameter Estimations with the DSSAT-GLUE Package

The generalised likelihood uncertainty estimation (GLUE) is a latest method which is used for sensitivity and uncertainty analysis (Yan et al. 2020). On the basis of experimental data, for estimating cultivar parameters, the GLUE method has been integrated into DSSAT (Hoogenboom et al. 2020). In DSSAT, the GLUE method doesn't determine parameters like dry biomass or leaf area, but it can determine parameters related to growth stages and grain characteristics (Li et al. 2018). Experimental data file (T-file) was added to DSSAT and GLUE tool was used to get the best fit. This procedure was repeated for both sites during both growing seasons.

19.3.3.2 Upscaling Strategies for Cultivar Parameters in Regional Simulation of Canola Growth

For cultivar genetic parameter estimations of canola, two upscaling strategies were established and evaluated for two experimental datasets. Split of these upscaling strategies into two types of solutions could be done. On the basis of recorded data for days to anthesis, days to end of flowering, days to maturity, leaf area index, biological yield, grain yield and harvest index, the first type of solution estimated genetic parameters of canola cultivars. The second type attempted to quantify the distribution of genetic parameters for canola cultivars. On the basis of observations for the conducted experiments at both sites NARC-Islamabad and URF-Koont for years 2019–2020 and 2020–2021, this type of solution was established for canola cultivars. In simulations of days to anthesis, days to end of flowering, days to maturity, leaf area index, biological yield, grain yield and harvest index, the upscaling strategies were compared.

19.3.3.3 Strategy 1: Single-Site Parameters (SSPs)

In this strategy, the different canola cultivars were assumed to be sown at both sites NARC-Islamabad and URF-Koont during years 2019–2020 and 2020–2021. Each cultivar was parameterised and validated to explore the uncertainties caused by cultivars during simulation. With the DSSAT-GLUE package, the cultivar genetic parameters were estimated for each site by using observed days to anthesis, days to end of flowering, days to maturity, leaf area index, biological yield, grain yield and harvest index of both years 2019–2020 and 2020–2021. During the study, we focused on uncertainties of SSPs in simulations of phenology.

19.3.3.4 Strategy 2: Virtual Cultivar Parameters (VCPs) Generated from the Posterior Parameter Distributions

Based on observations of eight canola cultivars sown at both sites, the genetic parameters were estimated for each cultivar during both growing seasons 2019–2020 and 2020–2021. The validation of estimated genetic parameters was done for both sites during both growing seasons. In model calibration, we input the required files in the model for its calibration, and the model does not provide automated procedure for its calibration. To validate the model, changes in the input parameters must be done. In DSSAT application, several types of files are generated to get simulated results which includes file X, file A, file T, soil file, climate file and genetic coefficients file. In the optimisation process for each cultivar, the two parameters that were changed $Vern_{sen}$ and TT_{PP}. Vernalisation sensitivity is the $Vern_{sen}$ needed for vernalisation saturation, a sum near 0 being insensitive and a sum near 50 d being very sensitive. These parameters were calculated for both emergence-start of flowering (SOF) and start of flowering-end of flowering (SOF-EOF). The goodness of fit of the model can be judged by the model's ability to predict the saturation from emergence-SOF and SOF-EOF at each site. A root mean square error (RMSE) of 5 days between the measured and predicted flowering dates on a national basis is similar to other canola models (Habekotté 1997; Deligios et al. 2013).

19.3.4 Model Performance Evaluation

During the canola growing season of 2019–2020 and 2020–2021 field experiments, the model was evaluated on the basis of collected data. Genotypic coefficient was changed until the simulation results were different at 10% of observed data for major development stages of canola. Comparison between observed and simulated values was developed for parameters regarding the growth and development of canola to improve cultivar coefficient and for sensitivity analysis of the model.

19.3.5 Statistical Analysis

Analysis of variance (ANOVA) was performed to test the significant difference between means of various parameters for eight varieties at two locations (Islamabad and Chakwal) for the year 2019–2020 and 2020–2021 growing seasons using Statistics 8.1. To find all possible interactions of varieties and locations, the ANOVA was performed. The collected data was statistically analysed and used to parameterise the DSSAT model to run simulating long-term daily climatic data (1988–2021) for selected sites.

19.4 Results and Discussion

19.4.1 Climatic Specifications

The weather conditions that prevailed during both growing seasons at URF-Koont have been shown in Figs. 19.3 and 19.4. The mean values of different climatic parameters were calculated at URF-Koont during the study years of 2019–2020 and 2020–2021. The seasonal mean maximum temperature was 22.3 °C and 23.7 °C, and the seasonal mean minimum temperature was 7.43 °C and 7.4 °C during years 2019–2020 and 2020–2021, respectively. The seasonal rainfall was 386.4 mm and 161.4 mm during growing seasons 2019–2020 and 2020–2021. The seasonal solar radiation was 14.54 and 15.74 MJ/m^2/d during growing seasons 2019–2020 and 2020–2021, respectively. The daily weather data was collected from the Pakistan

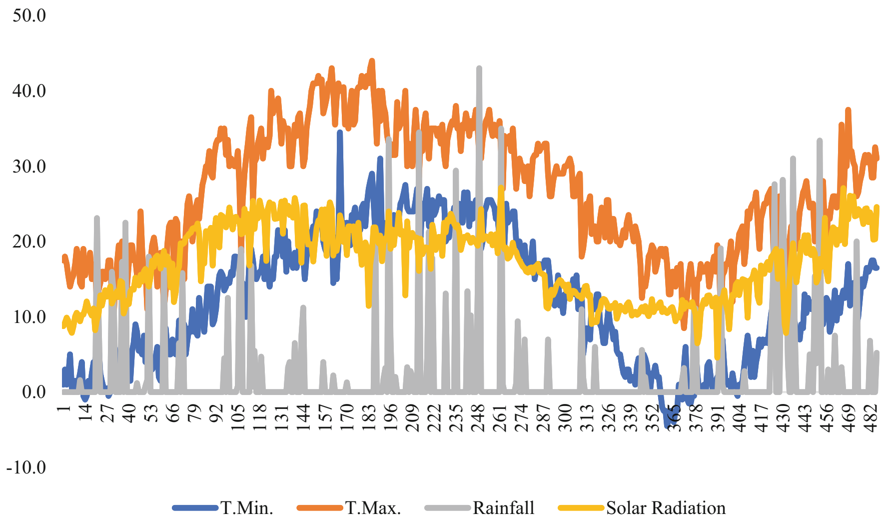

Fig. 19.3 Climatic characteristics of URF-Koont during growing season 2019–2020

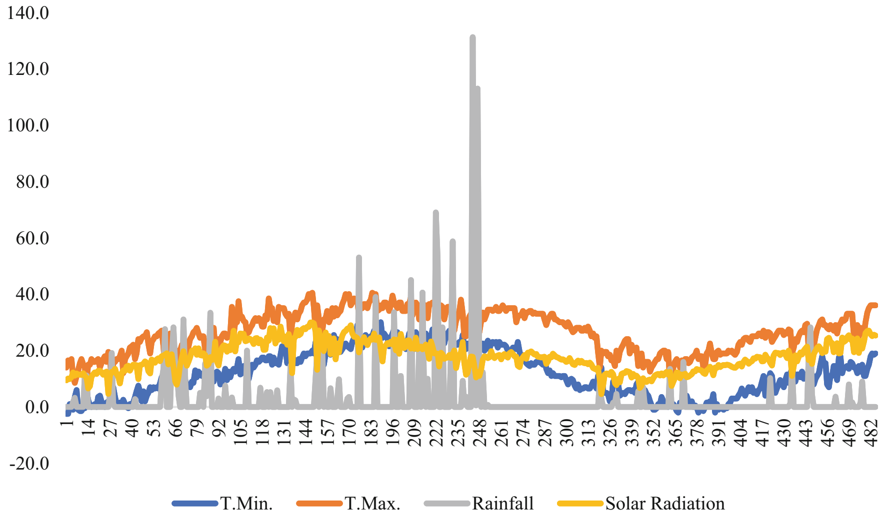

Fig. 19.4 Climatic characteristics of URF-Koont during growing season 2020–2021

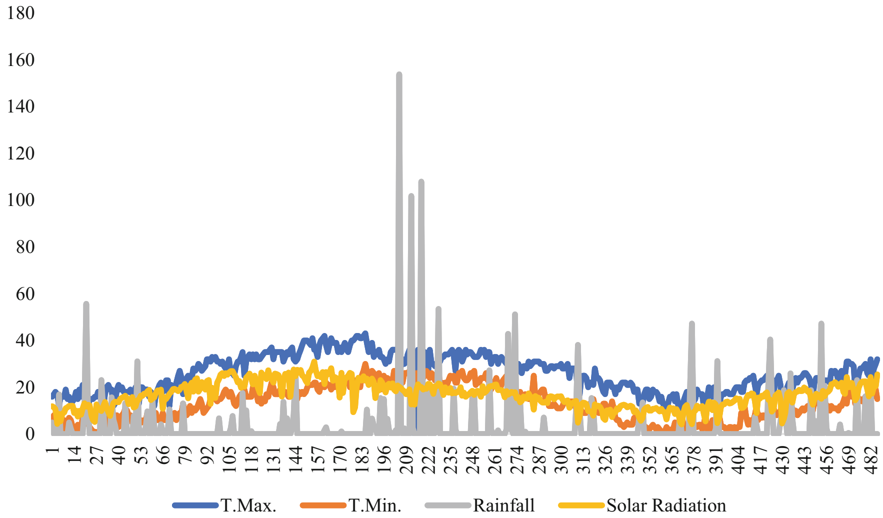

Fig. 19.5 Climatic characteristics of NARC-Islamabad during growing season 2019–2020

Meteorological Department (PMD). The weather conditions that prevailed during both growing seasons at NARC-Islamabad have been presented in Figs. 19.5 and 19.6. The mean values of different climatic parameters were calculated at NARC-Islamabad during study years of 2019–2020 and 2020–2021. The seasonal mean maximum temperature was 21.17 °C and 23 °C, and the seasonal mean minimum temperature was 8.7 °C and 8 °C during years 2019–2020 and 2020–2021,

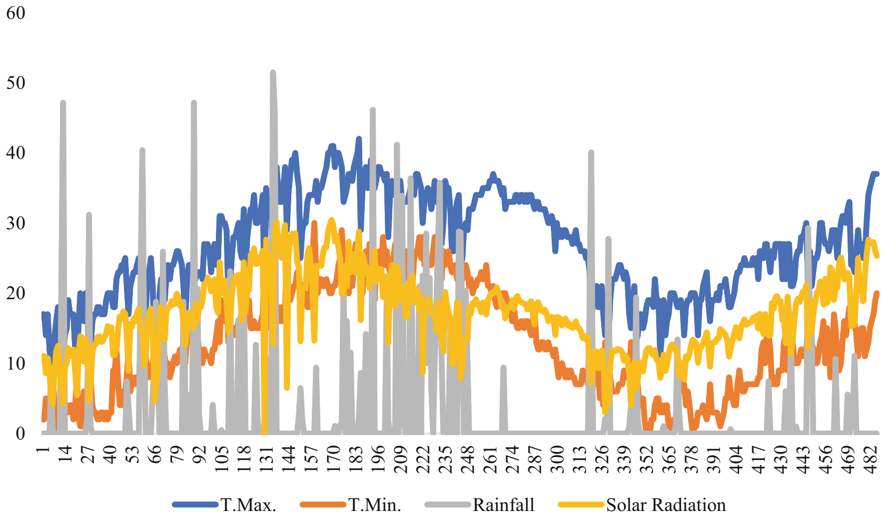

Fig. 19.6 Climatic characteristics of NARC-Islamabad during growing season 2020–2021

respectively. The seasonal rainfall was 555.16 mm and 244.86 mm during growing seasons 2019–2020 and 2020–2021, respectively. The solar radiation was 13.55 and 14.98 MJ/m^2/d during growing seasons 2019–2020 and 2020–2021, respectively. The daily weather data was collected from the Pakistan Meteorological Department (PMD).

19.4.2 Agronomic Parameters

19.4.2.1 Phenology

In the growing season of years 2019–2020 and 2020–2021 at NARC-Islamabad, days to emergence were 5 days after sowing (DAS) during both years, respectively, while at URF-Koont, days to emergence were 6–7 DAS during both years, respectively. According to our observed data, canola cultivars showed variation in days to anthesis at both locations during both growing seasons. At NARC-Islamabad during years 2019–2020, Cyclone took a maximum of 103 days and Faisal Canola took a minimum of 78 days to give the first flower after sowing. At URF-Koont, we observed that Faisal Canola took a maximum of 77 days and ROHI Sarsoon took a minimum of 57 days to give the first flower after sowing, respectively. During years 2020–2021 at NARC-Islamabad, we observed that Cyclone took a maximum of 102 and Faisal Canola took a minimum of 75 days to give the first flower after sowing. At URF-Koont, we observed that Super Canola took a maximum of 75 days and ROHI Sarsoon took a minimum of 54 days to give the first flower after sowing, respectively (Figs. 19.7, 19.8 and 19.9). Statistical analysis showed highly

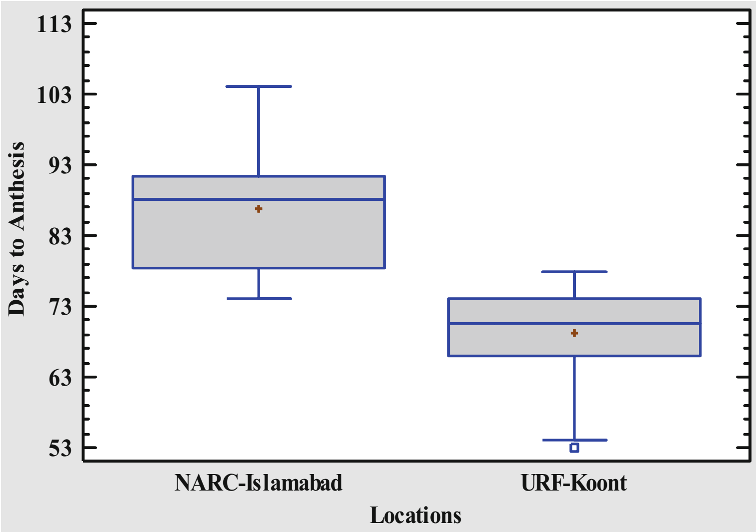

Fig. 19.7 Days to anthesis for both sites

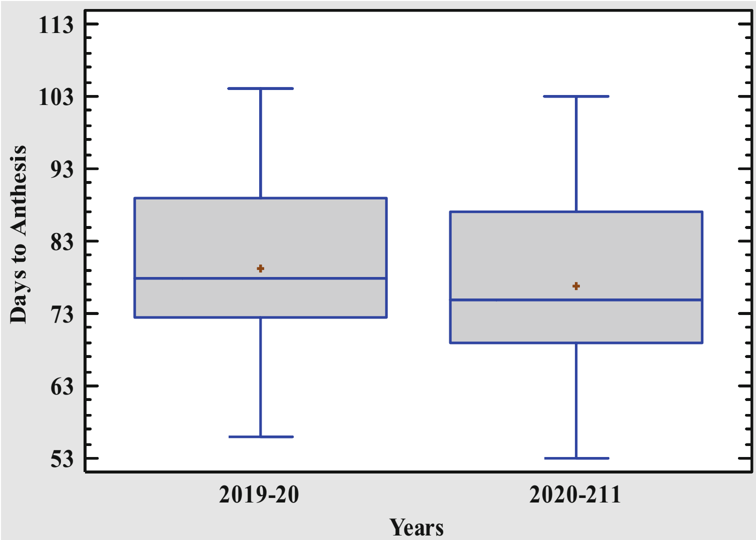

Fig. 19.8 Days to anthesis for growing seasons 2019–2020 and 2020–2021

significant results for locations (L), years (Y), cultivars (CUL) and L × CUL, while all other interactive effects, viz. L × Y, Y × CUL and L × Y × CUL, were non-significant at $p \leq 0.05$ (Table 19.3). The days to anthesis was less at URF-Koont during both years than NARC-Islamabad because the temperature was high at URF-Koont than at NARC-Islamabad during emergence to anthesis due to

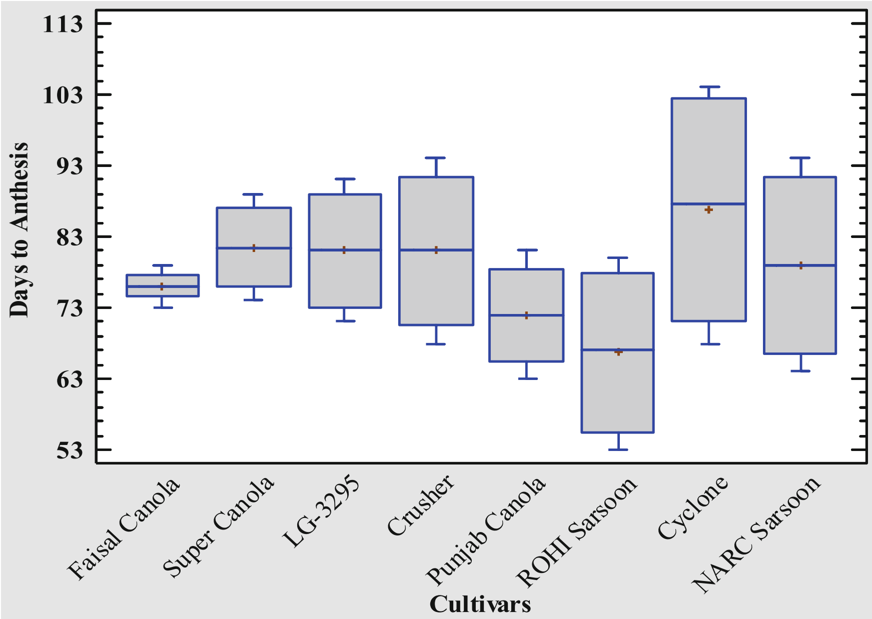

Fig. 19.9 Days to anthesis for cultivars

which the cultivars induce flowering in less days at URF-Koont. Crop growth and development rates are accelerated with an increase in temperature for most environments (Ahmad et al. 2016; Faraji et al. 2009). This increase in temperature has a direct effect on the duration of the phenological phases and ultimately impacts seed yield (Sommer et al. 2013; Tao et al. 2014; Xiao et al. 2016). Advancement of the phenological stages and a decrease in the duration of the phenological phases of crop cycles may occur due to an increase in temperature. Observed data showed variation in days to end of flowering for all cultivars at both sites during both growing seasons. We observed that during years 2019–2020 at NARC-Islamabad, the maximum and minimum days to end of flowering were taken by LG-3295 126 days and 79 days by ROHI Sarsoon. At URF-Koont, we observed that the maximum and minimum days to end of flowering were taken by Faisal Canola 118 days and 88 days by ROHI Sarsoon, respectively. During years 2020–2021, we observed that at NARC-Islamabad, the maximum and minimum days to end of flowering were taken by Crusher 122 days and 100 days by ROHI Sarsoon. At URF-Koont, we observed that the maximum and minimum days to end of flowering were taken by Super Canola 114 days and 81 days by ROHI Sarsoon, respectively (Figs. 19.10, 19.11 and 19.12). Statistical analysis showed highly significant results for L, Y, CUL, treatments and their interactions L × Y, L × CUL, Y × CUL and L × Y × CUL are highly significant. Increasing temperature resulted in variations in the duration of different phenological phases (Table 19.3). Therefore, an early shift in phenology will result in curtailed growth season under contemporary hop of increasing temperature. This

Table 19.3 For the three dependent variables, ANOVA table with degree of freedom with F values and significant levels are shown below

	F values and significant level of fixed effects							
Source	DF	DFF	DOF	DTM	LAI	B.Y	G.Y	H.I
R	2							
L	1	10672.1***	4947.12***	3350.15***	3313.22***	212.32***	4023.86***	48.90***
Y	1	236.73***	1451.50***	283.97***	17823.4***	2587.49***	36429.0***	234.47***
CUL	7	673.30***	779.74***	357.35***	2111.03***	203.42***	5440.39***	124.38***
LxY	1	2.15NS	34.35***	34.35***	735.64***	50.52***	470.17***	0.90**
LxCUL	7	384.27***	379.75***	311.88***	544.96***	74.38***	1432.30***	54.32***
YxCUL	7	0.84NS	52.76***	12.50***	131.96***	22.55***	295.15***	24.81***
LxYxCUL	7	1.23NS	42.94***	21.17***	194.72***	13.87***	139.59***	13.07***
Error	62							

R replication, *L* locations, *Y* years, *CUL* cultivars, *LxY* interaction of locations and years, *LxCUL* interaction of locations and cultivars, *YxCUL* interaction of years and cultivars, *LxYxCUL* interaction of locations, years and cultivars
**Significant level at 0.05 level
***Significant level at 0.01 level

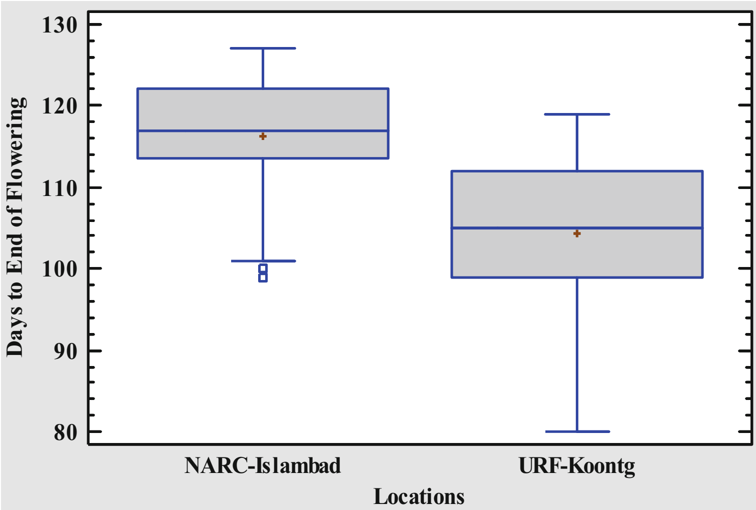

Fig. 19.10 Days to end of flowering for both sites

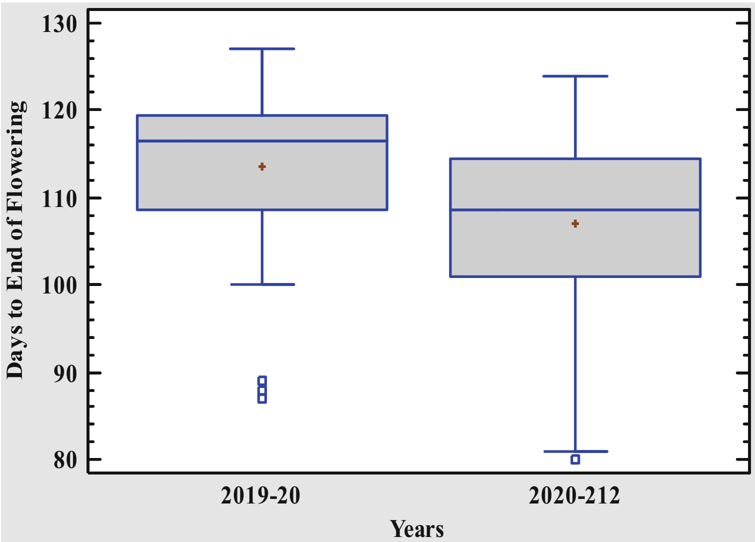

Fig. 19.11 Days to end of flowering for growing seasons 2019–2020 and 2020–2021

variability in phenological development under varying temperature regimes is confirmed by earlier findings (Roetzer et al. 2000; Hatfield et al. 2011; He et al. 2015). On the basis of our observed data, we conclude that during years 2019–2020 at NARC-Islamabad, the maximum and minimum days to maturity were taken by Crusher 186 days and by Faisal Canola 172 days. At URF-Koont, the maximum and minimum days to maturity were taken by Faisal Canola 180 days and by ROHI

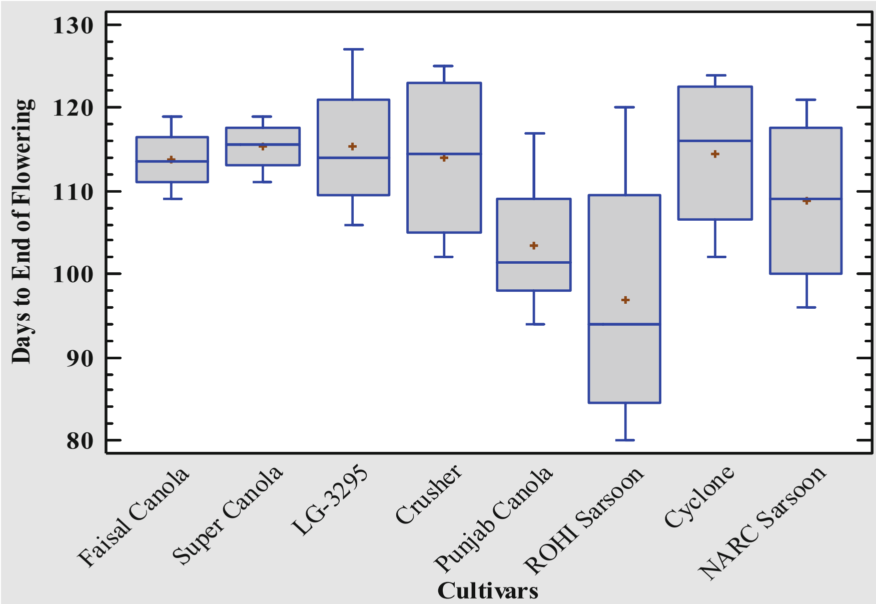

Fig. 19.12 Days to end of flowering for cultivars

Sarsoon 156 days, respectively. During years 2020–2021, we observed that at NARC-Islamabad, the maximum and minimum days to maturity were taken by Cyclone 186 days and by ROHI Sarsoon 170 days. At URF-Koont, we observed that the maximum and minimum days to maturity were taken by Faisal Canola 173 days and by ROHI Sarsoon 152 days, respectively (Figs. 19.13, 19.14 and 19.15). Analysis of variance showed highly significant results for L, Y, CUL, treatments and their interactions L × Y, L × CUL, Y × CUL and L × Y × CUL are highly significant (Table 19.3). The phenology of canola was highly influenced by varying climatic conditions of two selected study sites. The changes in canola phenology was caused by due to increase in temperature during growing seasons and at URF-Koont temperature was high during both growing seasons which results in shortening of phenological phases. Among different growth stages, start of flowering, anthesis and maturity are particularly found sensitive, and their durations were reduced under warming climate (Tao et al. 2013; Ahmad et al. 2015). Increasing temperature caused advancement in anthesis and maturity dates of crop and consequently shortened these phenological phases. This is in line with previous reports about different crops (Tao et al. 2012).

19.4.2.2 Biological and Grain Yield

During years 2019–2020 at NARC-Islamabad, the highest and lowest biological yield was observed in Super Canola 13842 kg h^{-1} and Faisal Canola 11860 kg ha^{-1}.

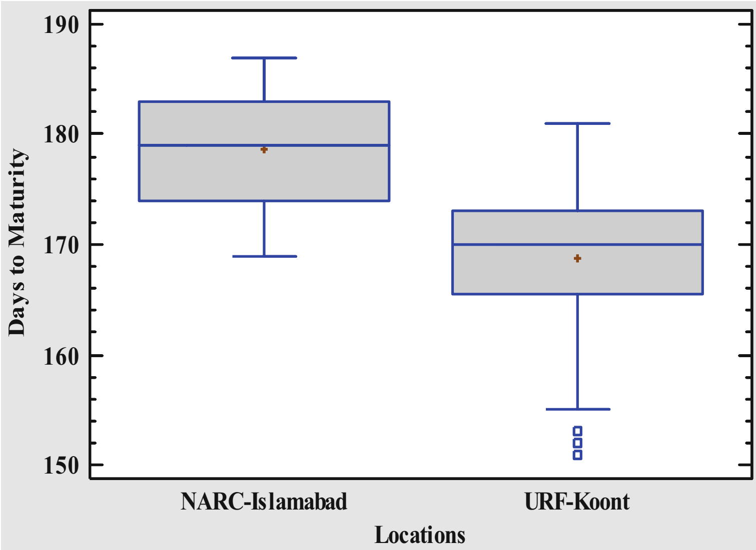

Fig. 19.13 Days to maturity for both sites

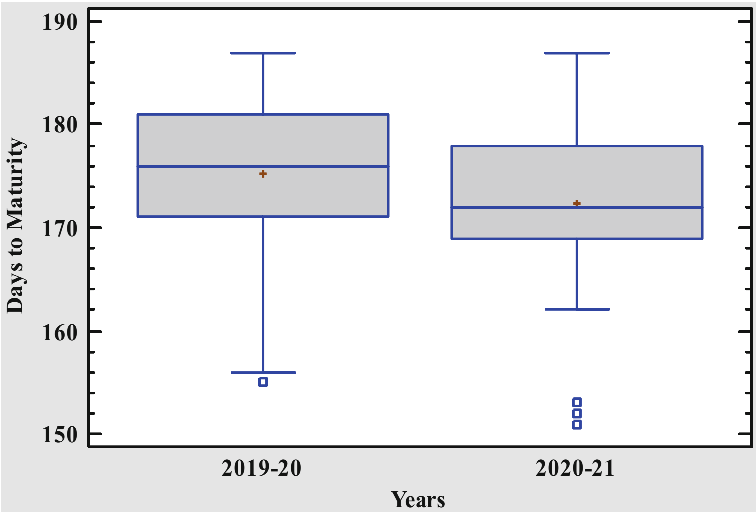

Fig. 19.14 Days to maturity for growing seasons 2019–2020 and 2020–2021

At URF-Koont, we observed the highest and lowest biological yield in ROHI Sarsoon 14100 kg ha^{-1} and Faisal Canola 11540 kg h^{-1}, respectively. During years 2020–2021 at NARC-Islamabad, the highest and lowest biological yield was observed in NARC Sarsoon 13092 kg ha^{-1} and Faisal Canola 11037 kg ha^{-1}. At URF-Koont, the highest and lowest biological yield was observed in NARC Sarsoon

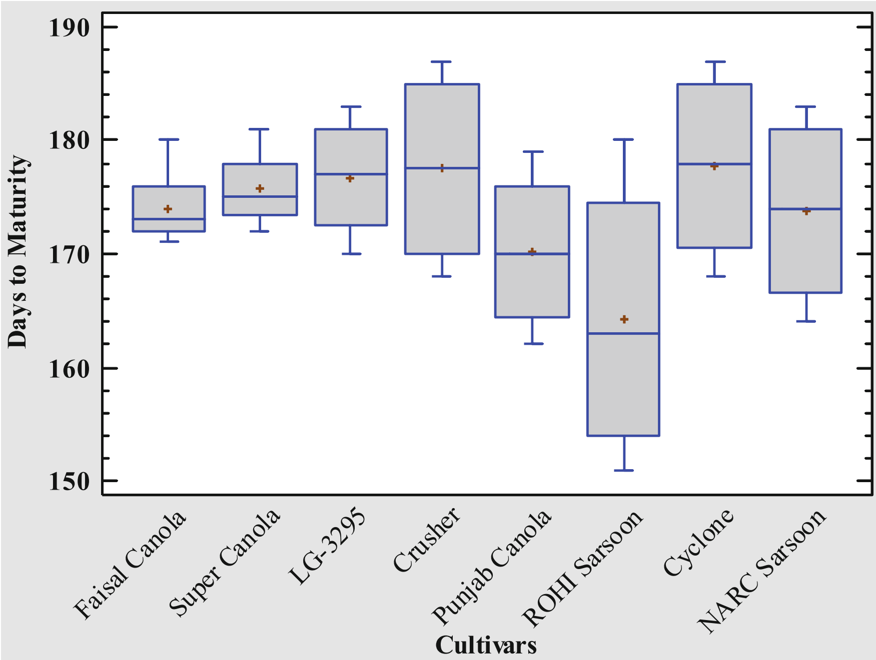

Fig. 19.15 Days to maturity for all cultivars

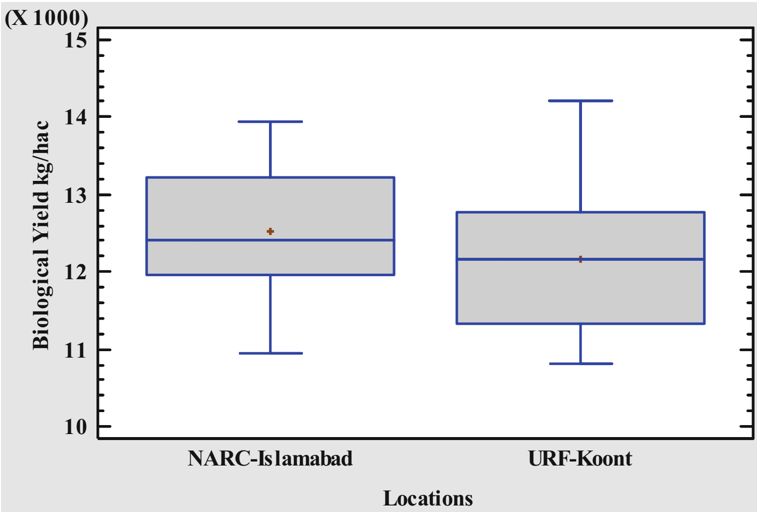

Fig. 19.16 Biological yield at both sites

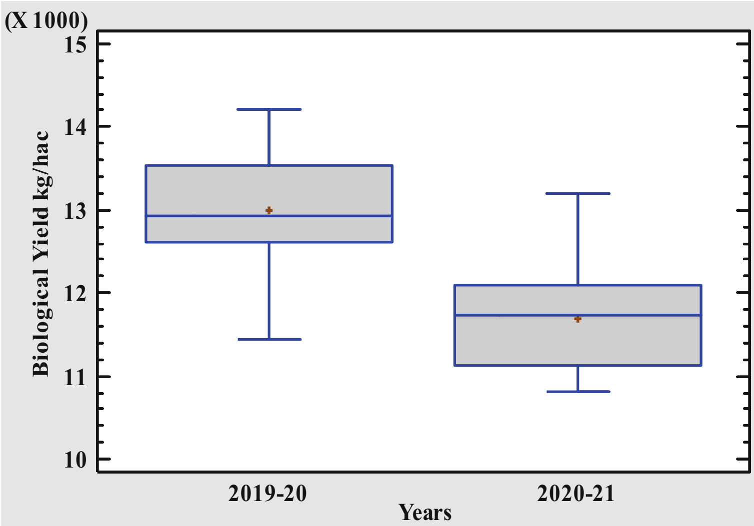

Fig. 19.17 Biological yield for growing seasons 2019–2020 and 2020–2021

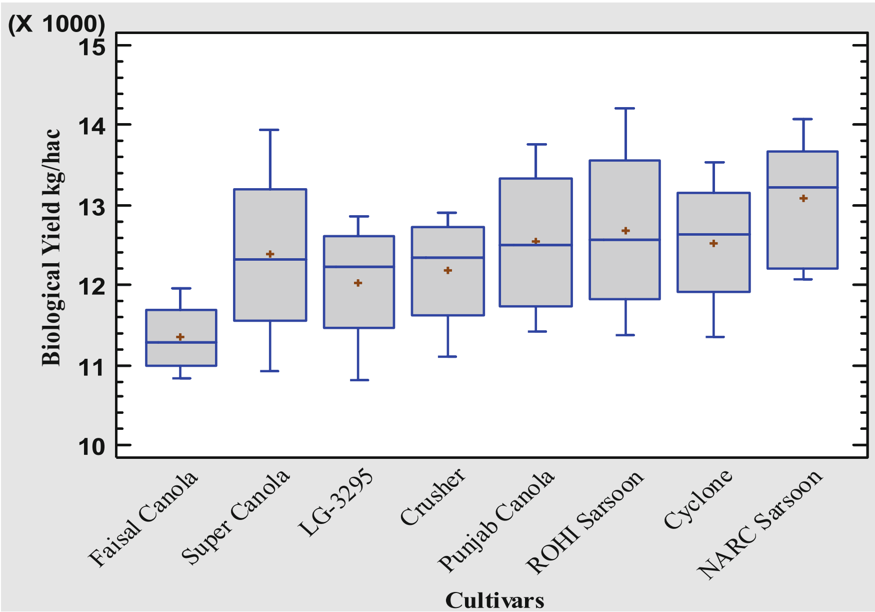

Fig. 19.18 Biological yield for cultivars

12166 kg ha^{-1} and LG-3295 10912 kg ha^{-1}, respectively (Figs. 19.16, 19.17 and 19.18). Biological yield showed variation among study sites. Analysis of variance table described those effects of L, Y, CUL, L × Y, L × CUL, Y × CUL and

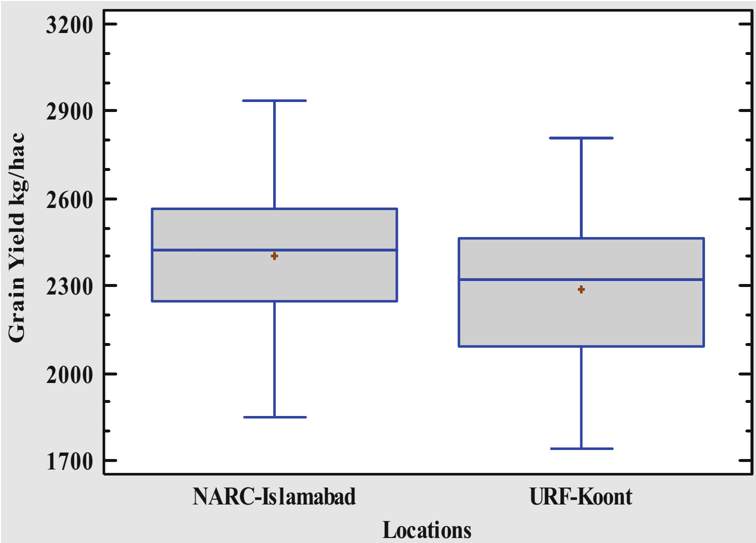

Fig. 19.19 Grain yield of both sites

L × Y × CUL were highly significant (Table 19.3). The growth and development of crop effected by temperature, which directly influences crop age and thus affects the biological and grain yield. Varying climatic parameters have their critical impact on yield. Challinor et al. (2009) also pointed that crop biomass was expressively affected due to change in environments. If the total period of growth and development of crop cultivars is short, then, consequently, there is a reduction of crop production because of the shorter time for total dry matter accumulation during the vegetative phase, particularly for high-input crops (Rezaei et al. 2015; Zhang et al. 2013). At NARC-Islamabad during years 2019–2020, the highest and lowest grain yield was observed for NARC Sarsoon 2926 kg h^{-1} and Faisal Canola 2231 kg h^{-1}. At URF-Koont, the highest and lowest grain yield was observed for ROHI Sarsoon 2796 kg h^{-1} and Faisal Canola 2112 kg h^{-1}, respectively. During years 2020–2021 at NARC-Islamabad, we noted the highest and lowest grain yield was observed for NARC Sarsoon 2667 kg h^{-1} and Faisal Canola 1862 kg h^{-1}. At URF-Koont, we noted the highest and lowest grain yield was observed for ROHI Sarsoon 2330 kg h^{-1} and Faisal Canola 1760 kg h^{-1}, respectively (Figs. 19.19, 19.20 and 19.21). Analysis of variance table showed that the effects of L, Y, CUL, L × Y, L × CUL, Y × CUL and L × Y × CUL were highly significant (Table 19.3). Climatic parameters had great influence on the production of canola crop. The temperature increased during years 2020–2021 at both sites which adversely affected the crop phenology and resulted in the shortening of crop duration, which further affected the grain yield negatively. Change in seasonal temperature impacted the crop production, and reduction in yield during 2020–2021 might be due to higher temperature. Due to warming trends, the biological and grain yield is reduced with early anthesis and maturity (Xiao and Tao 2014). By early anthesis and delayed

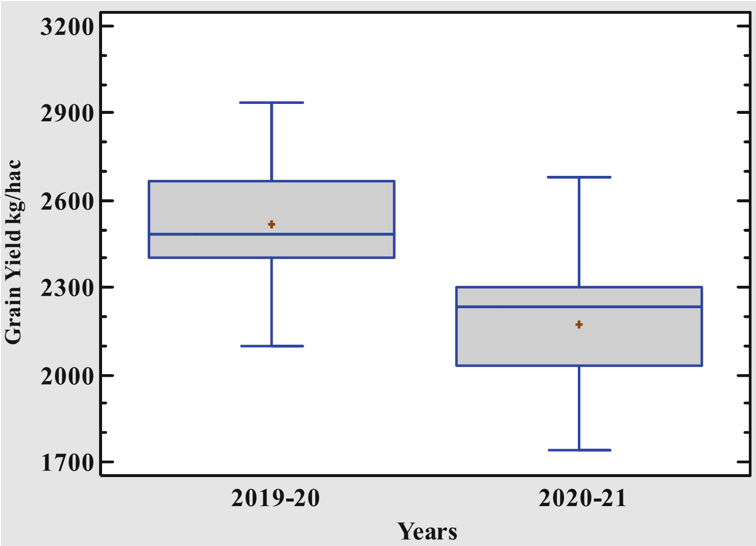

Fig. 19.20 Grain yield for growing seasons 2019–2020 and 2020–2021

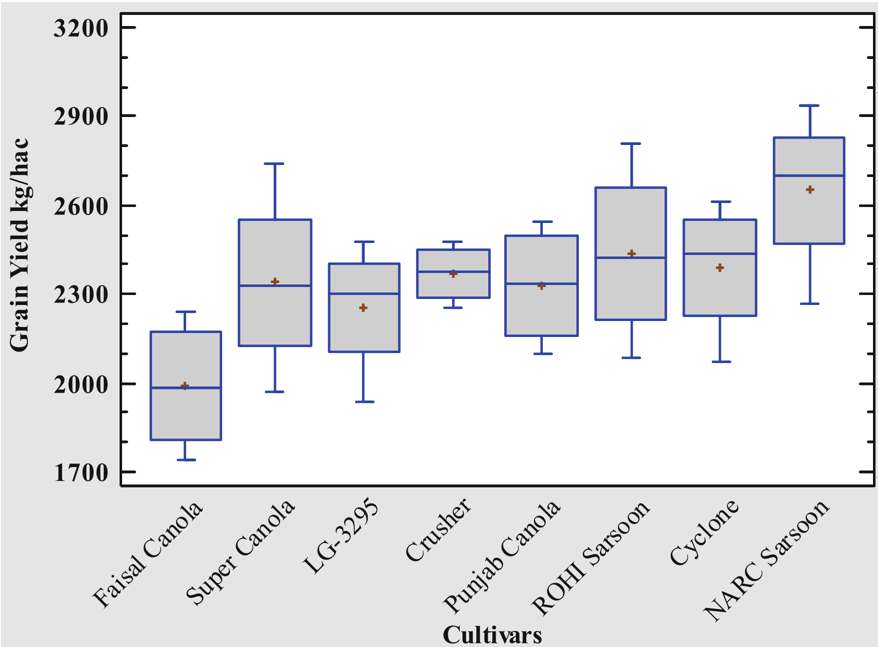

Fig. 19.21 Grain yield for cultivars

maturity, the production of several crops increased due to extended grain filling stage (He et al. 2015). The crop production is less if the duration of crop growth and development is short (Rezaei et al. 2015).

19.4.2.3 Harvest Index

At NARC-Islamabad during years 2019–2020, the highest and lowest harvest index was observed for NARC Sarsoon 21.91 and Faisal Canola 18.81. At URF-Koont, the highest and lowest harvest index was observed for ROHI Sarsoon 19.82 and Faisal Canola 18.30, respectively. During 2020–2021 at NARC-Islamabad, the highest and lowest harvest index was observed for NARC Sarsoon 20.37 and Faisal Canola 16.87. At URF-Koont, the highest and lowest harvest index was observed for ROHI Sarsoon 19.16 and Faisal Canola 16.1, respectively (Figs. 19.22, 19.23 and 19.24). Analysis of variance table explained that the main effects of L, Y, CUL, L × Y, L × CUL, Y × CUL and L × Y × CUL were highly significant (Table 19.3). Harvest index is the ratio between grain yield and biological yield. Variations in harvest index at both sites during growing seasons were observed due to climate change. At NARC-Islamabad, the temperature was lower than URF-Koont, and climatic conditions were favourable for better crop stand which resulted in the proper translocation of photosynthate into grains. Andarzian et al. (2015) also reported that under favourable climate, crop translocates its photosynthate into grains.

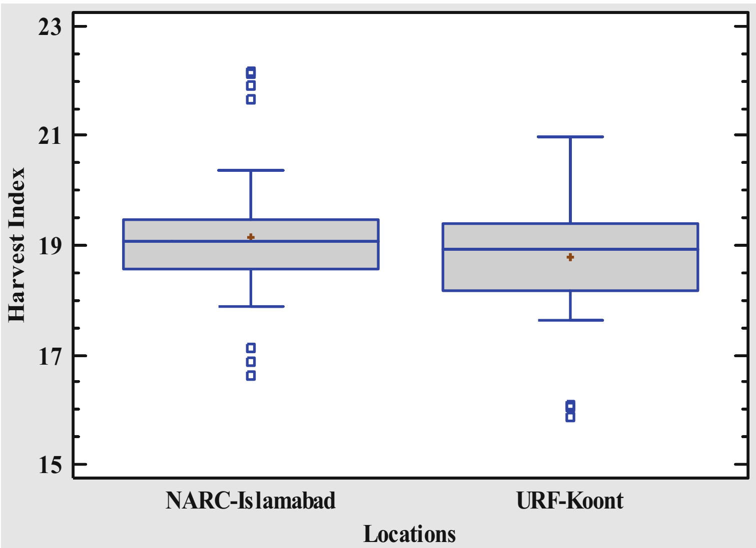

Fig. 19.22 Harvest index of both sites

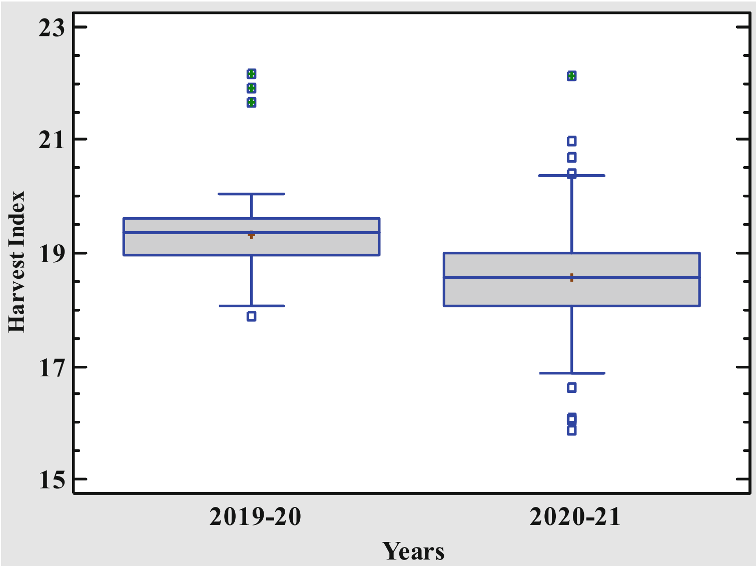

Fig. 19.23 Harvest index for growing seasons 2019–2020 and 2020–2021

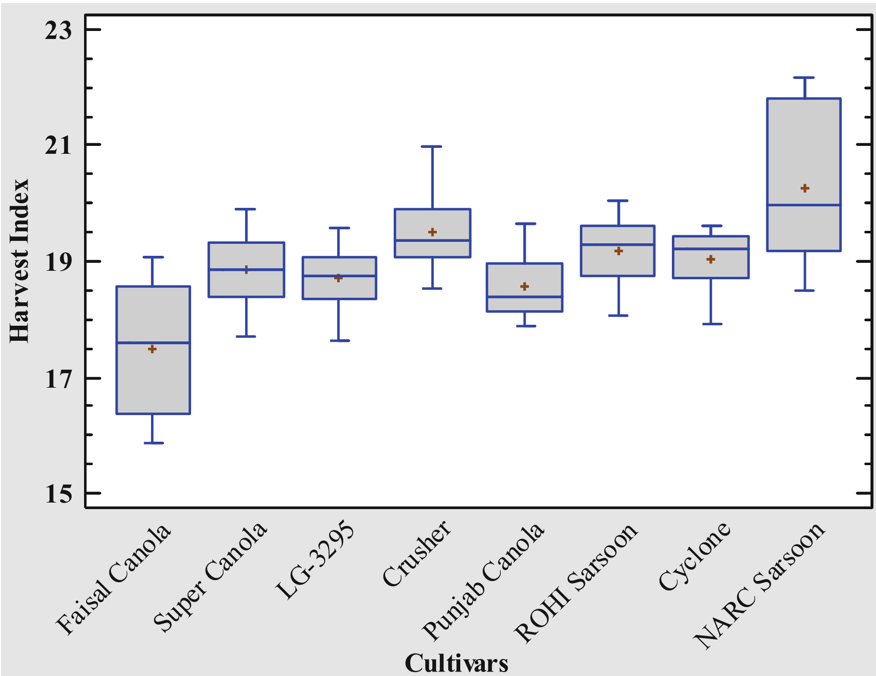

Fig. 19.24 Harvest index for cultivars

19.4.3 Phenology Modelling

For the eight cultivars of canola, a phenological model was established with varying sensitivities to vernalisation for both sites and growing seasons. All the cultivars show different vernalisation requirements under varying climatic conditions of both study sites during both growing seasons. At NARC-Islamabad during years 2019–2020 and 2020–2021, the vernalisation days required to achieve vernalisation for Faisal Canola were 29d and 26d, Super Canola 39d and 35d, LG-3295 41d and 37d, Crusher 44d and 39d, Punjab Canola 31d and 28d, ROHI Sarsoon 30d and 28d, Cyclone 54d and 51d and NARC Sarsoon 44d and 39d, respectively (days = d). At URF-Koont during years 2019–2020 and 2020–2021, the vernalisation days required to achieve vernalisation for Faisal Canola were 26d and 25d, Super Canola 26d and 26d, LG-3295 23d and 23d, Crusher 21d and 20d, Punjab Canola 16d and 15d, ROHI Sarsoon 10d and 9d, Cyclone 22d and 20d and NARC Sarsoon 17d and 16d, respectively (days = d). All the cultivars show weak sensitivities to vernalisation at URF-Chakwal and strong sensitivities to vernalisation at NARC-Islamabad during both growing seasons.

19.4.4 Simulation Outcomes

19.4.4.1 Phenology

We validated the DSSAT model for our experimental data; the model was used to extend our understandings for various crop parameters. Thus, the eight canola cultivars were simulated in our two different experimental locations with different sowing dates during years 2019–2020 and 2020–2021 using historical climate data. Model predicted that days to anthesis at both sites during growing seasons very close association with observed days to anthesis. The performance of DSSAT was compared by using validation skill scores (R^2, RMSE and d-index). During years 2019–2020 at NARC-Islamabad, the model predicted the maximum days to anthesis for Cyclone 103 and minimum days for Faisal Canola 77, and our observed data showed the maximum days for Cyclone 103 and minimum days for Faisal Canola 78. The values for R^2, RMSE and d-index were 0.99, 0.61 and 0.99, respectively, while at URF-Koont, the model predicted the maximum days to anthesis for Faisal Canola 77 and minimum days for ROHI Sarsoon 57, and our observed data showed the maximum days for Faisal Canola 77 and minimum days for ROHI Sarsoon 57. The values for R^2, RMSE and d-index were 0.99, 0.57 and 0.98, respectively, for years 2019–2020. During years 2020–2021 at NARC-Islamabad, the model predicted the maximum days to anthesis for Cyclone 101 and minimum days for Faisal Canola 74, and our observed data showed the maximum days for Cyclone 102 and minimum for Faisal Canola 75. The values for R^2, RMSE and d-index were 0.99, 0.63 and 0.99, respectively, while at URF-Koont, the model predicted the

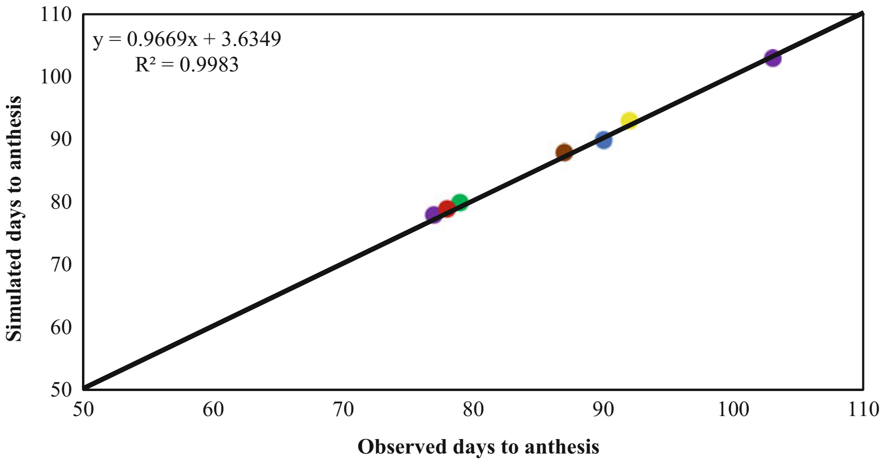

Fig. 19.25 Observed and simulated days to anthesis for NARC-Islamabad during years 2019–2020

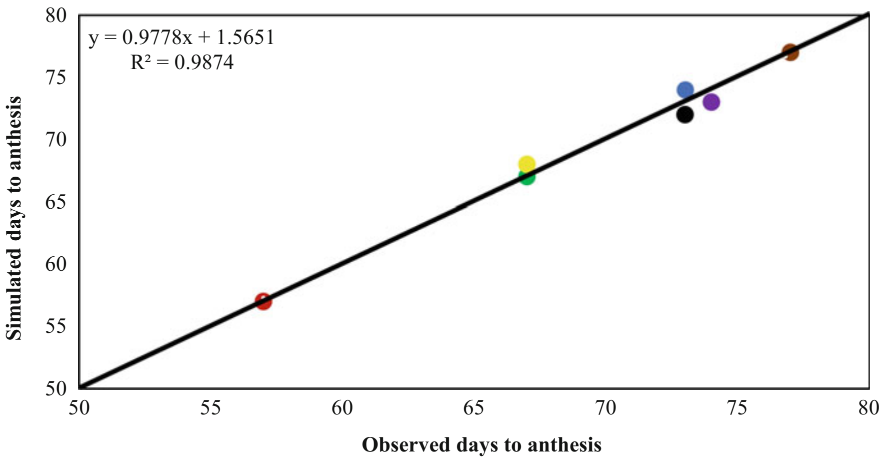

Fig. 19.26 Observed and simulated days to anthesis for URF-Koont during years 2019–2020

maximum days to anthesis for Super Canola 75 and minimum days for ROHI Sarsoon 54, and our observed days to anthesis was maximum for Super Canola 75 and minimum for ROHI Sarsoon 54. The values for R^2, RMSE and d-index were 0.99, 0.81 and 0.97, respectively. DSSAT shows performance with great accuracy and prediction of days to anthesis was close to observed days to anthesis. The model could predict better crop phenology under climate change and study sites by exhibiting the validation skill scores, viz. R^2, RMSE and d-index (Figs. 19.25, 19.26, 19.27 and 19.28).

Days to end of flowering was predicted by DSSAT with close association with observed days to end of flowering. During years 2019–2020 at NARC-Islamabad,

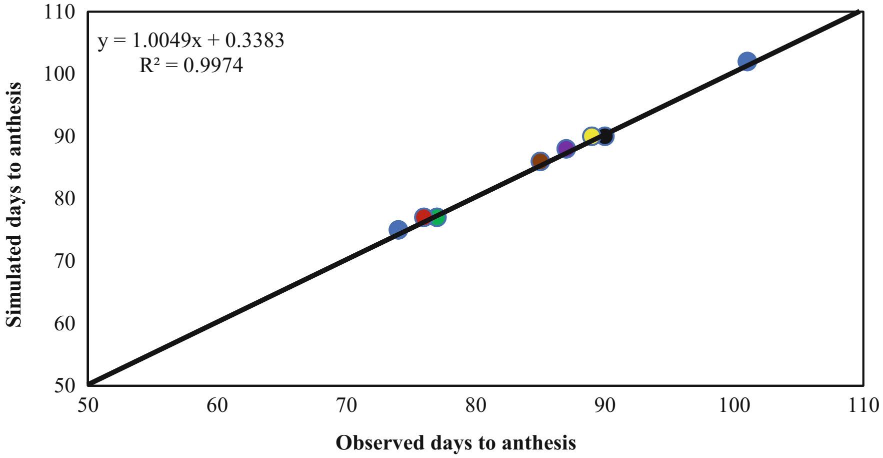

Fig. 19.27 Observed and simulated days to anthesis for NARC-Islamabad during years 2020–2021

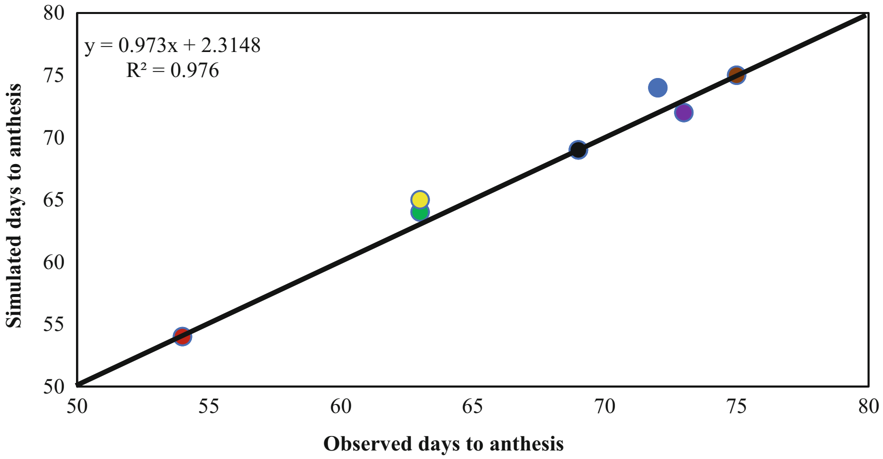

Fig. 19.28 Observed and simulated days to anthesis for URF-Koont during years 2020–2021

the model predicted the maximum days to end of flowering for LG-3295 125 and minimum days for Faisal Canola 114, and our observed maximum days to end of flowering was for LG-3295 126 and minimum days for Faisal Canola 115. The values for R^2, RMSE and d-index were 0.99, 0.59 and 0.99, respectively, while at URF-Koont, the model predicted the maximum days to end of flowering for Super Canola 129 and minimum days for ROHI Sarsoon 88, and our observed maximum days was for Super Canola 130 and minimum days for ROHI Sarsoon 88. The values for R^2, RMSE and d-index were 0.99, 0.62 and 0.99, respectively. During years 2020–2021 at NARC-Islamabad, the model predicted the maximum days to end of flowering for Cyclone 122 and minimum days for ROHI Sarsoon 99, and our

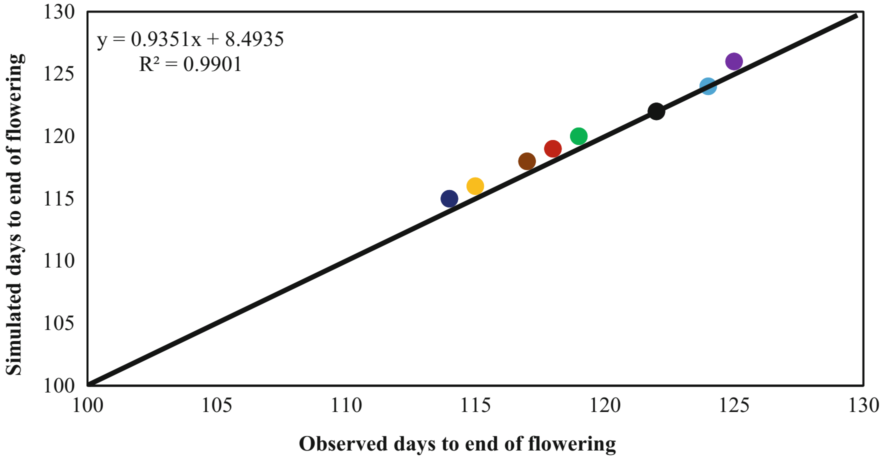

Fig. 19.29 Observed and simulated days to end of flowering for NARC-Islamabad during years 2019–2020

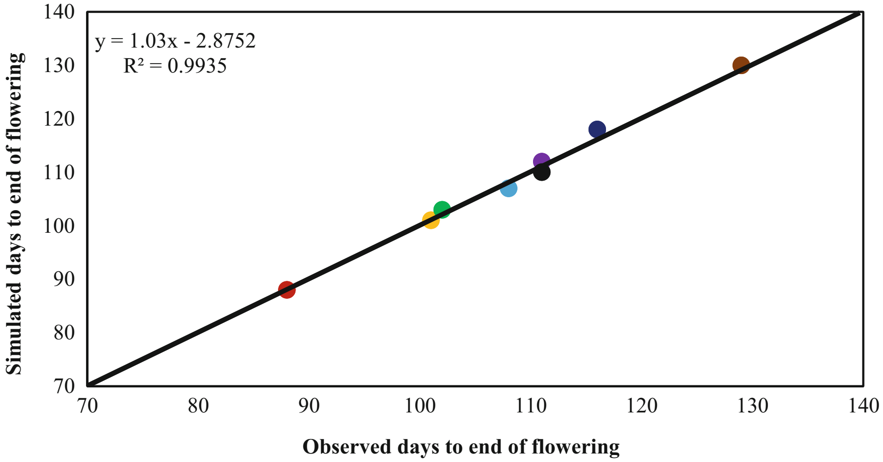

Fig. 19.30 Observed and simulated days to end of flowering for URF-Koont during years 2019–2020

observed maximum days was for Cyclone 123 and minimum days for ROHI Sarsoon 100. The values for R^2, RMSE and d-index were 0.99, 0.64 and 0.99, respectively, while at URF-Koont, the model predicted the maximum days to end of flowering for Super Canola 114 and minimum days for ROHI Sarsoon 81, and our observed maximum days was for Super Canola 114 and minimum days for ROHI Sarsoon 81. The values for R^2, RMSE and d-index were 0.99, 0.52 and 0.99, respectively. DSSAT shows performance with great accuracy and prediction of days to end of flowering was close to observed days to end of flowering. The performance of

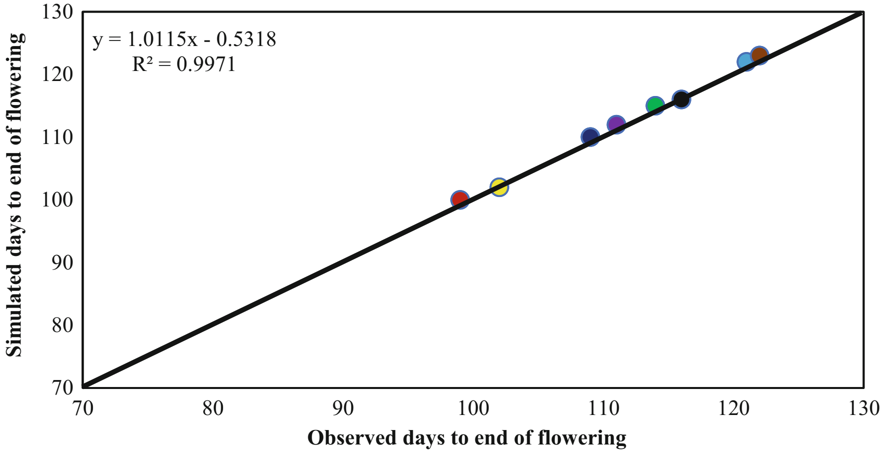

Fig. 19.31 Observed and simulated days to end of flowering for NARC-Islamabad during years 2020–2021

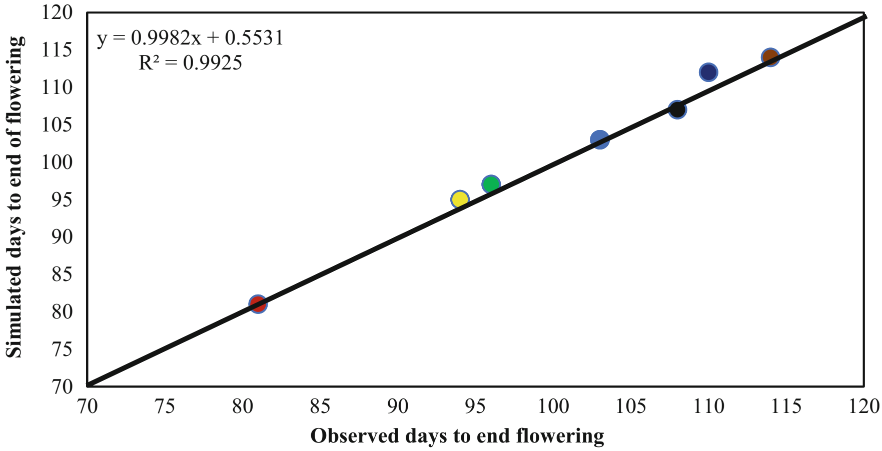

Fig. 19.32 Observed and simulated days to end of flowering for URF-Koont during years 2020–2021

DSSAT was compared by using validation skill scores (R^2, RMSE and d-index) (Figs. 19.29, 19.30, 19.31 and 19.32).

The model predicted the days to maturity with close association with our observed days to maturity. During years 2019–2020 at NARC-Islamabad, the model predicted the maximum days to maturity for Crusher 186 and minimum days for Faisal Canola 169, and our observed data showed the maximum days to maturity for Crusher 186 and minimum days for Faisal Canola 172. The values for R^2, RMSE and d-index were 0.97, 1.70 and 0.99, respectively, while at URF-Koont, the model predicted the maximum days to maturity for Faisal Canola 174 and

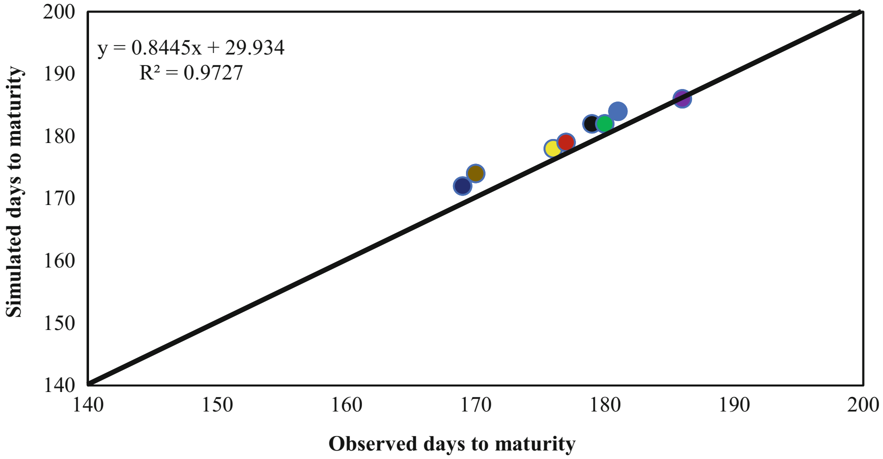

Fig. 19.33 Observed and simulated days to maturity for NARC-Islamabad during years 2019–2020

minimum days for ROHI Sarsoon 156, and our observed data showed the maximum days to maturity for Super Canola 180 and minimum days for ROHI Sarsoon 156. The values for R^2, RMSE and d-index were 0.92, 1.91 and 0.97, respectively. During years 2020–2021 at NARC-Islamabad, the model predicted the maximum days to maturity for Cyclone 184 and minimum days for ROHI Sarsoon 167, and our observed data showed the maximum days to maturity for Cyclone 186 and minimum days for ROHI Sarsoon 170. The values for R^2, RMSE and d-index were 0.97, 1.69 and 0.99, respectively, while at URF-Koont, the model predicted the maximum days to maturity for Super Canola 175 and minimum days for ROHI Sarsoon 151, and our observed data showed the maximum days to maturity for Super Canola 173 and minimum days for ROHI Sarsoon 152. The values for R^2, RMSE and d-index were 0.99, 0.55 and 0.99, respectively. DSSAT shows performance with great accuracy and prediction of days to maturity was close to observed days to maturity. The performance of DSSAT was compared by using validation skill scores (R^2, RMSE and d-index) (Figs. 19.33, 19.34, 19.35 and 19.36).

19.4.4.2 Leaf Area Index

The model predicted the leaf area index (LAI) with very close association with our observed leaf area index. During years 2019–2020 at NARC-Islamabad, the model predicted the maximum LAI for NARC Sarsoon 3.9 and minimum LAI for Faisal Canola 3.3, and observed data for the maximum and minimum LAI was the same for the same cultivars as the model predicted. The values for R^2, RMSE and d-index were 1, 0 and 1, respectively, while at URF-Koont, the model predicted the maximum LAI for ROHI Sarsoon 3.9 and minimum LAI for Faisal Canola 3.2, and our

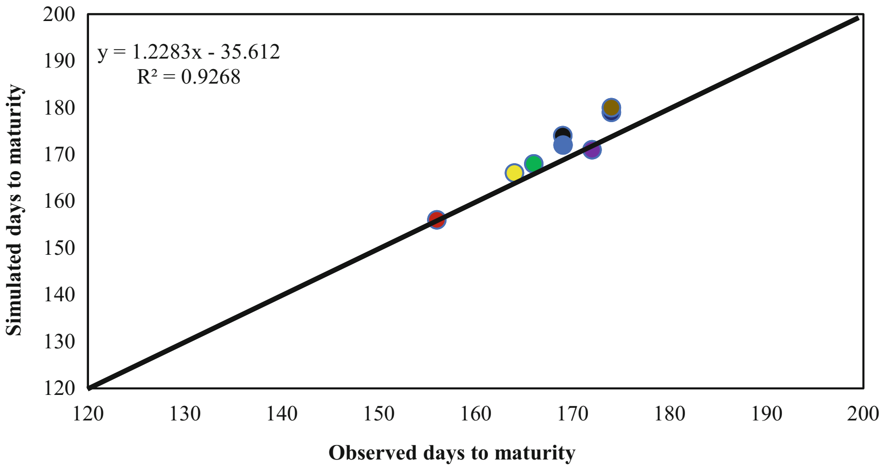

Fig. 19.34 Observed and simulated days to maturity for URF-Koont during years 2019–2020

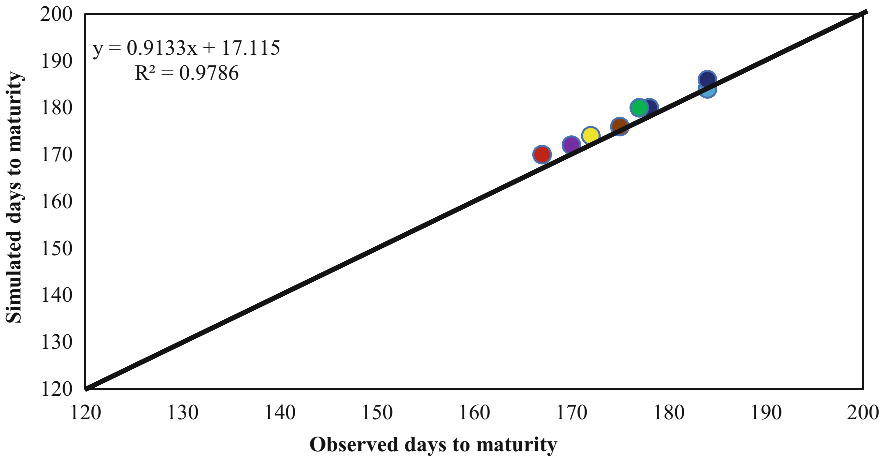

Fig. 19.35 Observed and simulated days to maturity for NARC-Islamabad during years 2020–2021

observed data showed the maximum and minimum LAI was the same for the same cultivar as the model predicted. The values for R^2, RMSE and d-index were 1, 0 and 1, respectively. During years 2020–2021 at NARC-Islamabad, the model predicted the maximum LAI for NARC Sarsoon 3.9 and minimum LAI for Faisal Canola 3.2, and our observed maximum and minimum LAI was the same for the same cultivars as the model predicted. The values for R^2, RMSE and d-index were 1, 0 and 1, respectively, while at URF-Koont, the model predicted the maximum LAI for ROHI Sarsoon 3.7 and minimum LAI for Faisal Canola 3.1, and our observed maximum and minimum LAI was the same for the same cultivars as the model

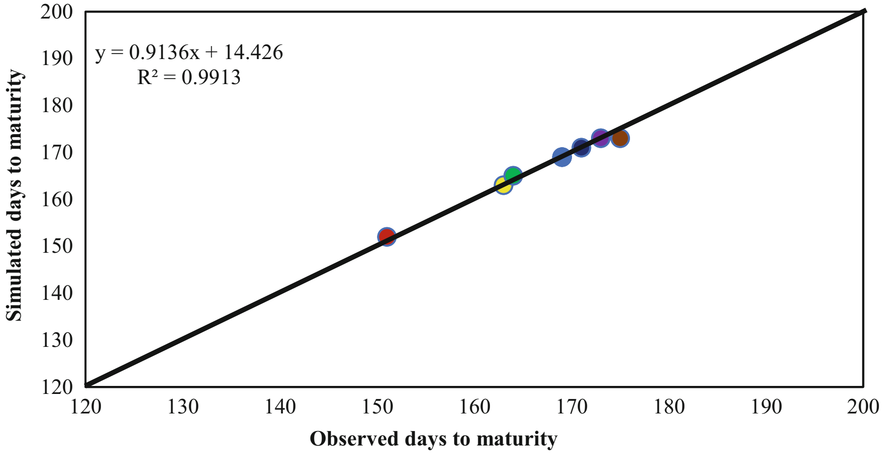

Fig. 19.36 Observed and simulated days to maturity for URF-Koont during years 2020–2021

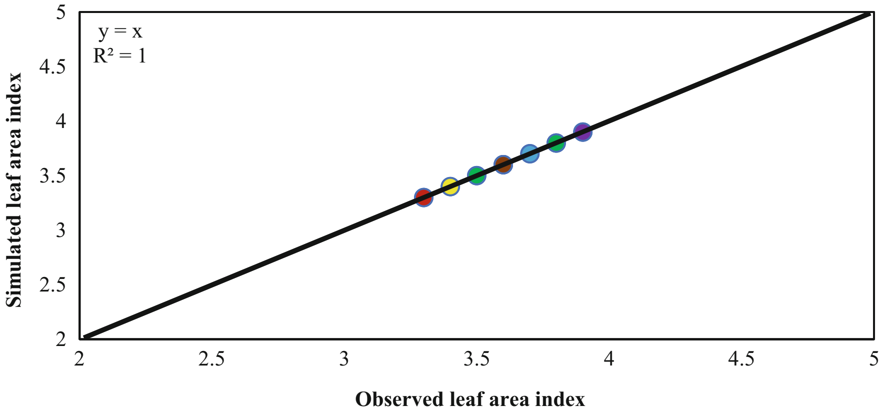

Fig. 19.37 Observed and simulated leaf area index for NARC-Islamabad during years 2019–2020

predicted. The values for R^2, RMSE and d-index were 1, 0 and 1, respectively. DSSAT shows performance with great accuracy and prediction of LAI was the same as the observed LAI for all cultivars during both years. The performance of DSSAT was compared by using validation skill scores (R^2, RMSE and d-index) (Figs. 19.37, 19.38, 19.39 and 19.40).

19.4.4.3 Biological Yield

The model predicted the biological yield with close association with our observed biological yield. At NARC-Islamabad during years 2019–2020, the model predicted

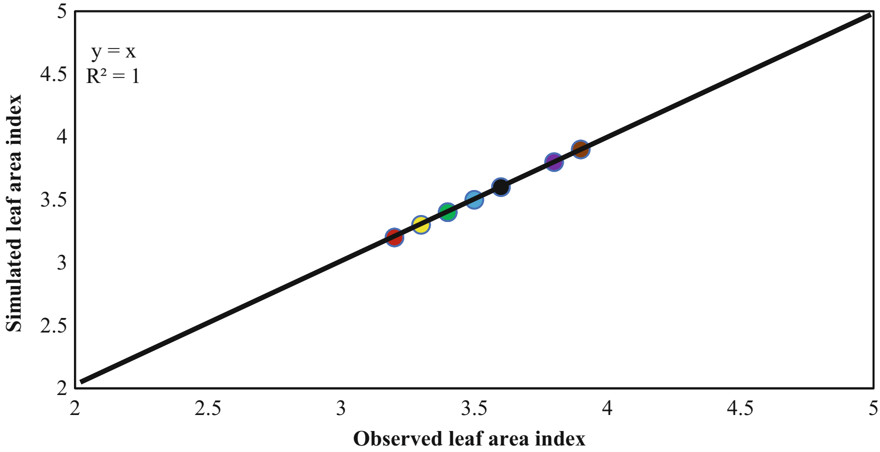

Fig. 19.38 Observed and simulated leaf area index for URF-Koont during years 2019–2020

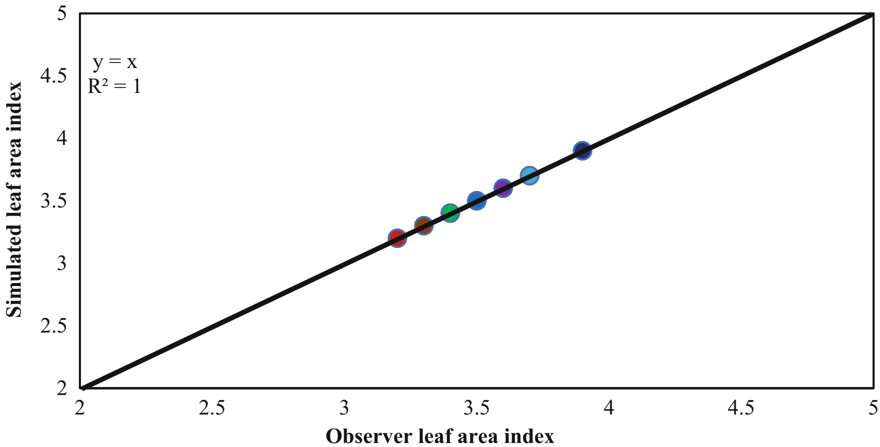

Fig. 19.39 Observed and simulated leaf area index for NARC-Islamabad during years 2020–2021

the maximum biological yield for Super Canola 13828 kg h^{-1} and minimum biological yield for Faisal Canola 11852 kg h^{-1}, and our observed data showed the maximum biological yield for Super Canola 13842 kg h^{-1} and minimum biological yield for Faisal Canola 11860 kg h^{-1}. The values for R^2, RMSE and d-index were 0.99, 67.46 and 0.99, respectively, while at URF-Koont, the model predicted the maximum biological yield for NARC Sarsoon 13971 kg h^{-1} and minimum biological yield for Faisal Canola 11500 kg h^{-1}, and our observed data showed the maximum biological yield for ROHI Sarsoon 14100 kg h^{-1} and minimum biological yield for Faisal Canola 11540 kg h^{-1}. The values for R^2, RMSE and d-index were 0.98, 108.37 and 0.99, respectively. During years 2020–2021 at

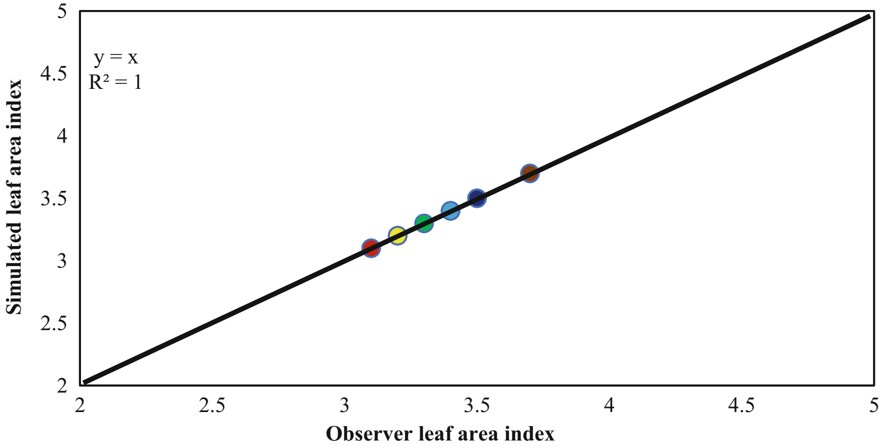

Fig. 19.40 Observed and simulated leaf area index for URF-Koont during years 2020–2021

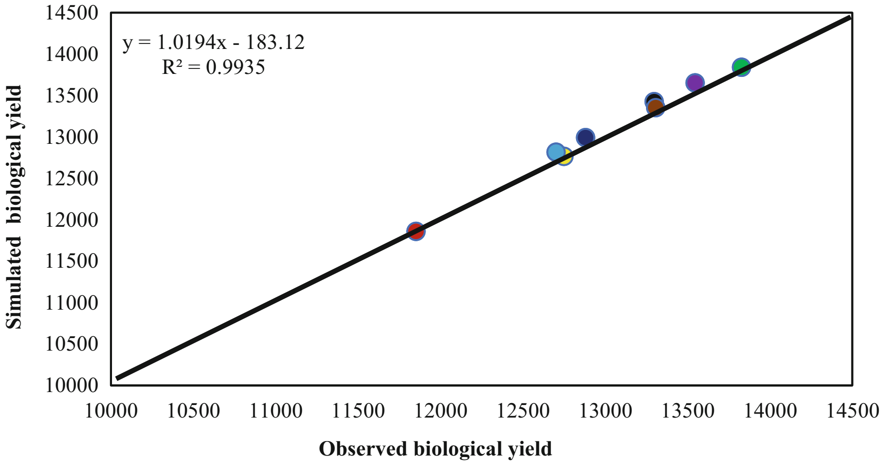

Fig. 19.41 Observed and simulated biological yield for NARC-Islamabad during years 2019–2020

NARC-Islamabad, the maximum biological yield was predicted for NARC Sarsoon 13079 kg h^{-1} and minimum biological yield for Faisal Canola 11014 kg h^{-1}, and our observed data showed the maximum biological yield for NARC Sarsoon 13092 kg h^{-1} and minimum biological yield for Faisal Canola 11037 kg h^{-1}. The values for R^2, RMSE and d-index were 0.99, 11.55 and 0.99, respectively, while at URF-Koont, the model predicted the maximum biological yield for ROHI Sarsoon 12382 kg h^{-1} and minimum biological yield for LG-3295 10886 kg h^{-1}, and our observed data showed the maximum biological yield for NARC Sarsoon 12166 kg h^{-1} and minimum biological yield for LG-3295 10912 kg h^{-1}. The values for R^2, RMSE and d-index were 0.92, 127.46 and 0.99, respectively. DSSAT shows

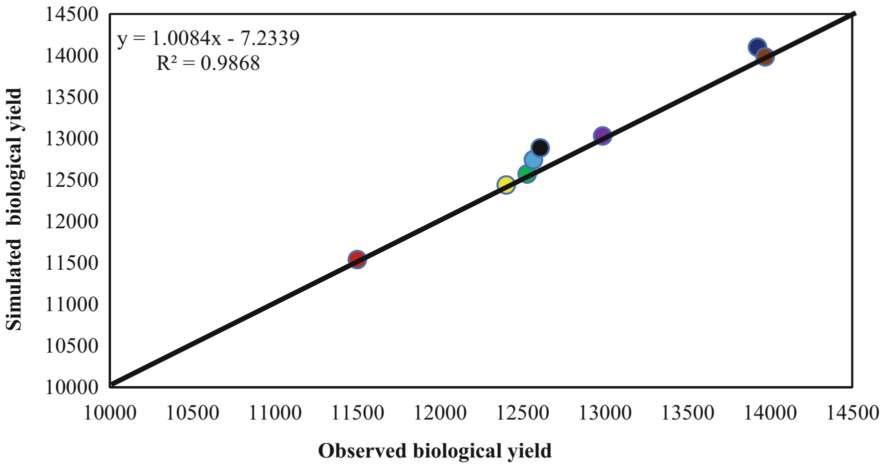

Fig. 19.42 Observed and simulated biological yield for URF-Koont during years 2019–2020

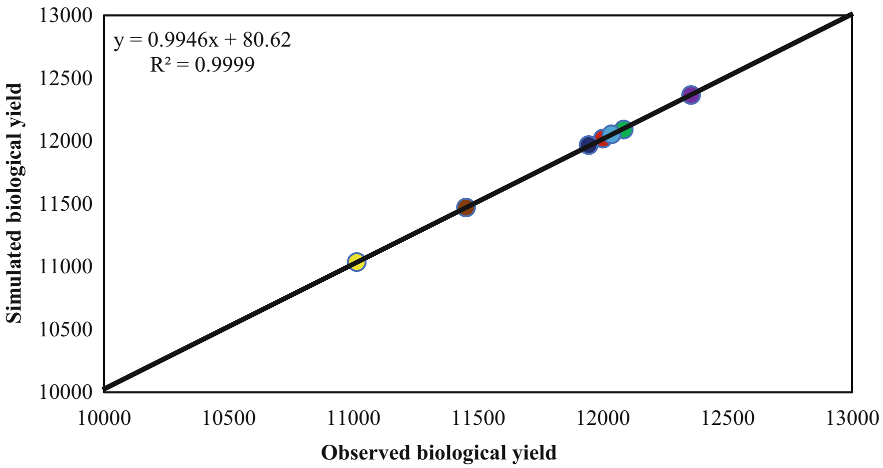

Fig. 19.43 Observed and simulated biological yield for NARC-Islamabad during years 2020–2021

performance with great accuracy and prediction of the biological yield was close to observed biological yield. The performance of DSSAT was compared by using validation skill scores (R^2, RMSE and d-index) (Figs. 19.41, 19.42, 19.43 and 19.44).

19.4.4.4 Grain Yield

Grain yield was predicted by DSSAT with close association with observed grain yield. Predicted grain yield was different for all cultivars, and the model predicted

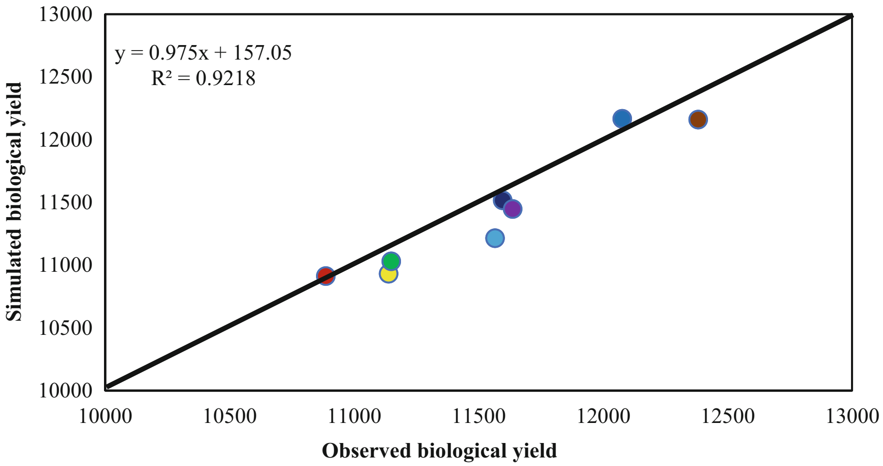

Fig. 19.44 Observed and simulated biological yield for URF-Koont during years 2020–2021

high grain yield for some cultivars and low grain yield for some cultivars than our observed grain yield for both sites during both years, respectively. During years 2019–2020 at NARC-Islamabad, the model predicted the maximum grain yield for NARC Sarsoon 2889 kg h^{-1} and minimum grain yield for Faisal Canola 2234 kg h^{-1}, and our observed data showed the maximum grain yield for NARC 2926 kg h^{-1} and minimum grain yield for Faisal Canola 2231 kg h^{-1}. The values for R^2, RMSE and d-index were 0.98, 29.39 and 0.99, respectively, while at URF-Koont, the model predicted the maximum grain yield for ROHI Sarsoon 2753 kg h^{-1} and minimum grain yield for Faisal Canola 2115 kg h^{-1}, and our observed data showed the maximum grain yield for ROHI Sarsoon 2796 kg h^{-1} and minimum grain yield for Faisal Canola 2112 kg h^{-1}. The values for R^2, RMSE and d-index were 0.99, 23.57 and 0.99, respectively. During years 2020–2021 at NARC-Islamabad, the model predicted the maximum grain yield for NARC Sarsoon 2652 kg h^{-1} and minimum grain yield for Faisal Canola 1853 kg h^{-1}, and our observed data showed the maximum grain yield for NARC Sarsoon 2667 kg h^{-1} and minimum grain yield for Faisal Canola 1862 kg h^{-1}. The values for R^2, RMSE and d-index were 0.99, 11.22 and 0.99, respectively, while at URF-Koont, the model predicted the maximum grain yield for ROHI Sarsoon 2380 kg h^{-1} and minimum grain yield for Faisal Canola 1800 kg h^{-1}, and our observed data showed the maximum grain yield for ROHI Sarsoon 2330 kg h^{-1} and minimum grain yield for Faisal Canola 1760 kg h^{-1}. The values for R^2, RMSE and d-index were 0.97, 27.11 and 0.99, respectively. DSSAT shows performance with great accuracy and prediction of the biological yield was close to observed biological yield. The performance of DSSAT was compared by using validation skill scores (R^2, RMSE and d-index) (Figs. 19.45, 19.46, 19.47 and 19.48).

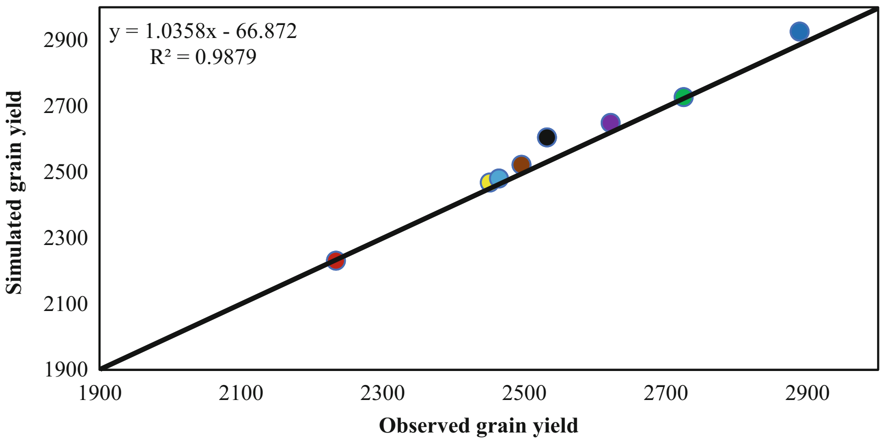

Fig. 19.45 Observed and simulated grain yield for NARC-Islamabad during years 2019–2020

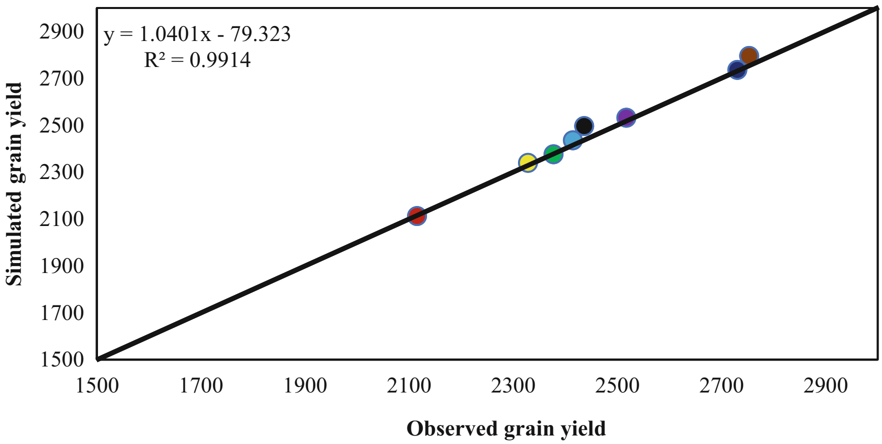

Fig. 19.46 Observed and simulated grain yield for URF-Koont during years 2019–2020

19.4.4.5 Harvest Index

Harvest index (HI) was predicted by DSSAT with close association with observed harvest index. During years 2019–2020 at NARC-Islamabad, the model predicted the maximum HI for NARC Sarsoon 21.71 and minimum HI for Faisal Canola 18.84, and our observed data showed the maximum HI for NARC Sarsoon 21.91 and minimum HI for Faisal Canola 18.81. The values for R^2, RMSE and d-index were 0.98, 0.139 and 0.99, respectively, while at URF-Koont, the model predicted the maximum HI for ROHI Sarsoon 19.77 and minimum HI for Faisal Canola 18.39, and our observed data showed the maximum HI for ROHI Sarsoon 19.56 and minimum HI for Faisal Canola 18.30. The values for R^2, RMSE and d-index were

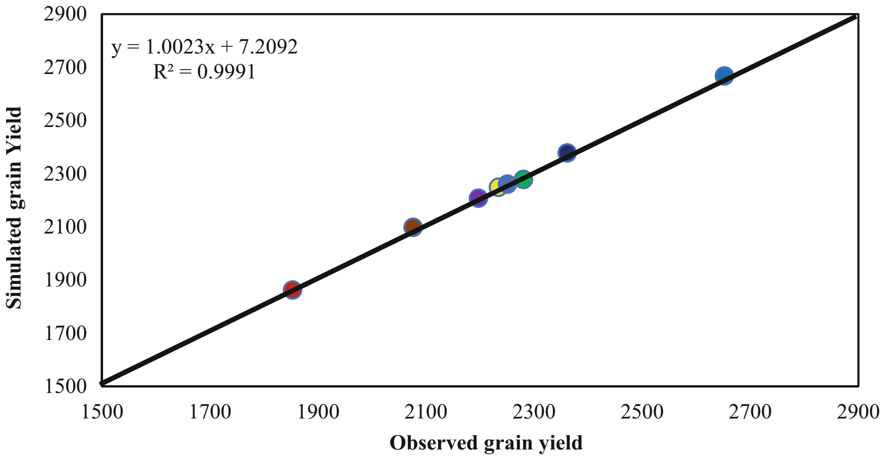

Fig. 19.47 Observed and simulated grain yield for NARC-Islamabad during years 2020–2021

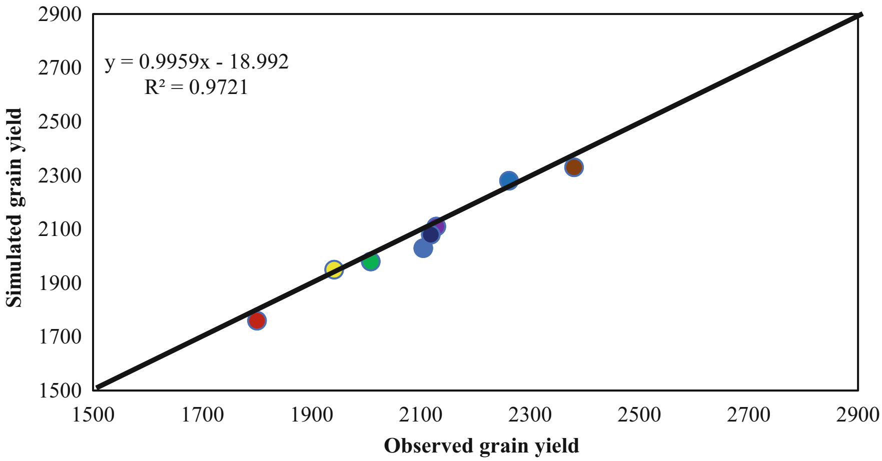

Fig. 19.48 Observed and simulated grain yield for URF-Koont during years 2020–2021

0.99, 0.03 and 0.99, respectively. During years 2020–2021 at NARC-Islamabad, the model predicted the maximum HI for NARC Sarsoon 20.27 and minimum HI for Faisal Canola 16.82, and our observed data showed the maximum HI was for NARC Sarsoon 20.37 and minimum HI was for Faisal Canola 16.87. The values for R^2, RMSE and d-index were 0.99, 0.07 and 0.99, respectively, while at URF-Koont, the model predicted the maximum HI for ROHI Sarsoon 19.22 and minimum HI for Faisal Canola 16.16, and our observed data showed the maximum HI was for ROHI Sarsoon 19.16 and minimum HI was for Faisal Canola 16.10. The values for R^2, RMSE and d-index were 0.99, 0.03 and 0.99, respectively. DSSAT shows performance with great accuracy and prediction of HI was the same as the observed HI for

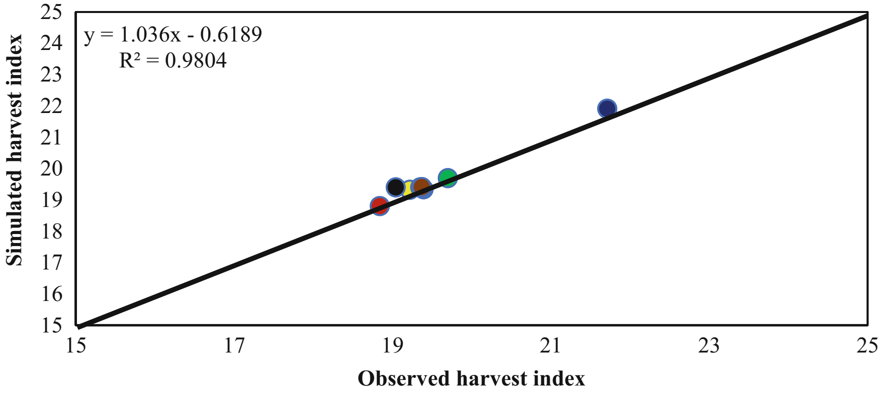

Fig. 19.49 Observed and simulated harvest index for NARC-Islamabad during years 2019–2020

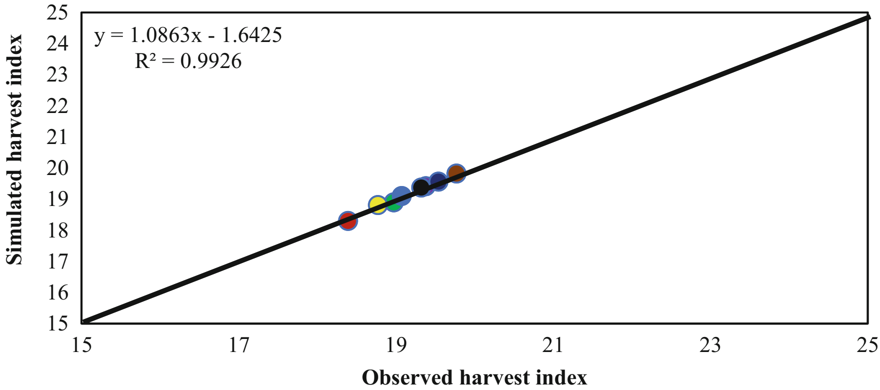

Fig. 19.50 Observed and simulated harvest index for URF-Koont during years 2019–2020

all cultivars during both years. The performance of DSSAT was compared by using validation skill scores (R^2, RMSE and d-index) (Figs. 19.49, 19.50, 19.51 and 19.52).

19.5 Conclusion

The phenology of canola was influenced by temperature at both sites during both growing seasons. The temperature was high at URF-Koont than at NARC-Islamabad during both growing seasons which directly influences the phenological phases of crop. Advancement of the phenological stages and a decrease in the duration of the phenological phases of crop cycles may occur due to an increase in temperature. Therefore, an early shift in phenology will result in curtailed growth season under

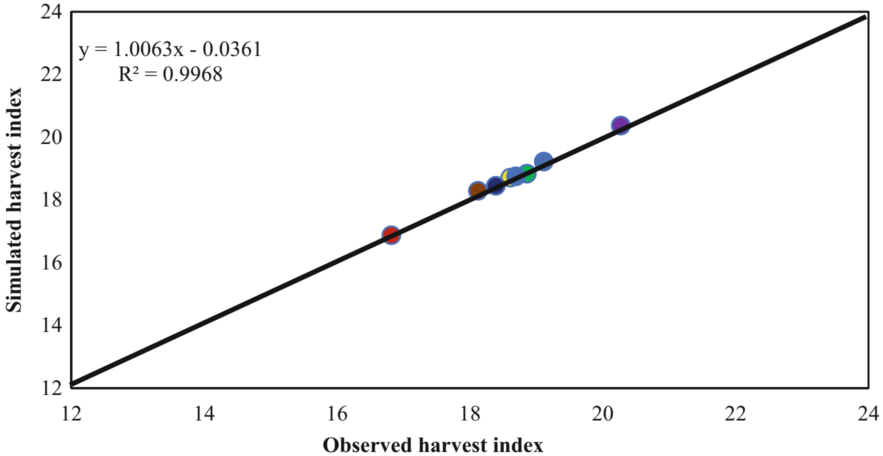

Fig. 19.51 Observed and simulated harvest index for NARC-Islamabad during years 2020–2021

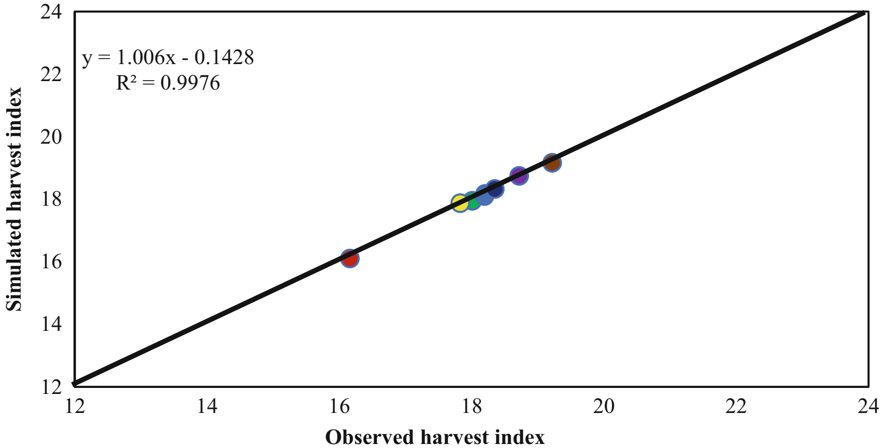

Fig. 19.52 Observed and simulated harvest index for URF-Koont during years 2020–2021

contemporary hop of increasing temperature. A phenological model was established with varying sensitivities to vernalisation for both sites and growing seasons. All the cultivars showed different vernalisation requirements under varying climatic conditions of both study sites during both growing seasons. All the cultivars showed weak sensitivities to vernalisation at URK-Chakwal and strong sensitivities to vernalisation at NARC-Islamabad during both growing seasons. The cultivars required more days to achieve their vernalisation requirement was strong sensitive to vernalisation and the cultivars required less days to achieve their vernalisation requirement was weak sensitive to vernalisation. During years 2019–2020 and 2020–2021 at URF-Koont, we observed that ROHI Sarsoon showed flowering in less days than other cultivars and gave the maximum yield among all the cultivars. So we can conclude that ROHI Sarsoon is an ideal variety for the study site URF-Chakwal and under its climatic conditions. However, NARC Sarsoon is an ideal variety for the study site NARC-Islamabad and under its climatic conditions.

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Chapter 20
Integrated Crop–Livestock System Case Study: Prospectus for Jordan's Climate Change Adaptation

Muhammad Iftikhar Hussain, Abdullah J. Al-Dakheel, and Mukhtar Ahmed

Abstract The integrated crop–livestock system (ICLS) is a multifaceted farming system in which various agricultural practices are combined for sustainable management of available natural resources (i.e., plant, soil, water), reducing the impact of climate change to improve soil properties, crop productivity, animal sector development and farmers' profit in an integrated way. Climate change poses considerable challenges for development, food security and poverty alleviation, particularly in Jordan. The chapter reviews the agricultural practices package adopted by farmers to enhance soil fertility, water use efficiency, resiliency to climate changes and putting more marginal lands and water resources into use in Jordan. These milestones were achieved through provision of distinct integrated plant production packages and distributing them to more marginalized farmers with poor economic conditions. In the livestock sector of Jordan, sustainable production and development of the forage sector is crucial for upscaling of quests with good nutritive value. Several factors were responsible for poor livestock productivity and include low-yield forage genotypes with low quality under marginal environments. To save the freshwater resources, reuse of nonconventional water (NCW), such as treated wastewater (TWW), low-quality saline water and rain harvesting, were vital alternate resources for the agriculture and forestry sectors in Jordan. The

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ICLS has been adopted in several countries but this concept still has not been adopted in the North African marginal environment. The farmers there are particularly vulnerable to climate change perturbations that include salinity and drought. This challenge requires adaptation of drought- and salt-tolerant genotypes of various forage crops with a high nutritive value. Among them, several forage crops (e.g., sorghum, Pearl millet and triticale) have been adopted by local farming communities in saline and marginal environments of Jordan where livelihood depends on agriculture. It has been concluded that farmers should adopt salt-tolerant forage crops and use NCW and marginal lands to elevate the agricultural and livestock sectors in the region, which will significantly support the local economy, food security and profit of the farmers.

Keywords Crop–livestock integration · Forage crops · Sorghum · Pearl millet · Triticale · Safflower · Dual-purpose crops · Wastewater · Nonconventional water resources · Marginal lands

20.1 Introduction

Jordan has a Mediterranean-style climate with drought episodes and very scarce water availability. The existing renewable freshwater resources have dropped drastically to a per capita share of 144 m^3 per year in 2007 compared to 3400 m^3 per year in 1946. The country is highly affected because of various drought episodes that ruined agriculture, forestry and landscaping activities. Those conditions reflected negatively on the farming community's stability, income and food security. On the other hand, the remaining 80% of the area that received less than 200 mm of annual rainfall per year either had abundant agricultural activities or were under stress from irrational grazing systems—that is, where in April many places converted naked to natural vegetation and warnings became obvious from numerous biodiversity studies.

The available crop options under the prevailing environment are limited, and knowledge about alternative profitable modified crops to alternative water resources for many farmers is lacking. Under the present situation of water shortage, government officials, policymakers and planners are considering nonconventional water resources (e.g., saline and TWW) to bridge the gap between water supply and demand. In Jordan, there is a real need to effectively use all the available nontraditional water resources—that is, TWW, saline and semi-saline water.

A shift toward nontraditional water resources to alleviate the shrinking of the agricultural production system in Jordan has beenobserved. Both treated wastewater and saline water are emphasized. Reclaimed wastewater and saline water are available in many areas, but they only are partially used. There are 22 wastewater treatment plants in Jordan that produce about 90 MCM of treated wastewater yearly from which 93% is used for restricted and unrestricted agriculture, after mixing with freshwater, and for industrial purposes. Introducing salt- and drought-tolerant crops to currently uncultivated areas will provide local residents with an economic base and reduce land degradation. In several parts of Jordan, saving freshwater resources and using alternate water (e.g., TWW, rainwater and desalinated water) are getting attention.

In Jordan, fertile and marginal land resources have not been fully studied. In recent research, it has been reported that there are about 67 natural saline water springs; of which 23 are at the Jordan River basin, 23 are in the Dead Sea basin, 8 are in the Wadi Arabah basin, 2 are in the Al-Jafer basin and 1 is in the Al-Azraq basin. Each year such natural saline springs discharge roughly 46 MCM. Additionally, because of excessive pumping, several subsurface wells changed from producing freshwater to saltwater.

Previous research findings in Jordan have shown plant adaptations to the nontraditional water resources. In this phase, efforts are focused on spreading the knowledge attained from previous phases on crop–forages adapted to saline and reclaimed wastewater in Jordan's agricultural system. The main objective of the work includes research and the extension of services; both produced knowledge transfer to the farmers at marginal environments including the women. Those farmers are using the nontraditional water sources; however, many left their jobs owing to unprofitable production when using the conventional crop genotypes and improper production packages. Improvements are tangible and better crops have been widely adapted to limits defined key farmers who took responsibility for production and dissemination of the adapted genotypes.

An average of five tons of adapted crop grains are produced annually; these include winter crops (e,g., barley, triticale and oats) and summer crops (e.g., Pearl millet and sorghum). Grain multiplication was concentrated at the Al-Khaledyiah Saline Research Station. Framers using nonconventional water sources were receiving the improved grains and cooperated with extension services in data availability for inputs and incomes. The project in Jordan built a new irrigation system of 12 hectares (ha) for the winter crops and developed a 2000 m^{-2} of covered land to produce the summer crops and to protect them from birds, as well as to establish a properly equipped seed store.

The target land area (140 ha) was employed in the project, which helped to achieve a final production of 12,500 kg of grain over a three-year period. This quantity was dispersed to $>$ 250 regional farmers of the target area. Winter crop yields varied from 3.5–5.0 tons per ha and from 8.0–11.0 tons per ha for grain and straw, respectively. "Farmers' field schools" events were planned and used through extension services' efforts to disseminate the production packages either at the farmers' fields or inside the research stations. Flyers, posters and pamphlets were created to aid in explaining the new crops that have been adapted and the alternate water sources.

Conventional and nonconventional are the two types of water resources. Conventional resources include water available from snowmelt and rainfall; this water may be used at the site or taken from streams, lakes, aquifers and rivers. Moreover, this resource can be recycled through a natural hydrological phase. Water resources other than natural, which are obtained from various sources by human intelligence (e.g., desalinated seawater, TWW, and rainfall water captured by water harvesting) are termed nonconventional resources.

Nonconventional water resources, in addition to conventional sources, provide efficient complementary supplies to alleviate water shortages in areas with depleted natural water resources. These sources of water can be used for agriculture and many other purposes through advanced techniques (e.g., harvest of rainwater; desalination of brackish and seawater; capture and reuse of agricultural drainage water; treatment, collection, and use of wastewater; and pumping of groundwater having multiple types of salt). In the present study, diverse means were followed to reach the farmers through field days, seminars and planned visits; and training courses as well as participating in social events. Besides, key farmers were involved in large events on advanced levels, as well as participated in external training courses.

20.2 Description and Characterization of Study Site

Jordan is located at the crossroads of climatic and botanic regions at the junction of three continents (e.g., Europe, Asia and Africa). The country has a Mediterranean climate and four major phyto-geographical regions—the subtropical valley, the highland mountains, the Badia and the Aqaba gulf regions. It harbors several rain-fed areas—arid (<200 mm), marginal (200–300 mm), semi-arid (300–500 mm) and semi-humid (≥500). Similarly, Jordan has four vegetation regions—Mediterranean, Irano-Turanian, Shahro-Arabian and Sudanian-tropical (Al-Eisawi 1996). This gives Jordan its vast range of diversity in weather, topography and geology which in turn reveal parallel diversity in plant habitats, starting from the Mediterranean to the Shahro-Arabian.

20.2.1 Animal Products

Adaptation of the ICLS should be integrated, which will enhance forage productivity that is a key for ruminant production (Carvalho et al. 2010). Tradition in Jordan's culture is built on growing sheep and goats for their meat, milk and dairy products (e.g., "Jameed," which used in the preparation of the famous local food the "Manssaf"). In addition, dairy cows play a vital role in the animal production sector for milk products (e.g., yogurt, cheese, skim milk). Other secondary products from animals include leather, wool, hair and organic manure. Despite extensive migration from rural areas to cities, demand and consumption habits for animal products increased with the population's increase.

Available statistics for the number of animal species in Jordan totals 67,590 cows, 752,250 goats and 2,262,630 sheep (Abu-Ashour et al. 2010; Tarawneh et al. 2022). Self-sufficiency in fresh cow's milk is 100%, whereas for cow's meat sufficiency it is only 13.8%. The adequacy in other milk products are 99.9%, 100%, 35.5%, 100% and 49.5% for yoghurt, yogurt, cheese, skim milk and Jameed, respectively (Abu-Ashour et al. 2010). Contribution of animal farming to the total agriculture is 55%, with a total income of 376 JOD in 2012. This vital sector requires a sustainable forage supply to meet the population's needs.

20.2.2 Types of Animal Farms

Animal farms in Jordan could be classified as organized (i.e., registered) and nonorganized (i.e., sporadic in rural areas) farms. The amount of sheep and goat farming is not as easy to study as the case of cow farms because cows are stable on farms, whereas sheep and goats, in most cases, are subjected to moves from one place to another—that is, looking for natural grazing lands. The total number of organized cow farms are 1293; 63% of these are classified as small-scale ones (5–50 head/farm), whereas the remaining have $>$ 50 head/farm. These farms are concentrated in four main cities—Zarka (26,810 heads), Mafraq (18,230 heads), Irbid (11,200 heads) and Amman (7690 heads) (Abu-Ashour et al. 2010; Tarawneh et al. 2022).

The nonorganized farms are important components in the animal farms' production; this type of farm is not reflected clearly by statistics. Still, it occupies a large size in total production. In the rural and at city margins, it is traditional to find small herds of sheep or goats in the family yard; similarly, for the crazing cow, families could have only one or two cows. Owners of these farms find their consumers either at their specific locality or abroad; in many cases, they develop a "family" brand name for their high-quality products that find its consumers beyond their locale (i.e., in the big cities). Also, there are small-scale farms with a holding of 5–50 head. In most cases, the women are responsible for growing, feeding, milking and selling the products with the help of family members while the man is working at urban job—that is, all individuals cooperate with each other to manage the family's life.

The number of people in the animal production sector is estimated to be about 50,000 workers (Tarawneh et al. 2022). This number is obtained from a survey of organized farms; however, the actual figure seems larger than this when the nonorganized farms' workers are added. The nonorganized farms are encouraged and supported by the government in the rural areas, where the owners are poor and vulnerable to any market instability—among which the shortage in forage supply, which equals between 60–70% of total animal production costs—adds to the entire effect of climate change. These are the most critical events that lead to terminating many projects.

20.2.3 Forage Production: Demand and Supply

To keep pace with the ICLS integration, it is imperative to have a sustainable forage supply. It also is important to maintain a supply of required quantity and quality of forages in the market. Because of insufficient fertile agricultural land in Jordan, only 8% has been devoted to forage production. There is a large lack in forage supply in the market and its price fluctuates. Available forages for animals in the local market are fresh green plants, dried green plants, dry straw and fermented plants (i.e., silage). Forage prices in tons, average 50, 120, 250 and 400 in Jordan Dinar (JOD) for green plants, silage, straw and dried green plants (alfalfa), respectively (personal communication).

Green plants are grown locally and include corn, alfalfa, sorghum, pearl millet and ray grass. Dry plants (i.e., straw and dried-green alfalfa) are grown locally as well as imported; they include wheat, barley, lentil, chickpea and alfalfa. Other forage sources are the low-quality natural weeds collected in spring from the roadside and from empty land inside the vegetables and fruit's tree farms; those forages prices in average 30 JOD/ton. In addition, the native range lands are limited in area as well as in time available (i.e., early spring only). The market of forage depends on the local production and on imports (Abu-Ashour et al. 2010; Tarawneh et al. 2022). The bill that allows importing has increased importation significantly during the last few years.

20.2.4 Plans Undertaken at a National Level

To rehabilitate the marginal and degraded lands is very much essential to fulfilling the ever-increasing demand of food, feed and fiber of the increasing population. This rehabilitation can be achieved with good management practices by using the nonconventional water resources, forage crops (i.e., resistance to salinity and drought stress) and marginal lands. The degraded lands are used for food, forest, pasture and bioenergy production. Many countries are using the degraded lands for production of biomass and bioenergy. To convert the degraded lands into a productive one with the nonconventional water resources are a good option on the eve of declining freshwater resources. There are opportunities to use this nonconventional water resource for degraded lands by means of physical water movement from the source point to the point of need after treating.

In Jordan, there is a real need to effectively use all the available nontraditional water resources (e.g., wastewater, saline and semi-saline water). Shifting toward nontraditional water resources to alleviate the shrinking of the agricultural production system in Jordan has been noticed. The Jordanian Ministry of Agriculture has adopted several plans to increase forage production and processing. In this regard, it has various packages and training schedules for increasing the capacity-building of farmers and selecting suitable forage species. The Ministry also is putting efforts into expanding the planted area under forage cultivation and to bringing more marginal areas under forage production through employing nonconventional water resources.

The government has encouraged investment in silage production by local companies. One of these investments is the Rum Agricultural Company at Dessah (South 100 km to Aqaba). Rum is investing in a governmental grains and forages project and is producing 20-thousand tons of silage (40% of local need) yearly (Sada et al. 2015; De Pauw et al. 2015). Still, activities of Rum will be stopped because their contract with the government to use the land and water at their project was terminated; this will increase the effect of silage shortage in the market.

Another investment has been initiated by the government at AL-Muhamadyah (South 20 km to Ma'an) and is now under development with a focus on barley and green forage production as well as silage production (personal communications). In 2011, an investment was started at Al-Safee Valley (South 50 km to Karak) by a local farmers' association in partnership with a privet agricultural company. Large areas of land were cultivated to produce silage from green forages but, unfortunately, after one season the farmers stopped the project because they were not able to produce quality silage as they lacked the proper production information. Other minor projects have been started at various locations, such as Al-Azraq (East 80 km to Zarka) and Dulyel (Center 20 km to Zarka).

20.2.5 Climatic Change Impact

Changes in the climate are considered to affect crop and livestock productivity as well as impacting negatively on water supply and soil conditions. The impact of climate change in Jordan is obvious because of frequent dry years, sporadic rain, greater winter and summer temperatures, dams' reserves, wells' salinity and range lands' degradation, particularly in the marginal dry areas. Development of alternative agricultural systems is one of the key adaptation measures to minimize climate change's impact in Jordan. Considerable efforts have been undertaken by the National Center for Agricultural Research and Extension in collaboration with international research centers.

The goal is to develop alternative plant production systems in marginal areas of Jordan that can cope with the impact of climate changes and provide sustainable systems to support the livelihood of poor farmers in the region. Forage–livestock-based systems are one of the most resilient ones in the dry environments and are key to supporting the livelihood of the farmers and Bedouins in the region. To develop resilient forage systems for the marginal areas, where saline and brackish water resources are the main source for supplementary irrigation, extensive number of forage species, varieties and genotypes were evaluated at various locations throughout the dry areas of Jordan under irrigation with saline water up to 8 dS/m.

The ICLS has several vital features (e.g., economic and environmental) that might differ from one region to another. Depending on the regional climatic situation, agricultural systems are organized in such a way as to get maximum benefit from

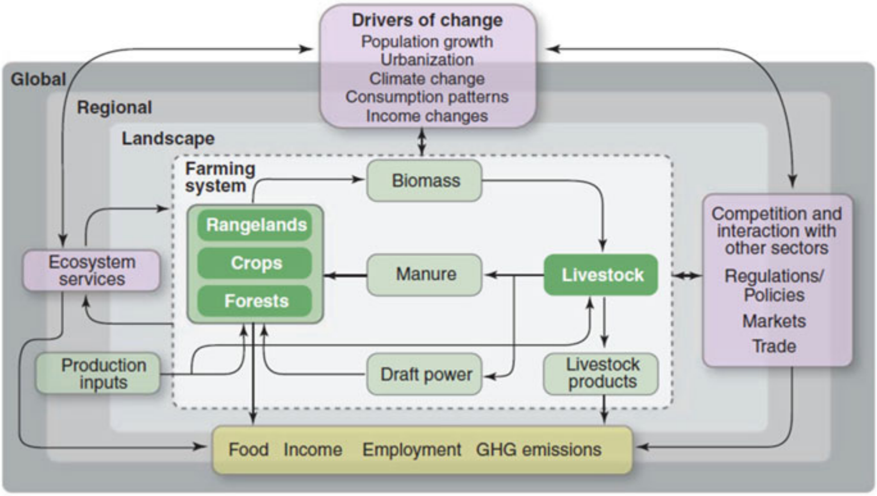

Fig. 20.1 Illustration to demonstrate the various components of the interaction of crop–livestock integration

crop genotypes, cropping systems and crop rotations, as well as integration of suitable livestock into the farming system (Carvalho et al. 2010; Salton et al. 2014). A general interaction of crop–livestock integration is illustrated in Fig. 20.1 to demonstrate all the players and stakeholders on one platform. The ICLS has several benefits over the traditional farming systems and includes enhancing forage and pasture crops' cultivation, increasing soil fertility, organic matter accumulation, increasing nutrient cycling and soil physical and biological properties (Carvalho et al. 2010; Salton et al. 2014).

This chapter contains an overview of the constraints and opportunities of integrated crop–livestock diversification for climate change adaptation in Jordan. It highlights the background, implementation and achievements of the Jordan project, "Adaptation to Climate Change in WANA Marginal Environments through Sustainable Crop and Livestock Diversification." This is important because marginal environment communities (rainfall < 200 mm), extensively subjected to the climate changes to improve their livelihood using nontraditional waters and forage crops.

20.2.6 Site Description

At the Al-Khalediyah Saline Agronomy Research Station in Central-Eastern Jordan, forage species were assessed. The area has a Mediterranean climate with warm winters and summers marked by dry, hot weather.

20.2.7 Species Adaptation and Production Potential

The selected forage crops attainment (about 25) was evaluated to study their adaptation potential under the prevailing environment. Based on this extensive work, promising genotypes were identified from most of the species evaluated that are environmentally and economically feasible under marginal and saline conditions in Jordan. The selected genotypes were tested with the forage–livestock production systems by several farmers. The components of the integrated forage production systems included summer and winter annual and perennial forages.

20.2.8 Farmers' Preference

The productivity of marginal environment and its contribution to the economy, food security and poverty reduction depends on the services provided by functioning of degraded marginal ecosystems, including maintaining soil fertility, freshwater delivery, pollination and pest control. Farmers using nontraditional water sources, primarily saline and TWW, were involved in the selection of appropriate forages. Farmers were invited to the research station because the best genotypes are grown on the farmers' fields; collaborative field days were held and extension service providers followed up. Barley, triticale, sorghum, Pearl millet and sesbania were among the forages that could be easily introduced to the framers' fields with a range of weights.

Saline-tolerant barley was the forage that farmers were most willing to use. Their understanding of the fodder, its growth characteristics and the assurance of a market for the grains and straw were credited with this. Triticale, on the other hand, was initially unwelcome because farmers were uncertain about its market appeal and the challenges of growing on treated soil. It is known locally as "forage wheat," and wheat growing was restricted and prohibited with the treated wastewater.

Farmers were confused about the market acceptance and the complications of growing conditions using TWW. When triticale eventually makes it to the market as animal feeds, farmers welcome it similar to how they would barley (i.e., grains and straw). Sorghum and pearl millet both performed well and were well-liked by farmers, in particular because several cuts could be used to ensure a high yield while also lowering the expense of the irrigation system. Farmers, however, were unable to produce their own seeds and constantly must rely on others. The research findings extracted from the previous phases and projects funded by the in-kind sponsors, with help from the extension servicers, were brought to the farmers' fields gradually. Many genotypes with high-yield potential (i.e., grain or forage), under saline conditions and treated wastewater irrigation, are the target materials to reach the farmers' fields using nontraditional water resources.

20.2.9 Adaptation Strategies

Increasing the quantities of promising grains distributed through each farmer affected the efficiency of the genotypes adopted and released by the project. This increase was from about 20 kg per farmer to reach 150 kg and, in certain cases, to 250 kg at a forerunner farmer. This action was started in the 2013–2014 season and reached acceptance at farmers' levels and thereafter proceeded with this action and distributed bigger quantities for the upcoming seasons.

1. The amount of production was concentrated at the saline research station (i.e., Al-Khlaediyah) by following the optimal production package as sowing date, seeding rate, seed drilling, optimal irrigation, harvesting date and proper threshing that have two major merits:
   (a) The total production increased by up to 5 tons per year, with yield ranging from 450–520 kg per dounoum from triticale and barley genotypes.
   (b) This helped farmers to compare the researcher's field outputs with their farms. This action was an acceptable "farmer's school" learning method with occasional and arranged visits; however, the researchers and extension servicers were always welcomed farmers regardless of their numbers.

   The visit of progressive farmers, researchers, agricultural experts and extension services (Figs. 20.2 and 20.3) were the major means for being in touch with the farmers frequently to answer their questions and to teach them the proper production techniques. Also, the researchers with extension services used to visit the farmers, which included the conduct of field days, general lectures, showing plant samples and conversations with certain pioneer key farmers at their farms.
2. The working team tends to expand their activities to new farmers and to new areas using the nonconventional water sources. The new areas included Shoubak, Karak and Wadi Arabah in the southern parts of Jordan and Al-Halabat in the middle of the country. Farmers agreed to grow the released genotypes in small areas and other farmers were encouraged to grow the crops gradually.
3. Triticale is now a well-known crop among the farmers in the northeast and middle of Jordan. At the beginning, they refused the crop as usual—they did not know it; they did not know whether it is marketable. Now the focus of farmers is on triticale because they found a good market for the grains at a price of 350 JOD per ton with a high-yield straw too.
4. A permanent field was established to multiply the promising grains of sorghum and millet using bird nets. The look of the project encouraged many farmers to test the potential of the adopted crops at rain-fed cultivation sites where the number of farmers received the grain during the winter season to test its potential under rainfall cultivation.
5. The number of farmer's benefits from this project increased gradually from only 15 in the first year to 882,014.
6. A poster was issued on successful farms' stories; they were used as models for other farmers and for new areas.

Fig. 20.2 Farmers, researchers and extension service officials visiting research station fields and farmers' fields

Fig. 20.3 Seed multiplication for winter grains and summer crops at the Khalediyah saline research station

7. To highlight the potential of the promising genotypes from their perspectives, the three pillars (i.e., researchers, extension service providers and farmers) were questioned and recorded in a movie clip during the growing season. These clips were reproduced and showed in the farms' fields or during farmers' visits to the research stations to increase the awareness and to get their viewpoints.

20.3 Integration of the Farming Community in Seed-Production Technologies

20.3.1 Growth, Advancement and Dissemination of Seed-Production Facilities and Genotype Adoption

Al-Khalediyah Saline Agriculture Research Station is one of the most important agricultural stations that belongs to the National Center for Agricultural Research and Extension (NCARE). It is situated in the target areas—Marfaq (TWW), Zarka stream (TWW), Al-Khalediyah (saline) and Azraq (saline). The latter areas are the places where the cooperated farmers grow their crops using the nontraditional water resources (e.g., mainly treated wastewater and saline water).

20.3.2 Seed Store

The research station had seed stored, but it lacked walls, doors, seed shelves, cracked ground and sufficient isolation. A digital scale (150 kg), shelves for small grains, painting, addition of electrical fans for aeration, wall and ground isolation and door modifications are all part of this seed store project's upgrade. Through this project, a seed coating unit, deep freeze, refrigerator and temperature and humidity controller also were added.

20.3.3 Machines

Various types of agricultural machines were available to serve the yield trials and seed production inside the station and for upcoming farmers' services. The potential in the near future was to authorize the machines' movement to cooperative farmers either at low or no cost; therefore to encourage the wide adoption of new and promising genotypes to be released through this project and by the future research findings. The collection of machines included harvesters, various sizes of cultivators, disc plows, tractors, mowers, threshers and sprayers. A forage shopper and a drill machine for seed drilling were donated to the station by the Al-Mafraq Agriculture Department. The cooperative's farmers can benefit from seed drilling during the sowing season.

20.4 Landscape Scale Analysis of Crop Diversification and Effects on the Climate Change Scenario in the Crop–Livestock Farming Context

Most of the West Asia–North Africa (WANA) area contains arid and semi-arid tropical regions with limited water resources. The situation is becoming worse for agricultural production because of the climate change scenario. According to reports of the Intergovernmental Panel on Climate Change (IPCC), greenhouse gasses CO_2, ozone ([O_3]), methane, nitrous-oxide and temperature are predicted to increase in the atmosphere (Collins et al. 2013). Nevertheless, drought episodes could occur in the region (Nyasimi et al. 2014). Therefore, screening, selection and development of salt- and drought-tolerant varieties and genotypes have been major adaptation strategies for better use of available arable land and water resources for agricultural growth (Hussain et al. 2018, 2019, 2020; Hussain and Qureshi 2020; Hussain and Al-Dakheel 2018).

In this context, climate resilient crops that can better adapt to marginalized lands in the WANA, especially cultivars and varieties with good yield potential, should be developed, upscaled and disseminated among the regional farming communities for better adaptation and to cope with climate change's impact. The productivity of the traditional farming system should be enhanced through integrated crop-livestock diversification using high-yield crop cultivars and employing nonconventional water resources (e.g., low-quality saline water and TWW). These production packages can enhance the agricultural crops' yield in Al-Zarka and Al-Mafraq (Northeast). Development, advancement and dissemination of seed production packages and identifying genotypes (i.e., 20) with better production potential, which can tolerate salinity and drought stress, under marginal lands of WANA is progressing (Hussain et al. 2018, 2019, 2020; Hussain and Qureshi 2020; Hussain and Al-Dakheel 2018).

Suitable genotypes were obtained from ICBA and screened, evaluated and selected through specific breeding programs at research stations (Table 20.1). Research and a field-based studies were conducted to evaluate the most appropriate crop cultivars and to identify a list of annual and summer salt-tolerant forage crops as integrated feed that can provide food resources throughout the growing season for multiplication and distribution to farmers (Hussain et al. 2018, 2019, 2020; Hussain and Qureshi 2020; Hussain and Al-Dakheel 2018). The higher yield potential varieties were multiplied at local research stations and farmers' fields for enhancing distribution among small and large farms (Hussain et al. 2018, 2019, 2020; Hussain and Qureshi 2020; Hussain and Al-Dakheel 2018).

Various regional and international crop science and breeding research centers and study groups have achieved significant success in the improvement of salt- and drought-tolerant genotypes of food crops, forages and cash crops such as sorghum, maize, Pearl millet, cowpea, buffelgrass, groundnut and sorghum (Hussain and Al-Dakheel 2018; Al-Rifaee 2015; Al-Dakheel et al. 2012; Massimi et al. 2015, 2016). Barley, safflower, quinoa, Pearl millet and sorghum are important forage and grain crops with the capacity to tolerate drought and water insufficiency (Nelson

Table 20.1 Mean Yield for Forage Species Under Saline Conditions in Jordan

	Forage crop	Accession name	Grain yield (t ha^{-1})	Herbage yield (t ha^{-1})
Winter forages	Triticale	Syria-1	4.5	8.0 (dry)
	Barley	Rum	3.3	11.1 (dry)
	Barley	Martin	2.9	17.0 (dry)
	Barley	Saida	3.2	12.3 (dry)
	Barley	Giza-125	2.8	7.2 (dry)
	Barley	Manel	2.9	12.3 (dry)
	Oat	F199084D4	1.5	7.5 (dry)
	Quinoa	NSL-106398	–	15 (dry)
	Egyptian clover	*	–	45 (green cuts)
	Fodder brassica	Hyola 61	1.4	63.4 (green cuts)
	Fodder beet	TINTIN	37.8 (tubers)	112.3 (green)
Summer forages	Sorghum	ICSR 93034	2.5	54 (green)
	Pearl millet	HHVBC tall	2.5	50 (green)
	Corn	White	1.9	72.5 (green)
	Sun flower	Carslien	2.6	18.1 (dry)
	Sudan grass	Sioux	1.9	44 (green)
	Broom corn	Reef1	1.1	52.1 (green)
	Safflower	–	3.5	25 (green)
Perennial forages	Cenchrus	–	–	95 (green)
	Atriplex halimus	–	–	125 (green)
	Cactus	–	–	350 (green)
	Sesbania	–	–	10.9 (green)
	Alfalfa	–	–	18 (green)
	Medicago arboria	–	–	5.2 (green)

et al. 2009) and are well suited to marginal environments of North Africa, especially Jordan. The farmers in North Africa are particularly vulnerable to climate change perturbations that include salinity and drought (Jarvis et al. 2011). Owing to yield losses in diverse field crops and forages, it was a challenge that needed to be addressed for developing, screening, selection and upscaling of drought- and salt-tolerant genotypes of sorghum and Pearl millet, as well as delivering them to the WANA region's farmers whose livelihood depends on agriculture.

Throughout this project thousands of tons of seeds of salt- and drought-tolerant genotypes of sorghum and Pearl millet have been provided to partners in WANA regions since 2011. Currently, several North African seed companies are engaged in research and breeding programs that are producing and marketing seed of the selected genotypes for further distribution to local farmers on demand. According to one estimation, about a million ha of land is planted with these varieties; consequently, they benefit millions of farmers in the target areas of Jordan. The drought- and salt-tolerant crops can be a good source of quality forage for livestock. Because of elevated water-use efficiency, sorghum can be grown under limited amounts of water from germination, early growth stages and up to maturity.

From long-term, field-based screening, selection and evaluation of various genotypes and cultivars of barley, Pearl millet, sorghum, triticale, fodder beet, sunflower and thistle have been selected and distributed among small-scale farmers and farmers' associations in Jordan for seed multiplication and further distribution to more marginalized farms. Several genotypes of rapeseed, quinoa and Pearl millet have been extensively tested and produced in the farmers' fields to produce excellent seed production. In the towns of Al-Zarka (Middle) and Al-Mafraq (Northeast), two nurseries have been set up to train and distribute fodder shrubs' seedlings to farmers.

The fodder shrubs were Sesbania, *Medicago arborium*, Kochia and *Acacia saligna*. They were produced and distributed to the participating farmers. According to research and development trials conducted by several colleagues (Hussain et al. 2018, 2019, 2020; Hussain and Qureshi 2020; Hussain and Al-Dakheel 2018; Al-Rifaee 2015; Al-Dakheel et al. 2012; Massimi et al. 2015, 2016; Nelson et al. 2009), the studies showed that sorghum, safflower, buffelgrass, Pearl millet and barley were preferred by farmers as forages. In this context, alfalfa also was liked by several small-scale farmers as a suitable perennial forage nutritive crop. Yet, some large-scale farmers and farmers' associations also promoted several other crops as forages, including barley, fodder beet, triticale and berseem.

20.4.1 Farmers' Field School

Progressive farmers were found and given training in seed production at chosen benchmark sites. Farmers accessing and using the nontraditional water resources (i.e., TWW and saline water) were contacted by the extension services in Al-Mafraq, Al-Kalediays, Al-Azraq and Al-Hashimiyah (along the Zarqa stream). To guide the local farmers in adopting and disseminating the best genotypes suited to their regions, forerunner key farmers were identified. Triticale dry grains could give 4–5 t/ha, which is a desirable yield for farmers. The average yields harvested from the promising barley grown were in the range of 3–4.5 t ha^{-1} of dry grains. The activities were arranged through extension services' programs, where several events were conducted.

The information was disseminated through publication of leaflets that described the major crops' growing packages as barley and triticale, which were tolerant for saline conditions and suitable for TWW irrigation. Farmers' training programs included special sessions related to triticale production technology, soil and water management strategies, forage crops, fertilizer recommendations, sunflower as an oil seed-crop cultivation technology and sugar beet production know-how (in English and Arabic). Information also included feeding schedules for Awasi lams with alfalfa produced under treated wastewater (Arabic).

20.5 Developing Seed Production Technology Packages: Guidelines and Application at the NARS and Farmers' Level (Cultural Practices, Purity Maintenance and Post-Harvest Handling)

20.5.1 Grain Purity Maintenance

To ensure the physical and genetic purity of the accepted genotypes, several hundred spikes of the winter crops (i.e., triticale and barley) that represent the mother crop were individually chosen from seed multiplication fields to retain the purity of the grains. In the following growing season, those individual spikes were cultivated in single rows to eliminate the impurities. The cultivated rows underwent new selection, whereas the others were bulked up and increased as foundational resources for the upcoming seasons. According to the following tables and figure, the project produced and distributed 12,424 kg of adapted forage grains in total between the years 2012 and 2014 (Tables 20.2, 20.3, 20.4 and 20.5).

Table 20.2 Detailed Grain Production during the Period from 2012 to 2014

	2011	2012	2013	2014	Total
Barley	Stock	2423	1875	2765	7063
Triticale	*	1800	890	1920	4610
Oat	*	216	170	270	656
Sorghum	*	*	30	40	70
Pearl millet	*	*	10	15	25

Table 20.3 Cultivated Areas (ha) for Varied Forage Crops

	2011	2012	2013	2014	2015	Total
Barley	3	20.5	31.4	14.3	18.9	88.1
Triticale	*	1.3	16.4	11.9	17	46.6
Oat	*	*	1	0.4	2.1	3.5
Pearl millet	*	*	*	0.8	0.5	1.3
Sorghum	*	*	*	*	0.8	0.8

Table 20.4 Cultivated Areas (ha) by Adapted Forage Crops at Various Sites

	2011	2012	2013	2014	2015	Total
Mafraq (NE)	3	20.5	34.5	12.5	20.1	90.6
Zarka (C)	*	1.3	14.4	12.7	16.1	44.5
Karak (SW)	*	*	*	1.3	0.7	2.0
Ma'an (SE)	*	*	*	0.2	1.8	2.0
Wadi Arabah (SW)	*	*	*	*	0.9	0.9

Table 20.5 Average Farm Size (ha) Cultivated by Adapted Forage Crops

	2011	2012	2013	2014	2015	Total
Barley	0.2	1.7	1.1	0.51	0.5	4.01
Triticale	*	0.2	0.5	0.66	0.5	1.86
Oat	*	*	0.02	0.4	0.21	0.63

20.5.2 Role of NARS's Formal Seed System, and Extension, and Dissemination of Conventional and Nonconventional Crops: Continuation of Screening and Evaluation

From the very beginning, farmers preferred barley as a fodder. Triticale initially was rejected, but thanks to the work of the extension specialists, farmers are increasingly beginning to accept this crop. Only educated farmers agree to grow oats because conventional farmers believe the enhanced variety will act like the wild types and invade their fields as weeds. To introduce the oat to local cultivation, more time is required. Over time, the size of the farms for each adapted forage changed. According to Tables 20.3, 20.4 and 20.5, triticale is grown in the second-largest areas after barley.

20.5.3 Integrated Crop Management Packages to Improve Livestock Production

The ICLS plays a vital role in agricultural development of both large- and small-scale farmers and thus also enhancement of the livestock sector (Salton et al. 2014). The availability of suitable forages (e.g., barley, sorghum and Pearl millet) can secure 60–75% of feed for livestock that will ultimately help in the ICLS. This also enhanced the importance and benefits of the production system and farmers' wealth. The project also achieved its goals through providing technical services to farmers to increase their capacity to convert forage crops into high-quality feed. Various forages were screened and chosen to include in diverse nutritive ration programs for livestock. The ICBA has provided them with salt- and drought-tolerant genotypes of sorghum, Pearl millet, barley and other forages (e.g., lucerne, saltbush, sesbania and kochia) that have demonstrated good yield potential at various farmers' fields.

Several morphological, physiological and quality-based experiments were conducted at the designated experimental research station and suitable varieties were identified that have excellent potential for inclusion in ruminant feeds (Massimi et al. 2015, 2016; Abu et al. 2017). Several authors and project partners observed that for a high-quality nutrient and balanced rations, various crops (e.g., alfalfa and berseem including fodder beets) should be thoroughly mixed with other forages (i.e., sorghum, barley) and forage grasses.

Other crops (e.g., Pearl millet and *Panicum turgidum*) should to be tested on an alternative basis that will provide energy, nutrition and crude protein substances (Massimi et al. 2015, 2016). The project demonstrated on-farm techniques for feed processing and usages to improve storage capacity and feed values. The main methods used were silage treatment, treatment of food blocks, production of food in covered piles and biological treatments; these technologies have been demonstrated for a total of more than 1500 farmers (Massimi et al. 2015, 2016; Abu et al. 2017).

20.5.4 Socioeconomic Impact of Improved Production Systems on Farmers' Livelihoods in Marginal Environments

The project showed significant impact on livelihood and socioeconomic characteristics of the farmers of the target WANA marginal lands. The economic viability of integrated crop management packages (ICMPs) introduced into the marginal environment has been assessed, while production and information on soils and water also was documented. The costs and benefits of feed production packages are based on the use of various types of noconventional water (Hussain et al. 2019, 2020; Hussain and Al-Dakheel 2018; Massimi et al. 2015, 2016; Nelson et al. 2009; Jarvis et al. 2011; Abu et al. 2017).

Demonstration areas for efficient production systems have been built with the full participation of farmers, as well as gender-based participation (i.e., women farmers). A 25–35% increase was observed in farmers' income following adoption of improved production packages, highly nutritive genotypes, higher yield potential varieties and farm management practices. Socioeconomic indicators, production and information on soils and water were collected after reconstitution and adoption by farmers to test whether the candidate technologies were viable, sustainable and value-added.

The results of the assessment of the economic value of crop systems operating on salt-tolerant yields increased agricultural incomes by 70% compared to traditional practices (Massimi et al. 2015, 2016). Farmers who have been involved in genotype testing with experiments at their farms have demonstrated the superiority of the selected millet and sorghum types, which have a feed yield at least 30% higher than their conventional crops. A survey of several farms showed that the introduction of salt-tolerant staples into farmers' "farming systems improves farmers" incomes by 50% compared to traditional practices (Massimi et al. 2015, 2016; Nelson et al. 2009; Jarvis et al. 2011; Abu et al. 2017). One of the major achievements of the project was the rapid growth in the number of participants who delivered and deployed new technologies.

20.5.5 Improving Knowledge and Skills of Farmers and Agricultural Extension Staff in Marginal Environments

Separate training activities and capacity-building programs were started by the project team to enhance the technical skills of farmers and extension staff in farm production (e.g., variety selection, conservation practices for water, seed multiplication) and management actions. Such capacity-building activities were carried out through farmers' field schools and training workshops.

20.6 Summary

The ICLS climate change is greatly influencing ecosystem services, agriculture and water resources. Therefore, various crop production packages, integrated with suitable forage species and livestock, should be given opportunities to prevail to combat the awful consequences of climate change. Several salt- and drought-tolerant forage crops (e.g., barley, sorghum, Pearl millet, fodder beets, lucerne, kochia, saltbush and sesbania) were selected and distributed among the farming communities for seed multiplication and further provision to other small and large farms for better adaptation in the marginal lands of Jordan.

It is necessary to save freshwater resources and use alternate water sources (e.g., TWW and low-quality saline water) to avoid further land degradation and to protect fragile land resources that are resilient to climate change. Sustainable livestock production should be adapted through breeding of salt- and drought-tolerant crops and producing climate-resilient animals. This will also provide an opportunity to increase income, livelihood and socioeconomic situations for owners of small farms. The present model of the ICLS can be further improved and adapted in other degraded marginal environments with similar problems and that are under threat of climate change to get maximum benefits from the crop–livestock integration.

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Chapter 21
Effect of Salinity Intrusion on Sediments in Paddy Fields and Farmers' Adaptation Initiative: A Case Study

Prabal Barua, Anisa Mitra, and Mazharul Islam

Abstract Bangladesh, with a population of 150 million, is the most overcrowded nation on the Earth. The agricultural sector is facing the effect of congestion at various levels and ways because of climate change-induced disaster. The study for this chapter was conducted to analyze the impact of saline water intrusion on the production and soil conditions in paddy fields of the Southeastern coast of Bangladesh. It reveals that surface water salinity was high everywhere and soil quality was alarming. Communities in the study area stated that the salinity problem in the crop fields led to low production and economic loss for the farmers of Banshkhali upazila of the Chittagong district. The authors found that the salinization process guided not only changing of crop rotation but also discouraged farmers from cultivating food crops in the area. Repairing levees, producing a native high-yield variety, using organic fertilizer and executing Integrated Coastal Zone Management (ICZM) could raise the production of crops and the fertility of sediments there. The study helped to establish that farmers' adaptation practices for reducing the salinity level of agricultural fields could be useful for controlling climate change in the vulnerable areas and worldwide, while addressing the salinization problem.

Keywords Climate change · Agricultural land · Salinization · Adaptation practices

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21.1 Introduction

Changing climate is among the most dreaded troubles during the new millennium. The effects of it are visible everywhere internationally. One of the extremely severe outcomes of weather change is that human beings are being forced to leave their homes, lands and livelihood because the of consequences of climate change which has destroyed some areas. Such factors stand to displace many thousands and thousands of people in the coming years. The coast of Bangladesh is at risk of intense herbal failures, which include cyclones, typhoon surges and floods in aggregate with other natural and humanmade threats, including erosion, excessive arsenic content in groundwater, saline water intrusion, water logging and water and soil salinity; these breakdowns have made coastal dwellers especially susceptible and threatens the entire coast and marine environment (Islam 2004). Regions of the coast constitute approximately 2.5 million hectares (ha), which amounts to about 25% of the total cropland of Bangladesh. Nearly 0.84 million ha have been affected by various intensities of salinity, ensuring exceptionally negative land utilization (Barua and Rahman 2017; Barua et al. 2017).

Among the 181 vulnerable nations that experience a changing climate, Bangladesh is positioned at 165, as well as being the 30th susceptible nation to climate change (IDMC 2021). The geographical and landscape position of Bangladesh makes it particularly susceptible to tremendous weather changes (e.g., cyclone, flood, coastal erosion and storm surges). Its susceptibility is generated not only through its biophysical location but also by its poor socioeconomic conditions (Barua et al. 2017; Barua and Rahman 2020).

Bangladesh is an agricultural sector-dependent nation. Agriculture, however, is surprisingly predisposed to weather changes. It is expected that a changing climate will have a worse effect on agriculture and manufacturing in the new millennium, besides the hassle of excessive temperatures, abnormal rainfall and severe weather patterns brought about by activities such as floods, cyclones, droughts and increasing sea levels (Shameem and Momtaz 2015; Hazbavi et al. 2018).

Soil salinity is a significant land degradation problem in Bangladesh’s agriculture sector, which adversely affects the productivity of the land. The Chittagong district, located in the Southeastern coastal area, is susceptible to cyclones, storms and tidal surges, tidal floods, water logging and other natural disasters. There have been 30 devastating cyclones and storm surges in Chittagong and the Cox’s Bazar coastal area between 1960 and 2016. The most damaging and powerful cyclone of the last century hit Chittagong on 1991; after that another one ravaged the area in July 2016 when *Ruano* hit the coast of Banshkhali—the Anwara upazila Subdistrict of Chittagong. Saline water (i.e., salinization) is the main associated calamity; its source and process are from various natural disasters, which cause tidal fluctuations because a huge amount of saline water comes ashore inundating coastal areas (Barua et al. 2016; Barua and Rahma 2018, 2019).

Rice is the most significant and demanded agricultural crop product required for feeding and survival of global communities (Shimono et al. 2010). Almost 60% of the world's population completely depends on production in rice paddies (Maclean et al. 2002). In Bangladesh, a paddy is the fastest yielding among all other products in developing countries. Nearly 80% of all fertile land is now used for rice production. Therefore, several declines in paddy production because of a changing climate becomes grave, spoiling food security of the nation (Islam et al. 2020). Therefore, measuring the influence of changing climate on paddy cultivation, and appraising the agricultural cultivators' coping capability, has become a theme of imperative research.

21.2 Effect of Changing Climate on Crop Production

The most susceptible sectors to climate change are recognized to be agricultural activities because of their enormous size and consideration of the weather-related variabilities, causing gigantic economic effects (Mendelsohn 2009). The changes in climate behavior (e.g., rainfall and temperature) drastically impact crop yield. The influence of increasing temperatures, variation in precipitation and fertilization of CO_2 diverges according to the characteristics of the crop, place, zone and degree of the change in the factors. The increasing pattern of temperature rise has verified a decline in crop production, even as the rise in precipitation is expected to counterbalance or decrease the effect of increasing temperature (Adams 1998).

As predicted by the climatic variables observed in Iran, productivity of the crops varied based on adaptation capacities and types of crop, climate condition and CO_2 fertilization's impact (Karimi et al. 2018). Farmers' net profits were found to decline considerably with a reduced level in rainfall or temperature rise in the African nation of Cameroon which faced an absence of a standard approach to responsive policymaking; this was followed by a small necessity for export of agricultural products of the country, thereby resulting in fluctuations in national revenue (Molua 2017). High temperatures affect coffee production in Mexico, and it has been found that yields might not remain cost-effective. Continued coffee-growing may not be feasible for producers in coming years because there is an indication of a 34% decline in production (Gay et al. 2016).

Although climate change affects various economic segments, the damage is significant for rain-fed agriculture (Ochieng et al. 2016, 2017) that predicts a decline on the African continent in major crop yields of 9–25% by 2050 (Schlenker and Lobell 2010). Since the 1964 to 2014 period, 12 droughts and 20 major floods have occurred in Kenya, which affected five million people because of low crop production and food insecurity (Parry et al. 2012). In addition, three million people of Malawi have been impacted by floods in 2015–2016 because of fluctuation in climate factors as a consequence of droughts, floods and other disasters, as well as increased climate variability. Since 2015–2018, six million people have been affected owing to significant drought and resulting food production decline (Katengeza et al. 2019).

As a result of raised monsoon unpredictability and melting of Himalayan glaciers, even an unassuming moderate 1.5–2 °C temperature rise could insensitively affect the accessibility and steadiness of the water assets in South Asia (Vinke et al. 2017); it is predicted that large areas of the countries in South Asia will become used to a reduction in crop productivity (IPCC 2014; Vinke et al. 2017). Aryal et al. (2020) stated that temperature increase has pessimistically influenced India's crop production—5–30% for wheat production, 6–8% for rice production and 10–30% for maize yield.

Consequently, without taking any measures for sustainable climate adaptation, South Asia is expected to drop nearly 2% of its yearly GDP by 2050 and approximately 9% during the twenty-first century (Ahmed and Suphachalasai 2014). In South Asian countries, 70% of the people completely depend on agricultural activities, which ensures 22% of the gross domestic product (GDP), and any reduced rate of GDP will damage the livelihood and economic situation of the substantial number of agricultural farmers (Wang et al. 2019; Aryal et al. 2020).

The influence of climate change recorded on agricultural crop production depends on the location and application of the irrigation activities in the fields. Production could be raised by increasing irrigated places, which could have a damaging effect on the surrounding environment (Kang et al. 2019). The increasing pattern of temperature rise is expected to decrease the production of various crops through abandoning their traditional cycle (Mahato 2014). The collective production of maize, rice and wheat are anticipated to decrease if both the tropical and temperate regions experience warming of 20 °C; generally, climate change has substantial effects on temperate zones because the tropical agriculture products mature earlier than their ideal growth period. Temperature is a problem, thus knowledge of high-temperature stress is important at higher limits of heat (Challinor et al. 2014).

Furthermore, diseases and various species of insect pests are more widespread in warmer and humid regions of the Earth (Rosenzweig 2018). Other variables (e.g., wind speed and humidity, besides rainfall and temperature) also affect crops' production, and when these climatic variables are nonexistent, there is a probability of overforecasting the value of climate change. In addition, it has been recorded that changing climate is expected to decrease China's wheat, corn and rice production from 19%, 13% and 45% to 12%, 36% and 11% by 2100 (Zhang et al. 2017).

Severe weather-related natural hazards have turned out to be more recurrent since the early 1900s in the Netherlands and have drastically impacted the production of wheat in the country. Li et al. (2019) stated that there will be occurrences of long-duration droughts in the upcoming years becasuse of climate change in almost all regions of the Earth, and a raise in the drought-impact placement area from 15.5–45.0% is projected by 2100. Among the most affected continent, Africa will be a more vulnerable region for drought conditions soon. The production of commercially important crops in drought regions is expected to decrease by a rate of 50% by 2050 and nearly 90% by 2100 (Stevanovic et al. 2016).

Loss of production of agricultural crops could increase the price of foods and could have a ridiculous impact on agriculture's benefit around the world, with annual losses of 0.3% of future GDP by 2100 (Barua and Rahman 2020). Yet, Kumar and

Gautam (2014) mentioned that climate change has an inadequate influence on the global food supply, although developing nations could tolerate harsh negative effects. Temperature is forecast to increase by 2.33 °C and 4.78 °C in India along with a replication in CO_2 level and permanence of the heat waves, which could have a harmful impact on agricultural activities.

In Pakistan, farmers could loose US$300 per acre annually by 2100 with an increase of 1 °C in temperature, whereas the average income could be raised by US $120 and US$250 with an increase in rainfall of 9% and 15%, respectively (Shakoor et al. 2019). The loss of production for three different cereal grains (e.g., rice, wheat and maize) are predicted to deteriorate by 10–25% with a 1 °C raise in the global average of surface temperature (Deutsch et al. 2018). Average crop production is anticipated to drop by 6–25% because of climate change in Southern Africa (Waha et al. 2019).

Malhi et al. (2021) stated that climate change is a universal risk to the nutritional and food security of the planet; this is because of the increasing rate of global temperature leading to a raised crop respiration rate and evapotranspiration, elevated pest invasion, changing trends in weed flora and decreased length of crop growth. Climate change is responsible for impacts on the increasing of microbial population and their enzymatic actions in sediments. Population growth has created a massive pressure on agriculture to ensure the safekeeping of food, livelihood and nutrition for the global population—that is, prevent further deterioration because of climate change. With the rate of increasing climate change factors, the study explored the reduction of agricultural production in Bangladesh during the coming years.

21.3 Climate Change and Agriculture Sectors

Changing climate and its consequences for the impact on rice production is not the newest incident in the situation. Mean values of the temperature rise with steady dry spells at the moment before and during the rainy season, superior seasonal rainfall factors and serious consecutive downpours during the last moment of a monsoon are regularly recorded (Kabir et al. 2017). Temperatures have increased over the last three centuries, particularly at the period of the monsoon season, and they have increased by 0.7 °C per decade all over Bangladesh (Ahsan and Islam 2011). It is predicted that by 2030, the mean temperature will increase by 1 °C and by 1.4 °C by 2050 (FAO 2016). Rainfall is awfully erratic and the allocation has been increasing at a jagged rate (Ahsan and Islam 2011). The number of days without rain has raisen, even though the total yearly rainfall remains approximately the same. Rainfall creates intense events (e.g., floods and droughts) that have perceptibly unfavorable effects on rice, and Aman rice production was reduced by 20–30% in the North-western areas of the country in 2006 during the time of drought. The possibility for tropical cyclones, erosion and tidal floods continues to rise in the coastal salinity-prone areas of Bangladesh, where 10% of the zone is 1 m above mean sea level and has more exposure to the tidal inundation problem (Alam et al. 2020).

The intrusion of salinity presents substantial danger to sparkling groundwater bodies as well as sparkling herbal water aquatic wetlands (Talukder et al. 2015). The World Bank said that a converting climate was grounds for sizeable submergence inside the low mendacity areas and enhanced the increased cost of salinity intrusion. Climate change has brought about worldwide warming, which is the main reason for the rise in seawater temperature (IPCC 2013). Except, clean water glide from the upstream vicinity has steadily declined, in particular during the summer and winter seasons. Such incidents are responsible for the additional occurrences of excessive salinity interference in the coastal regions of Bangladesh.

The forecast is that the area of freshwater locations could decrease from 46% to 35%, and that the moderate region of a saline area could decline from 51% to 46% because of the oceans' temperature rise. Additionally, it is a noteable statistic that the area of salt water in surrounding areas will rise from 6% to 18% by 2030 (Barua and Rahman 2021). As a result of growing salinity, 21% of the greater land area in comparison to 1990 could be gravely impacted, and the intensity of salinity could be amplified by 15% (Barua et al. 2020, 2021). Alam et al. (2020) showed that the increasing cost of the salinity stage in the sediment should be set at 0.95%, in line with the year. There are exclusive sources of salinity intrusion around the coastal areas, which are a part of the Southeastern coastal sector of Bangladesh.

Paddy land becomes salty as it comes into contact with seawater and continues to be flooded during high tides and intrusion of water from the Sangu River and its streams; as a result salinization processes reduce soil fertility, alter original or old agricultural practices and discourage farmers from cultivating. The primary objectives of the study were to determine soil and water salinity and the current soil fertility status of the rice land and to begin some measures to reduce the salinization processes and improve the study area's fertility status.

21.4 Case Study

Chittagong is a coastal district situated in Southerneastern shore of Bangladesh and is a natural combination of hills and sea. The study was done in the Anwara upazila (Subdistrict), which is under the Division of Chittagong. Among the 11 unions of the Anwara subdistricts, the study concentrated mainly on two areas (i.e., Gohira and Bottali) affected by climate change.

The authors took the sediment samples from the 11 study areas from November 2019 to August 2020 to estimate the fertility circumstances and surface water salinity level. They also used the Global Positioning System (GPS) to document the absolute locations of the samples (Table 21.1).

The major livelihood of the people depends on agriculture, fishing, small-scale business or shopkeeping. Most of the rice fields are suitable for three crops.

Table 21.2 summarizes the selected parameters of surface water salinity, soil quality and fertility status in paddy fields.

Table 21.1 Sampling location of the study area

S. No	Sampling station	GPS value
Site 1	Gohira Hill (valley area)	21°255′50.9″–91°59′13.2″
Site 2	Jakulia Hill (valley area)	21°25′22.2″–91°59′30.7″
Site 3	EPZED area (valley area)	21°25′50.8″–91°59′18.5″
Site 4	KAFCO area (valley area)	21°24′09.3″–91°59′31.3″
Site 5	College area (Plain land)	21°24′23.4″–92°01′2.5″
Site 6	Parkee Ghona (P. area)	21°24′40.4″–92°01′71″
Site7	Chandro pahar (P. area)	21°24′42.5″–92°01′9.9″
Site 8	South Rubber Dam (P. area)	21°25′2.6″–92°01′10.7″
Site 9	North Rubber Dam (P. area)	21°25′7.7″–92°01′12.8″
Site 10	Khurulia (P. area)	21°24′52.3″–92°01′44.6″
Site 11	Link road (P. area)	21°24′6.6″–92°01′38.8″

Table 21.2 Summary of surface water salinity, soil quality and fertility status

Water qualityfactors	No. of sample	Minimum	Maximum	Mean	Std. deviation
Salinity ($\%_0$)	11	0.42	45.10	24.8291	14.65116
Soil quality					
Ph	11	1.80	3.60	2.8955	0.54150
Color	11	Reddish	Blackish		
Temperature (°C)	11	26.00	35.00	31.8182	2.60070
Salinity ($\%_0$)	11	1.00	30.50	19.1727	12.01491
Fertility status					
Structure and textural class	11	Sandy	Sandy loam		
Bulk density (g/cm^3)	11	1.51	1.66	1.5809	0.04949
OC (%)	11	0.13	0.77	0.4473	0.18347
OM (%)	11	0.22	1.32	0.7718	0.31654

The authors found a maximum salinity level of 45.10 ds/m at study area 5 and an average salinity of 24.83 ds/m and a minimum salinity of 0.42 ds/m at site 4, with a standard deviation of 14.65 ds/m (see Table 21.1). Temperature affects soil biota activity directly by determining the level of physiological activity (e.g., enzyme activity) and indirectly by affecting physicochemical properties (e.g., nutrient diffusion and solubility, mineral weathering, evaporation rate and so on). The authors found that the maximum temperature is 26 °C at study area 2, the minimum temperature is 35 °C at study area 6 and the mean temperature is 31.8 °C, with a standard deviation of 2.6 °C (see Table 21.2).

The authors explored the soil color condition in the study areas and found the black or blackish, brown and red or reddish color of sediments in the crop fields. About 54.54% of the samples were black or blackish, 36.36% were brown and 9.09% were red or reddish in the study area (Table 21.3).

Table 21.3 Soil color in the paddy fields of the study areas

Range of limit	Number of samples	Percentage (%)
Black or blackish	6	54.54
Brown	4	36.36
Red or reddish	1	9.09
Total	11	100.0

Table 21.4 Findings of soil structure and texture in the study areas

	Soil structure or separation				Soil texture	
Site no.	% sand	% silt	% clay	Fertility status	Textural class	Fertility status
Site 1	92.9	2.5	4.6	Poor	Sandy	Poor
Site 2	62.9	30	7.1	Poor	Sandy loam	Medium good
Site 3	37.9	52.5	9.6	Good	Silt loam	Good
Site 4	57.9	35	7.1	Medium good	Sandy loam	Medium good
Site 5	60.4	35	4.6	Poor	Sandy loam	Medium good
Site 6	75.4	17.5	7.1	Poor	Sandy loam	Medium good
Site 7	75.4	17.5	7.1	Poor	Sandy loam	Medium good
Site 8	50.4	40	9.6	Good	Loam	Very good
Site 9	32.9	60	7.1	Very good	Silt loam	Very good
Site 10	35.4	57.5	7.1	Very good	Silt loam	Very good
Site 11	45.4	45	9.6	Very good	Loam	Very good

Table 21.4 indicates that the soil textures in the study areas and that flat surface (i.e., plane) land soil was more fertile than hill soil because the portion of silt loam particles was high in the plane soil; on the other hand, the portion of sandy loam and sand particles was high in the hill soil. It is important that in some flat surface land, soil status was sandy loam and the fertility status was medium good.

From these findings, the authors observed that the bulk density of sediment shifts in the total pore space present in the soil; it provides a good estimate of soil porosity. Table 21.5 shows that the authors found the mean soil density in bulk to be 1.5 gm/cc, which indicated that the present level of density was moderate for paddy cultivation in the study areas. The table shows that soil bulk density was poor in valley area soil and soil bulk density was good in flat surface land soils. This highlighted that study sites 5 and 6 both were plane areas but their bulk density was poor.

It was discovered that salinity created a degraded environment and imbalance of the hydrological situation that hampered the regular agricultural crops' production throughout the study areas—that is , the range of salinity level. Maximum salinity content was calculated at 30.5 ds/m in study site 5 and minimum content was found to be 1.0 ds/m at sites 2, 3 and 4. For the other sites, soil salinity was very good because these areas were active with tidal fluctuations and inundation of paddy land by saline water; at site 5, along with tidal creeks, was directly active with the Bay of Bangle and the Sangu River (Table 21.6).

Soil electircal conductivity (EC) was found to be low with respect to the referring level (2.0–4.0 ds/m) (see Table 21.6). According to the findings, it was discovered

Table 21.5 Findings of soil bulk density in the study areas

Sample location	Bulk density (g/cm^3)	Fertility status
Site 1	1.66	Poor
Site 2	1.60	Poor
Site 3	1.51	Good
Site 4	1.59	Poor
Site 5	1.61	Poor
Site 6	1.63	Poor
Site7	1.63	Poor
Site 8	1.53	Good
Site 9	1.55	Good
Site 10	1.55	Good
Site 11	1.53	Good

Table 21.6 Findings of soil factors in the study areas' sample sites

Sample No	pH	Salinity	EC mS/cm	% O.C	% O. M	Total % N	Total % P	Total % K	Total % Ca	Total %Mg
1	3.0	22.3	0.08	0.13	00.22	0.06	0.3075	0.20	0.0037	0.110
2	3.5	1	0.05	0.31	00.53	1.00	0.28	0.54	0.0009	0.434
3	1.8	1	0.01	0.62	10.07	1.02	1.135	1.04	0.0000	0.532
4	2.3	1	0.05	0.49	00.85	0.98	0.69	0.56	0.0002	0.160
5	2.8	30.5	0.10	0.53	00.91	1.04	1.0225	0.51	0.0003	0.115
6	3.0	25.5	0.09	0.27	00.47	0.73	1.03	0.33	0.0001	0.061
7	3.0	23.2	0.08	0.47	00.82	0.78	0.7875	0.26	0.0006	0.078
8	2.8	29.4	0.15	0.58	00.01	1.00	1.51	0.64	0.0001	0.313
9	2.6	22	0.12	0.77	00.32	1.23	0.3425	1.05	0.0003	0.584
10	3.5	29.4	0.05	0.46	00.79	0.88	0.7975	0.78	0.0003	0.614
11	3.6	25.6	0.01	0.29	00.50	0.31	0.8325	0.70	0.0001	0.029

that the percentage of the total nitrogen status was good and very good in the study areas but only site 1 was in the hill area. From the findings, it is revealed that nitrogen levels in the agricultural crop fields indicate that they are fertile, and farmers used various types of organic and inorganic fertilizers, especially urea on paddy land.

Potassium (K) is another important nutrient; it is not only important for the increase of fertility status but also it directly involves plants' growth. Optimum limit of the percentage of total K is for four categories—that is, low (< 0.15), medium (0.150–0.30), high (0.30–0.375) and very high (> 0.375) (SRDI 2010; Chowdhury et al. 2011). Minimum percentage of total K was found to be 0.20, maximum was 1.05 and mean was 0.6009; this shows that the percentage of total K was good and very good for crop cultivation.

Islam (2004) reported that many coastal areas, including Chittagong, are facing increased salinity levels in agricultural fields. Nearly 1.5 million ha of arable land in Bangladesh are affected by salinity intrusion caused by slow-onset and fast-onset events (SRDI 2010). It also points out that 71% of the cultivated areas in Banshkhali upazila are affected by high levels of salinity (> 12 dS/m). According to BBS, the net cultivated area in Chittagong decreased by about 7% from 1996 to 2015 (BBS 2016). It has been found that in the immediate aftermath of cyclone *Mahasen*, which hit the Southeastern coast on June 13, 2013, total rice production in Chittagong decreased from 0.70 million tons in 2013 to 0.40 million tons in 2015 (BBS 2013, 2015). The report also stated that the production of the main rice crop (i.e., Aman) in Chittagong declined substantially, from about 0.8 million tons in 2013 to 0.4 million tons in 2015.

Salinity infiltration allegedly increased significantly during the previous 10 years, particularly over the last 5 years, according to focus group participants and survey responders. Cyclone *Mahasen*, which struck the region in 2013, is mostly to blame for the current high salinity in rice fields. When the fieldwork was conducted in 2016, high salinity in rice fields was a problem for roughly 65% of agricultural households. All saline-free and low-salinity farmland has been discovered to have changed into medium- or high-salinity farmland, which has a detrimental impact on crop output.

The majority of the rice grown by farmers in the research areas is an Aman variety, which blooms from April to August. Khankhanabad Union's Aman production pattern has been highly erratic over the last 20 years. The results indicate that between 2000 and 2005, the overall production of Aman was more than 10,000 tons, whereas between 2006 and 2011, it was less than 7500 tons. Aman production was roughly 6800 tons in 2012. Since then, it has significantly fallen by 25% and 15%, respectively, in the study union in 2013 and 2014 (UAO 2015). A similar tendency has been seen in the other studied unions, according to UAO statistics. Farmers reported that in 2013, "zero production" of rice occurred in all four study villages in both of the previously mentioned unions.

Farmers said that in 2013, shortly following the impact of *Mahasen*, all four study villages in both of the unions had "zero production" of rice. More precisely, according to local farmers, the high salinity in the rice fields caused the yield of the Aman crop to change from an average of 3.5 tons per ha in 2012 to 0 tons per ha in 2013 in all the research villages. Despite high saline levels in the years following *Mahasen*, several farmers in the study villages tried Aman farming once more, even though their yields were less than 1 ton per ha. Farmers were able to raise Aman yields marginally in 2015 to an average of 1.5 tons per ha in all four villages; however, the yield was lower before cyclone *Mahasen*.

Regarding the modifications in rice production throughout the previous 20 years, there were many reactions. In the study communities, roughly 76% of farmers thought that rice production had declined over time. In the research areas, rice output has "decreased a lot" over the previous 20 years, according to 51% of respondents. According to the findings of the survey, 98% of households cited saline intrusion as the primary factor contributing to reduced rice output, followed by a lack of rainfall (65%). Other issues mentioned included pest infestation, too much or too little fertilizer, water logging, expensive cultivation costs and a lack of irrigation water. Excessive rainfall over short periods of time, also known locally as "sky floods," was also listed. Other factors cited included pest attack, not having fertilizer at the right time and high cost of cultivation.

All the farmers firmly believed that salinity intrusion into soil and water is the main challenge to rice farming in the study areas. The study also revealed that loss and damage associated with salinity intrusion in rice production affects income groups (e.g., extremely poor, poor and non-poor) in different ways. The income of extremely poor households from rice cultivation was affected the most. In 2013, the loss incurred by the extremely poor was about 70% of their past annual household income, whereas other households lost 40–45% of their previous annual income. In addition, from 2013 to 2016, all the sampled households were gradually adapting in some way to reduce the shortfall in rice production. But the poor and extremely poor households were recovering their situation at a slower rate than non-poor families. The results of correlations among soil salinity levels and studied physicochemical properties of agriculture and field soils of the study areas are shown in Table 21.7.

21.5 Farmers' Adaptation Practices for Reducing the Salinization Problem

Farmers in the study areas noted that climate change and variability directly affected the agricultural sector, especially crops, fisheries and livestock production. That situation led the people to adaptation strategies to mitigate the risk. Based on their experiences, knowledge and resources, they looked for strategies to cope with the changing climatic conditions. The changes in rainfall pattern and temperature rise resulted in changes to crops' emergence, germination and insect pests.

In the research areas, farmers claimed that they were unfamiliar with the idea of preemptive adaptation. They usually waited until a problem occurred before making any preparations; only then did they make adjustments. Then they considered how they were farming and looked at areas farther South. As a potential adaptation strategy, new tree plantations (i.e., quick-growing timber) were of interest to participants in the Southern section. They started paying attention because they believed the trees could change the microclimate and bring more rain. In addition, it would be possible to cultivate watermelon and pumpkin (on a limited scale) if they could prevent the salinity increase. New sesame cultivars that can withstand unexpected stagnant water are needed. The medium highland produces the best yield from sesame, whereas the medium lowland produces the worst yield.

Women have become better educated, and they pass their knowledge on to offspring (future generations) so that they can change with the times. Concerns about local control over tidal water drainage are shared by both genders. Larger farms block canals for their fish farming operations (i.e., reduction of drainage pathways). Coasal embankments could give way at any moment. Farmers in Banshkhali, including the Southeastern coast of Bangladesh, suggested some

Table 21.7 Relationships among the soil salinity and soil physiochemical properties

Physicochemical properties	1	2	3	4	5	6	7	8	9	10
1. Soil pH	–									
2. Soil temperature (°C)	.783**	–								
3. **EC (dS/m)**	**.917****	**.808****	–							
4. Bulk density (g/cm^3)	−.427	−.158	**−.326**	–						
5. OM (%)	−.775**	−.896*	**−.712***	.251	–					
6. Total N (%)	−.875**	−.809**	**−.830****	.500	.853**	–				
7. Total P (%)	.848**	.624*	**.762****	−.298	−.480	−.601	–			
8. Exchangeable K (%)	.808**	.828**	**.653***	−.291	−.738**	−.738**	.833**	–		
9. Exchangeable ca (%)	.115	.289	**−.101**	.041	−.579	−.244	−.159	.250	–	
10. Exchangeable mg (%)	.884**	.800**	**.785****	−.510	−.879**	−.870**	.597	.714*	.435	–

Note. $^{*}p = .05$, $^{**}p = .01$.

adaptation options for reducing the salinization in their agricultural fields, as can be found in Table 21.8.

Table 21.8 Adaptation practices in the study areas: responses of men and women

Proposed adaptation option	Responses of women	Responses of men
Substituting a short-duration variable (125–130 day) for the long-duration *T. Aman* rice variety (BR-23, 150 day) to increase intensity or lower risk.	(i) Superior for early harvest, which may lower the risk of damage to sesame from water logging with rainwater and may enable the risk of heavy rainfall for stormy weather throughout BR23 maturity. (ii) By August 20, short-term Aman rice transplants must receive the ideal amount of rainfall.	In the study areas, men gave the same responses as women, but they placed more emphasis on easy harvesting, proper drainage of rain or tidal water, and a community approach to rodent damage.
The authors found that cowpea and grass pea replanting with *T. Aman* rice in a single *T. Aman* cropping area.	It is possible in the medium highlands.	The concept is good for the medium highlands, but it must be a community-based operation to protect open grazing.
Direct dry seeded/dibbled or transplanted rice cultivation in the rice Aus season.	There was no response.	(i) Farms could be tried in the medium highland areas after sesame or mungbean production, but requires cultivars with short duration. (ii) Rice Aus is dependent on early Kharif-1 bathe.
Deepening existing inner side canal of the rice–fish culture under gher to store more surface water for irrigation.	Absence of rejoinder.	(i) It is possible to go 30–60 cm deeper in an existing canal that is 120–150 cm wide and 60 cm deep. (ii) If there are more, the canal's width must be increased, but they are concerned about taking up too much land.
Ponds designed specifically for irrigating the dry season crop.	Absence of reply.	(i) Ponds with an area of 80–100 m^2 and a depth of 180–210 cm could be used to store fresh surface water for irrigating rabi crops. (ii) They are concerned about cost and area expansion.
The authors recommended special fertilizer application to combat salinization in the crop field.	Lacking of reply.	In the coastal areas, few crop farmers use a solution of gypsum and sugar to decrease salt level in the paddy seedbed.
Paddy field preparation.	Women support men for paddy field preparation.	Tillage of rice fields on a frequent basis to decrease the salt level during cultivation.

21.6 Climate-Smart Agriculture in Bangladesh

Because crop land has shifted to urban, peri-urban and industrial purposes, the country is behind by around 85,000 ha of cultivable land every year. The annual loss of crop land during 1976–2020 was 50,240 ha and accessibility of crop land was in a decreasing pattern, with much larger rates since 2000–2020 (Rahman et al. 2020). Nearly 22% of the country's GDP comes from agricultural sectors, which turns out to be the source for 65% of the nation's labor force. It was estimated that more than 50% of the cultivable land of Bangladesh has been impacted by salinity interference, water logging and drought-related natural events. The nation requires immediate assistance in adopting the climate-smart crop production if its communities are to stay alive and flourish for longer periods.

Changing climate is influencing socioeconomic development of Bangladesh in many ways. For example, increasing sea level is the significant reason for crop lands in coastal zones to become salty and infertile for the long term. The effect of climate change for the agricultural sector becomes indisputable and would definitely depreciate with climate-tolerant cultivation options, not the traditional and resilient ones. In the Southeastern coastal areas of Bangladesh, anywhere the soil is the merely elevated compared to the Eastern water, huge swathes of the crop land are getting parched. Production of the crops is retreating because of increased salinity and as a result of the rising level of the water in the Bay of Bengal. The authors observed that in the coastal zones, the common commercially important plants (i.e., betel nut and coconut trees) were not harvested 60% of the time over two decades, whereas the fruit of banana trees will be disappearing completely within 100 years.

Farmers in the study areas produced various vegetables that are available in the local trade centers of Chaittagong, Dhaka, Rajshahi and Khuln; they are absolutely flavorless and bring in little value compared to the production in zero-salinity areas of the other parts of the country. Nearly 90% of families in communities live in rural areas; it is for this reason that Bangladesh always has required assistance in promoting climate-resilient agriculture as the best options of climate change adaptation (Barua et al. 2021). This will help to prime activation to facilitate crop farmers to raise food security by adaption. To solve the climate change-induced problem, agricultural farmers absolutely need to increase their vegetable beds, keep up the soil's moist condition by encasing the nursery—using leaves and straw to put off excessive loss of water and the threat of coastal erosion. In addition, they need to increase the quantity of the sediments' bioorganic composting ingredients and diversify the patterns of crop rot in their fields.

Developed in 2013, the National Agriculture Policy also considered it necessary to include part of each of the following: Environment Policy of 1992, Fisheries Policy of 1998, Agricultural Land Use Policy of 2001, Policy of 1994, National Jute Policy of 2002, National Livestock Development Policy of 2007, National Food Policy of 2008, Livestock Resources Policy and Action Plan 2005 and National Poultry Development Policy 2008. The major goals and objectives of these policies were to develop sustainable and climate-resilient agricultural activities for

Bangladesh; they were in response to the vulnerability to climate change through increasing crop production. This has continued to place importance on surveys, research, extension facilities, modern technology transfer and updated information-sharing to make this happen. Although this is limited, there are no definite action plans, according to the country's agro-ecological zones (Fig. 21.1).

The authors found that 31.3% of the crop farmers of the Southeastern coast of Bangladeh have typical or adapted substitute land-use options (e.g., coastal farming)

Photographs of Some Climate Smart Agriculture Practice in Bangladesh

Picture: Heat Tolerant Tomatoo and Brinjal production using marching paper

Picture: Climate Resilient High Yielding Red Cabbage Production

Picture: Production of High nutrient short duration crop Rock Melon

Picture : Using Trico-Compost for high yielding crop production

Picture : Climate resilience all year round watermelon production through using marching paper and rotation cropping

Picture : Disaster resilient high yielding disease free rice production (BRRI-87)

Fig. 21.1 Some of the farmers' adaptation practices in the study areas

Picture : Production of high yielding rich nutrient Dragon Fruits

Picture: Disaster Resilient Rich Nutrient Vegetables production

Picture: Short duration, high nutrient Brocoli production

Picture: Climate Resilient high nutrient Scouas production

Picture: Flood Resilient high nutrient black rice production

Picture: Climate Resilient Vegetable production with plastic shed

Picture: Climate Resilient Integratted Pesticide free pond dyke farming

Fig. 21.1 (continued)

Picture: Climate Resilient all year round multilayerd Vegetable production around the homestead

Picture: Salinity Resilient Wheat Production

Picture: Salinity Tolerant Fish Farming in sweet pond

Picture: Platform shed goat rearing as climate resilient livestock technology

Picture: Vegetables and fruits plant production without soil through using COCODUST

Picture: Platform shed duck rearing as climate resilient livestock technology

Fig. 21.1 (continued)

as an alternative to agricultural crop production. Although the crops' farming land is declining steadily, there are various alternative opportunities for the agriculture (e.g., coastal embankment cropping practices, coastal affoestation, relay crop patterns, farming of salinity-resilient grass, mulching, application of pheromone traps, farming of saline- and flood-resilient rice and so on). Table 21.9 lists of some significant climate-resilient agricultural practicesfor the coastal areas of Bangladesh.

Farmers of the coastal areas of Bangladesh are practicing the following production strategies: salinity-resilient rice, cage fishing, mele (reed), farming through floating dhap, changing the time of planting, high-yield and short-duration rice, methos of Sorjan, raising plums and sunflowers, floating bed vegetables, organic fertilizers, urea deep placement, integrated cultivation, feeding crabs and small

Table 21.9 Agro-based resilient practices in the study areas

Resilient sector	Options
Salinity resilient *T. Aman*	Farmers culitvating Bina shail, BR-22 (Kiran) and BR-23 (Dishari).
Salinity resilient BRRI paddy crop	Farmers familiar to cultivating BRRI-33, 34, 35, 56, 57 and 62
Salinity resilient BINA rice	Farmers producing BINA-7, 8, 10 and 16
Salinity resilient Aus rice	Farmers cultivating BRRI-65
Salinity resilient alternate cultivating	Farmers' experiences of producing salinity-resilient grass production, multistage farming
Cultivation of vegetables	Farmers cultivating vegetables through floating stages, farming in homestead areas and farming in pond and road dykes
Climate-resilient livestock farming	Farmers are practicing goat, duck, hen and sheep semi-scavenger housing
Aquaculture	Fish farmers using cage culture, net culture approach for fish farming
Wheat tolerant to salt	BAU-1059, BARI wheat-25, Bijoy
Potato tolerant to salt	Farmers cultivating BARI Alo-22, CIP clone-86, 88 and 163 for production
Salinity resilient sweet potato	Farmers using BARI Mishti Alo-7, 8 and 9 for high yield
Pulses tolerant to salt	Farmers cultivating BARI-2, 3, 4, 5, 6, BM-01, BM-08 BARI Falon-1, BARI Sola-9 for high yield
Quick-acting oilseeds	Farmers cultivating various species of oil seeds like BARI Sharisha-14, 15; BARI Chinabadam-9, BINA China badam-1, BINA China badam-2, BARI Soybean-6 BARI Til-2, 3, 4
Salt-resilient jute production	Farmers now cultivating HC-2, HC 95, CVL 1 species for jute production
Salt-resilient sugarcane production	ISWARDI-40 is cultivated by sugarcane farmers
Climate-resilient other crops	Farmers trying for land use changing practice, integrated farming, crab patenting, shifting plantation timing

indigenous fish, use of nearby dykes, net fishing, salt-resilient wheat (e.g., Bijoy, BAU-1059 line, BARI Gom-25), tomatoes, potatoes and sweet potatoes, heat- and salt-resilient pulsations, salt-resilient and short-time tolerant oilseeds, salt- and heat-salt-resilient jute cultivation, high-yield and salt-resilient sugarcane, platform shed or semi-scavenger rearing processes for livestock (e.g., goats, sheep, ducks and chickens), salinity-resilient fish culture, short-duration fish and vegetable integrated farming, crab farming and so forth. These are all ways to practice climate change adaptation in the coastal communities.

It is also significant that coastal area farmers are cultivating vegetables in crop fields year-round to cope with salinity, brief duration and small cultivation spaces. Some have the support of government and non-governmental organizations that deal with crop production—for example, homestead cultivation; roadside, embankment and dyke farming; dhap/gher and pesticide-free cultivation; storage capacity increase of paddy seeds; guti uria application in rice fields; and organic biocomposting or integrated farming. This also assesses vegetable and crop production that do not have large-scale potential in Bangladesh's coastal areas—that is, farmers who practice crop production only for household consumption and small-scale usage.

21.7 Conclusions and Recommendations

From the findings in the study areas, it has been observed that the relationship between every climate-smart agriculture practice, with per capita food expenditures, the most significant options for coastal farmers' household food security are: flood- and salinity-resilient crop species, production near roads, pond-side vegetable husbandry and various water-harvesting techniques. The results covered in this book's chapter appears steady, allowing for the geographical location on the Southeastern coast of Bangladesh, where salinity intrusion has become the major catastrophe for the coastal communities. Agricultural fields stay waterlogged for long periods of time and pond areas have increased the ease of production of diverse short-duration and high-yield vegetables, especially during the rainy season. Throughout the dry season (November–February), crop farmers can supply water to their crops and vegetable-producing lands by using water they preserved in ponds or canals during the rainy season (July–September). So, it has been found that various salinity- and flood-resilient crops, as well as road, pond and dyke vegetable production options for distinct types of water-harvesting processes were positively correlated with per capita food security in coastal Bangladesh (Fig. 21.2).

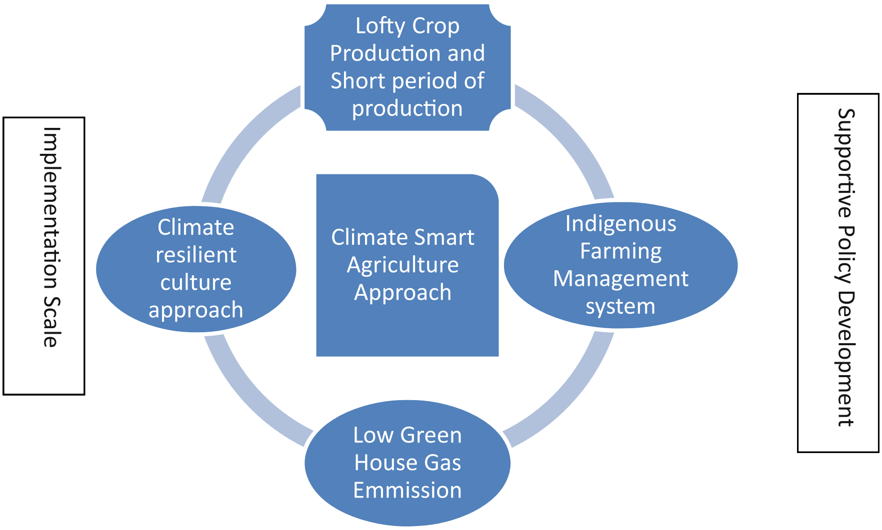

Fig. 21.2 Climate-smart agricultural practices in response to climate change

In this book's chapter, the authors pointed out a poor connection between the climate-smart agriculture coping approach and food security of agricultural households in coastal Bangladesh according to the per capita yearly food costs. Farmers' existing adaptation strategies are insufficient to deal with the rising salinity levels, especially those brought on by extreme events. Along with these climate-related dangers, the level of poverty, low resilience and lack of alternative livelihoods result in significant losses for not just the study communities but also residents of the entire coast.

People are leaving the shore in greater numbers, mostly because of decreased prospects for employment. As sea levels rise and extreme weather events become more common, and if adaption choices are insufficient, this internal movement (i.e., rural–urban, coastal–central) will escalate. Underprivileged families' final destination is an urban slum. Such migration brought on by numerous climatic variables (e.g., saline intrusion) would make it more difficult for the Capital and neighboring cities and towns to provide both former and new city residents with adequate utilities and other services.

Constant research studies, field observations, monitoring, crop and weather information management and technology-related innovative ideas and applications are urgently required for adaptation to climate change and its effects. An exhaustive training program for climate-displaced populations is necessary to increase the ability to cope with new circumstances. The climate change issue is understood to have special significance because of the accumulation of global-warming evidence; currently, this turns out to be a great challenge for the world. Almost all countries have been impacted, and it has become a large threat for global development and food security. Because of low agricultural production and land becoming infertile owing to salinity intrusion a country like Bangladesh is one of the most hands-on of the developing nations.

A universal scenario is needed to tackle the challenges induced by climate change. Climatic changes and their significant effects have been deemed hampered through some oppositions created, together with attempts to reduce the impacts of the national poverty condition and to achieve sustainable development goals (MDG). Besides, a cooperative land execution management process should be formed wherever coastal aquacultural production is to be carried out. Under the approach of community-based management methods, it will permit minor landholders to navigate through the deteriorating political nexus of the bulky and the influential. The salinity-resilient rice varieties or other vegetables, crops, floating gardening and integrated cultivating systems (i.e., shrimp/prawn plus rice) could be applied in a more widespread process to decrease the climate change impact and earnings weaknesses in the coastal areas of Bangladesh. Furthermore, the government should take on programs to set up and reinforce shore embankments so that marginalized communities can return to their own cultural technologies that could reduce susceptibility to climate change and food deficiency in coastal areas.

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Chapter 22
Climatic Challenge for Global Viticulture and Adaptation Strategies

Rizwan Rafique, Touqeer Ahmad, Tahira Kalsoom, Muhammad Azam Khan, and Mukhtar Ahmed

Abstract Climate change has posed mammoth challenges for the global viticulture, and almost all the growing regions are facing the mounting pressure exerted owing to this unchecked climatic challenge. Pedo-climatic and topographic features largely affect the production and quality of table and wine. Climatic variability in the form of rising CO_2 and elevated global temperature with increased intensity of water scarcity during the growing season has contributed to the unsustainability of global viticulture. Early phenological development, shortening of phenophases, poor berry development, early maturity with lower yield and inferior quality are the consequences of these challenges. Moreover, the physiological activities of vines, e.g. photosynthetic activity, transpiration and stomatal conductance, are negatively affected along lower water use efficiency (WUE), hence higher irrigation demands.

Keywords Viticulture · Climate change · Temperature · CO_2 · Water deficit · Phenology · Physiology · Berry quality

22.1 Introduction

Grapevines of *Vitis vinifera* are a distinct crop belonging to family Vitaceae. They are a non-climacteric fruit species, commonly used as table grapes and dried raisins and in vinification (wine production) and distillation to produce liquors (Kuhn et al. 2013; Ruel and Walker 2006). Grapes contribute about 16 percent of global fruit production (Bhat et al. 2017). Grapevines are cultivated on an area of 7.4 million hectares with an annual production of 77.8 million tons globally in 2018 with five countries, Spain (13%), China (12%), France (11%), Italy (9%) and Turkey (6%),

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contributing about 51% of the viticulture industry. The major share of viticulture industry is occupied by the wine industry (246 mhl consumption) with 57% production of wine grapes (OIV 2019). Bordeaux, Burgundy, California, Champagne, La Mancha, Cape/South Africa, Porto/Douro, La Rioja, Mendoza, South Australia, Mosel and Tuscany are home to major wineries globally (Fraga et al. 2012). Table and dried grapes contribute 36% and 7% (Fig. 22.1), respectively, in the total grape production, and now there is a rising popularity of table grapes with fresh grape's juice and dried grapes or raisins with 1.3 million tons production (OIV 2019).

Grape cultivation originated in Armenia near the Caspian Sea region, and gradually, it spread westwards to Europe and eastwards particularly in Iran and Afghanistan (Creasy and Creasy 2018). Viticulture regions are widespread, but usually concentrated in temperate climatic zones. Europe consists of the largest viticulture zones in the world (about 40%), although many areas in Asia, such as India, China, Turkey, Afghanistan, Iran and Pakistan, are emerging as the new high-quality table grape-producing regions. China, in Asia, has recorded major increase in grape production over the last few years. Similarly, viticulture has made inroads in US regions, e.g. California, Georgia, Washington and Florida, with good fruit quality for wine and fresh consumption. In the southern hemisphere, Argentina, Australia, New Zealand, Chile, Brazil and South Africa are among the rapidly flourishing viticulture regions. The major grape producers and global viticulture distribution in different regions are given in Figs. 22.2 and 22.3.

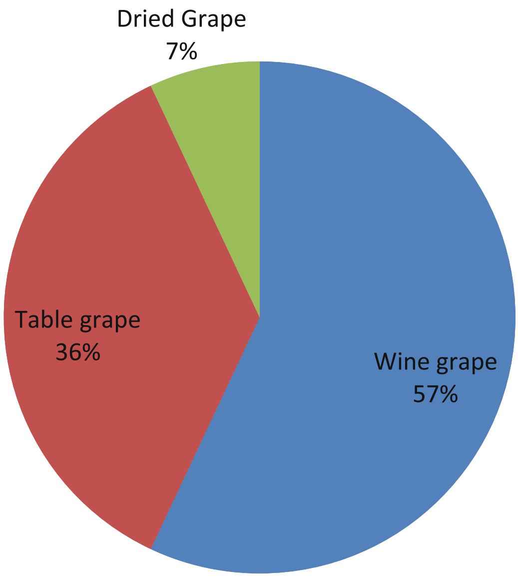
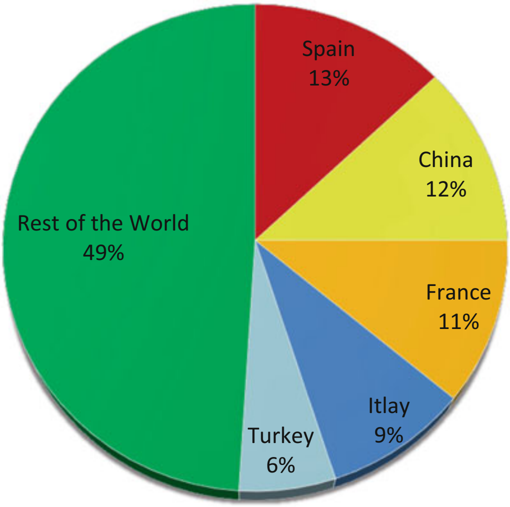


Fig. 22.1 Global viticulture with respect to usage as wine, table and dried grapes

Fig. 22.2 Global grapevine production trends and share of five leading producers



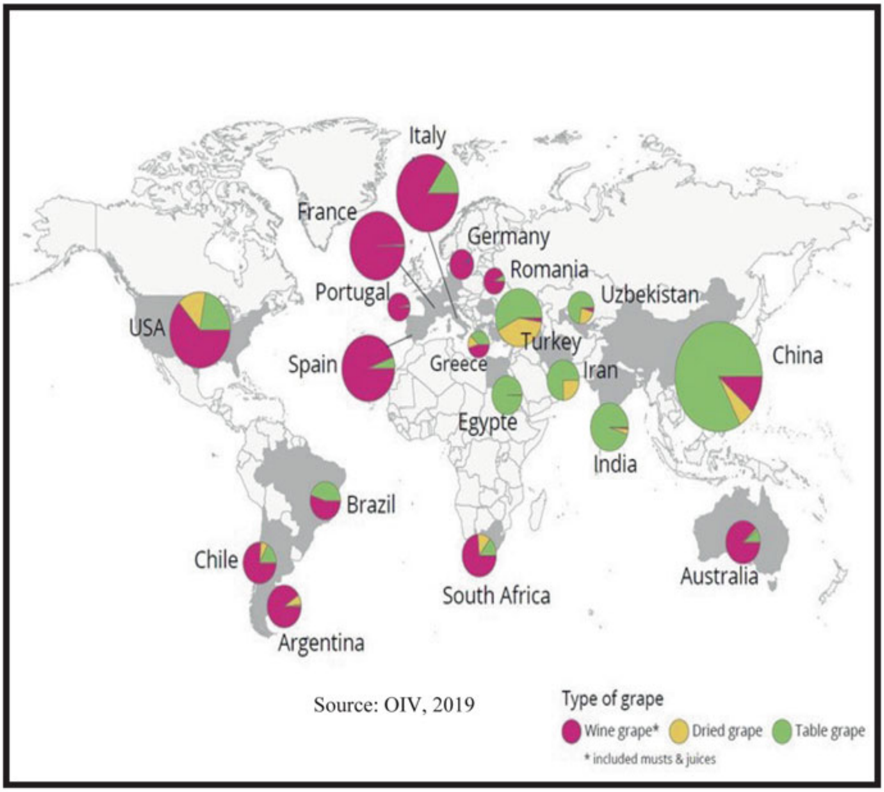


Fig. 22.3 Global distribution of grapevine in different climatic zones of the world

22.2 Botanical and Anatomical Characteristics

Like all other members of Dicotyledoneae, grapevines start their life cycle with two cotyledons. Family Vitaceae's members are termed grapevines, and it contains about 1000 species with 17 genera. Although most members of this family belong to in the tropics or subtropics, even then a species (*Vitis vinifera*) from the temperate zones has become the world's chief fruit producer in about 90 countries. Cultivated grapes belong to either genus *Vitis* (2n 38 chromosomes) or genus *Muscadinia* (2n 40 chromosomes) and have distinct floral morphology (Fig. 22.4). Roots of this family are generally fibrous and well branched and can grow to several metres in length. Vines climb through tendrils which act to provide support, and leaves grow alternatively on branches (Creasy and Creasy 2018; Mullins et al. 1992). There are about 24,000 named cultivars, but there is often more than 1 name for the same cultivar; the number of different and distinguishable cultivars is about 4000 (OIV 2013).

22.3 Factors Influencing Viticulture

Grapevine development is affected by a highly intricate system, consisting of soil characteristics, climate features and vineyard management (Magalhaes 2015). The concept of terroir emerged in this system of interacting factors such as physical, biological and environmental components along with viti-vinicultural techniques which give distinctive characteristics to the products (OIV 2010; Van Leeuwen et al. 2004; Fraga et al. 2013). All the elements in the terroir strongly affect the growth and development of grapevine cultivars. Moreover, these factors also influence the wine type, fruit yield and berry quality. A brief description of these factors is given in Sects. 22.3.1 and 22.3.2.

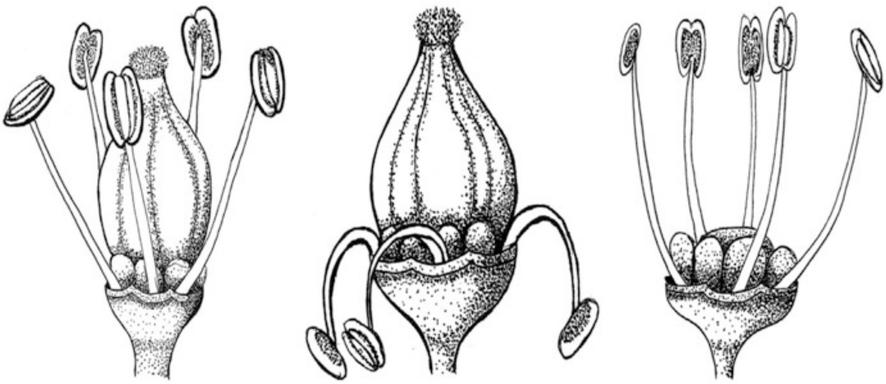


Fig. 22.4 Flower types in the genus *Vitis*: perfect (left), female (centre) and male flower (right). (Keller 2010)

22.3.1 Climate

Grapes are cultivated between 50°N and S, where suitable areas lie in small limits. Vines need cool winter and warm to hot and dry summer for good quality of fruit. Subtropics with winter rains are the most suitable areas for viticulture. Rains and cloudy weather at flowering adversely affect the fruit set, while excessive rains during berry ripening lead to berry and bunch rot. Raisins are produced by sun-drying between the vine rows in areas with at least 1 warm, sunny month without rain after harvest is essential (FAOSTAT 2016). Regional climate is the key element of terroir affecting grape production (OIV 2010; Jones and Davis 2000). Base temperature of 10 °C is one of the most important climatic thresholds for budburst in grapevines (Winkler 1974).

Climate is a key factor driving phenology, vine growth and physiological development, thereby affecting the production and quality of grapevine (OIV 2010; Keller 2010; Costa et al. 2019). Furthermore, vineyard's geographical distribution is affected by climatic variables (Fraga et al. 2019). Weather parameters such as temperatures, solar radiation, rainfall pattern and inter-annual seasonal variability affect vine productivity as discussed by Fraga and Santos (2017). Extreme weather events, e.g. heat waves, hailstorms, excessive rainfall and late spring frost, have detrimental impacts on grapevine productivity (Greer and Weedon 2013; Mosedale et al. 2015).

22.3.2 Topographic Features

Topographic features such as land elevation and slope are of significant importance for viticulture (Jones et al. 2004; Yau et al. 2013). Surface elevation affects the temperature in vineyards at farm scale as vertical temperature gradient, and it exerts a strong influence on the site suitability and varietal selection (Magalhaes 2008). Solar exposure to vines is affected by the degree of slope; thus, it has a main impact on canopy microclimate, viticultural management, water drainage and soil erosion in vineyards (Zsofi et al. 2011).

22.3.3 Soil Requirements

Soil consists of organic and inorganic matter, and it is a source for providing water and nutrients which are critical for grapevine growth, physiology and yield responses. It is a key part of terroir and an important factor for viticulture (Magalhaes 2008). In fact, the composition of berries is influenced by the soil's physical and chemical properties and hence affects wine quality (Mackenzie and Christy 2005). Grapevines are well adapted to a wide range of soils; however, poorly drained soils and areas with exceptionally high salinity levels are considered as unsuitable. Light soils with high water-holding capacity are preferred for grape cultivation. Similarly, the water-holding capacity of soils is also essential and has a direct effect on vine performance (Yau et al. 2013; Field et al. 2009). Grapevines are moderately sensitive to salinity, and yield is affected by it. Nevertheless, vine yield is not affected up to 1.5 mmhos/cm, while 10% reduction at 2.5, 25% at 4.1, 50% at 6.7 and 100% at 12 mmhos/cm have been observed. Deep fertile soils result in high yields, but in less fertile soil or soil with limited depth, yield is usually poor. Nutrient requirements of grapevine are 100–160 kg/ha N, 160–230 kg/ha K and 40–60 kg/ha P. More nitrogen is required during early spring when the vines are undergoing rapid vegetative and inflorescence development. Nevertheless, nitrogen level must be low during ripening to prevent excessive vegetative growth (FAOSTAT 2016).

22.4 Climate Change and Viticulture

Climate change is no doubt the major challenge that the viticulture industry has to deal with in the coming decades. Significant changes in temperature have been observed during the past century which include, surface temperature increase of 1.06 °C over a period of more than 100 years, however major increased, i.e. 0.85 °C occurred over the past two decades (IPCC 2014a). Air temperature variations were prominent, i.e. 2–5 °C increase in traditional viticulture zones in different parts of Europe (Christensen et al. 2007). Climatic projections for the twenty-first century indicate temperature increase in different ranges, i.e. stabilization at 1.5 °C higher than the current reference period to more than 4 °C increase in the mean global temperature (IPCC 2014b). The key driver of the temperature increase has been the emission of greenhouse gases; among these, CO_2 is more pertinent in terms of volume and effect (IPCC 2014b). Atmospheric CO_2 levels have increased from 280 μL L^{-1} (preindustrial) to more than 400 μL L^{-1} in 2016, with predicted a rapid increase for the end of century, i.e. 421–936 μL L^{-1} (Meinshausen et al. 2011). Furthermore, a decrease in rainfall has been observed in major viticulture regions, particularly, Southern Europe (IPCC 2014a; Christensen et al. 2007), and it is expected to decrease further in the future.

22.4.1 *Elevated CO_2 and Impacts on Viticulture*

The global concentration of CO_2 has increased from 280 to 400 ppm; this increase was more rapid after 1950 as indicated in Fig. 22.5. The rise in CO_2 levels may change the global viticulture outlook. As an outcome of elevated CO_2 levels in the future, grapevine physiological activity and growth may be affected.

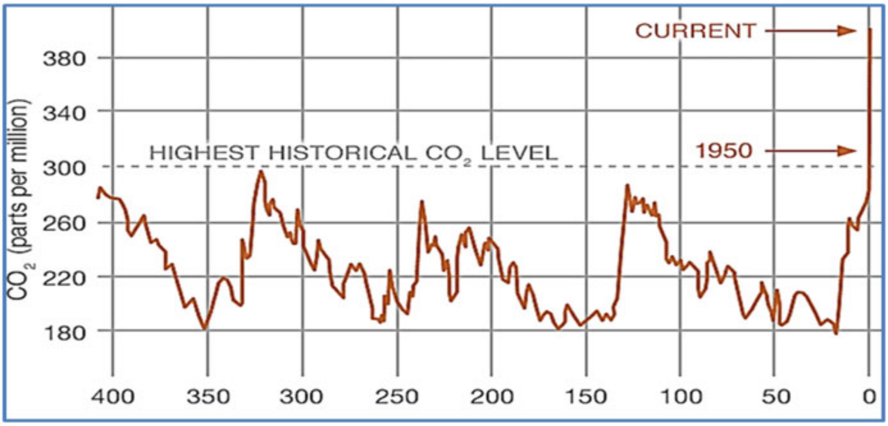


Fig. 22.5 Historical and current atmospheric CO2 level. (Courtesy of NASA)

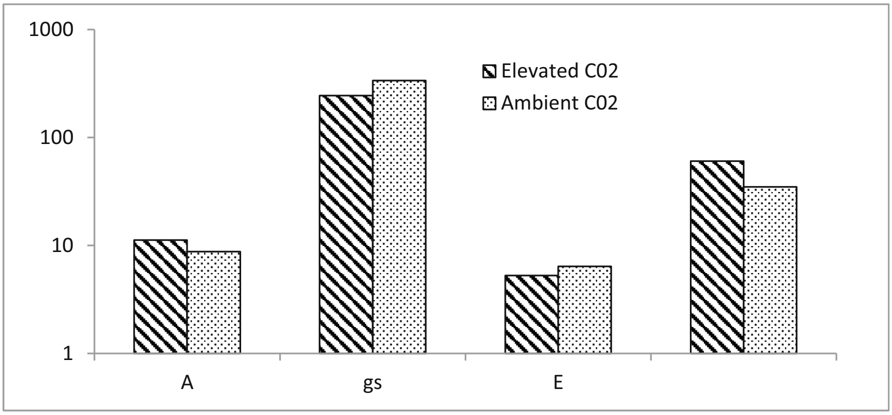


Fig. 22.6 Effect of elevated CO_2 on the rate of photosynthesis (A), stomatal conductance (gs), transpiration rate (E) and photosynthesis/stomatal conductance (A/gs) in vine leaves. (Moutinho-Pereira et al. 2009)

22.4.1.1 Effect of Elevated CO_2 on Vine Physiology

The effect of elevated CO_2 on physiological responses of table grape cultivars is shown in Fig. 22.6. Leaf physiological and anatomical characteristics and vine productivity were accessed for grapevine (*V. vinifera* L.) cultivar Touriga Franca under high CO_2 level of 500 ppm compared to ambient CO_2 level, i.e. 365 ppm. Photosynthetic rate, water use efficiency (WUE), leaf thickness and Mg concentration with C/N, K/N and Mg/N ratios were increased under elevated CO_2; however, stomatal density and N concentration were decreased. On the other hand, transpiration rate (E), stomatal conductance (gs), leaf water potential, photochemical efficiency (Fv/Fm), SPAD value and transmitted red/far-red light were not significantly

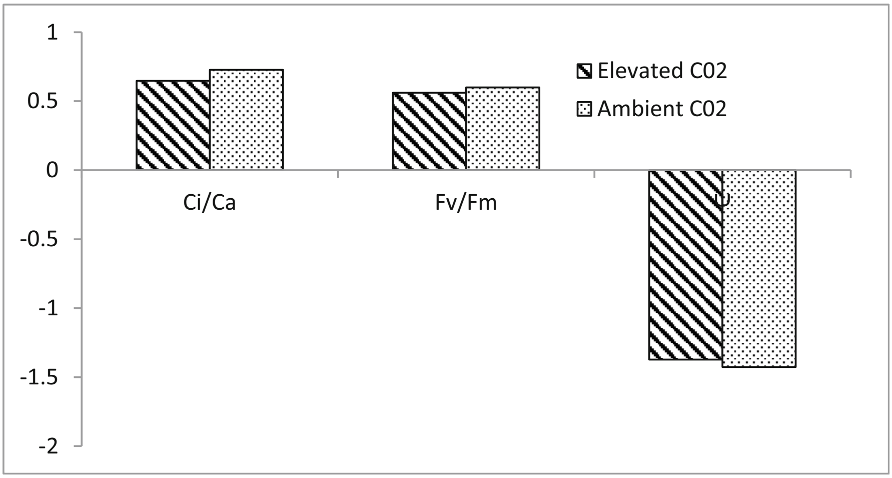


Fig. 22.7 Effect of elevated CO_2 on internal CO_2/ambient CO_2 concentration (Ci/Ca), photochemical efficiency (Fv/Fm) and water potential. (Moutinho-Pereira et al. 2009)

affected by higher CO_2 levels (Moutinho-Pereira et al. 2006, 2009). It is obvious that the photosynthetic activity (A) in grapevine will increase in the future in response to rising CO_2 levels, while stomatal conductance (gs) and transpiration would decrease; however, the ratio of photosynthetic activity to stomatal conductance will increase (Fig. 22.6). Rising CO_2 will also affect Ci/Ca ratio and Fv/Fm ratio negatively, while water potential levels will slightly increase as shown in Fig. 22.7. These trends depict that the climate challenge would have a profound impact on the physiological responses of grapevine.

22.4.1.2 Vine Growth, Yield and Anatomical Characteristics

Elevated atmospheric CO_2 levels affect the growth and anatomical characteristics of grapevine. Data presented in Fig. 22.8 show that elevated atmospheric CO_2 levels resulted in the decreased thickness of total parenchyma, palisade parenchyma, spongy parenchyma and palisade/spongy parenchyma ratio. Despite significant changes in anatomical characteristics along with leaf mass per unit area, may be due to higher light red/far-red light ratio, the stomatal conductance and SPAD values were not much affected as indicated in Table 22.1. Enriched CO_2 also increased vine yield, number of clusters, cluster weight, number of shoots per vine, pruning weight, shoot weight and Ravaz index (Table 22.2) as indicated by Moutinho-Pereira et al. (2009) and Wohlfahrt et al. (2019). The yield gain due to elevated CO_2 was demonstrated under free air carbon dioxide enrichment (FACE) experiments. Recently, increased vine growth and vigour owing to higher rates of photosynthesis under elevated CO_2 have also been noticed (Wohlfahrt et al. 2018). Available records from literature also indicate that higher photosynthetic activity owing to

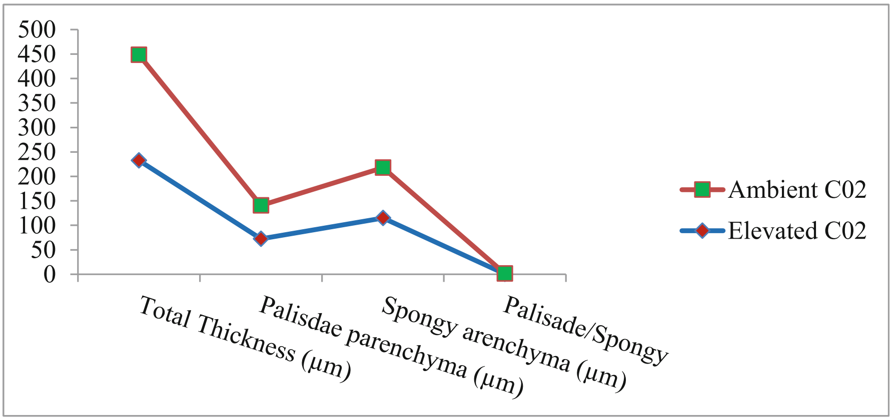


Fig. 22.8 Effect of elevated CO_2 on grapevine anatomical features

Table 22.1 Effect of elevated CO_2 on grapevine stomatal density, SPAD value, infrared light and leaf mass per unit area

CO_2 scenario	Stomatal density	SPAD	Red/far-red	LMA ($g \cdot m^{-2}$)
Elevated CO_2	147.85	45.25	0.202	83.6
Ambient CO_2	147.85	44.45	0.187	72.6

Table 22.2 Effect of elevated CO_2 on grapevine yield, vegetative growth, light interception, leaf mass and Ravaz index

CO_2 scenario	Vine yield (kg)	Clusters per vine	Cluster weight (g)	Shoots per vine	Pruning weight (Kg)	Shoot weight (g)	Ravaz index
Elevated CO_2	5.22	15.57	336.23	14.83	0.75	52.13	8.13
Ambient CO_2	7.28	17.97	403.33	17.90	1.04	64.73	7.13

Table 22.3 Effect of elevated CO_2 on main elements (g kg^{-1}) in grapevine leaves

CO_2 scenario	C	N	P	K	Ca	Mg	Fe
Elevated CO_2	507	21.5	1.56	6.80	17.0	3.94	158
Ambient CO_2	497	23.7	1.63	5.78	19.2	2.01	152

elevated CO_2 would favour yield with higher biomass accumulation (Goncalves et al. 2009; Kizildeniz et al. 2015; Edwards et al. 2016, 2017). The main leaf elements, i.e. N, P, K, Ca, Mg and Fe, were also affected as indicated in Table 22.3. Hence, the effect of CO_2 enrichment on vine phenology will be positive if not complicated by other factors (Moutinho-Pereira et al. 2006, 2009). But, it may not be so in the future due to rising temperature, berry ripening in hot summer and drought effects coupled with rising CO_2. It is obvious here that grapevine leaf anatomical and growth characteristics are affected by rising CO_2. Among quality traits, sugars, acids and berry size were more affected, while juice, wine quality, anthocyanins and proanthocyanidins were not affected by eCO_2 (Martinez-Luscher et al. 2015; Bindi et al. 2001; Salazar-Parra et al. 2012; Wohlfahrt et al. 2021). Recently, it is indicated that elevated CO_2, i.e. 700 ppm, in combination with elevated temperature, i.e. +4 °C, decreased anthocyanin and sugar decoupling due high temperature for cv. Tempranillo (Arrizabalaga-Arriazu et al. 2020).

22.4.2 Effect of Water Stress on Viticulture

Precipitation is an important climatic factor, which affects water availability and use by grapevine (Ferreira et al. 2015). Moderate water stress has some positive effects, e.g. wines of high quality are associated with slight water stress during berry ripening. Dry weather conditions during ripening are favourable for high-quality wine production (Greenspan 2005; Munitz et al. 2017). Severe water stress during early developmental stages may considerably delay the growth and development of grapevine. On the other hand, excessive soil water during the growing season results in vigourous vines, more disease incidence and connected problems which negatively affect wine quality (Magalhaes 2008; Vanden and Centinari 2021). Contrarily, excessive rainfall near maturity is unfavourable, as it causes sugar dilution and diseases (Keller 2010; Munitz et al. 2018; Pellegrino et al. 2005). The impact of water stress depends on vine development stage, e.g. optimal soil moisture levels during budburst, shoot growth stages and inflorescence development are crucial for better vine growth (Poni et al. 1994). Water stress at these stages negatively affects shoot growth, floral cluster development and berry set as discussed in the next sections.

22.4.2.1 Phenology, Growth and Yield Under Water Stress

Water deficit in the beginning of active growth period after dormancy break negatively affects budburst as the rate of mobilization is affected. Rapid shoot growth occurs after budbreak mainly at the expense of stored food reserves in vine during the preceding vegetative cycle (Keller 2005). However, water deficit at active growth phase reduces vine growth, e.g. reduction in shoot growth 20 days after budbreak was noticed for cvs. Cabernet Sauvignon, Pinot Gris and Merlot when midday leaf water potential reached 1.0 MPa (Greenspan 2005; Shellie 2006). Similar reduction in leaf area of cv. Merlot due to water stress was observed by Munitz et al. (2017). Relatively prolonged exposure to moderate water deficit increases root-to-shoot ratio (Chaves et al. 2010). The most active period for vine growth is between budbreak and veraison, and a maximum growth is reached during the early growth cycle usually 60 days after budbreak (Junquera et al. 2006;

Ben-Asher et al. 2006; Munitz et al. 2016; Intrigliolo and Castel 2010). Vine growth then progressively decreases until a vegetative standstill is reached near veraison.

Similarly, reproductive growth correlates with water availability at different developmental stages of the vine. The relationship between yield and water availability from budbreak to harvest was observed in cv. Cabernet Sauvignon (Junquera et al. 2006). Reduced vine yield may be associated with intense and persistent water deficit as it reduces bud fertility along with poor inflorescence development. Vine fertility is reduced by both limited and excessive water availability. Water deficits near flowering limit ovary growth, leading to smaller berries, but the effects on pollen formation and germination and pollen tube growth are even more severe. For instance, sugar uptake and starch accumulation in developing pollen grains are limited under water deficit conditions, causing sterility and poor inflorescence development and fruit set (Keller 2010, 2005; McCarthy 2005).

22.4.2.2 Effects on Vine Physiological Processes

Water stress causes physiological changes, such as reduced leaf photosynthetic activity in response to stomatal closure. Leaf stomatal closure acts as the first line of defence for vines from withering due to heat and drought stress. However, transpiration is a unique component of the radiation energy which is converted into latent heat through the regulation of stomatal closure (Lovisolo et al. 2010). Under high vapour pressure deficit (VPD) levels, stomatal conductance declines up to a threshold. For instance, stomatal conductance of cv. Chardonnay significantly declined at temperatures above 30 °C and high VPD (Poni et al. 1994; O'Neill 1983). Transpiration is the main component of energy balance and provides a cooling mechanism through leaves in plants (Naor et al. 1993) and helps keep leaf temperatures in permissible limits. Even a relatively lower leaf transpiration may lower the leaf temperature by a few degrees and help maintain growth and avoid wilting to a limited extent.

22.4.2.3 Effects on Grape Berry Quality and Composition

Berry total soluble solids (TSS) give an estimation of berry ripening. Rapid TSS as Brix accumulation takes place under water deficit conditions. For example, higher TSS levels per berry weight have been recorded for rainfed vines compared to irrigated vines as indicated by Intrigliolo and Castel (2010) and Esteban et al. (2002). During berry ripening, acid contents of the berry decrease with an increase in pH. A positive relationship between water availability and total acidity was indicated by Intrigliolo and Castel (2010) and Junquera et al. (2012). Increases in titratable acidity due to water stress regardless of the developmental stage were indicated by Girona et al. (2009) for cv. Tempranillo. Higher tartaric acid and lower malic contents were recorded in water deficit vines of cv. Doña Blanca under warm conditions (Uriarte et al. 2017). Similarly, for cv. Tempranillo/110R, (Santesteban et al. 2011) obtained higher titratable acidity values in the higher irrigation treatments. Contrarily, insignificant effects of irrigation treatments on acidity, pH, malic acid and tartaric acid were noticed in cvs. Monastrell/1103 Pa, Cabernet Sauvignon and Merlot as indicated by Munitz et al. (2016). Romeroz et al. (2013) and Acevedo-Opazo et al. (2010).

Water stress early in the season negatively affects vigour, berry size and photosynthetic rate which ultimately lowers acidity and phenolic contents (Esteban et al. 2002; Salon et al. 2005). Controlled deficit irrigation is used to improve berry ripening and wine quality (Uriarte et al. 2015), e.g. elevating the levels of terpenes by modulating structural and regulatory genes (Cramer et al. 2013). Water deficit stimulated the biosynthesis of anthocyanins and phenolic contents (Rogiers et al. 2011). Moreover, the timing and intensity of water deficit affect the metabolism, colour, aroma and flavour compounds of berries. Certainly, water deficit increases the skin-to-pulp ratio in berries compared to well-watered grapevines (Zufferey et al. 2012) while enhancing skin tannin and anthocyanin contents. Increased biosynthesis of anthocyanins in response to water deficit causes differences in colour development (Rossouw et al. 2017).

22.5 Effect of Elevated Temperature on Viticulture

Higher temperature during the active growing season strongly affects grapevines because it is a major driver of developmental stages of grapevine (Parker et al. 2013) and global warming is expected to accelerate phenological events. The phenological shifts at key developmental stages have a strong influence on vineyard management. Moreover, heat events during maturation period will affect wine quality and typicity. Extreme heat stress during the ripening period abruptly reduces grapevine metabolism. It may result in higher sugar levels and lower acidity with potential increase in chances of wine spoilage, hence affecting grapevine production and quality attributes (De Orduna 2010; Fraga et al. 2018) as discussed in Sects. 3.3.1, 3.3.2, and 3.3.3.

22.5.1 Phenology, Growth and Yield Under High Temperature

Grapevine phenology is a good indicator of heat stress and may be used to evaluate the effects of climate change on vine developmental stages like flowering, veraison and grape ripening (Greer and Weston 2010; Bernardo et al. 2018). Air temperature is the key factor driving the timing of phenological stages (Fig. 22.9) along with the duration of phenophases in grapevine (Kose 2014); hence, it affects the inter-annual variability in vine yield and berry quality (De Orduna 2010; Fraga et al. 2014).

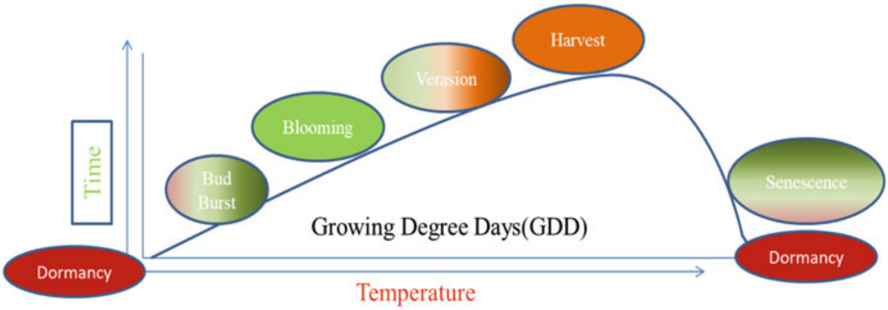


Fig. 22.9 Thermal time model for studying the growth stages of temperate perennial crops

Rising temperature trend is expected to advance grapevine phenology and derive berry ripening during the warmest period of the year (Webb et al. 2007; Duchene et al. 2010) interferes with the quality traits (Van Leeuwen and Seguin 2006). Phenological shifts of 10–24 days from 1975 until 2015 have been noticed in south-west Germany give an alarming situation for global viticulture (Koch and Oehl 2018). Shortening trends for the periods budburst to flowering, flowering to veraison and veraison to maturity have been recorded due to elevated temperatures, e.g. flowering to veraison interval shortened about 1 day for every 5 years (Jones and Davis 2000; Tomasi et al. 2011; Duchene and Schneider 2005). A similar trend with strong correlations between maturity timing and the maximum springtime temperatures under Australian conditions was noticed (Jarvis et al. 2017). The most obvious phenological shifts recorded are for blooming and veraison (Caffarra and Eccel 2011). Similarly, grapevine harvest dates are associated with maximum air temperatures (Koufos et al. 2020). However, significant trends were not observed for the shortening of the veraison to maturity period (Cameron et al. 2021). Previously, it was indicated that among a range of temperature variables, maximum temperature for March–April influenced flowering and veraison timings (Malheiro et al. 2013).

A significant advance is expected in the onset timings of grapevine phenological stages; however, the phenophase duration depends on soil type and grape variety (Fraga et al. 2013; Bernardo et al. 2018). Phenological advancement for 2–3 weeks is expected until 2050, and this advancement is more apparent for the northern hemisphere vineyards (Neethling et al. 2017; Van Leeuwen et al. 2019). In a related study, it was depicted that in the future, many areas presently considered suitable for grapevine production would be eliminated with 81% reduction in acreage for premium quality grape at temperature above 35 °C (White et al. 2006).

Moreover, elevated temperatures are considered detrimental for the reproductive performance and consequently yield of grapevine (Keller et al. 2010), and for temperature at 40 °C, reduction in flowers per inflorescence under warmer conditions was by one-third. Previously, it has been established that day temperature of 35–40 °C near flowering is highly detrimental for good fruit set with lower ovule fertility, hence fewer berries per cluster (Ebadi et al. 1995; Ewart and Kliewer 1977;

Kliewer 1977). Furthermore, pollen germination is also highly temperature sensitive, e.g. in grapevines (Staudt 1982), less pollen germination was noticed at 15 °C, while temperature at 28 °C is considered optimum for better pollen germination and pollen tube growth (Rajasekaran and Mullins 1985). High temperature near flowering negatively affects the carbohydrate contents of pistil and pollen tube growth with lower fruit set (Snider et al. 2011; Pagay and Collins 2017). Furthermore, short periods of extreme temperatures are considered highly detrimental particularly for key developmental stages, e.g. flowering and fruit set, which may negatively affect vine yield and berry quality (Ferris et al. 1998; Hedhly et al. 2005; Prasad et al. 1999).

22.5.2 Fruit Quality and Composition

Rising temperature owing to global warming is expected to change the composition of grape berries. The rate metabolism of grape berries depends on air temperature, whereas elevated temperatures beyond ambient level perturb metabolic pathways and cause changes in the biosynthesis of several important metabolic compounds crucial for maintaining quality (Blancquaert et al. 2018). Elevated air temperatures promote berry sugars coupled with the degradation of berry organic acids. In a rising temperature scenario, juice and wine acidity would be more drastically affected compared to sugar contents as indicated in Fig. 22.10. Such weather conditions would result in unbalanced wines having higher alcohol contents due to high sugars and lower acidity and deprived of essential aromatic compounds (Kose 2014; Van Leeuwen and Destrac-Irvine 2016). Relatively lower titratable acidity has been observed at 30 °C compared to 20 °C (Poudel et al. 2009). Under heat stress

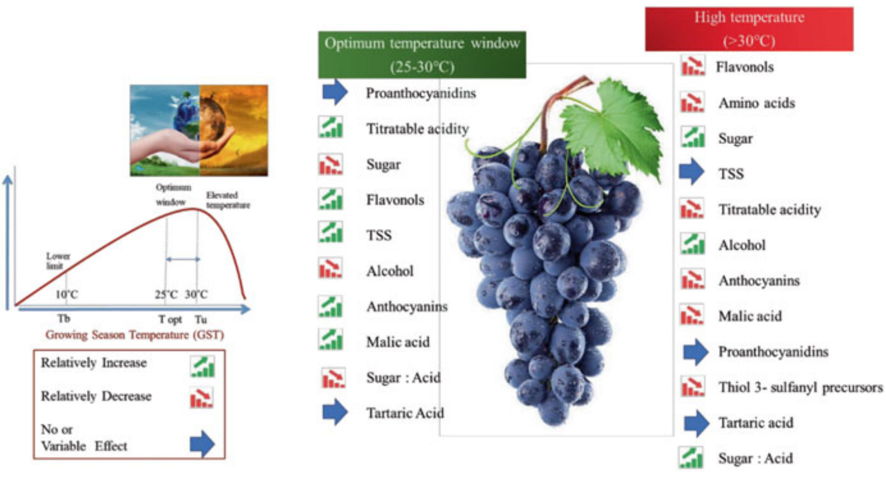


Fig. 22.10 Key quality traits of grape berries under ambient and elevated temperatures

conditions, potassium concentration of berries increases near maturity along with high pH value and lower total acidity (Bernardo et al. 2018). Moreover, malic acid is metabolized relatively faster than tartaric acid at elevated temperature, and the optimum temperature for malate biosynthesis is 20–25 °C; however, a major decrease in its biosynthesis has been noticed at 40 °C (Keller 2010).

For most of the grapevine varieties, optimum temperature at maturation stage for the biosynthesis of aroma compounds is 20–22 °C (Van Leeuwen and Destrac-Irvine 2016). Berry colour development is reduced when air temperature exceeds 30 °C, and higher temperatures (above 37 °C) cause major decline in berry colour along with higher volatilization of aroma compounds (Bernardo et al. 2018; Neethling et al. 2017). Total sugars of grapes and ethanol contents of wines have also increased, e.g. wines with ethanol levels have increased by 3% during the last few weeks (Neethling et al. 2012). Anthocyanins are the main pigment-imparting compounds in berries largely found in the skins of coloured varieties, e.g. red grapes. Elevated temperatures lower anthocyanin contents and flavour compounds of berries grown in temperate areas (Poudel et al. 2009; Yamane et al. 2006). Moreover, reduction in delphinidins, anthocyanins, peonidin and petunidins based anthocyanins contents of grape berries was noticed, however biosynthesis of malvidin derivatives was less affected under high temperature conditions (Bernardo et al. 2018).

22.5.3 Elevated Temperature and Grapevine Physiology

Among physiological functions, photosynthesis is directly affected by temperature variations as highlighted by Sharma et al. (2019) and Luo et al. (2011), and it is reduced earlier before the onset of other symptoms of high temperature beyond optimum limits. The optimum temperature window differs among species (Xiao et al. 2017; Kun et al. 2018), and for grapevine, it lies between 25 and 35 °C (Ferrandino and Lovisolo 2014). When temperature goes below 10 °C, most of the physiological processes are weakened. On the other hand, heat acclimation mechanisms are activated when the temperature reaches 35 °C, (Bernardo et al. 2018; Greer and Weedon 2012). Similarly, extremely high temperatures, e.g. 40 °C or above, may cause the disruption of the photosynthetic apparatus of plants. Reduction in photosynthetic activity at 45 °C compared to 25 °C has been quantified up to 60% by Lamaoui et al. (2018). Similarly, it was observed (Xiao et al. 2017) that photosynthetic activity does not decrease up to 35 °C; however, it is limited above 40 °C, and this reduction in photosynthesis may be attributed to 15–30% lower stomatal conductance (Lamaoui et al. 2018). The discussion also bears forth that heat and drought stresses are related to each other and reduced stomatal conductance may increase the effects of heat stress due to rise in leaf temperature (Costa et al. 2012). The effects of heat stress on vine stomatal conductance vary among cultivars, and it was noticed that for a common wine cultivar Touriga Nacional, under mild heat stress conditions, leaf stomata remained open which might be beneficial for lowering the leaf temperature to retain normal photosynthesis (Wang et al. 2010).

The lower leaf photosynthetic activity under high temperature might be attributed to disturbed vine biochemical processes, e.g. reduction in ribulose-1,5-bisphosphate (RuBP) regeneration along with the activation of ribulose bisphosphate carboxylase oxygenase (Rubisco) activity (Wen et al. 2005). Under heat stress, photosystem II (PSII) is suspended earlier, and other cellular functions are disrupted as it is highly temperature sensitive (Ferrandino and Lovisolo 2014; Bensalem-Fnayou et al. 2011). Thermal stress even for short periods, e.g. 15 min at 40 °C, may cause irreparable damage to thylakoid membrane permeability and functioning of PSII in grapevines (Ferrandino and Lovisolo 2014; Liu and Fang 2011). Recently, it was revealed that for heat treatments at 35 °C and 40 °C, photosynthetic activity was reduced significantly; however, total chlorophyll contents, chlorophyll fluorescence and thylakoid membrane leakage were not much affected for cvs. Cabernet Sauvignon and Junzi vines (Nievola et al. 2017). For more elevated temperature at 45 °C, lower total chlorophyll contents and increased fluidity of thylakoid membrane were observed along with other obvious stress symptoms. Moreover, structural disarrays of thylakoids have also been reported in prolonged heat stress conditions, i.e. for 3 months. Injury to thylakoid structures is associated with a deterioration in chlorophyll contents which indicates the inhibition of PSII (Hu et al. 2020; Kadir et al. 2007). Hence, chlorophyll fluorescence may help to identify changes in photosynthetic apparatus as an indicator for heat stress tolerance in grape cultivars (Kadir et al. 2007).

Leaf transpiration increases under elevated temperature as observed by Greer (2019) that transpiration rates in grapevine increased up to five times for the corresponding increase in temperature from 15 to 40 °C. This increase in transpiration activity was from 0.5 mmol m^{-2} s^{-1} to about 2.5 mmol m^{-2} s^{-1}; however, further increases in temperature (45 °C) did not affect leaf transpiration. Similarly, for cv. Semillon, substantial increase in transpiration was observed with increase in leaf temperature above 35 °C; the increase is mainly to meet up the enhanced evaporative cooling demands (Keenan et al. 2010). In another related study, four time increases in transpiration of cv. Chardonnay were noticed as the temperature increased from 15 to 30 °C, while this rate was even higher for cv. Cabernet Sauvignon at 35–40 °C (Keller 2010). A linear trend for the transpiration rates was noticed with temperature increase from 20 to 40 °C. Moreover, genotypes have varying responses to temperature, e.g. relatively higher transpiration rates have been observed for cv. Semillon vines compared to many other cultivars (Rogiers et al. 2009); thus, its cooling capacity owning to better transpiration may help to retain the canopy temperature relatively lower than the atmospheric temperature. In addition to climatic variables, the quality and growth of grapevine vegetative and reproductive growth, ripening and yield may also be affected by vineyard management such as pruning type, crop load, training systems, grafting and timings of cultural practices as discussed by Winkler (1974). It is highly crucial to acquire the knowledge of the varietal specificities for high-quality grape production (Jones and Davis 2000).

Henceforth, optimizing vineyard management is required for enhancing vineyard productivity and profitability.

22.6 Adaptation Strategies for Viticulture in the Wake of Climate Change

The elaborated climate change impacts on viticulture make it imperative to plan and apply suitable adaptation measures. It included short-term adaptation measures and changes in viticulture management practices and techniques, such as irrigation scheduling, protection from sun burns, improving water use efficiency (WUF) and devising long-term adaptation strategies such as selection of suitable varieties and identifying new suitable viticulture regions for a sustainable crop production (Fraga 2019) in consultation with stakeholders is an upheaval task for modeller, policy makers and viticulturists.

In order to adapt viticulture, physiologists and breeder must focus on improving water use efficiency (WUE) to minimize the impact of elevated CO_2 and climate change by integrating the knowledge from genomics and phenomics to incorporate characteristics from promising QTLs. Moreover, improvements in photosynthetic efficiency and WUE by introducing C4-like characteristics in C3 plants coupled with modelling approaches need to be focused (Ahmed and Ahmad 2019). Climate change necessitates identifying new genotypes and incorporating resilience such as heat and drought tolerance from wild cultivars. Moreover, the existing viticulture may not remain suitable for premier-quality table and wine grape cultivation under future climate; hence, identifying new viticulture zones based on crop heat unit requirements is the need of time. Furthermore, improving vineyard management practices, e.g. pruning, thinning and canopy management for maintaining vine balance, is necessary to cope with these challenges.

22.7 Conclusion

Currently, global viticulture is facing sustainability challenge owing to climate change. Rising CO_2 coupled with high temperature and lower rainfall negatively affected grapevine production. Phenological advancements with poor inflorescence development, less fruit set and low yield have been observed in many viticulture regions. Although elevated CO_2 levels may have some positive impacts on photosynthetic activity, the overall impact in conjugation with increasing temperature and water stress would be negative. Moreover, the physiological activities of vines such as photosynthesis activity, stomatal conductivity and water use efficiency are also severely affected under heat and drought stress. Similarly, key quality attributes of wine and table grapes, e.g. berry sugar, acidity levels, polyphenols and anthocyanin, may not reach desirable levels for premier-quality grape production. The impact of climatic trends on viticulture would be more in the coming decades, e.g. major grapevine cultivars originating from cooler climates would not be able to withstand heat stress. Indigenous and wild grapevine germplasm from relatively warm and dry regions may serve as an alternative. Henceforth, it is crucial to identify the key components of grapevine regulatory networks controlling heat stress response and acquisition of tolerance against environmental stresses for sustainable viticulture.

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