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Effect of Climate Change on Agricultural Crops

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2.1 Introduction

The increasing world population is putting stress on rising demands for crop production. By 2050, global agricultural production may need to be doubled to meet increasing demands [1–4]. For food security, several studies have recommended that increasing crop yield, rather than clearing more land for food production, is the most sustainable way [5,6]. However, several reports indicate that yields are not improving fast enough to keep up with projected demands in 2050, and certainly the world is going to face a food crisis [4]. Evidence comes from agricultural science research as well as an analysis of crop production data that climate variability matters as much to crop production as the mean values of climate variables during the crop season [7–11]. Crop productivity in world faces weather adversities, especially extreme events that jeopardize socioeconomic demands; therefore there is a need to create a better policy and plan disaster risk reduction for the future [12–21].

Climate projections have also continued to predict increasing atmospheric carbon dioxide (CO_2) and water vapor along with changes in surface temperature and rainfall patterns [22]. The most imminent climatic change is an increase in atmospheric temperatures resulting from increased levels of greenhouse gases such as CO_2, methane (CH_4), ozone (O_3), nitrous oxide (N_2O), and chlorofluorocarbons (CFC_S). Because of the increasing concentrations of those radiating or greenhouse gases, there is much concern about future changes in our climate and their direct or indirect effects on agriculture [16,22–26].

The increasing CO_2 concentration in the atmosphere and the anticipated climate changes owing to global warming are likely to affect future global agricultural production through changes in the rates of plant growth [27–29], transpiration [30–32], respiration [33], and photosynthesis [34]. Worldwide agricultural production is governed by the

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combination of climate, soil tilth, technology, genetic resources, and farm management decisions such as tillage, manure and fertilizer applications, and crop variety selection [8,13,35–40]. Uncertainties related to the representation of CO_2, nitrogen, and high-temperature effects demonstrated that further research is urgently needed to better understand effects of climate change on agricultural production and to devise targeted adaptation strategies [41].

The question thus arises, how can productivity be increased while ensuring the sustainability of agriculture and the environment for future generations? Decision makers need information supplied by research to make informed choices about new agricultural technologies and to devise and implement policies to enhance food production and sustainability. There is now great concern about the decline in soil fertility, the change in the water table, rising salinity, resistance to many pesticides, and the degradation of irrigation water quality in some parts of the world [42–45]. It is clear that over time more nutrients have been removed than added through fertilizers, and farmers have to apply more fertilizers to achieve the same yield they were getting with less fertilizer 20–30 years ago. Climate change will further affect soil conditions. Changes in temperature and precipitation patterns and amount will influence soil water content, runoff and erosion, salinization, biodiversity, and organic carbon and nitrogen content. The increase in temperature would also lead to increased evapotranspiration. The specific regional soil-related problems are closely linked to the global environmental change. Therefore, there is a need to quantify the effect of this change on the soil-fertility and function that governs the crop growth and production.

Global warming may also threaten food security if there is a negative effect on agriculture. Although the effect of increasing CO_2 concentrations will increase the net primary productivity of plants, climate changes, and the changes in disturbance regimes associated with them, may lead to increased or decreased net ecosystem productivity. In many tropical and subtropical regions, potential yields are projected to decrease for most projected increases in temperature. Indirectly, there may be considerable effects on land use as a result of snow melt, spatial and temporal rainfall variability, the availability of irrigation, the frequency and intensity of inter- and intraseasonal droughts and floods, soil organic matter transformations, soil erosion, a change in pest profiles, a decline in arable areas due to the submergence of coastal lands, and the availability of energy. All these can have a tremendous impact on agricultural production and hence the food security of any region [15,16,23,24]. The rising temperatures and CO_2 and uncertainties in rainfall associated with global warming may or may not have serious direct and indirect consequences on crop production. It is therefore important to have an assessment of the direct and indirect consequences of global warming on different crops, especially on cereals, contributing to food security [23]. Mechanistic crop growth models are now routinely used to assess the impacts of climate change. Several crop simulation models are available for the same crop that can be employed to assess the impact of climate change [23,46,47].

2.2 Climate Change

2.2.1 Observed Climate Change During the Past Century

The Intergovernmental Panel on Climate Change (IPCC) [48] reported that each of the past 3 decades has been successively warmer at the Earth's surface than any preceding decade since 1850 (Fig. 2.1). The period from 1983 to 2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere, where such an assessment is possible (medium confidence). The globally averaged surface temperature shows a warming trend of 0.85°C (0.65–1.06°C) over the period 1880 to 2012. Over the period 1901–2010, global mean sea level rose by 0.19 (0.17–0.21) m. The rate of the rise in sea level since the mid-19th century has been larger than the mean rate during the previous two millennia. Changes in many extreme weather and climate events have been observed since about 1950. Some of these changes have been linked to human influences, including a decrease in cold temperature extremes, an increase in warm temperature extremes, an increase in extreme high sea levels and an increase in the number of heavy precipitation events in a number of regions.

In the past several decades, air temperatures have been warming in most of the major cereal cropping regions around the world. Average increasing trends were roughly 0.3°C per decade for maximum temperature and 0.2°C per decade for minimum temperature.

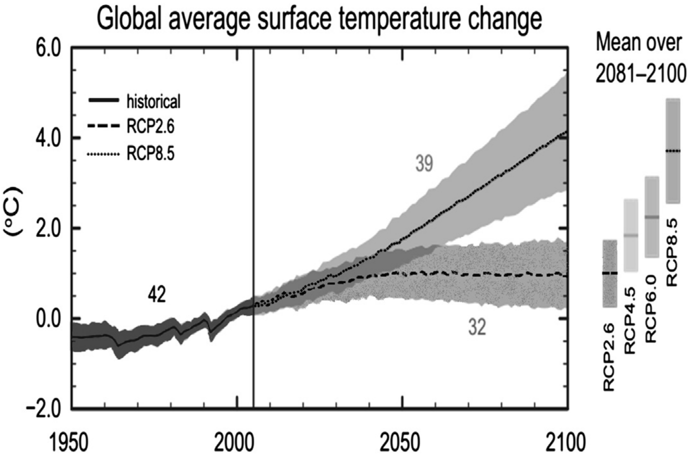

FIGURE 2.1 Coupled Model Intercomparison Project phase 5 (CMIP5) multimodel simulated time series from 1950 to 2100 for changes in global annual mean surface temperature relative to 1986–2005. Time series of projections and a measure of uncertainty (*shading*) are shown for scenarios Representative Concentration Pathways (RCP)2.6 (blue (light gray in print versions)) and RCP8.5 (red (dark gray in print versions)). Black (*gray shading*) is the modeled historical evolution using historical reconstructed forcings. Mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as *colored vertical bars*. The number of CMIP5 models used to calculate the multimodel mean is indicated. *IPCC, Working Group 1, Fifth Assessment Report on Climate Change 2013: The Physical Science Basis, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2013; IPCC, in: Core Writing Team, R.K. Pachauri, L.A. Meyer (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland, 151 pp., 2014.*

There is a larger range in trends for maximum temperature compared with minimum temperature owing to the greater impact of changes in cloudiness and radiation (associated with both natural variability and air pollution) on daytime relative to nighttime temperature [49–52]. Long-term measurements of soil moisture are rare but since 1970 significant increases in the extent of drought and severity have been estimated for Africa, southern Europe, east and south Asia, and eastern Australia [53,54].

2.2.2 Projections of Future Climate Change

The surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is likely that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and the global mean sea level will rise [48]. The increase in global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is likely to be 0.3–1.7°C under RCP2.6, 1.1–2.6°C under RCP4.5, 1.4–3.1°C under RCP6.0, and 2.6–4.8°C under RCP8.5 (Fig. 2.1). Temperature extremes are projected to increase with greater frequency and greater duration with occasional cold winter extremes. Changes in precipitation will not be uniform. The high latitudes and the equatorial Pacific are likely to experience an increase in annual mean precipitation under the RCP8.5 scenario. In many midlatitude and subtropical dry regions, mean precipitation will likely decrease, whereas in many midlatitude wet regions, mean precipitation will likely increase under the RCP8.5 scenario. Extreme precipitation events over most of the midlatitude landmasses and over wet tropical regions will likely become more intense and more frequent [48]. A lower warming target, or a higher likelihood of remaining below a specific warming target, will require lower cumulative CO_2 emissions. Accounting for warming effects of increases in non-CO_2 greenhouse gases, reductions in aerosols, or the release of greenhouse gases from permafrost will also lower the cumulative CO_2 emissions for a specific warming target (Fig. 2.2).

2.3 Soil Ecology and Plant–Microbe Interactions Under Changing Climate

There is a growing consensus that the changing climate will negatively affect agricultural production by altering plant–microbe interactions and other vital soil system functions [55]. The major concern is the effect of climate change on soil ecology and plant–microbe interactions and its subsequent effect on agricultural productivity [56]. It is well known that plants and associated microbial interactions are critical factors affecting the growth, survival, yield, and nutritional quality of agricultural crops [57]. Although ample studies demonstrate the effect of climate change on aboveground responses, there is still a paucity of information regarding the effect of climate change on belowground interactions (Fig. 2.3), i.e., plant–microbe interactions and their effect on soil fertility, nutrient cycling, emissions of trace gases from soil, and agricultural production [58,59].

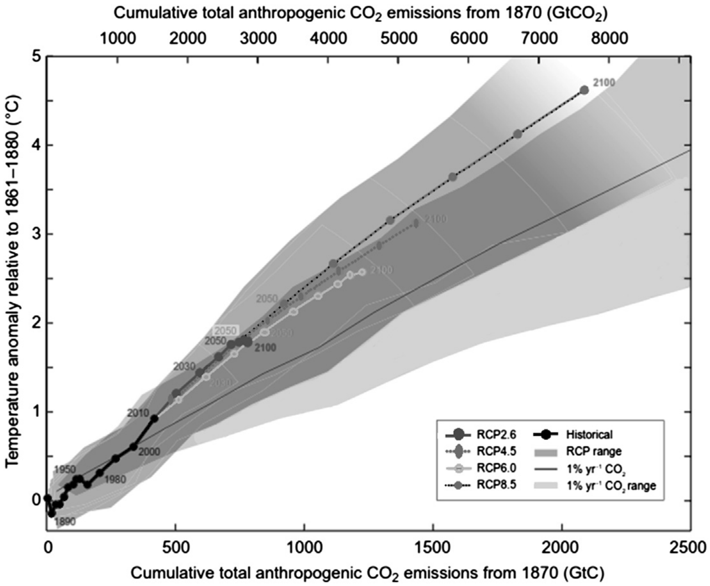

FIGURE 2.2 Global mean surface temperature increase as a function of cumulative total global CO_2 emissions from various lines of evidence. Multimodel results from a hierarchy of climate–carbon-cycle models for each RCP until 2100 are shown in the figure with different lines and decadal means (*dots*). Some decadal means are labeled for clarity (e.g., 2050, indicating the decade 2040–49). Model results over the historical period (1860–2010) are indicated in black. The grey plume illustrates the multimodel spread over the four RCP scenarios and fades with the decreasing number of available models in RCP8.5. The multimodel mean and range simulated by CMIP5 models, forced by a CO_2 increase of 1% per year (1% year^{-1} CO_2 simulations), is given by the *thin black line* and *gray area*. For a specific amount of cumulative CO_2 emissions, the 1% per year CO_2 simulations exhibit lower warming than those driven by RCPs, which include additional non-CO_2 forcings. Temperature values are given relative to the 1861–80 base period, emissions relative to 1870. Decadal averages are connected by *straight lines*. *IPCC, Working Group 1, Fifth Assessment Report on Climate Change 2013: The Physical Science Basis, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2013; IPCC, in: Core Writing Team, R.K. Pachauri, L.A. Meyer (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland, 151 pp., 2014.*

Plants shape interactions in the rhizosphere as they exude rhizo deposits, which help in structuring the rhizospheric microbial community [60,61]. Although it is believed that rising atmospheric CO_2 concentrations will have a fertilization effect on plants and will enhances the litter turnover and root exudation rate in plants, the warming condition will also lead to the rapid dissipation of dissolved organic carbon from the soil as a result of enhanced volatilization [58]. Furthermore, the reduced soil water content will decrease the mineralization and stabilization of organic matter and nutrient cycling in soil [62]. The previous studies also reported that elevated CO_2 will decrease the N_2 content in plants and thereby alter the C:N ratios, which in turn will alter the lignin content in plants. Moreover, an increase in the lignin content of leaf litter will slow down the litter decomposition rate and thereby lead to an increase in fungal to bacterial diversity with a dominance of lignocellulolytic fungi in soil [63]. Such changes in litter

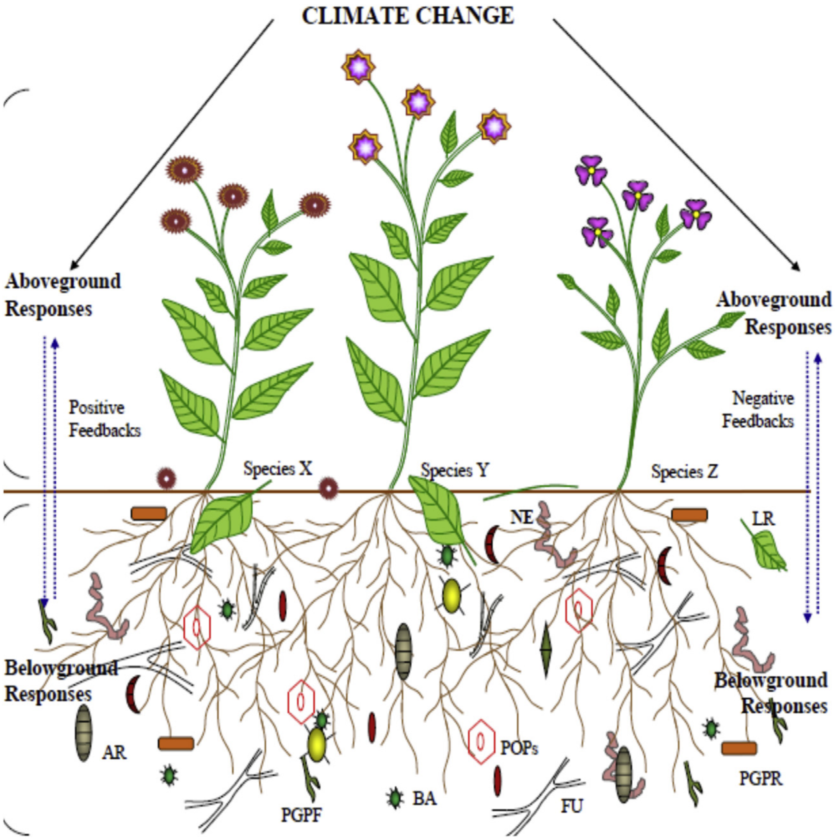

FIGURE 2.3 Schematic representation of plant–soil interactions under changing climatic conditions. AR, arthropods; PGPF, plant growth promoting fungi; BA, bacteria; POPs, persistent organic pollutants; FU, fungi; PGPR, plant growth promoting rhizobacteria; LR, litter; NE, nematodes; Species X, Y and Z are any variety of plants assumed to show the interaction. *Modified from Abhilash and Dubey [59].*

composition and consumption may alter the structure of the litter layer, soil surface, and nutrient dynamics and thereby affect the decomposer community, composition, ecosystem regulation, and carbon feedback.

Apart from alterations in these interactions in the rhizosphere, the changing climate can affect plant–pathogen interactions by altering the pathogen life cycle, expression of host resistance, disease epidemiology and severity of disease epidemics, development of new races or pathotypes, virulence, overwintering or oversummering of the pathogen, and so forth [64]. In addition, the warming climate can alter the mobility, leaching, bioavailability, volatilization, and global transport of chemical pollutants in agroecosystems [63,65,66] and facilitate the enhanced contamination of global soil resources, bioaccumulation, and biomagnification of pollutants in the food chain. As a result, changing climatic conditions coupled with subsequent changes in biotic and abiotic stress factors will drastically affect the quantity and quality of agricultural produce [67].

Therefore, integrated research into multitrophic interactions under changing climatic conditions is essential for understanding the real response of agroecosystems to such changing conditions and for developing innovative climate-resilient strategies for harnessing such beneficial interactions as low-input biotechnology to enhance the productivity of agroecosystems under changing climatic conditions.

2.4 Projected Impact of Climatic Changes on Crop Production

Climate change is projected to undermine food security. Because of projected climate change by the mid-21st century and beyond, for wheat, rice, and maize in tropical and temperate regions, climate change without adaptation is projected to affect production negatively for local temperature increases of 2°C or more above late–20th century levels, although individual locations may benefit. Global temperature increases of about 4°C or more above late–20th century levels, combined with an increasing food demand, would pose large risks to food security globally. Climate change is projected to reduce renewable surface water and groundwater resources in most dry subtropical regions [48]. Global wheat production is estimated to fall by 6% for each degree Celsius of further temperature increase and become more variable over space and time [68].

Comprehensive reviews [23,52,69] around the globe point to clear evidence of a decline in the yields of important cereal crops under climate change conditions. Overall, the agronomic modeling literature at a global level indicates the potential negative effects of climate change. Selective reports published to date are shown in Table 2.1, some of which have been discussed in this chapter. Although an increase in CO_2 is likely to be beneficial to several crops, associated increases in temperatures, and increased variability in rainfall would considerably affect food production. Several studies indicate a considerable probability of loss of global crop production with increases in temperature. There are a few studies on this theme and they generally confirm a similar trend of agricultural decline with climate change [70]. Lobell and Gourdji [52] reviewed global scale grain productivity and found that over the next few decades, CO_2 trends will likely increase global yields by roughly 1.8% per decade. At the same time, warming trends are likely to reduce global yields by roughly 1.5% per decade without effective adaptation, with a plausible range from roughly 0% to 4%. The upper end of this range is half of the expected 8% rate of gain from technological and management improvements over the next few decades. Many global change factors that will likely challenge yields, including higher O_3 and greater rainfall intensity, are not considered in most current assessments.

Teixeira et al. [71] assessed the impact of climate change on wheat, rice, maize, and soybean crops at a global level and reported that temperate and subtropical agricultural areas might bear substantial crop yield losses owing to extreme temperature episodes. The authors highlighted the need to develop adaptation strategies and agricultural policies able to mitigate heat stress impacts on global food supply. In a study, all the General

Table 2.1 Selective Studies on Effect of Climate Change on Crop Production

Crop	Location	Yield Impact	Scenario	References
Rice	Korea	Increase 12.6–22%	CO_2 elevation	[97]
		Decrease 22–35%	Temperature	
	Eastern China	7.5–17.5%	2020	[78]
		0.0–25%	2050	
		−10.0% to 25%	2080	
	Italy (Po Valley)	Increase	CCSM4	[98]
		Constant	ECHAM6	
		Decrease	RCP2.6	
		Increase	RCP4.5	
	Northeastern China	7.19%	(RCP4.5) 2010–39	[99]
		12.39%	2040–69	
		14.83%	2070–99	
	India	Decrease and increase (region-wise)	–	[100]
			2010, 2070	[101]
			2020, 2050, 2080	[93]
			2100	[87]
			2100	[91]
Wheat	Northeastern Austria (Langenlois)	Decrease 2%, 8%, 7–10%	2020, 2050, 2080	[102]
	Global	Decrease (15–45%)	2080	[103]
	South Asia	Decrease (20–75%)		
	Southeast Asia	Decrease (10–95%)		
	South America	Decrease (12–27%)		
	Europe	Decrease 1.13%, 0.9%, 0.68%	2020, 2050, 2080 (A1F1)	[104]
	Europe	Decrease	2050	[95,105]
	Africa	Decrease 17%	2050	[106]
	South Africa	Increase 6.2%	Empirical model (2055)	[74]
		Increase 15.2%	Mechanistic model	
	South Asia plus East Asia	Decrease	A1B	[11]
	North China Plain	Increase 37.7% (18.6%)	2020	[107]
		67.8% (23.1%)	2050	
		87.2% (34.4%)	2080	
	Europe	Increase	2060	[108]
	Global	Decrease 6%	1°C rise	[68]
	Europe (north)	Increase 10–20%	2050	[109]
	Europe (southern)	Increase	HadCM3 202, 2030	[110]
	Australia	Decrease 2–10%	2030, 2060, 2090	[81]
	India	Decrease	2021, 2050	[83]
			2020, 2050, 2080	[84]
			2100	[87]
			2050, 2080	[86]

Table 2.1 Selective Studies on Effect of Climate Change on Crop Production—cont'd

Crop	Location	Yield Impact	Scenario	References
Maize	United States (Midwestern)	Decrease 0% to −45% (South and Central) Increase (North)	2050–59	[111]
	Sub-Saharan Africa	Decrease 22%	2050	[112]
	Europe	Increase	2050	[95]
	Africa	Decrease 5%	2050	[106]
	South Asia	Decrease 16%		
	Central Asia plus Russian Federation; South Asia plus East Asia; North America; South America	Decrease	A1B	[71]
	Italy (Po Valley)	Decrease Increase	CCSM3 and ECHAM5 HADCM3 and PCM	[113]
	South Africa	Decrease −3.6% Increase 6.5%	Empirical model (2055) Mechanistic model	[74]
	Panama	Decrease 0.5% and 0.1% Increase 2.4% and decrease 0.8% Increase 4.5% and 1.5%	Near-term A2 and B1 Midcentury A2 and B1 End-century A2 and B1	[114]
	Ethiopia (Central Rift Valley)	Decrease 20%	2050	[73]
	Northeastern China	2.92% 3.11% 2.63%	(RCP4.5) 2010–39 2040–69 2070–99	[99]
	United States (Midwestern)	Decrease 1.6–2.7%		[115]
	India	Decrease	2020, 2050, 2080 2100	[75] [87]
Rapeseed	Europe	Yield improvement in some parts of Europe Decrease 5–30% in Germany and United Kingdom	2020 2030	[110]
Sunflower	Europe	Decrease (France and Germany) Decrease 10–30% (Eastern Europe)	2020 2030	[110]
Potato	India	Decrease		[85,86]
Sorghum	Africa	Decrease 15%	2050	[106]
	South Asia	Decrease 11%		
	India	Decrease	2030 2100 2020, 2050, 2080	[90] [87] [76]
Mustard	India	Decrease	2025, 2050, 2080	[116] [93] [77]

Continued

Table 2.1 Selective Studies on Effect of Climate Change on Crop Production—cont'd

Crop	Location	Yield Impact	Scenario	References
Millet	Africa	Decrease 10%	2050	[106]
Coconut	India	Increase	2030, 2080	[79]
Groundnut	India	Decrease	2071–2100	[117]
Pulses Chickpea and Pigeon pea	India	Decrease	2030, 2100	[87,90]
Soybean	Northeastern Austria	Increase	GCM climate scenarios	[102]
	Central Asia plus Russian Federation; South Asia plus East Asia; North America; South America	Decrease	A1B	[71]
	United States (Midwestern)	Decrease 1.6–2.7%		[115]
	India	Decrease/increase	2100	[72]
Cereals	China	Increase 5–23%	HadCM3 and NCAR; CSIRO and CGCM2	[103]
	Argentina	Increase 7–24%		
	South Africa	Decrease 10–30% Decrease		
	China	Increase 13–22%	B2 to A2 (2050)	[118]
All crops	Global	0–5% negative impacts	HadCM3 SRES scenarios	[119]
	United States	Decrease 30–46% and 63–82%	B1 and A1F1	[120]
	Global	Decrease (rice, wheat, maize)	Without adaptation	[96]
		Increase 7–15% (rice, wheat, maize)	With adaptation measures	
	Global	Decrease 17%	2050	[70]
	Global	Increase/decrease 10%	5 GCM scenarios	[41]

CCSM4, Community Climate System Model, version 4; *ECHAM6*, European Centre HAmburg Model, version 6; *RCP*, Representative Concentration Pathways; *HadCM3*, Hadley Centre Coupled Model, version 3; *A1F1*, Scenario represents Fossil-intensive; *A1B*, Scenario represents Balance across all sources; *CCSM3*, Community Climate System Model, version 3; *ECHAM5*, European Centre HAmburg Model, version 5; *PCM*, Parallel Climate Model; *A2*, Scenario represents a very heterogeneous world; *B1*, scenario represents a convergent world with rapid change in economic structures and involvement of clean technologies; *B2*, Scenario represents local environmental sustainability; *GCM*, General Circulation Model; *NCAR*, National Centre for Atmospheric Research; *CGCM2*, Canadian Global Coupled Model, version2; *CSIRO*, Commonwealth Scientific and Industrial Research Organization; *SRES*, Special Report an Emissions Scenarios.

Circulation Model (GCM) projected climate change scenarios (at the time of doubling of CO$_2$ concentrations) predicted decreased soybean yields for almost all locations. Mean decline in yields across different scenarios ranged from 14% in Pune (West India) to 23% in Gwaliar (Central India). The decline in soybean yield was less in west and south India compared with other parts of the country. The mean yield was going to be significantly affected under the UK Meteorological Office (UKMO) model-generated climate scenarios for both the current and doubled CO_2 atmosphere [72].

Kassie et al. [73] reported that maize yield in Ethiopia will decrease by 20% in 2050 relative to 1980–2009 owing to climate change. Estes et al. [74] also reported a negative effect on maize production in South Africa during 2055. Byjesh et al. [75] reported that the monsoon maize yield in India is reduced most in the Southern Plateau (up to 35%), whereas the winter yield is reduced most in the Mid Indo-Gangetic Plains (up to 55%) and yields are relatively unaffected in the Upper Indo-Gangetic Plains. Few studies were conducted using calibrated and validated InfoCrop-MAIZE and SORGHUM models in for analyzing the impacts of increase in temperature, CO_2, and change in rainfall on maize and sorghum crops apart from the HadCM3 A2a scenario for 2020, 2050, and 2080 in major maize and sorghum-producing regions of India [75,76]. It was revealed that climate change may reduce the productivity of maize in some regions of India during both the monsoon and winter seasons. With a rise in temperature, the reduction in yields is projected to be larger in warmer locations than in the other locations. However, in areas with low temperature during winter, the crop is projected to benefit. Some changes in the phenology such as a reduction in flowering days of the crop were also observed. Also, in the event of a reduction in rainfall by 30–40%, water stress predominates in crop failure rather than a rise in temperature. In the case of sorghum, climate change impacts are projected to reduce the grain yield of sorghum more during winter than in monsoon season in many sorghum-producing regions in India.

Boomiraj et al. [77] found that mustard yields are likely to be reduced under both irrigated and rain-fed conditions under future climate change scenarios. However, these reductions have spatial variations in different mustard growing regions of India. In both irrigated and rain-fed conditions, yield reduction would be higher in eastern India (67% and 57%) followed by central India (48% and 14%) and northern India (40.3% and 21.4%). This was due to a maximum temperature rise in the eastern part of the country, projected for 2080. In northern India, the yield reduction of irrigated mustard was comparatively less owing to the prevailing lower temperature in this region during the crop growth period. However, the rain-fed crop was more susceptible to the changing climate in north India because of the projected reduction in rainfall in future scenarios.

Tao and Zhang [78] found that the impact of climate change on rice productivity in China remains highly uncertain because of uncertainties from climate change scenarios, parameterizations of biophysical processes, and extreme temperature stress in crop models. They showed that across the study region, relative to 1961–90 levels, the rice yield would change on average by 7.5–17.5% (from −10.4% to 3.0%) and 0.0–25.0% (from −26.7% to 2.1%), and from −10.0% to 25.0% (from −39.2% to 26.4%) during the decades of 2020, 2050, and 2080, respectively, in response to climate change, with (without) consideration of CO_2 fertilization effects. The rice photosynthesis rate, biomass, and yield would increase as a result of increases in mean temperature, solar radiation, and CO_2 concentration, although the rice development rate could accelerate particularly after the heading stage. Meanwhile, the risk of high-temperature stress on rice productivity would also increase notably with climate change. Naresh Kumar et al. [79] concluded that climate change is likely to reduce the irrigated rice yield in India by about 4% in 2020, about 7% in 2050, and about 10% in 2080. They also projected that rain-fed rice yield in India is likely to be reduced by about 6% in 2020 scenarios, but in 2050 and 2080 scenarios they are projected to decrease only marginally. However spatial variation exists for the magnitude of the impact, with some regions likely to be affected more than others.

Numerous studies have assessed the effects of climate change on crop productivity in rain-fed cropping systems in Australia and have suggested that considerable decreases in wheat yield can be attributed to reductions in rainfall in the projected climates [80,81]. Increases in wheat yield between 29% and 37% and between 16% and 28% under rain-fed and irrigated conditions, especially in different genotypes, were observed under a modified climate in northwest India. A 3°C increase in temperature or more should cancel the positive effects of CO_2 [82]. Vashisht et al. [83] found that in the changed climate, increased temperature would cause a reduction in wheat yield to the extent of 4%, 32%, and 61% in the midcentury periods between 2021 and 2030, 2031 and 2040 and 2041 and 2050, respectively, by increasing water stress and decreasing utilization efficiency of photosynthetically active radiation in the Punjab state of India.

Haris et al. [84] used an InfoCrop crop model and found that under a changed climate, the wheat yield decreased whereas the yield of winter maize increased owing to warmer winters and enhanced CO_2 compared with baseline. The duration of both crops decreased owing to the higher temperatures during the growing period. The increase in yield of winter maize points to the suitability of the region for its cultivation in future.

An impact assessment of climate change on potato productivity in Punjab showed that a rise in temperature alone will result in a decrease in yield. However during this period, CO_2 fertilization is expected to increase tuber productivity from +3.9% to +4.5%, depending on the cultivar and location. However, in 2055, a decrease in productivity is likely as a result of only a rise in temperature, whereas the expected rise in CO_2 is likely to bring an increase in potato productivity. It is estimated that under the combined influence of change in temperature and CO_2, the productivity of potato cultivars will not be affected in 2020 with the baseline scenario, but it will decline in 2055, when the total geographical area of Punjab is considered. It is further shown that if the current distribution of potato acreage within Punjab remains unaltered in future, there will be benefits from climate change as the potential productivity will increase in 2020, although potential productivity will again decline to baseline values in 2055 [85]. Naresh Kumar et al. [86] studied the impact of climate change on potatoes in the Indo-Gangetic Plains of India and projected that the potato yield will be reduced by 2.5%, 6%, and 11% in 2020, 2050, and 2080, respectively.

Birthal et al. [87] reported that rainfall had a positive effect on most crops, but it could not counterbalance the negative effect of temperature. The projections of climate impacts toward 2100 suggested that with significant changes in temperature and rainfall, the rice yield will be lower by 15% and wheat yield by 22%. Coarse cereals will be affected less, whereas pulses will be affected more than will cereals. If the changes in climate are not significant, damage to crops will be smaller. In the short run, climate impacts will not be as severe. Economists have estimated the climate change impacts on agriculture using the

Ricardian theory of land rent [88,89], assuming that farmers maximize profits by allocating land to different crops in a declining order of fertility and climate, and everything else remaining constant, the regional differences in land value or productivity are due to differences in the climatic conditions. In most of these studies land value or net revenue per unit of land from a cross-section of heterogeneous units has been regressed on a normal climate. A major criticism of this approach is the assumption of no variation in crop choices and production technology over time, regardless of climate change [87].

Arumugam et al. [90] reported that by the year 2030, the yield of pulses is estimated to decline in all zones (Northeast, Northwest, Western, Cauvery delta, South and Southern zones), with significant declines in the Northeast zone, Cauvery delta zone, and South zone. Sorghum yield may be less in the Western zone, Southern zone, and Northeast zone. Moreover, the yield of spiked millet is more likely to decrease in the Southern zone, Northeast zone, and Cauvery delta zone, and the yield of cotton may also decline in the Northeast zone, Northwest zone, and Western zone of Tamil Nadu, India.

There may be a 10% decline in rice yield and a 9% decline in sorghum yield by the end of the 21st century relative to average yields during 1971–2009 in the South Indian state of Tamil Nadu [91]. Despite the large number of uncertainties [92,93] simulation studies are one of the main methods for investigating the potential impacts of climate change on agroecosystems [24,84].

These studies shows that climate change may affect food systems in several ways ranging from direct effects on crop production (e.g., changes in rainfall leading to drought or flooding, or warmer or cooler temperatures leading to changes in the length of growing season) and availability and quality of groundwater for irrigation, to changes in markets, food prices, and supply chain infrastructure. The relative importance of climate change for food security differs between regions [42]. For example, in India the direct impacts of climate change would be small on "kharif" crops but will become more vulnerable owing to the increased incidence of extreme events such as changes in rainfall intensity, rainy days, duration and frequency of floods and drought, the diurnal temperature range, and the pest incidence and virulence. Winter "rabi" crop production will be more vulnerable owing to increases in temperature, diurnal variations in temperature, and rainfall uncertainties. The impacts of the climate change on Indian agriculture would be small in the near future, but in long run Indian agriculture may be seriously affected depending on the season, level of management, and magnitude of climate change [23]. Lobell and Gourdji [52] stated that factors such as changes in the rates of human population growth, income growth and distribution, dietary preferences, disease incidence, increased demand for land and water resources for other uses (i.e., bioenergy production, carbon sequestration, and urban development), and rates of improvement in agricultural productivity will shape global food security over the next few decades.

2.5 Adaptation Strategies

Increases in temperature reduce the total duration of crop by inducing early flowering and shortening the grain fill period. The shorter the crop duration, the lower is the yield per unit area; a rise in temperature should therefore lead to a fall in agricultural production in a warmer atmosphere. Reports of heat-stressed crops have become common in India. Even irrigated crops experience high evaporation losses and heat stress. Under these conditions, photosynthesis declines and the plant switches from a growth path to a survival mode, thus reducing yields. A clear understanding of the relationship among climatic variability, crop management, and agricultural productivity is critical in assessing the impacts of climatic variability and change on crop production, identifying adaptation strategies and appropriate management practices, and formulating mitigating measures to minimize the negative effects of climatic variability including extreme events on agriculture [94,95].

Challinor et al. [96] reported that without adaptation, losses in aggregate production are expected for wheat, rice, and maize in both temperate and tropical regions by 2°C of local warming. Crop level adaptations increase simulated yields by an average of 7–15%, with adaptations more effective for wheat and rice than maize. Yield losses are greater in magnitude for the second half of the century than for the first. Consensus on yield decreases in the second half of the century is stronger in tropical than temperate regions, yet even moderate warming may reduce temperate crop yields in many locations. Attri and Rathore [82] suggested adaptation strategies for the sustainable production of wheat and for ensuring food security. Results obtained by Mall et al. [72] on the mitigating option for reducing the negative impacts of temperature increases indicate that delaying the sowing dates would be favorable for increased soybean yields at all locations in India. Sowing in the second season would also be able to mitigate the detrimental effects of future increases in the surface temperature caused by global warming at some locations. Boomiraj et al. [77] recommended that adopting adaptation measures such as late sowing and growing long-duration varieties would be helpful to prevent yield loss of irrigated mustard in different locations of the country.

Olesen et al. [95] found that farmers across Europe are currently adapting to climate change, in particular in terms of changing the timing of cultivation and selecting other crop species and cultivars. A wide range of adaptation options exists in most European regions to mitigate many of the negative impacts of climate change on crop production in Europe. However, considering all effects of climate change and the possibilities for adaptation, impacts are still mostly negative in wide regions across Europe.

Naresh Kumar et al. [79] suggested that adaptation strategies comprising agronomic management can offset negative impacts in the near future, particularly in rain-fed conditions, but in the longer run, developing suitable rice varieties coupled with improved and efficient crop husbandry will be essential. For irrigated rice crops, genotypic and agronomic improvement will be crucial. Vashisht et al. [83] recommended that planting wheat up to November 25 until the years 2030–31 may be helpful to mitigate the effects of climate change, but not beyond that. Naresh Kumar et al. [86] concluded that changing the planting time of potatoes is the single most important adaptation option which may lead to yield gains by about 6% in 2020, and it combination with an improved variety or additional nitrogen may be required to adapt to climate change to lead to positive gains by about 8% in 2020 and by about 5% even in 2050. However, by 2080 adoption of all three adaptation strategies may be needed for positive gains. Intraregional differences in the impact of climate change and adaptation gains are projected: a positive impact in northwestern Indo-Gangetic Plains (IGP), gains in central IGP with adaptation, and a yield loss in eastern IGP even with adaptations.

Kassie et al. [73] suggested that adaptation options such as increasing nitrogen fertilization, using irrigation, and changing planting dates could compensate for some of the negative impacts of climate change on maize production. They also concluded that future research therefore needs to include socioeconomic effects of the various adaptation options at a farm level. The multimodel based analysis allowed for an estimation of some of the climate change impact and adaptation uncertainties, which can provide valuable insights and guidance for adaptation planning processes. Haris et al. [84] concluded that an increase in maize cultivation in a subhumid climatic environment with poor wheat yield could well be considered an adaptation option. Saravanakumar [91] indicated the need for new seed varieties that are less sensitive to rainfall and temperature thresholds, and for adaptation practices such as adjustments in sowing time.

Developing adaptation strategies exclusively to minimize the negative impact of climatic changes may be risky in view of large uncertainties associated with their spatial and temporal magnitude. We need to identify “no-regrets” adaptation strategies that may be needed for the sustainable development of agriculture. These adaptations can be at the level of the individual farmer, society, farm, village, or watershed, or at a national level. Some possible adaptation options on the basis of these studies are:

- *Adjustment of planting dates*: Adjusting planting dates are among the most widely studied strategy of adapting to climate change.
- *Weather-based agro-advisories services*: Owing to increasing uncertainties in weather, it is necessary to provide agro-advisories to farmers for real-time decision making. This requires a state-of-the-art infrastructure to measure and record weather variables; standardized data protocols; systems for data storage, assimilation, and dissemination; and access to short-, medium-, and extended-range weather forecasts and seasonal climate forecasts at desired spatial and temporal scales.
- *Early-warning system and crop insurance policies*: Improved risk management by encouraging crop insurance can provide protection to farmers if farm production is reduced owing to natural calamities. In view of these climatic changes and uncertainties in future agricultural technologies and trade scenarios, it will be useful to have an early warning system of environmental changes and their spatial and temporal magnitude. Such a system could help to determine potential food-insecure areas and communities given the type of risk. Modern tools of information technology could facilitate this greatly.

- *Augmenting production*: There are large yield gaps in all crops and across all ecosystems; bridging them could ensure increased food demands are met in the future. Even if a fraction of these yield gaps could be bridged, food security in the region will be strengthened and vulnerability to climate change will be reduced. A fragile seed sector, poor technology dissemination mechanisms, lack of adequate capital for inputs, and poor markets and infrastructure are the key reasons for yield gaps.
- *Alternative crops/new varieties*: Studies have shown that responses to climate change are strongly variety specific and hypothetical new varieties would respond to climate change. The current simulation analysis, however, considers variety characteristics to be almost the same in the future as at present. In reality, it is likely that the plant breeding research will develop newer high-yielding varieties under the projected climatic conditions, thus alleviating the climate change impact to some extent. Changes in land use and management including cultivating alternate crops or cultivars more adapted to changed environment; watershed management, and resource conservation technologies can provide multiple benefits in future climatic stress conditions.
    - Intensify the search for genes for stress tolerance across the plant and animal kingdoms
    - Intensify research efforts on marker-aided selection and transgenic development for biotic and abiotic stress management
    - Develop heat- and drought-tolerant genotypes
    - Attempt transforming C3 plants to C4 plants
    - Change sowing dates and make seasonal changes
- Mainstreaming adaptation in current policy considerations: Climate change impacts and adaptations should be considered in all major development planning activities.
- Develop new infrastructure, policies, and institutions to support the new land use arrangements identified by science and technology.
- Enhance investment in water harvesting and conservation options, and promote small farm mechanization and efficient water use technologies.
- Explore international partnerships for collaborative research on adaptation of climate change research.
- Intensify efforts for increasing climate literacy among all stakeholders of agriculture, including students, researchers, policy planners, science administrators, and industry, as well as farmers.

2.6 Conclusions

As evidenced by trends in a rise in temperature and increased CO_2 concentrations, climate change is a major concern. In the recent past the number of studies conducted to assess the impact of climate change on crop production has increased. Crop growth simulation models have been developed, modified, calibrated, and validated for different crops of this region. They were also used for impact assessment using different climate change scenarios. To date, projection of future climate from different climate models are considered uncertain. The ability of current climate models to predict rainfall is not promising. In addition, uncertainties involved in predicting extreme weather events by the models are large. There is considerable uncertainty in the projected magnitude of change in temperature and rainfall around the world. Therefore, it is difficult to convince planners and development agencies to incorporate the impact of climate change into their projects and agricultural systems.

However, the best available science related to climate change and crop physiology indicates that climate change represents a credible threat to sustaining global productivity growth at rates necessary to keep up with demand. Increasing the scale of investments in crop improvement, and increasing the emphasis of these investments on global change factors, will help to sustain yield growth over the next few decades [52]. Therefore, given the potential adverse impacts on agriculture that could bring about climate change, it is worthwhile to conduct more in-depth studies and analyses to gauge the extent of problems that the country may face in future. We must focus on how possible climate change will affect the intensity and spatial and temporal variability of rainfall, surface and groundwater availability for irrigation, evaporation rates, and temperature in different agro-climatic regions. For this, more studies are needed on the direct or indirect effect of climate change on crop growth, uncertainties of the onset of rainfall, spatial and temporal rainfall variability, duration and frequency of drought and floods, availability of irrigation, changes in groundwater level, soil transformations, crop–pest interaction, and submergence of coastal land owing to a rise sea level. The crop–pest–weather interaction and socioeconomic components are relatively weaker and need to be strengthened. The chances of error and uncertainties with regard to impact need to be evaluated and presented along with results.

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