agronomy

Review

A Critical Review of Climate Change Impact at a Global Scale on Cereal Crop Production

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Abstract: Food security can be under threat due to climate change, which has the potential to alter crop yield. Wheat, maize, and rice are major crops contributing to global food security. The impact of climate change on crop yield with different models and techniques has been projected; this article reviewed the worldwide impact of climate change on future wheat, rice, and maize production. Wheat and maize crop yields may increase due to climate change in colder regions and may decrease in the countries near the equator. The increase in carbon dioxide concentration in the atmosphere may help wheat and maize crops regarding increased carbon intake in colder regions. The rice crop yield may decrease in almost all major rice-producing countries due to water scarcity, which can be amplified due to climate change. The impact of climate change on crop yield prediction involves uncertainties due to different crop models, global circulation models, and bias correction techniques. It is recommended to use multiple climatic models and more than one bias correction technique for better climatic projections. Adaptation measures could help to reduce the adverse impacts of future climate on agriculture. Shifting the planting calendar, irrigation and nutrient management, improving crop varieties, and expanding the agricultural areas are suggested as the most effective adaptation actions in response to climate change. The findings of this study may help policymakers to achieve Sustainable Development Goal (SDG) 2 (Zero Hunger) and SDG 13 (Climate Action).

Keywords: climate change; wheat; rice; maize; production

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1. Introduction

Climate change has significant impacts on agri-food systems. Ten percent of the currently suitable area for major crops is projected to be climatically unsuitable by the midcentury under high-emission scenarios (SSPs) of the IPCC's 6th Assessment Report on Climate Change [1]. Increased, potentially concurrent climate extremes will periodically increase simultaneous losses in major food-producing regions [2]. Climate change hits the world's poor the hardest. Over 70% of the world's low-income population relies on agriculture and natural resources for their livelihood. The global population is projected to reach around 10 billion by 2050 [3]. Due to the rapid change in demography, economic growth, and lifestyle, the production of primary crops was 9.2 billion tons globally in 2018, which was around 50% more than in 2000 [4]. World cereal equivalent food demand is projected to increase by around 10,094 million tons in 2030 and 14,886 million tons in 2050 due to intensification of social, economic, and demographic pressures [5].

In 2020, nearly one out of three people lacked regular access to adequate food [6]. Cereals are a good source of minerals, carbohydrates, vitamins, proteins, and micronutrients, essential for proper functioning of the body. Due to the hike in prices, developing countries, consuming more cereals (166 kg/capita/annum) than developed countries (133 kg/capita/annum) and having less resilience, may suffer more [7]. Furthermore, the Ukraine crisis triggered food shortages for the world's poorest people. Ukraine and the Russian Federation supply 30% and 20%, respectively, of the global exports of maize and wheat [6]. Moreover, cereals are considered a reliable source of calories. Calories intake from cereals in developing and developed countries are 60% and 30%, respectively. Figure 1a elaborates on the global production and cultivated area statistics of three major cereal crops (wheat, rice, and maize), and Figure 1b the production share of cereal by region from the years 1994–2020. Around the world, rice, wheat, and maize are important staples critical to the daily survival of billions of people [8].

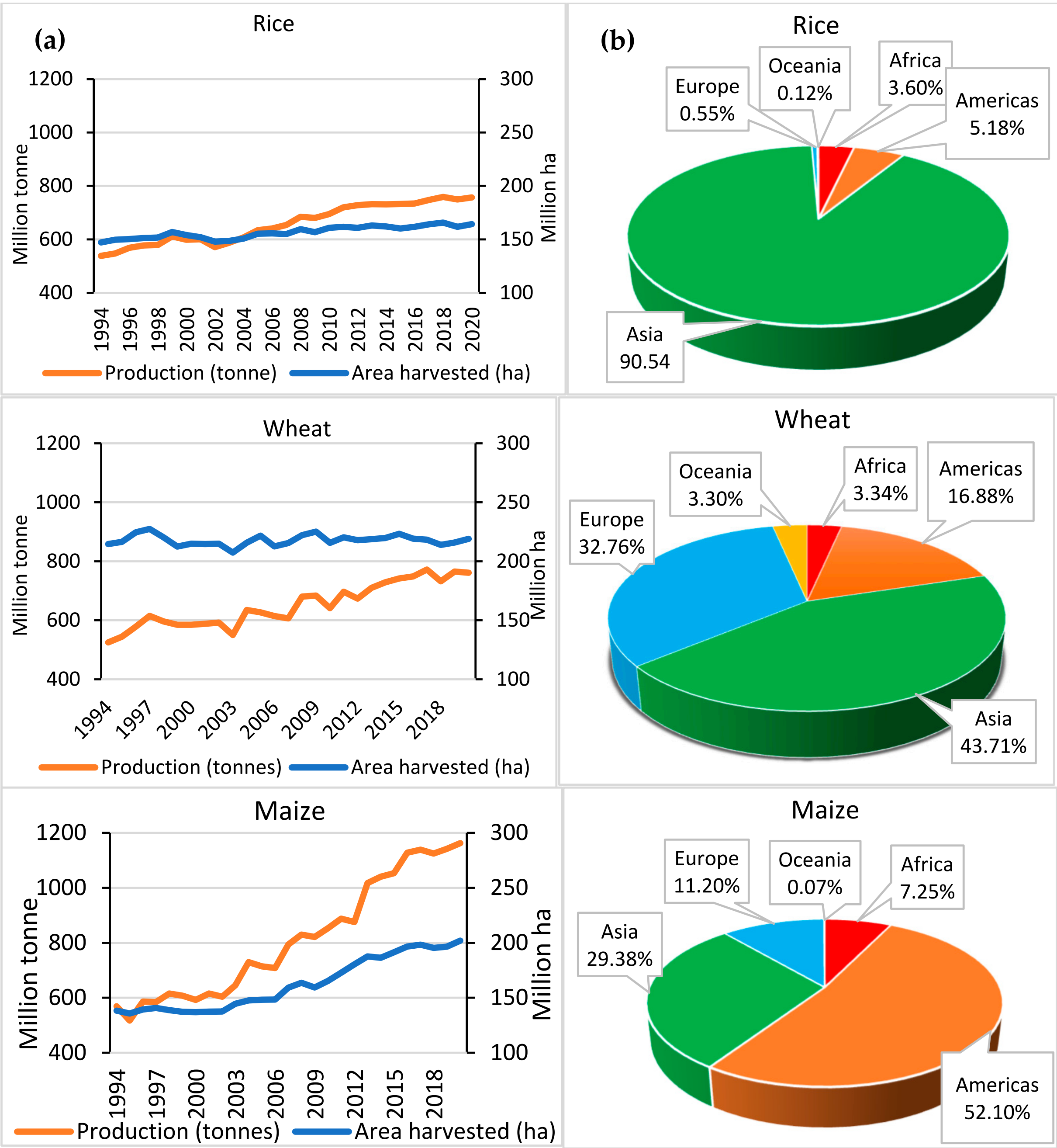

Figure 1. Worldwide (**a**) total production, harvested area, and (**b**) production share by region of wheat, rice, and maize 1994–2020 [9].

Earth's temperature is predicted to increase from 2.5 °C to 4.5 °C due to an increase in greenhouse gas (GHG) emissions by the year 2100. The increased level of atmospheric CO_2 may cause an inefficient uptake of net carbon by plants, resulting in decreased crop yield, thus asking food security questions in the future [10]. Climate change has a direct influence on the environment, e.g., biodiversity loss, changes in the soil, and water shortages, making sustainable food production difficult for the increasing population. The Intergovernmental Panel on Climate Change (IPCC) expressed high confidence that crop production would be consistently and negatively affected by climate change in the future in low-latitude countries, while climate change may have positive or negative effects in the northern latitudes. Although some high-latitude regions may become more climatically viable for crops, soil quality and water availability might constrain sustained agricultural production increases in these locations. Based on the climatic models under the highest scenario of warming, it was estimated that the yield of wheat and rice may decline by 17 percent globally by 2050 relative to a scenario with an unchanging climate [11]. To cope with this issue, it is an urgent need today to use the available resources efficiently and determine imperative actions regarding agricultural production to deal with the prevailing climate risks in the future [12]. According to IPCC, adaptation measures are defined as modifications/adjustments in the natural systems to reduce the harmful impacts associated with climate change [13–15]. As expressed by IPCC, different regions may face different levels of severity of climate change impact on crop yield. That is why researchers are investigating the effects of climate change on different crops in different regions by using different crop models and climatic models under different emission scenarios. Moreover, sharply changing climate is threatening the food security for the fast-growing global population. Lately, many review studies have been conducted to examine the impacts of climate change on agriculture or crop production. However, all these studies have some limitations regarding spatial coverage, consideration of climate models, crop models, climate change scenarios, or types of crops investigated. For instance, studies including [16–20] investigated the impacts of climate change on crop production at the country or regional level and found limited regarding spatial coverage. On the other side, studies including [21] are found limited regarding spatial coverage and types of crops considered as they examined the climate change impact only on regional crops at the country or regional level. Further, [21] was found limited regarding crop coverage as it focused only on the impacts of climate change on rice. Moreover, all the above-mentioned studies only investigated the concerned region/crop-specific climate change mitigations, adaptations, and/or policy implications. However, this study emphasized the impacts of climate change by focusing on the world's top three grown cereal crops, namely maize, wheat, and rice. Moreover, the scope of the study is broadened by considering the major contributing countries in the production of concerned crops at the global scale for eliminating the limitation of spatial coverage. Furthermore, the review is performed without the limitation of considering climate models, climate change scenarios, and crop models to increase the level of abstraction of the study. The study also generally summarized the challenges faced by crop production due to climate change and the potential mitigation and adaptation strategies by using the drivers–pressures–state–impact–response (DPSIR) framework. The main objectives of this review are to evaluate the worldwide climate change impact on wheat, maize, and rice production and analyze the universal impacts of adaptation actions to produce cereal crops. The countries with major wheat, rice, and maize production are presented in Figure 2.

This study can be helpful for policymakers to possess insightful details on the impact of climate change on cereal crops, providing a gateway to cope with this issue, and a comprehensive overview and research gaps for the researchers regarding further assessment.

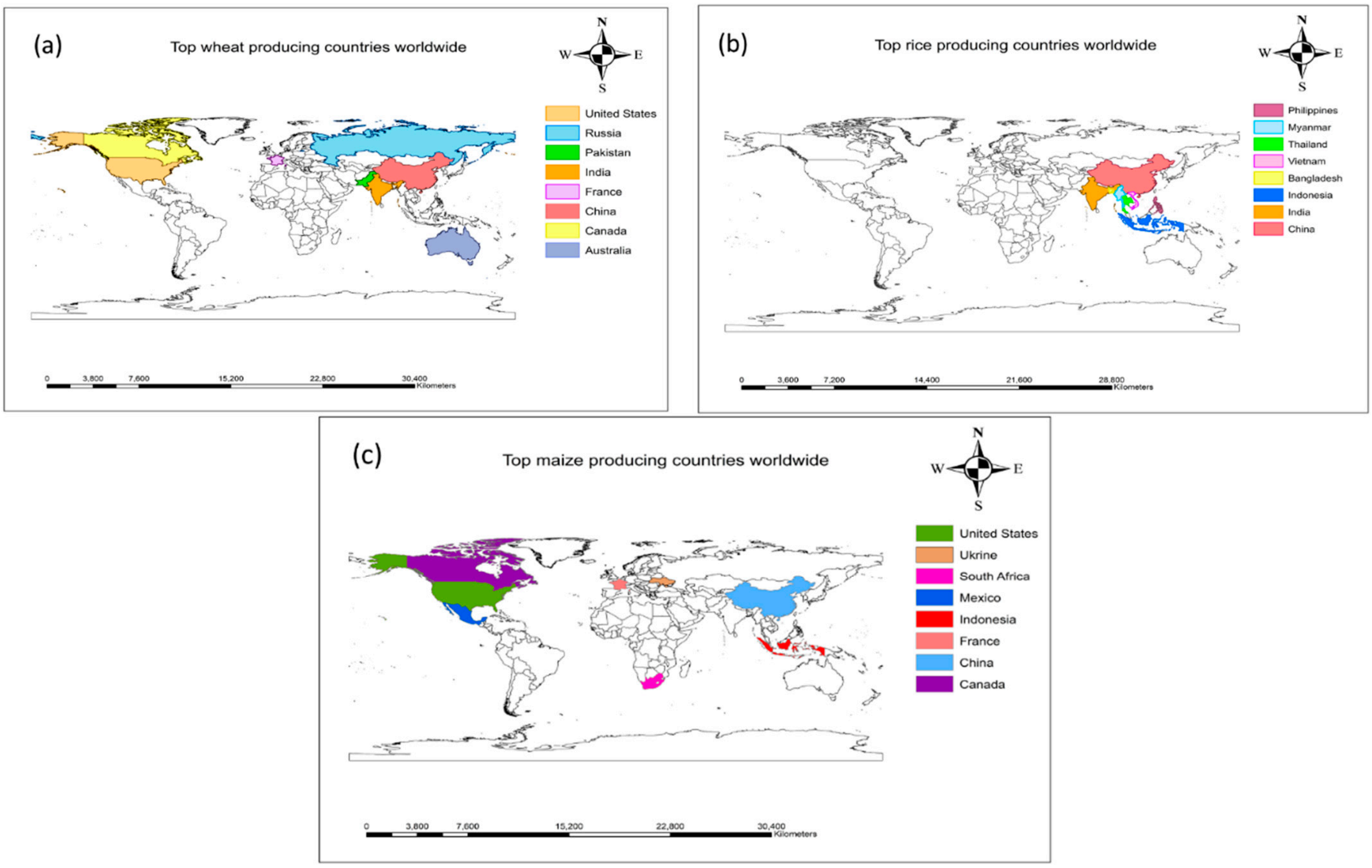

Figure 2. Major countries contributing to cereal crop production: (**a**) wheat, (**b**) rice, and (**c**) maize [9].

2. Materials and Methods

This review was based on a thorough evaluation of the existing literature to determine the present status of research examining the impact of climate change on cereal crops (wheat, rice, and maize). To preserve the review's quality, peer-reviewed articles were given priority in the review of the literature. The articles were selected focusing on the climate change impact on wheat, rice, and maize in major countries that produce these cereals. Moreover, uncertainty aspects of climate change impact on cereal crops have also been discussed.

3. Role of Climatic Models and Scenarios for Future Climatic Predictions

Before analyzing the potential impacts caused by climate change, it is necessary to have accurate information about the future climate to formulate policies built on different adaptation actions in controlling the impacts of this global issue (climate change) [14]. Existing climatic scenarios' emissions vary between scenarios depending on socio-economic assumptions, levels of climate change mitigation for aerosols and non-methane ozone precursors, and air pollution controls [14]. Optimal selection of climate change scenarios plays an imperative role throughout assessment of future climate [13]. The climate change scenarios have been classified into three major types by the Intergovernmental Panel on Climate Change (IPCC), namely synthetic (incremental), analog, and climate-model-based scenarios. The synthetic scenarios can be generated using a technique (adding random values to the realistic baseline data) to adjust the temperature and precipitation for future climate conditions. In analog scenarios, the historical climatic data are analyzed thoroughly on a temporal basis to construct possible future analog climatic conditions. Model-based scenarios can be generated by completing adjustments in the baseline data by some downscaling technique (arithmetic-based corrections in the data after comparing/analyzing historical and future extracted model-based data) [15]. Regional climate models (RCMs) and global circulation models (GCMs) provide numerical/quantitative estimation of climatic projections in the future at regional and global scales at different temporal resolutions (a day, a month, or a year). Therefore, RCMs and GCMs are used for projecting various climate parameters, such as temperature, precipitation, humidity, etc., at different temporal and regional scales [22].

The outputs from GCMs are rather coarse, with a spatial resolution of about 100 km, and provide the climate trends at a global scale rather than regional predictions, while RCMs are derived from GCMs and can provide better results at a resolution scale of about 10 km. The outputs from large-spatial-scale GCMs may contain uncertainties and ambiguities in the projected results of temperature and rainfall by considering the topographical and land use impact at a larger longitudinal distribution [23]. Instead, RCMs may provide a better understanding of variations in spatial features due to their high aerial resolution. Therefore, different climate-based models have their pros and cons; their selection should be made depending on the objectives and goals of the studies [24]. Aiding climate change studies, climatic scenarios hold a significant role in predicting the future climate. In the IPCC fourth assessment report (AR4), four different scenarios (A1, A2, B1, and B2 scenarios) were reported [25]. IPCC AR5 had four different emission scenarios based on representative concentration pathways (RCPs) RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 [22]. Recently, IPCC AR6 provided five emission scenarios based on shared socioeconomic pathways (SSPs) SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 [1]. A comprehensive list of climate change scenarios established by the IPCC is provided in Table 1.

Table 1. Description of SRES, RCP, and SSPs emission scenarios.

Assessment Report (AR)	Scenario	Detail Description	Source
AR4	A1F1	A rapid increase in the economic and population growth	[26]
	A1T	No use of fossil fuels but some alternative source of energy that will not emit GHGs	[26]
	A1B	A rapid increase in economic growth with effective technologies, low population growth, and balanced consumption of energy sources	[26]
	A2	A continuous rise in the world population, regional-based economic growth with lower per capita economic growth	[26]
	B1	A world with increasing resource-efficient technologies, an increase in the world population till 2050 and then declines, and rapid changes in economic development with less material intensity	[26]
	B2	This scenario is more focused on economic, social, and environmental sustainability at the local and provincial levels	[26]
AR5	RCP 2.6	Low range mitigation scenario, the CO_2 concentration of 421 ppm, temperature rise by 1.6 °C till 2100	[22]
	RCP 4.5	Medium range emission scenario (referenced as B1 scenario), the CO_2 concentration of 538 ppm, temperature rise by 2.4 °C till 2100	[22]
	RCP 6.0	Medium range emission scenario (referenced as B2/A1B scenario), the CO_2 concentration of 670 ppm, temperature rise by 2.8 °C till 2100	[22]
	RCP 8.5	High range emission scenario (referenced as A2/A1F1 scenario), the CO_2 concentration of 936 ppm, temperature rise by 4.3 °C till 2100	[22]
AR6	SSP1-1.9	Scenarios with very low and low GHG emissions and CO_2 emissions declining to net zero around 2050, followed by varying levels of net negative CO_2 emissions (SSP1-1.9)	[1]
	SSP1-2.6	This scenario with 2.6 W/m^2 by the year 2100 is a remake of the optimistic scenario RCP2.6 and was designed to simulate a development that is compatible with the 2 °C targets. This scenario also assumes climate protection measures are being taken.	[1]

Table 1. *Cont.*

Assessment Report (AR)	Scenario	Detail Description	Source
	SSP2-4.5	As an update to scenario RCP4.5, SSP2-4.5 with an additional radiative forcing of 4.5 W/m^2 by the year 2100 represents the medium pathway of future greenhouse gas emissions. This scenario assumes that climate protection measures are being taken.	[1]
	SSP3-7.0	With 7 W/m^2 by the year 2100, this scenario is in the upper-middle part of the full range of scenarios. It was newly introduced after the RCP scenarios, closing the gap between RCP6.0 and RCP8.5.	[1]
	SSP5-8.5	With an additional radiative forcing of 8.5 W/m^2 by the year 2100, this scenario represents the upper boundary of the range of scenarios described in the literature. It can be understood as an update of the CMIP5 scenario RCP8.5, now combined with socioeconomic reasons.	[1]

4. Impacts of Climate Change on Wheat under Different Modeling Systems and Adaptations

Climate change is a global issue having numerous effects on agricultural products. Crops may experience a water shortage or a decrement in yield due to the changing climate. Various studies have been conducted at the global level to assess the potential impacts of climate change on wheat yield [27]. A range of climatic models along with climate change scenarios were used to predict future impacts of climatic variations on wheat production using various quantification methods. From a comprehensive literature review (see Table 2), it can be stated that a wide range of potential impacts were expected for wheat production at a global scale.

Several crop simulation models, such as APSIM-Wheat, DSSAT-CERES-Wheat, CSM-CROPSIM-CERES-Wheat, and DSSAT-NWHEAT, have commonly been used for simulating wheat yield under present and future climatic conditions [28]. The APSIM-Wheat model was used in various environments; it was used in China to assess the climate change impact on wheat yield. The results elaborated the advancing trend of the wheat phenological stage under RCP 4.5 and RCP 8.5 scenarios, and increased CO_2 concentration is expected to have a positive impact on wheat, with an increased level of water productivity at less evapotranspiration demand in the future [27]. Climate change impact was assessed using the DSSAT-CERES model under two representative concentration pathways (RCP 4.5 and RCP 8.5) for the periods of 2010–2039, 2040–2069, and 2070–2099. The impacts of climate change atmospheric CO_2 concentration in the Huang-Huai-Hai Plain of China were assessed. The results revealed a positive correlation between increasing rainfall and atmospheric CO_2 concentration to wheat production, but a negative relation was foreseen with increasing future temperature, concluding that the positive impacts of CO_2 and rainfall in the future might be offset by rising temperature [29]. Wheat production vulnerability to climate change was analyzed in Pakistan from arid to humid zones using the CSM-CROPSIM-CERES-Wheat model. The most severe impacts on wheat were in arid and the least in humid regions of the country as humid zones might be somehow able to withstand the increased effect of temperature in the future [30]. Around the world, about 800 million people are persistently underfed or suffering from food shortages, especially in southern Asia and Africa. These regions depend on agriculture to feed themselves, but the harvested crop area is reducing almost all over the world. Therefore, great importance is associated with adaptation action plans according to the United Nations Framework Convention on Climate Change (UNFCCC) [31].

Many adaptation actions were performed in the past for moderating the impacts of climate change on wheat production. Two adaptation strategies (introducing new heat-tolerant varieties and expanding irrigation set-up) in response to climate change were implemented for wheat production at a global scale (for main wheat-producing countries, i.e., France, United Nations, Pakistan, Germany, India, Canada, China, Russia, and Turkey). The results suggested implementation of these adaptations based on the current production level and yield accomplishment for each country. For Pakistan, China, and India, adaptations, i.e., expanding irrigation area and use of heat-tolerant varieties, were proposed to gain the required wheat production in the future. Meanwhile, other countries might be able to gain the required yield in the future either by expanding irrigation areas or switching to other crop varieties. For example, in Canada and Russia, the level of adaptation was a bit lower; the yield in the future can be maintained at the required levels only by an increase in the irrigated area by using the existing wheat varieties [32]. The InfoCrop-Wheat model was used to simulate crop yield under future climatic conditions for Indian wheat production; its production was expected to be more vulnerable to climate change in the southern and central parts of India (warmer regions). Shifting crop planting dates, earlier planting of late-sown crops, and by using higher irrigation, fertilizers, seeds, etc., could prove beneficial adaptations to reduce the severe impacts of climate change in the future [33]. China is one of the most populous countries in the world, with a large amount of food consumption. Wheat is widely grown in China and is expected to be one of the crops affected by climatic variations in the future. It has been recommended that delayed planting of wheat in China may help the plant to grow well under changing climatic conditions. In addition, more heat-tolerant varieties, rotary tillage instead of conventional, and improved irrigation levels during critical growth stages (when crop water demand is high) of the crop are some of the useful strategies for wheat production under changing climate [33].

Table 2. Summary of past research on global wheat production under climate change.

Sr. No.	Study Area	Purpose of the Study	Climatic/Weather Conditions	Quantification Method	Climatic Model	Climatic Scenarios	Study Period	Main Findings	References
1	Northern China	To assess the climate change impact on wheat yield	Varying conditions	APSIM-Wheat model	28 GCMs	RCP 4.5 & RCP 8.5	(1981–2010), (2031–2060), & (2071–2100)	Reduction in yield from 0.7 to 22.7% compared to the baseline under constant CO_2 concentration & the increase in yield under elevated CO_2 concentration	[27]
2	Northern China	Evaluating the impact of climate change on winter wheat yield	The temperate zone, monsoon climate	Cobb –Douglas analysis model	5 climatic models	RCP 4.5 & RCP 8.5	(1981–2005) & (2021–2050)	From baseline, yield increased by 1.47% (RCP 4.5) and 2.16% (RCP 8.5)	[34]
3	Northwest India	Estimating the impact of climate change on wheat production until 2050	-	CERES-Wheat model	-	Scenario 1 (existing climatic conditions with 350 ppm CO_2); Scenario 2 (maximum & minimum temperature with an increase of 1.0 °C and 1.5 °C, respectively, & 460 ppm plant functional CO_2 concentration; & Scenario 3 (maximum and minimum temperature with an increase of 2.0 °C & 2.5 °C, respectively & 460 ppm plant functional CO_2)	(1969–1999) & (2040–2049)	Increase in yield by 29–37% (rainfed) & 16–28% (irrigated) under Scenario 2 and Increased by 22–30% (rainfed) & 12–23% (irrigated) under Scenario 3	[35]
4	India	Assessing the impacts under existing and adaptation conditions on wheat yield for the future climatic conditions	Tropical to sub-tropical	InfoCrop-Wheat model	1 GCM & 1 RCM	A1b and B1 (for GCM) & A1b, A2, and B2 (for RCM)	(2000–2007), (2020–2050), & (2070–2100)	The yield may reduce from 6 to 52% for the timely, late, and very late sown situations, & the impacts were predicted to be more in the warmer climatic zones, such as the central and southern parts of India	[33]
5	European Russia	Assessing the long-term climatic effects on the winter wheat yield	Varying climate	Climate-Soil-Yield	RCM	RCP 8.5	(1990–1999), (2030–2039), (2050–2059), & (2090–2099)	In different parts of European Russia, the yield was expected to decrease from 7 to 87% (RCP 8.5)	[36]
6	Oklahoma, United States	Estimating the impact of climate change on wheat yield under different climatic scenarios	-	DSSAT-CERES-Wheat model	4GCMs	RCP 6.0 & RCP 8.5	(1980–2014) & (2040–2060)	Yield may increase by 3–10% (RCP 6.0) & 4–20% (RCP 8.5)	[37]
7	North America and Eurasia	Simulating the impact of future climatic conditions on spring wheat yield	Varying climate conditions (varying latitudes and longitudes)	Comparing average yields of 1981–1990 and 2006–2015 based on real data	-	-	(1981–1990) & (2006–2015)	On-station and the province (state) average yield may increase by 33 and 45%, respectively, in North America, while the average yield in Eurasia may change by −1.9% and +11.5% for on-station and province (state) scales, respectively.	[38]

Table 2. *Cont.*

Sr. No.	Study Area	Purpose of the Study	Climatic/Weather Conditions	Quantification Method	Climatic Model	Climatic Scenarios	Study Period	Main Findings	References
8	United Kingdom (UK) and France	Estimating the climate change impact on wheat yield and suggesting adaptation measures based on agricultural management practices	-	AFRCWHEA T2	3 GCMs	Business as Usual scenarios (no control on CO_2 emissions)	(1959–1989), (2010, 2030), & 2050	An increase in wheat yield was expected in the UK as well as in France, but the increase in the UK was projected to be 40% more than that of France, with the highest increase in 2050, i.e., +12% (UK) and +9% to 10% (France)	[39]
9	Western Europe (France)	Estimating the adverse future climatic impacts on cereal crops, including wheat	-	Fixed-effects regression model	5 GCMs	RCP 2.6, RCP 4.5, RCP 6.0, & RCP 8.5	(1976–2005), (2037–2065), & (2071–2099)	Under less temperature, i.e., 7–12 °C, it was expected to have a positive impact on wheat crop yield, while, under higher temperatures, i.e., 12–32 °C, wheat showed a negative impact. The wheat yield is expected to decrease from 3 to 13% (mid-century) & 17% (end-century)	[40]
10	Quebec, Prairie provinces, and Ontario (Canada)	Assess the effect on the existing cultivated crop yield (including wheat)	-	(DayCent) and (DNDC)	20 GCMs	The temperature increased by 1.5, 2, 2.5, and 3 °C under only RCP 8.5	(2006–2015), 2025, 2040, 2052, & 2063	Wheat yield showed a considerable increase under all crop models. The increase in the yield was the highest for a 2 °C rise in temperature for Canada.	[41]
11	Southern Canada	Climate change impact assessment on wheat production is an important bioenergy crop	Semiarid	DSSAT-CSM	1 GCM	A1B, A2, and B1 under the direct impact of CO_2 and dual effect (climate change + CO_2), CO_2 = 550 ppm (A1B and A2), CO_2 = 450 ppm (B1)	(1961–1990) & (2040–2069)	With the increased future rainfall and temperature, wheat biomass production is expected to increase from 12 to 28% (direct effect of CO_2) and 41–74% (dual effect, climate change + CO_2) relative to the baseline	[42]
12	Pakistan	Estimating the climate change impact on wheat production in various climatic environments	Arid, semiarid, sub-humid, and humid	CSM-Cropsim-CERES-Wheat model	-	A combination of six scenarios of temperature from 0 to 5 °C & 3 scenarios of changing atmospheric CO_2 concentration, i.e., 375, 550, & 770 ppm	Baseline (CO_2) concentration level of 375 ppm	An expected decrease in wheat yield in sub-humid, semiarid, and arid regions with the increased temperature levels, while a positive impact was foreseen in humid zones.	[30]
13	Western Australia	Determining the impact of increasing temperature, increased atmospheric CO_2, and varied rainfall amount on wheat production	Varying climate for different sites	APSIM-Wheat model	-	Three scenarios of temperature (+2, +4, & +6 °C), five scenarios of rainfall (historical rain, −15%, −30%, −60%, and +10%)	(1954–2003), 2050, & 2100	Wheat yield is expected to increase from 38 to 48% under varying amounts of N-fertilizer application. The increase in temperature and lowering the rainfall both have negative impacts on yield during winter.	[43]
14	Southern Australia	Quantifying the impact of change (temperature, CO_2 level, and rainfall) on wheat production	Varying climatic conditions from site to site	APSIM-Wheat model	9 GCMs & RCMs	B1, B2, A1, A2, A1B, A1T, A1F	(1900–1999) & 2080	Based on 648 model simulations, rainfall is considered to be the most affecting climatic parameter, followed by temperature. The wheat yield may vary from −87 to +131% compared to the baseline)	[44]

5. Climate Change Impact on Rice under Different Modeling Systems and Adaptations

According to an estimate by the Food and Agricultural Organization of the United Nations (FAO), globally, the population depending on rice will reach 3.5 billion by the year 2025. Asian countries are highly dependent on rice, and about 60% of the total rice production takes place on this continent [45]. With urbanization and population growth, the demand is increasing, especially in low-income countries [46]. The existing available land and water resources are reduced to generate enough food supplies for the increasing population [47]. Climate change research on global rice production showed an alarming situation for its sustainable production and distribution around the world. Rising temperatures and changes in rainfall and distribution patterns may change the availability of land and water resources for rice cultivation in the future [43]. Climate change may have different impacts on rice cultivation in different geographical locations, as shown in Table 3. A decrease in rice yield was predicted in many parts of the world, such as China, Thailand,

and Vietnam, while an increase was expected especially in some parts of Myanmar based on the literature reviewed in this study and also as reported in [43]. Overall, a significant increase in precipitation is possibly the main reason of increase in crop yield in Myanmar.

Different modeling approaches have been used in estimating global rice production under climate change impact. The modeling approach is a well-structured way of simulating crop yield under different climatic and management conditions. Crop models have many benefits as follows: (1) defining the gaps between the observed and obtainable/potential yield in a specific region, (2) estimating the most optimized adaptations to be followed to avoid vulnerable outcomes of future climate on crop production, and (3) providing information regarding use of right timing and amount of inputs (e.g., irrigation, fertilizers, etc.) [48].

Rice yield was estimated in India by using the decision support system for agrotechnology transfer (DSSAT) model with the help of three RCMs under two scenarios (RCP 4.5 & 8.5). Rice yield is expected to decrease 30–60% of the study area in the future. A mean rainfed yield gap of 1.49 t/ha is expected by mid-century [49]. The vector autoregression model was used to assess the impact of climate change on rice yield in Pakistan. The results showed an increase in the temperature (2–5 °C) with a rise in rainfall (8–11%) in the future, projected to have a declining effect on rice yield (0.3–0.6% lower than the base period). The decline in the yield was predicted due to increasing crop water demand during critical growth stages, and the future increase in rainfall might not be sufficient to nullify the effect of dramatically increasing temperature [50]. The Shierary rice model, a yield simulation model that simulates yield by building a relationship between crop growth stages concerning the seasonal climatic conditions right from planting to the harvesting stage of the crop, was used along with the climatic models for simulating the rainfed and irrigated rice yield in different provinces in Indonesia. Generally, the model results depicted a negative change in rice production (both for rainfed and irrigated rice) under changing climatic conditions [51].

Rice is a staple food for most Asian countries. It is considered a thirsty crop as it needs a great deal of water to grow properly, but climate change may accelerate impacts on global rice cultivation due to water shortages (because of increasing future temperatures and changing rainfall patterns). The Organization for Economic Corporation and Development (OECD) has reported a decrease in rice production by about 15% in southeast Asian countries, which may lead to a 50% increase in rice prices by the middle of this century. Therefore, adaptation actions must be devised in response to climate change to technically improve rice production in southeast Asian region [52]. Many adaptations can be implemented by farmers in the future for sustainable rice production, e.g., introducing smart crop varieties (heat-tolerant, stress-tolerant, cold-tolerant, and salt-tolerant), agricultural management (optimized use of irrigation and fertilizers, shifting cropping calendars, and crop rotation), improved pest and disease management, improved seed rate, and improving the technical knowledge of the growers to help them maintain their yields in response to climate change [43].

A rice study was conducted in northeast Thailand estimating the potential future climatic impacts on rice and suggesting adaptations to maintain the rice yield in this region. Adaptation measures such as (1) delay in rice planting to avoid the grain-filling phase occurring in the hotter periods, (2) introducing heat-resistant and stress-tolerant varieties in areas of water shortage, and (3) improving the nitrogenous fertilizer rate under future climate conditions were suggested to ensure global food security as Thailand is one of the major producers, consumers, and exporters of rice in the world [53]. The integrated impact of climate change and AquaCrop simulations showed a decrease and increase in the rice yield for winter and summer planted crops, respectively. Delayed planting, improved nutrient application, additional irrigation, and introduction of new crop varieties were suggested as the most effective adaptations for sustainable rice cultivation in Vietnam under future climatic patterns [54]. Another study was conducted in Hunan Province of China for simulating rice yield under climatic variability in the future and suggesting the most suitable adaptation plans for sustainable rice cultivation in China. The results suggested a decrease in the yield from 12–47% due to early occurrence of rice maturity phases, which might influence proper grain filling of the crop under future climatic conditions. It was suggested that changing the rice cultivar (late-maturing rather than early-maturing varieties) and planting rice 15 days earlier than the existing planting date would help the crop to attain the maximum potential yield in the region by an increase between 16 and 17% (by changing cultivar) and 14–22% (by 15 days earlier planting) under future climate change scenarios [55].

Table 3. Summary of past research on global rice production under climate change impact.

Sr. No	Study Area	Purpose of the Study	Climatic/Weather Conditions	Quantification Method	Climatic Model	Climatic Scenarios	Study Period	Main Findings	References
1	China	Visualizing the impact of climate change on rice production	Varying climate and topography for different study sites	CERES-Rice model	17 GCMs	RCP	(2000s), 2030s, 2050s,& 2070s	Except for northeast China, the rice yield was expected to decrease in the other parts, such as central and southern China	[56]
2	India	Assessed the rice yield gap under the projected climate change scenario	Rainfed conditions	Decision Support System for Agrotechnology Transfer (DSSAT)	3RCMs	RCP 4.5 & RCP 8.5	(1981–2005),(2016–2040),& (2026–2050)	Rice yield is expected to decrease in 30–60% of the study area in the future. Mean rainfed yield gap of 1.49 t/ha is expected in future	[49]
4	Thailand (Khon Kaen province)	The impact of climate change and suggesting the optimal adaptations for rice production for rainy and dry weather	Temperature = 19–37 °C (range), rainfall = 1040 mm (for about 100 rainy days)	DSSAT	GCM	B2	(2010–2019), (2050–2059),& (2090–2099)	Varying trends of yield for different rice cultivars and quantity of nitrogen-fertilizers applied	[57]
5	Thailand	The effect of climatic parameters on rice yield variability	Temperature = 0.84–4.85°C (variation), rainfall = 1107–2104 mm (for growing season)	Just–Pope Production Function	RCM	A2 & B2	(1989–2009), 2030, 2060, & 2090	A decrease between 5–34% was predicted compared to the baseline	[58]
6	Vietnam	Assessing climate change impact on rice yield and market price of rice	-	Double-log specification Equilibrium displacement model (EDM) for estimating the rice market	-	-	(1980–1999), 2020, 2030, & 2040	A negative correlation of temperature with yield and a positive correlation was foreseen with precipitation. The yield may reduce between 0.25 and 0.49%	[59]
7	Vietnam	The climatic variations will have an impact on winter and summer rice production	-	Komogorov–Smirnov and Shapiro–Wilk test	-	-	1986–2012	Climatic variations had a mixed trend on the rice yield; i.e., average rainfall and minimum temperature showed positive while maximum temperature showed negative correlation	[60]
8	Indonesia (Ujungjaya, Sumedang in West Java province)	Analyzing the impact of climate change and adaptation actions on rice yield	-	CROPWAT	17 GCMs	RCP 4.5 & RCP 8.5	(1981–2010), (2011–2040), & (2041–2070)	Based on GCM results, the yield is predicted to decrease between 2.8–29.3% for RCP 4.5 and 3.6–30.2% for RCP 8.5	[61]
9	Indonesia (Subang)	Assessing the changing rainfall and temperature on rice yield in the future	Monsoon (tropical), rainfall = 1500–3000 mm, average temperature variation = 23–34 °C	AquaCrop	GCM	RCP 8.5	(2010–2015) & (2021–2050)	A 2 °C rise in temperature and a 15% decrease in rainfall may lead to a decrease in yield by 23%	[62]
10	Bangladesh (South-west)	Simulating the climate change impact on rice production	Minimum temperature=19–22 °C, maximum temperature = 29–32 °C, average annual rainfall = 1800–4100 mm	Just–Pope Production Function	-	-	(1972–2009), 2030, 2050, & 2100	A different climatic parameter was predicted to affect varying rice cultivars in a different way (positive/negative) in the future	[63]
11	Myanmar (Southern part)	Assessing the irrigation water requirement and rice yield under climate change impact	Sub-tropical (average rainfall = 2700 mm, temperature = 22–36 °C)	AquaCrop	2 GCMs	A1, B1, A2 & B2	(1961–1990), 2020s, 2050s, & 2080s	With a decrease in the irrigation requirement, the yield was supposed to increase from 16 to 40% under future climatic conditions	[64]
12	Philippines	Estimating the effect on rice yield with climate variability at different times and locations	Tropical	Standard correlation analysis (gives a relationship between yield and climatic parameters)	GCM	RCP 8.5	(1980–1999) & (2080–2099)	Rice yield varied with change in soil moisture content (due to climatic variability), with more effect foreseen in the rainfed areas rather than in the irrigated areas	[65]

6. Climate Change Impact on Maize under Different Modeling Systems and Adaptations

Maize is one of the most important cereal crops followed by rice and wheat and is considered the queen of all cereal crops due to its greater yield potential. The highest maize cultivation takes place in the United States, which accounts for about 35% of the total worldwide production. This crop has many health-beneficial impacts, one of them being resistance to chronic diseases, such as malignancy and obesity [66]. Warming due to climate change impact is inducing negative impacts on agriculture, especially in food-insecure regions. On average, maize yield is predicted to decrease by 7.4% for every 1 °C rise in the temperature. Many regions worldwide have an increasing rainfall trend, but that rise is foreseen to be offset by the continuously increasing effect of temperature due to climate change [67]. African countries (such as Tanzania, Malawi, etc.) depend heavily on maize to fulfill their food requirement and have come under food-compromising countries worldwide. In addition, the climate change impact (changing rainfall patterns and rising temperature) might harm the population of such poor countries and can make food security questionable in the future [68–70].

Many studies in the past were conducted to assess climate change impact on maize production at global and national levels. Global climate change impacts maize yield in different parts of the world by using various crop and climate change models and under different climate change scenarios, which are presented in Table 4. The results show an overall decrease in maize yield in different maize-producing countries, such as the US, China, Mexico, Ukraine, South Africa, and Indonesia. For Canada, different impacts were predicted under different modeling approaches (DSSAT, DNDC, and DayCent). In the US, the impacts of climate change were analyzed on maize yield [71] by using crop statistical and regression analysis models that provide a relation between crop yield and weather parameters. A negative correlation was observed between maize yield and increasing temperature under all warming scenarios, i.e., 1 °C, 3 °C, and 5 °C, according to the future predicted climate. Some regions in the US located in the north are somehow expected to be positively influenced by all the expected warming scenarios. Climate change is supposed to negatively influence the maize yield in southern African countries under increasing future temperatures [72]. The APSIM crop simulation model was used in predicting the future climatic impacts on maize production in three countries of southern Africa (Makoni, Zimbabwe, and Hwedza) for three future periods (near future, mid-century, and end-century). A negative change in maize yield was found in all study regions due to continuously increasing temperatures, which were expected to accelerate the plant maturity phase with reduced grain filling time and produce less biomass (which is directly linked to grain yield) [73]. A comprehensive double logarithmic production function was set up between maize yield and other parameters (agricultural machinery, labor, applied fertilizers, and weather parameters) to predict the impact on maize production in the northeast and southwest regions of China. It was found that the climatic parameters in the future would have a strongly negative impact on future maize yield all over China [74].

For sustainable production of crops, the most common and effective adaptations are considered as follows: (1) adjusting sowing density, (2) management of irrigation infrastructure, (3) crop rotation, (4) introducing new crop varieties, (5) shifting the crop calendar, and (6) expanding the agricultural areas [75]. By using the DSSAT model (version 4), two sets of adaptations (changing sowing dates and nitrogen level application) were analyzed for maize production in Chile. To avoid frost damage, early sowing of maize was suggested with a nitrogen application rate of 450 kg per hectare [76]. A study indicated that adaptation strategies in the form of earlier planting and changing crop variety can considerably reduce maize yield loss under future climatic conditions in China [77].

Table 4. Summary of past research on global maize production under climate change.

Serial No.	Study Area	Purpose of the Study	Climatic/Weather Conditions	Quantification Method	Climatic Model	Climatic Scenarios	Study Period	Main Findings	References
1	USA (Iowa)	Estimating the climate change impact on maize yield and yield loss index in the 21st century	-	Agro-Integrated Biosphere Simulator (Agro-IBIS Model)	6 GCMs	RCP 4.5 & RCP 8.5	(1981–2000), (2041–2060),& (2081–2100)	The expected decrease in the yield is between 2–16% for RCP 4.5 and 4–23% for RCP 8.5	[78]
2	China	Simulating the impact of climate change on maize, wheat, and rice	-	Crop–Weather relationship over a large area (MCWLA) family crop model	4 GCMs	Temperature increases up to 1.5 °C & 2 °C	(2006–2015) & (2106–2115)	Maize yield was expected to be negatively affected by the warming scenarios in the future	[79]
3	Mexico	Assessing the impact of future rainfall conditions on rainfed maize yield	-	Simple Linear Relationship between rainfall and yield	GCM	RCP 2.6, RCP 4.5, RCP 6.0, & RCP 8.0	(2000–2009) & (2090–2099)	The maize yield was predicted from no change in yield to a decrease of 30% under RCP 8.5	[80]

Table 4. *Cont.*

Serial No.	Study Area	Purpose of the Study	Climatic/Weather Conditions	Quantification Method	Climatic Model	Climatic Scenarios	Study Period	Main Findings	References
4	Canada	Estimating the impact of climate change on maize, canola, and wheat	-	DayCent, DSSAT, and DNDC	20 GCMs	RCP 8.5 with warming scenarios of 1.5 °C (2025), 2.0 °C (2040), 2.5 °C (2052) & 3.0 °C (2063)	(2006–2015), (2025, 2040, & (2052 2063)	DSSAT model projected a minor increase in the yield. However, DNDC and DayCent predicted substantial increase and decrease in yield, respectively	[41]
5	Ukraine	Assessing the impact of future climate conditions on different crops (including maize)	-	Crop Growth Monitoring System (CGMS)	3 GCMs	A2 & B1	(1990–2008), (2020–2040, (2040–2060), & (2080–2100)	The maize yield was expected to decrease between 5 and 26% in Ukraine	[81]
6	France	Analyzing the future impacts of climate change on maize production	-	Generalized additive empirical model	16 GCMs	A1B	(1991–2010) & (2016–2035)	The maize yield in France was expected to increase by 12%	[82]
7	Southern Africa (Eastern Zim-babwe)	Quantifying the response of maize yield to climate change until the year 2100	Dry sub-humid to semiarid tropical with varying amounts of rainfall	APSIM crop model	5 GCMs	RCP 4.5 & RCP 8.5	(1976–2005), (2010–2039), (2040–2069),& (2070–2099)	Maize yield may decrease from 13% to 20%	[73]
8	Indonesia	Analyzing the economic significance of climate change due to losses in production inputs	-	International Model for Policy Analysis of AgriculturalCommodities and Trade combined with Computable General Equilibrium	4 GCMs	A1B	(2005–2030)	The maize yield is expected to decrease due to future climate	[83]

7. Uncertainties in Agricultural Yield Predictions

Climatic and crop models are important tools in predicting agricultural yield under different time series climatic data, but model uncertainties are some of the limitations of such models [84]. There could be two kinds of uncertainties in predicting agricultural yields as follows: (1) uncertainties occurring due to crop simulation models and (2) uncertainties due to climatic models used for future climatic projections.

7.1. Possible Uncertainties in Crop Growth Models

Crop simulation models are extensively used for predicting the amount of biomass produced, yield projections, and evaluating crop management techniques for agricultural production. The predictions of growth models may contain various uncertainties, namely uncertainties in input data (crop parameters, soil parameters, irrigation data, nutrient management data, weather data, etc.), model calibration parameters, and management assumptions of the crop model [85]. There could be many uncertainties involved due to a lack of sufficient knowledge about the crop and soil parameters for a particular cultivar type. Moreover, application of fertilizers may contain many uncertainties due to a lack of knowledge about the initial conditions of the soil and its fertility level (an input to the crop models). In addition, weather- and soil-related data required by the crop models contain many measurement errors due to longitudinal and sequential variations [85]. Uncertainties are caused due to differences in the model structure, such as (1) which calibration parameters does a model consider? (2) What type of fertilizers (N-, P-, or K-based) can be input into the model? (3) What irrigation methods and scenarios can be applied to a specific crop within the developed model structure? One of the main origins of uncertainties is from different data sources because uncertainties are not only occurring during data records but may also occur while collecting and combining different data sources (to represent the actual scenario applied in the field) that may involve many random and human errors. Therefore, the output from such models may contain many uncertainties as it is directly associated with the inputs entered into the model [86].

7.2. Possible Uncertainties in Climate Change Predictions

Climate with absolute certainty cannot be predicted as there are plenty of uncertainties while researching climate change [87,88]. The climatic models' predictions are featured with too many uncertainties due to the difference in the model structure based on different initial conditions (i.e., type of scenario used; see Table 1) [89]. Various GCMs predict the climate based on the level of GHGs released as a consequence of anthropogenic activities. The level of GHGs may not be predicted with accuracy, which can be considered the first and most probable uncertainty in predicting the future climate [90]. Further uncertainties may occur when regional climatic models (RCMs) take the output from the GCMs (with coarser resolution) in projecting the future climate at a regional scale. In that way, RCMs may contain not only their inherent uncertainties but also those from the GCM's output [91]. All climatic models cover a continuous period of 1860–2099; uncertainties may occur when different researchers extract the climatic data for different periods, e.g., 2020–2030 (10 years), 2020–2040 (20 years), or 2020–2050 (30 years), etc. [92]. Bias correction is usually applied to represent the output of a GCM as a reference climatology. Different impact outcomes are expected while using different bias correction techniques and varying sets of reference weather data, which may lead to another source of uncertainty in the climatic data [93].

7.3. Suggestions for Reducing the Uncertainties in Agricultural Yield Predictions

Process-based crop models are essential and useful tools in predicting agricultural yield under present and future climatic conditions. These models can relate the weather conditions to the crop yields through a strong physiological mechanism. However, crop simulation models may have a limitation of including the actual conditions of the agricultural fields, i.e., the effect of pest or disease control in a certain environment, which depends upon the farmer's behavior and how he manages in such circumstances. That kind of information input (amount of pesticides and insecticides applied, etc.) may not be in the model structure during its development phase [94]. Moreover, the crop models have specific threshold values for temperature. Hence, crop simulation models may not be able to show the explicit relation between agricultural production in response to values of temperature over the threshold under future climatic conditions. Under such situations, collective use of simulation models (multi-model ensemble) following different physical processes has been suggested to omit uncertainties in agricultural yield predictions [95]. It has been reported that more uncertainties come from crop growth models rather than climatic models [96]. The most common and highly occurring uncertainty is from the crop response to temperature. Those uncertainties could be reduced by developing a set of temperature response functions to the main physiological processes that may have a considerable reduction in the errors occurring during crop yield simulations [97].

Greenhouse gas measurement tells us about the changes happening in our environment due to natural and anthropogenic activities. Careful and explicit calculation of radiative forcing as a consequence of GHG emissions can help to provide an easy and more accurate assessment of climatic model projections by reducing uncertainties [98]. Uncertainties arising from bias correction techniques may be reduced by using a Bayesian-based indicator weighting approach in which the output from bias correction is compared with past observations. In that way, it can be decided which projection from which GCM can be used for further analysis [99].

8. Challenges

Crop production is facing multiple challenges across the globe due to climate change. Food insecurity is the largest challenge that is very likely to arise due to climate change impact on crop production at the global, regional, and local scale. Food insecurity comprises both crop production and inequitable access to food. Major consequences of climate change that create challenges in crop production include rise in temperatures, changes in precipitation patterns, reduced water availability, and increase in extreme weather events [100,101]. In the past few years, extreme events, such as droughts, floods, etc., due to climate change are becoming frequent. Such extreme events can threaten crop production significantly [102]. However, estimation of climate change impact on crop production with high precision by using existing models is very challenging [103]. Especially, estimating the projected impact of climate change on crop production is associated with high uncertainty. These are the main and critical challenges for policymakers for policy formation and implementation of these policies. By overcoming these challenges, policymakers will be able to ensure food security for a growing population. It is essential to estimate and minimize uncertainty in the projected assessment with technological improvement because relatively few researchers addressed the uncertainty in the assessment. In Figure 3, the challenges for crop production due to climate change and their potential solutions are illustrated with the help of the drivers–pressures–state–impact–response (DPSIR) framework.

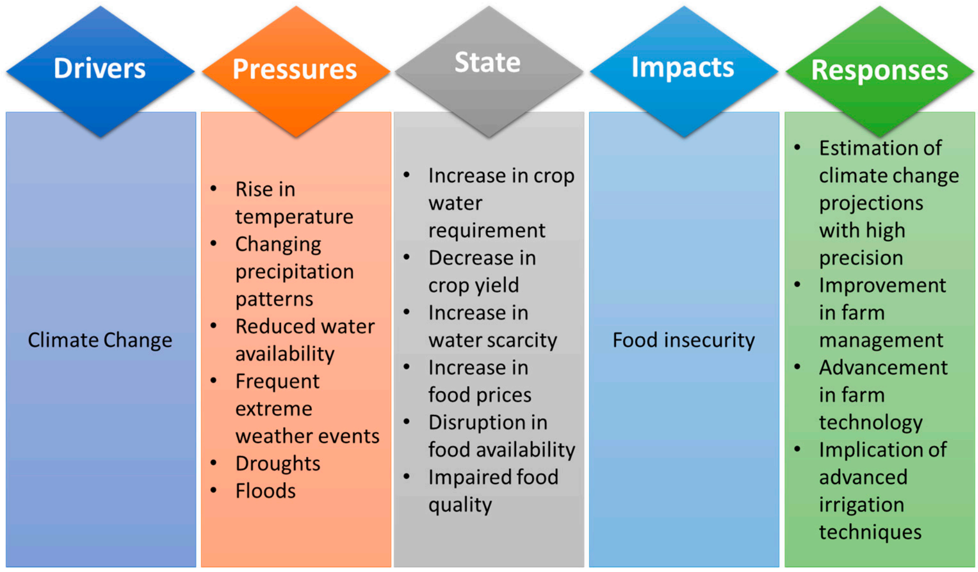

Figure 3. DPSIR framework to examine the impacts of climate change on crop production.

9. Conclusions

This review elaborates on the importance of climatic models for their use in the agricultural field of research. Many studies in the past have used different climate change models to predict agricultural yields. Under climate change impact, the projections of the temperature show an increasing trend, but rainfall may increase or decrease under future climatic projections due to spatial variations and the type of climatic models used. Various crop models have been used to evaluate climate change impact on three main cereal crops (wheat, rice, and maize). Based on a review of different studies, it can be concluded that almost all the main wheat-producing regions, such as Canada, Oklahoma in the United States, and the United Kingdom, may experience an increase in wheat yield. Moreover, the wheat yield in the northern regions of China and India also may increase. However, Pakistan and European Russia may face reverse effects. On the other hand, rice yield is more likely to decrease in most of the main rice producing countries around the world. However, the rice yield is more likely to be increased in Myanmar due mainly to the significant increase in precipitation. Maize yield is more likely to increase due to climate change, especially near the North Pole, such as in Canada. However, the maize yield is expected to decrease in countries that are relatively near the equator, such as Indonesia and Mexico. The decrease in cereals crop yield can be more significant in countries where the temperature may increase and precipitation may decrease.

Based on the projected variation in cereals crop yield due to climate change, the most important recommended adaptation actions are shifting the crop calendar, irrigation management, crop variety improvement, better nutrient management, and expanding agricultural areas to gain more yields under sustainable resource consumption. These adaptation measures are suggested to be the most important and effective plans to increase farmers' total production in different parts of the world.

Future yield predictions may have a different source of uncertainties; their occurrence may either be from crop models or climate projecting models. Crop models are considered to incorporate more uncertainties in future yield predictions than climatic models due to the difference in the model structure, data assimilation errors, and other human and random errors. Meanwhile, climatic uncertainties may occur due to different GCM, bias correction techniques, and periods used by climate change researchers. Developing a temperature response function and the multi-model ensemble are suggested to be helpful to reduce crop model uncertainties. Moreover, correct radiative forcing measurement as a consequence of GHG emissions and comparing the bias correction results with the past climatic trends may reduce uncertainties in future climatic projections.

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References

1. IPCC. *Climate Change 2021: The Physical Science Basis Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 6th ed.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021.
2. Campbell, B. Climate Change Impacts and Adaptation Options in the Agrifood System—A Summary of the Recent Intergovernmental Panel on Climate Change Sixth Assesment Report. Rome, Italy. 2022. Available online: https://www.fao.org/documents/card/en/c/cc0425en (accessed on 14 November 2022).
3. UN. Growing at a Slower Pace, World Population is Expected to Reach 9.7 Billion in 2050 and Could Peak at Nearly 11 Billion Around 2100 | UN DESA | United Nations Department of Economic and Social Affairs. United Nations Department of Economic and Social Affairs. 2019. Available online: https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html (accessed on 14 November 2022).
4. FAO. FAOSTAT—Crops and Livestock Products. Food and Agriculture Organization (FAO). 2020. Available online: https://www.fao.org/faostat/en/#data/QCL (accessed on 14 November 2022).
5. Islam, S.M.F.; Karim, Z. World's Demand for Food and Water: The Consequences of Climate Change. In *Desalination—Challenges and Opportunities*, 1st ed.; Farahani, M.H.D.A., Vatanpour, V., Taheri, A., Eds.; IntechOPen: London, UK, 2019; pp. 225–240.
6. UN. *The Sustainable Development Goals Report 2022*; UN: New York, NY, USA, 2022.
7. McKevith, B. Nutritional aspects of cereals. *Nutr. Bull.* **2004**, *29*, 111–142. [CrossRef]
8. Awika, J.M. Major cereal grains production and use around the world. In *Advances in Cereal Science: Implications to Food Processing and Health Promotion*, 1st ed.; Awika, J.M., Piironen, V., Bean, S., Eds.; American Chemical Society (ACS): Washington, DC, USA, 2011; pp. 1–13.
9. Corr, E.G. Societal Transformation for Peace in El Salvador. *Ann. Am. Acad. Political Soc. Sci.* **1995**, *541*, 144–156. [CrossRef]
10. Wang, J.; Vanga, S.K.; Saxena, R.; Orsat, V.; Raghavan, V. Effect of climate change on the yield of cereal crops: A review. *Climate* **2018**, *6*, 41. [CrossRef]
11. FAO. Climate Change and Food Security: Risks and Responses. Rome, Italy. 2015. Available online: https://www.fao.org/3/i5188e/i5188e.pdf (accessed on 14 November 2022).
12. Abelson, P.H. Agriculture and climate. *Science* **1992**, *257*, 9–10. [CrossRef]
13. UNFCCC. Climate Change Scenarios. In *CGE Training Materials for Vulnerability and Adaptation Assessment*, 1st ed.; United Nations Framework Convention on Climate Change (UNFCCC): Rio de Janeiro, Brazil; New York, NY, USA, 2006; pp. 1–35.
14. White, P.; Hilario, F.D.; de Guzman, R.G.; Cinco, T.A. *A Review of Climate Change Model Predictions and Scenario Selection for Impacts on Asian Aquaculture*; Kasetsart University: Bangkok, Thailand, 2009.
15. Santoso, H.; Idinoba, M.; Imbach, P. *Climate Scenarios: What We Need to Know and How to Generate Them*; CIFOR: Bogor, Indonesia, 2008; p. 45.
16. Chari, F.; Ngcamu, B.S. Climate change and its impact on urban agriculture in Sub-Saharan Africa: A literature review. *Environ. Socio-Econ. Stud.* **2022**, *10*, 22–32. [CrossRef]
17. Bedeke, S.B. Climate change vulnerability and adaptation of crop producers in sub-Saharan Africa: A review on concepts, approaches and methods. *Environ. Dev. Sustain.* **2022**, *2022*, 698. [CrossRef]
18. Reza, M.S.; Sabau, G. Impact of climate change on crop production and food security in Newfoundland and Labrador, Canada. *J. Agric. Food Res.* **2022**, *10*, 100405. [CrossRef]
19. Habib-ur-Rahman, M.; Ahmad, A.; Raza, A.; Hasnain, M.U.; Alharby, H.F.; Alzahrani, Y.M.; Bamagoos, A.A.; Hakeem, K.R.; Ahmad, S.; Nasim, W.; et al. Impact of climate change on agricultural production; Issues, challenges, and opportunities in Asia. *Front. Plant Sci.* **2022**, *13*, 925548. [CrossRef]

20. Suranny, L.E.; Gravitiani, E.; Rahardjo, M. Impact of climate change on the agriculture sector and its adaptation strategies. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1016*, 012038. [CrossRef]
21. Rezvi, H.U.A.; Tahjib-Ul-Arif, M.; Azim, M.A.; Tumpa, T.A.; Tipu, M.M.; Najnine, F.; Dawood, M.F.; Skalicky, M.; Brestič, M. Rice and food security: Climate change implications and the future prospects for nutritional security. *Food Energy Secur.* **2022**, *2022*, e430. [CrossRef]
22. Stocker, T.F.; Qin, D.; Plattner, G.K.; Tignor, M.M.; Allen, S.K.; Boschung, J.; Nauels, A.; Xia, Y.; Bex, V.; Midgley, P.M. Technical Summary. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1st ed.; Joussaume, S., Penner, J., Tangang, F., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013; p. 84.
23. UNDP. *Formulating Climate Change Scenarios to Inform Climate-Resilient Development Strategies*; UNDP: New York, NY, USA, 2011.
24. Kang, Y.; Khan, S.; Ma, X. Climate change impacts on crop yield, crop water productivity and food security—A review. *Prog. Nat. Sci.* **2009**, *19*, 1665–1674. [CrossRef]
25. Ferrand, E.A. Rainwater harvesting as an effective climate change adaptation strategy in rural and urban settings. In *Managing Water Resources under Climate Uncertainty*; Springer: Berlin/Heidelberg, Germany, 2007. [CrossRef]
26. IPCC. Summary for policymakers. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014.
27. Xiao, D.; Bai, H.; Liu, D.L. Impact of future climate change on wheat production: A simulated case for China's wheat system. *Sustainability* **2018**, *10*, 1277. [CrossRef]
28. Hussain, J.; Khaliq, T.; Ahmad, A.; Akhtar, J. Performance of four crop model for simulations of wheat phenology, leaf growth, biomass and yield across planting dates. *PLoS ONE* **2018**, *13*, e0197546. [CrossRef]
29. Chun-hong, Q.U.; Xiang-xiang, L.I.; Hui, J.U.; Qin, L.I.U. The impacts of climate change on wheat yield in the Huang-Huai-Hai Plain of China using DSSAT-CERES-Wheat model under different climate scenarios. *J. Integr. Agric.* **2019**, *18*, 1379–1391. [CrossRef]
30. Sultana, H.; Ali, N.; Iqbal, M.M.; Khan, A.M. Vulnerability and adaptability of wheat production in different climatic zones of Pakistan under climate change scenarios. *Clim. Chang.* **2009**, *94*, 123–142. [CrossRef]
31. Verchot, L.V.; Van Noordwijk, M.; Kandji, S.; Tomich, T.; Ong, C.; Albrecht, A.; Mackensen, J.; Bantilan, C.; Anupama, K.V.; Palm, C. Climate change: Linking adaptation and mitigation through agroforestry. *Mitig. Adapt. Strateg. Glob. Chang.* **2007**, *12*, 901–918. [CrossRef]
32. Tanaka, A.; Takahashi, K.; Masutomi, Y.; Hanasaki, N.; Hijioka, Y.; Shiogama, H.; Yamanaka, Y. Adaptation pathways of global wheat production: Importance of strategic adaptation to climate change. *Sci. Rep.* **2015**, *5*, 14312. [CrossRef]
33. Kumar, S.N.; Aggarwal, P.K.; Rani, D.S.; Saxena, R.; Chauhan, N.; Jain, S. Vulnerability of wheat production to climate change in India. *Clim. Res.* **2014**, *59*, 173–187. [CrossRef]
34. Geng, X.; Wang, F.; Ren, W.; Hao, Z. Climate Change Impacts on Winter Wheat Yield in Northern China. *Adv. Meteorol.* **2019**, *2019*, 2767018. [CrossRef]
35. Attri, S.D.; Rathore, L.S. Simulation of impact of projected climate change on wheat in India. *Int. J. Climatol.* **2003**, *23*, 693–705. [CrossRef]
36. Pavlova, V.; Shkolnik, I.; Pikaleva, A.; Efimo, S.; Karachenkova, A.; Kattsov, V. Future changes in spring wheat yield in the European Russia as inferred from a large ensemble of high-resolution climate projections. *Environ. Res. Lett.* **2019**, *14*, 2–12. [CrossRef]
37. Dhakal, K.; Kakani, V.G.; Linde, E. Climate Change Impact on Wheat Production in the Southern Great Plains of the US Using Downscaled Climate Data. *Atmos. Clim. Sci.* **2018**, *8*, 143–162. [CrossRef]
38. Morgounov, A.; Sonder, K.; Abugalieva, A.; Bhadauria, V.; Cuthbert, R.D.; Shamanin, V.; Zelenskiy, Y.; DePauw, R.M. Effect of climate change on spring wheat yields in North America and Eurasia in 1981- 2015 and implications for breeding. *PLoS ONE* **2018**, *13*, e0204932. [CrossRef]
39. Semenov, M.A.; Porter, J.R.; Delecolle, R. Climatic change and the growth and development of wheat in the UK and France. *Eur. J. Agron.* **1993**, *2*, 293–304. [CrossRef]
40. Gammans, M.; Mérel, P.; Ortiz-Bobea, A. Negative impacts of climate change on cereal yields: Statistical evidence from France Negative impacts of climate change on cereal yields: Statistical evidence from France. *Environ. Res. Lett.* **2017**, *12*, 054007. [CrossRef]
41. Qian, B.; Zhang, X.; Smith, W.; Grant, B.; Jing, Q.; Cannon, A.J.; Neilsen, D.; McConkey, B.; Li, G.; Bonsal, B.; et al. Climate change impacts on Canadian yields of spring wheat, canola and maize for global warming levels of 1.5 °C, 2.0 °C, 2.5 °C and 3.0 °C. *Environ. Res. Lett.* **2019**, *14*, 1–13. [CrossRef]
42. Wang, H.; He, Y.; Qian, B.; McConkey, B.; Cutforth, H.; McCaig, T.; McLeod, G.; Zentner, R.; Campbell, C.; DePauw, R.; et al. Impact of Climate Change on Wheat Production for Ethanol in Southern Saskatchewan, Canada. In Proceedings of the World Renewable Energy Congress, Linköping, Sweden, 8–13 May 2011. [CrossRef]
43. Ludwig, F.; Asseng, S. Climate change impacts on wheat production in a Mediterranean environment in Western Australia. *Agric. Syst.* **2006**, *90*, 159–179. [CrossRef]

44. Luo, Q.; Bellotti, W.; Williams, M.; Bryan, B. Potential impact of climate change on wheat yield in South Australia. *Agric. For. Meteorol.* **2005**, *132*, 273–285. [CrossRef]
45. Bua, B. Assessing the Importance of Rice as Food and Income Security Crop in Puti-puti Sub-county, Pallisa District, Uganda. *Am. J. Exp. Agric.* **2014**, *4*, 532–540. [CrossRef]
46. Ouma-onyango, A. Exploring Options for Improving Rice Production to Reduce Hunger and Poverty in Kenya Exploring Options for Improving Rice Production to Reduce Hunger and Poverty in Kenya. *World Environ.* **2014**, *4*, 172–179. [CrossRef]
47. Horie, T. Global warming and rice production in Asia: Modeling, impact prediction and adaptation. *Proc. Jpn. Acad. Ser. B* **2019**, *95*, 211–245. [CrossRef]
48. Timsina, J.; Humpherys, E. Applications of CERES-Rice and CERES-wheat in research policy climate change studies in Asia: A review. *Int. J. Agric. Res.* **2006**, *1*, 202–225. [CrossRef]
49. Saseendran, S.A.; Singh, K.K.; Rathore, L.S.; Singh, S.; Sinha, S.K. Effects of climate change on rice production in the tropical humid climate of kerala, india. *Clim. Chang.* **2000**, *44*, 495–514. [CrossRef]
50. Shakoor, U.; Saboor, A.; Baig, I.; Afzal, A.; Rahman, A. Climate variability impacts on rice crop production in. *Pak. J. Agric. Res.* **2015**, *28*, 19–27.
51. Yuliawan, T.; Handoko, I. The Effect of Temperature Rise to Rice Crop Yield in Indonesia uses Shierary Rice Model with Geographical Information System (GIS) Feature. *Procedia Environ. Sci.* **2016**, *33*, 214–220. [CrossRef]
52. FAO. *Rice Landscapes and Climate Change*; FAO: Bangkok, Thailand, 2019.
53. Babel, M.S.; Agarwal, A.; Swain, D.K.; Herath, S. Evaluation of climate change impacts and adaptation measures for rice cultivation in Northeast Thailand. *Clim. Res.* **2011**, *46*, 137–146. [CrossRef]
54. Shrestha, S. *Climate Change Impacts and Adaptation in Water Resources and Water Use Sectors Case studies from Southeast Asia*, 1st ed.; Springer: Cham, Switzerland, 2014.
55. Li, Y.; Wu, W.; Ge, Q.; Zhou, Y.; Xu, C. Simulating Climate Change Impacts and Adaptive Measures for Rice Cultivation in Hunan Province China. *Am. Meteorol. Soc.* **2016**, *55*, 1359–1376. [CrossRef]
56. Lv, Z.; Zhu, Y.; Liu, X.; Ye, H.; Tian, Y.; Li, F. Climate change impacts on regional rice production in China. *Clim. Chang.* **2018**, *147*, 523–537. [CrossRef]
57. Kawasaki, J.; Herath, S. Impact assessment of climate change on rice production in Khon Kaen province, Thailand. *J. ISSAAS Int. Soc. Southeast Asian Agric. Sci.* **2011**, *17*, 14–28.
58. Sinnarong, N.; Chen, C.C.; McCarl, B.; Tran, B.L. Estimating the potential effects of climate change on rice production in Thailand. *Paddy Water Environ.* **2019**, *17*, 761–769. [CrossRef]
59. Le, T.T.H. Effects of climate change on rice yield and rice market in Vietnam. *J. Agric. Appl. Econ.* **2016**, *48*, 366–382. [CrossRef]
60. Chung, T.T.; Jintrawet, A.; Promburom, P. Impacts of Seasonal Climate Variability on Rice Production in the Central Highlands of Vietnam. *Agric. Agric. Sci. Procedia* **2015**, *5*, 83–88. [CrossRef]
61. Candradijaya, A.; Kusmana, C.; Syaukat, Y.; Syaufina, L.; Faqih, A. Climate Change Impact on Rice Yield and Adaptation Response of Local Farmers in Sumedang District, West Java, Indonesia. *Int. J. Ecosyst.* **2014**, *4*, 212–223. [CrossRef]
62. Science, E. Quantification the Impact of Climate Change on Paddy Field Yield Production in Subang, Indonesia Quantification the Impact of Climate Change on Paddy Field Yield Production in Subang, Indonesia. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *187*, 012059.
63. Kabir, H. Impacts of Climate Change on Rice Yield and Variability; an Analysis of Disaggregate Level in the Southwestern Part of Bangladesh Especially Jessore and Sathkhira Districts. *J. Geogr. Nat. Disasters* **2015**, *5*, 1000148. [CrossRef]
64. Shrestha, S.; Thin, N.M.M.; Deb, P. Assessment of climate change impacts on irrigation water requirement and rice yield for Ngamoeyeik irrigation project in Myanmar. *J. Water Clim. Chang.* **2014**, *5*, 427–442. [CrossRef]
65. Stuecker, M.F.; Tigchelaar, M.; Kantar, M.B. Climate variability impacts on rice production in the Philippines. *PLoS ONE* **2018**, *13*, e0201426. [CrossRef] [PubMed]
66. Shah, T.R.; Prasad, K.; Kumar, P. Maize—A potential source of human nutrition and health: A review. *Cogent Food Agric.* **2016**, *2*, 1166995. [CrossRef]
67. Tigchelaar, M.; Battisti, D.S.; Naylor, R.L.; Ray, D.K. Future warming increases probability of globally synchronized maize production shocks. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 6644–6649. [CrossRef] [PubMed]
68. Msowoya, K.; Madani, K.; Davtalab, R.; Mirchi, A.; Lund, J.R. Climate Change Impacts on Maize Production in the Warm Heart of Africa. *Water Resour. Manag.* **2016**, *30*, 5299–5312. [CrossRef]
69. Barimah, P.T. Impact of climate change on maize production in Ghana. *A review. J. Agric. Sci. Appl.* **2014**, *3*, 89–93. [CrossRef]
70. Stevens, T.; Madani, K. Future climate impacts on maize farming and food security in Malawi. *Sci. Rep.* **2016**, *6*, 36241. [CrossRef] [PubMed]
71. Zilberman, D.; Goetz, R.; Garrido, A. *Climate Smart Agriculture Building Resilience to Climate Change*, 1st ed.; Springer Nature: Cham, Switzerland, 2018; Volume 52.
72. Akpalu, W.; Hassan, R.M.; Ringler, C. *Climate Variability and Maize Yield in South Africa: Results from GME and MELE Methods*; International Food Policy Research Institute: Washington, DC, USA, 2007.
73. Rurinda, J.; van Wijk, M.T.; Mapfumo, P.; Descheemaeker, K.; Supit, I.; Giller, K.E. Climate change and maize yield in southern Africa: What can farm management do? *Glob. Chang. Biol.* **2015**, *21*, 4588–4601. [CrossRef] [PubMed]

74. Li, X.; Takahashi, T.; Suzuki, N.; Kaiser, H.M. Impact of Climate Change on Maize Production in Northeast and Southwest China and Risk Mitigation Strategies. *APCBEE Procedia* **2014**, *2013*, 11–20. [CrossRef]
75. Moradi, R.; Koocheki, A.; Mahallati, M.N.; Mansoori, H. Adaptation strategies for maize cultivation under climate change in Iran: Irrigation and planting date management. *Mitig. Adapt. Strateg. Glob. Chang.* **2013**, *18*, 265–284. [CrossRef]
76. Meza, F.J.; Silva, D. Dynamic adaptation of maize and wheat production to climate change. *Clim. Chang.* **2009**, *94*, 143–156. [CrossRef]
77. Tao, F.; Zhang, Z. Adaptation of maize production to climate change in North China Plain: Quantify the relative contributions of adaptation options. *Eur. J. Agron.* **2010**, *33*, 103–116. [CrossRef]
78. Xu, H.; Twine, T.E.; Girvetz, E. Climate Change and Maize Yield in Iowa. *PLoS ONE* **2016**, *11*, e0156083. [CrossRef]
79. Chen, Y.; Zhang, Z.; Tao, F. Impacts of climate change and climate extremes on major crops productivity in China at a. *Earth Syst. Dyn.* **2018**, *9*, 543–562. [CrossRef]
80. Murray-tortarolo, G.N.; Jaramillo, V.J.; Larsen, J. Agricultural and Forest Meteorology Food security and climate change: The case of rainfed maize production in Mexico. *Agric. For. Meteorol.* **2018**, *253–254*, 124–131. [CrossRef]
81. Supit, I.; Van Diepen, C.A.; de Wit, A.J.; Wolf, J.; Kabat, P.; Baruth, B.; Ludwig, F. Assessing climate change effects on European crop yields using the Crop Growth Monitoring System and a weather generator. *Agric. For. Meteorol.* **2012**, *164*, 96–111. [CrossRef]
82. Hawkins, E.; Fricker, T.E.; Challinor, A.J.; Ferro, C.A.T.; Ho, C.K.; Osborne, T.M. Increasing influence of heat stress on French maize yields from the 1960s to the 2030s. *Glob. Chang. Biol.* **2013**, *19*, 937–947. [CrossRef] [PubMed]
83. Oktaviani, R.; Amaliah, S.; Ringler, C.; Rosegrant, M.W.; Sulser, T.B. *The Impact of Global Climate Change on the Indonesian Economy*; Food Policy Research Institute: Washington, DC, USA, 2011.
84. Fengmei, Y.A.O.; Pengcheng, Q.I.N.; Jiahua, Z.; Erda, L.I.N.; Vijendra, B. Uncertainties in assessing the effect of climate change on agriculture using model simulation and uncertainty processing methods. *Chin. Sci. Bull.* **2011**, *56*, 729–737. [CrossRef]
85. Aggarwal, P.K. Uncertainties in crop, soil and weather inputs used in growth models: Implications for simulated outputs and their applications. *Agric. Syst.* **1995**, *48*, 361–384. [CrossRef]
86. Wallacha, D.; Thorburnb, P.J. Estimating uncertainty in crop model predictions: Current situation and future prospects. *Eur. J. Agron.* **2017**, *88*, 1–7. [CrossRef]
87. Murphy, J.M.; Sexton, D.M.; Barnett, D.N.; Jones, G.S.; Webb, M.J.; Collins, M.; Stainforth, D.A. Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature* **2004**, *430*, 768–772. [CrossRef]
88. Stainforth, D.A.; Aina, T.; Christensen, C.; Collins, M.; Faull, N.; Frame, D.J.; Kettleborough, J.A.; Knight, S.; Martin, A.; Murphy, J.M.; et al. Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature.* **2005**, *433*, 403–406. [CrossRef]
89. Benjamin, D.M.; Budescu, D.V. The role of type and source of uncertainty on the processing of climate models projections. *Front. Psychol.* **2018**, *9*, 403. [CrossRef]
90. New, M.G.; Hulme, M. Representing uncertainty in climate change scenarios: A Monte-Carlo Representing uncertainty in climate change scenarios: A Monte-Carlo approach. *Integr. Assess.* **2000**, *1*, 203–213. [CrossRef]
91. Jacob, D.; Bärring, L.; Christensen, O.B.; Christensen, J.H.; de Castro, M.; Déqué, M.; Giorgi, F.; Hagemann, S.; Hirschi, M.; Jones, R.; et al. An intercomparison of regional climate simulations for Europe: Assessing uncertainties in model projections. *Clim. Chang.* **2007**, *81*, 53–70. [CrossRef]
92. Giorgi, F.; Francisco, R. Evaluating uncertainties in the prediction of regional climate change. *Geophys. Res. Lett.* **2000**, *27*, 1295–1298. [CrossRef]
93. Iizumi, T.; Takikawa, H.; Hirabayashi, Y.; Hanasaki, N.; Nishimori, M. Contributions of different bias-correction methods and reference meteorological forcing data sets to uncertainty in projected temperature and precipitation extremes. *J. Geophys. Res. Atmos.* **2017**, *122*, 7800–7819. [CrossRef]
94. Roberts, M.J.; Braun, N.O.; Sinclair, T.R.; Lobell, D.B.; Schlenker, W. Comparing and combining process-based crop models and statistical models with some implications for climate change. *Environ. Res. Lett.* **2017**, *12*, 095010. [CrossRef]
95. Maiorano, A.; Martre, P.; Asseng, S.; Ewert, F.; Müller, C.; Rötter, R.P.; Ruane, A.C.; Semenov, M.A.; Wallach, D.; Wang, E.; et al. Crop model improvement reduces the uncertainty of the response to temperature of multi-model ensembles. *Field Crop. Res.* **2017**, *202*, 5–20. [CrossRef]
96. Xiong, W.; Asseng, S.; Hoogenboom, G.; Hernandez-Ochoa, I.; Robertson, R.; Sonder, K.; Pequeno, D.; Reynolds, M.; Gerard, B. Different uncertainty distribution between high and low latitudes in modelling warming impacts on wheat. *Nat. Food* **2010**, *1*, 63–69. [CrossRef]
97. Wang, E.; Martre, P.; Zhao, Z.; Ewert, F.; Maiorano, A.; Rötter, R.P.; Kimball, B.A.; Ottman, M.J.; Wall, G.W.; White, J.W.; et al. The uncertainty of crop yield projections is reduced by improved temperature response functions. *Nat. Plants* **2017**, *3*, 1–11. [CrossRef]
98. Soden, B.J.; Collins, W.D.; Feldman, D.R. Reducing uncertainties in climate models. *Science* **2018**, *361*, 326–327. [CrossRef]
99. Asefa, T.; Adams, A. Reducing bias-corrected precipitation projection uncertainties: A Bayesian-based indicator-weighting approach. *Reg. Environ. Chang.* **2013**, *13*, 111–120. [CrossRef]
100. EPA. Climate Impacts on Agriculture and Food Supply. United States Environmental Protection Agency. 2017. Available online: https://climatechange.chicago.gov/climate-impacts/climate-impacts-agriculture-and-food-supply (accessed on 23 December 2022).

101. Future Learn. Impact of Climate Change on Agriculture. University of Reading, 2016. Available online: https://www.futurelearn.com/info/courses/climate-smart-agriculture/0/steps/26565 (accessed on 14 November 2022).
102. Beillouin, D.; Schauberger, B.; Bastos, A.; Ciais, P.; Makowski, D. Impact of extreme weather conditions on European crop production in 2018: Random forest—Yield anomalies. *Philos. Trans. R. Soc. B* **2020**, *375*, 20190510. [CrossRef]
103. Sharafati, A.; Tayyebi, M.M.; Pezeshki, E.; Shahid, S. Uncertainty of climate change impact on crop characteristics: A case study of Moghan plain in Iran. *Theor. Appl. Climatol.* **2022**, *149*, 603–620. [CrossRef]