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Review

Does Climate Change Affect the Yield of the Top Three Cereals and Food Security in the World?

Dhurba Neupane [1,*], Pramila Adhikari [2], Dwarika Bhattarai [3], Birendra Rana [4], Zeeshan Ahmed [5], Umanath Sharma [6] and Debraj Adhikari [7]

1 Department of Biochemistry & Molecular Biology, University of Nevada, 1664 N. Virginia St., Reno, NV 89557, USA
2 Department of Social Work, University of Nevada, Reno, NV 89557, USA; adhpramila@yahoo.com
3 Department of Agronomy, Horticulture, and Plant Science, South Dakota State University, Brookings, SD 57007, USA; Dwarika.Bhattarai@sdstate.edu
4 Department of Geography, University of Nevada, 1664 N. Virginia St., Reno, NV 89557, USA; brana@nevada.unr.edu
5 Cele National Station of Observation and Research for Desert-Grassland Ecosystem, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China; zeeshanagronomist@yahoo.com
6 Department of Biology, Memorial University of Newfoundland, 232 Elizabeth Avenue, St. John's, NL A1B 3X9, Canada; unsharmaa@gmail.com
7 Ministry of Agriculture and Livestock Development, Kathmandu 44600, Nepal; adhikari.debraj@gmail.com
* Correspondence: dneupane@unr.edu; Tel.: +1-775-409-2265

Abstract: Climate prediction models suggest that agricultural productivity will be significantly affected in the future. The expected rise in average global temperature due to the higher release of greenhouse gases (GHGs) into the atmosphere and increased depletion of water resources with enhanced climate variability will be a serious threat to world food security. Moreover, there is an increase in the frequency and severity of long-lasting drought events over 1/3rd of the global landmass and five times increase in water demand deficits during the 21st century. The top three cereals, wheat (*Triticum aestivum*), maize (*Zea mays*), and rice (*Oryza sativa*), are the major and staple food crops of most people across the world. To meet the food demand of the ever-increasing population, which is expected to increase by over 9 billion by 2050, there is a dire need to increase cereal production by approximately 70%. However, we have observed a dramatic decrease in area of fertile and arable land to grow these crops. This trend is likely to increase in the future. Therefore, this review article provides an extensive review on recent and future projected area and production, the growth requirements and greenhouse gas emissions and global warming potential of the top three cereal crops, the effects of climate change on their yields, and the morphological, physiological, biochemical, and hormonal responses of plants to drought. We also discuss the potential strategies to tackle the effects of climate change and increase yields. These strategies include integrated conventional and modern molecular techniques and genomic approach, the implementation of agronomic best management (ABM) practices, and growing climate resilient cereal crops, such as millets. Millets are less resource-intensive crops and release a lower amount of greenhouse gases compared to other cereals. Therefore, millets can be the potential next-generation crops for research to explore the climate-resilient traits and use the information for the improvement of major cereals.

Keywords: top three cereals; crop yield; climate change; greenhouses gases; population growth; food security; ABM practices; molecular techniques

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1. Introduction

Agriculture and climate change are interconnected with each other in different ways because climate change is the main cause of biotic and abiotic stresses that have adverse effects on agricultural production [1]. Climate change affects the global land area and its agricultural production in various ways, such as the differences in annual rainfall; average temperature; heat waves; CO_2 and ozone concentration; modifications in weeds; pests or microbes; wind composition; and the occurrence of natural disasters, for example, landslides, floods, and drought, exacerbating food security in the world [1,2]. The top three cereal grains, wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and rice (*Oryza sativa*), are the primary crops, globally consumed as staple foods by most of the population [3]. With the rapid increase in the world's population, as well as the concerns about environmental sustainability, a corresponding increase in food demand is a global concern [4,5]. To meet the projected demand of the estimated 9 billion global population by 2050, the world's food supply needs to be increased by approximately 70% [5,6] and 2–3% (annually) [7]. However, in the last decade, the productivity of the top three cereals, rice, maize, and wheat, has increased at a lower rate, with wheat presenting the lowest rate of increase. Nonetheless, the problem is further aggravated by a dramatic reduction in the amount of fertile and arable land, and water use to grow these crops, as well as by using agricultural products, such as biofuels [7].

Climate projection models (CPMs) have predicted that agricultural productivity will be significantly affected due to the depletion of water resources with enhanced climate variability, the frequent occurrence of drought events, rise in average global temperature because of GHG emissions, and a five times increase in water demand deficits during the 21st century, which is a serious threat to global food security [8–10]. Further, CPMs suggested that warmer temperatures and a reduced or seasonal redistribution of precipitation will lower maize yields if no sustainable adaptation majors are implemented by the mid and late 21st centuries [11,12]. The magnitude of the losses is predicted to be more severe in the regions with higher evapotranspiration rates (water vapor deficits) [13]. However, an indirect effect of higher temperatures on climate change includes shortening the number of calendar days allocated to the grain fill period by 15–25% because of less time for the starch deposition. Planting longer-season maize hybrids, which have the advantage of the additional thermal time for grain fill, can sustain or even increase maize yields under projected future climates compared to the currently used hybrids [14]. The Intergovernmental Panel on Climate Change (IPCC) [15] signals that a minimal increase in temperature can reduce agricultural productivity at lower latitudes and, at above two degrees of warming, can reduce potential yields in most regions of the globe. Further, FAO [16] concludes that over 800 million people are experiencing some form of food shortage in the food supply in recent years. A long-term study (1979–2016) conducted in China using a feasible generalized least square (FGLS) model to observe the impact of climate change on maize yield, reported the adverse effect of temperature on the maize yield, with a reduction in the maize yield by 5.2 kg from a 667 m^2 study area (77.8 kg ha^{-1}) for every 1 °C rise in temperature. However, the study reported a positive but overall negligible impact of precipitation on the maize yield [17]. Another study reveals that climate change decreased global agricultural productivity by ~1–5% per decade over the last three decades [18], and it is predicted that a decline in crop production by over 82% would be observed over the next century due to climate change [19]. Studies demonstrate a negative but significant relationship between agricultural productivity and climate change in African [20] and Asian countries and regions [21], which exacerbate food security and malnutrition problems in the regions.

Combating global climate change and providing sufficient food (nutritional) and energy requirements for an ever-increasing human population are the greatest challenges in recent years [22–25]. Expanding the global food supply, increasing agricultural productivity, and tackling nutritional challenges, while adapting to climate change, would seek alternative adaptative approaches over traditional approaches [26]. Thus, this necessitates developing climate-resilient crops that can maintain their productivity under extreme climate change scenarios, such as developing climate-resistant cultivars using conventional breeding techniques, as well as the use of modern molecular and genomic techniques [27,28]. Another approach to combat climate change while maintaining crop productivity would be the application of agronomic best management (ABM) practices, including an improvement of irrigation and fertilizer use efficiencies. Further, replacing resource-intensive crops with the less intensive crops, for example, millet (*Panicum miliaceum* L.), which use minimal amounts of water and fertilizer inputs compared to rice and maize, and are adapted to marginal lands, would be our major target for achieving food and nutritional security [3].

Therefore, this article provides a comprehensive review on the area and production of the top three cereal crops, their growing conditions, greenhouse gas (GHG) emissions from different crops, the response of climate change on cereal yields, and the morphological, physiological, biochemical, and hormonal response of plants to drought. This review also highlights the strategies to combat climate change and increase crop yield.

2. Current and Future Projected Areas under Cultivation and Total Production of Top Three Cereals

The production of cereal crops is affected by various factors that include resource and weather factors (e.g., rainfall/irrigation, latitude/radiation, soil properties/nutrients/fertilizers, and temperature and length of the growing season), and management and genetic factors (e.g., planting date/method, seeding rate/seeding depth, and cultivar, herbicide) [29]. Environmental factors, such as temperature and water availability, are vital for crop production. For example, wheat prefers a cooler temperature whereas rice requires a flooded condition. The production of crops, thus, varies by country and region of the world. In the last 60 years, the total area under cereal production has increased. According to Rithie and Rozer [30], approximately 37.6% (i.e., 4889 million hectares) of the total land area of the world (i.e., 13,003 million hectares) is classified as "agricultural area", out of which approximately 720 million hectares (ha) are used for cereal production, which is around 70 million ha more compared to the land area used for cereal production in 1961. Recent global market analysis by USDA [31] showed that the total area under the top 3 cereal crops production in the world was approximately 570.64 million ha in 2019/20, which is projected to increase by 2.87% (~to 587.03 million ha) in the 2021/22 growing season (Table 1). Accordingly, the total world production of maize, rice, and wheat in 2019/20 was approximately 1118, 498 and 763 million MT, respectively, which is projected to increase by 77, 8 and 29 million tons by 2021/22, respectively (Table 1).

Table 1. Area and production of rice, maize, and wheat crops in the world, according to the USDA Global Market Analysis report, 2021.

Crops	Area (Million Hectare)			Production (Million Tons)		
	2019/20	2020/21 (Pre.)	2021/22 (Pro.)	2019/20	2020/21 (Pre.)	2021/22 (Pro.)
Rice	160.39	162.56	162.90	497.74	504.94	506.04
Maize	194.05	197.28	199.64	1117.56	1120.65	1194.80
Wheat	216.20	221.86	224.49	763.49	775.82	792.40

Pre—preliminary data; pro—projected on July 2021.

The trend analyzed in the Global Market Analysis report by USDA [31] corroborates with the area (cultivated over 20 years) and the production trend, reported by FAOSTAT [32], produced in Figures 1–4. Overall, the global rice production area (156.83 million ha in 1999 to 162.05 million ha in 2019) and total production (611.17 million tons in 1999 to 755.47 million tons in 2019) increased by approximately 3.3% and 23.6% (Figure 1a,c, Table S1). However, from 2015 to 2019, the increases were negligible or decreasing trends were observed (Figure 1a,c). The future projected area for rice (170.49 million ha in 2050 to 176.17 million ha in 2070) and the total production (1049.30 million tons in 2050 to 1297.04 million tons in 2070) (generated using the ARIMA model) increased by 3.3% and 23.6%, respectively (Figure 1b,d).

Among different continents, the rice cultivated area and total production were highest in Asia, followed by Africa and South America, respectively (Figure 2a,c, Table S1). However, the rice production area was surpassed by Africa after 2016 (Figure 2c). Similar trends were observed for the simulated area and production of rice (Figure 2b,d, Table S1). The trends showed that rice production is dominant in tropical regions. The highest rice production in Asia can be attributed to the contribution of China and India, which together account for 49% of the world's rice production [33].

Similarly, an area attributed to maize production (137.25 million ha in 1999 to 197.2 million ha in 2019) and the total maize production (607.4 million tons in 1992 to 1148.48 million tons in 2019) significantly increased by 43.67% and 89.1%, respectively, from 1999 to 2019, throughout the world (Figure 1a,c, Table S2). However, in the major maize-producing regions, decreasing trends were observed since 2015/16. The simulated area and production of maize revealed an increase of 46.38% and 100%, respectively (Figure 1b,d, Table S2). Observing the scenarios of maize production area and total production among different continents, Asia shares the greatest maize production area; however, the highest total maize production was reported in Asia and North America (Figure 3a,c, Table S2). The ARIMA model showed similar trends, in which the highest maize production area and total production were reported on the Asian continent (Figure 3b,d). The trends of the maize production areas in other continents are stagnant from 1999 to 2019 and 2050 to 2070 (Figure 3a–d). The highest production of maize in Asia and North America can be due to better performing maize varieties and commercial-scale farming. The greatest projected increase in maize production from 2050 to 2070 can be attributed to the C4 photosynthesis of maize, because maize can produce greater yields, even at higher temperature and drought conditions, which is expected to occur in the future.

Furthermore, the overall wheat production area was consistent from 1999 to 2019 (212.53 million ha in 1999 to 215.9 million ha in 2019, which is ~1.6%) (Figure 1a, Table S3). However, the total production has increased drastically by 31%, from 584.76 (1999) to 765.76 million tons (2019). Nonetheless, total production started to decline in 2014/2015, which is now stagnant (Figure 1c, Table S3). The future simulated area and production of wheat (generated using the ARIMA model) suggested that the area under cultivation would be consistent with the recent area (1999 to 2019); however, production is estimated to increase by 18.62%, which is lower compared to the recent increase in production (Figure 1b,d, Table S3). Among different continents, Asia shares the greatest production area as well as the total production of wheat, followed by Europe and North America, respectively (Figure 4a,c, Table S3). The graph shows an almost similar wheat production area across a 20-year history, with some ups and downs; however, the overall wheat production in Asia and Europe increased in 2019, when compared to 1999. Similar trends of area under production and total production of wheat were projected from 2050 to 2070 (Figure 4b,d).

Across different continents, the average area and production (1999 to 2019) and simulated area and production (2050 to 2070) of rice, maize, and wheat are shown in Figures S1–S3, respectively. An average area under cultivation and the total production of rice and wheat are highest in Asia and lowest in Oceania. However, the average maize production is highest in North America. Based on our predicted trends, we found that the global yields of these top three cereal crops (rice, maize, and wheat) are increasing at 1.07%, 2.99%, and 1.20% per year, at non-compounding rates, respectively (Tables S1–S3) (Source: FAOSTAT [32]). However, these rates are less than the 2.4% per year rate needed to double global production by 2050 [34]. At these rates, the global production of these crops would increase on average by 23.6%, 100%, and 18.82%, respectively, which is far below what is needed to meet the projected demands for 2050.

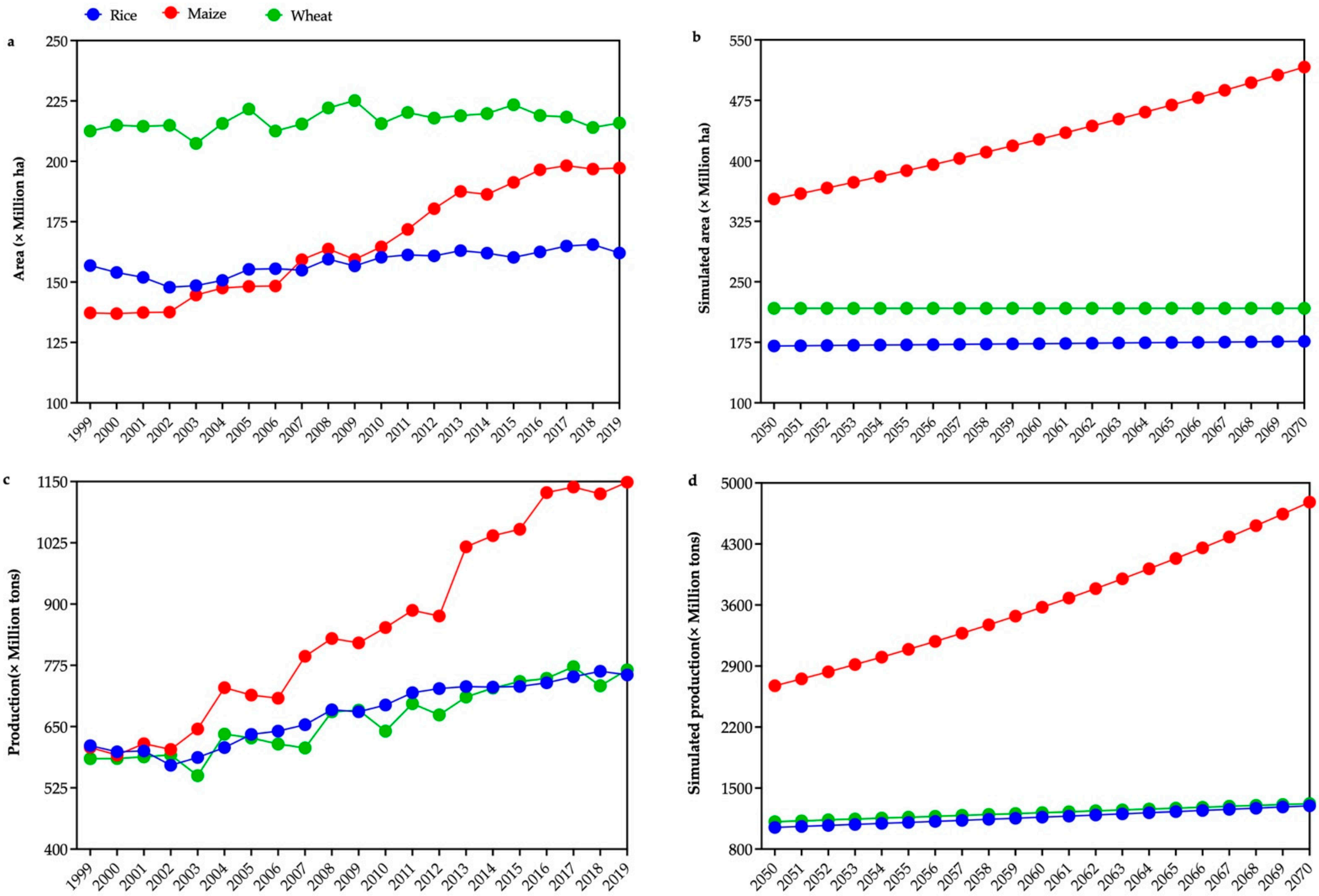

Figure 1. The overall trends of the rice, maize, and wheat (**a**) areas, (**b**) simulated area, (**c**) production, and (**d**) simulated production across the world. Area of production was measured in million ha and the total production was measured in million tons. Data source: FAOSTAT [32]. Under the Eview 12 software [35], the autoregressive integrated moving average (ARIMA) model was used to generate the simulated data for both the harvested crop area and total production. For the comparison, we obtained recent data (for the period ranging from 1999 to 2019) and the future simulated data (for the years ranging from 2050 to 2070). Data were visualized using GraphPad Prism version 9 (GraphPad Software, www.graphpad.com) (accessed on 1 August 2021).

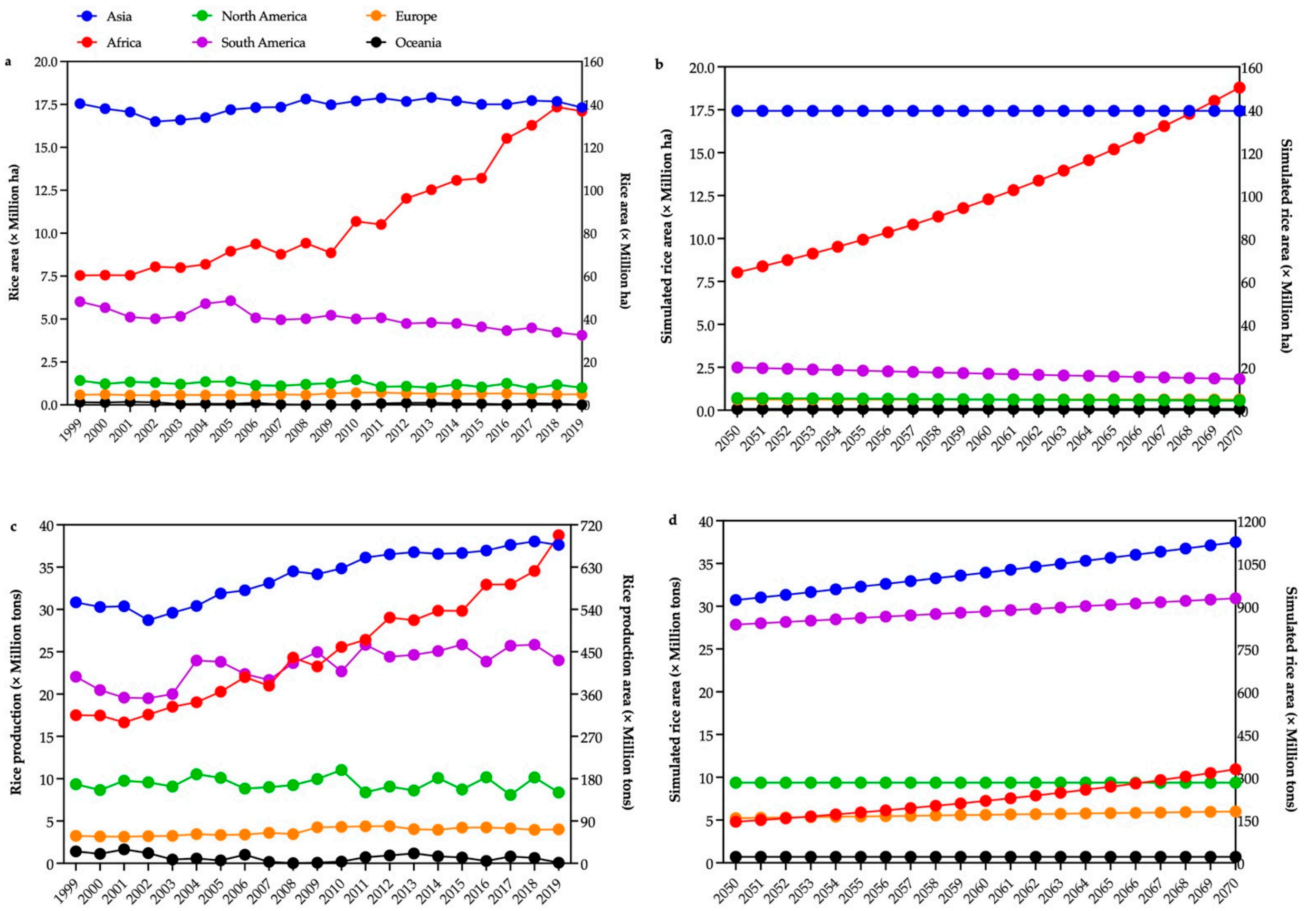

Figure 2. The trends of the rice (**a**) area, (**b**) simulated area, (**c**) production, and (**d**) simulated production across different continents of the world. Area of production was measured in million ha and the total production was measured in million tons. Area (Asia), simulated area (Africa and Asia), production (Asia), and simulated production (Africa, Asia, and South America) were shown on the right *Y*-axis, and other data were shown on the left *Y*-axis. Data source: FAOSTAT [32]. Under the Eview 12 software [35], the autoregressive integrated moving average (ARIMA) model was used to generate the simulated data for both the crop area harvested and total production. For the comparison, we obtained recent data (for the period ranging from 1999 to 2019) and the future simulated data (for the years ranging from 2050 to 2070). Data were visualized using GraphPad Prism version 9 (GraphPad Software, www.graphpad.com) (accessed on 1 August 2021).

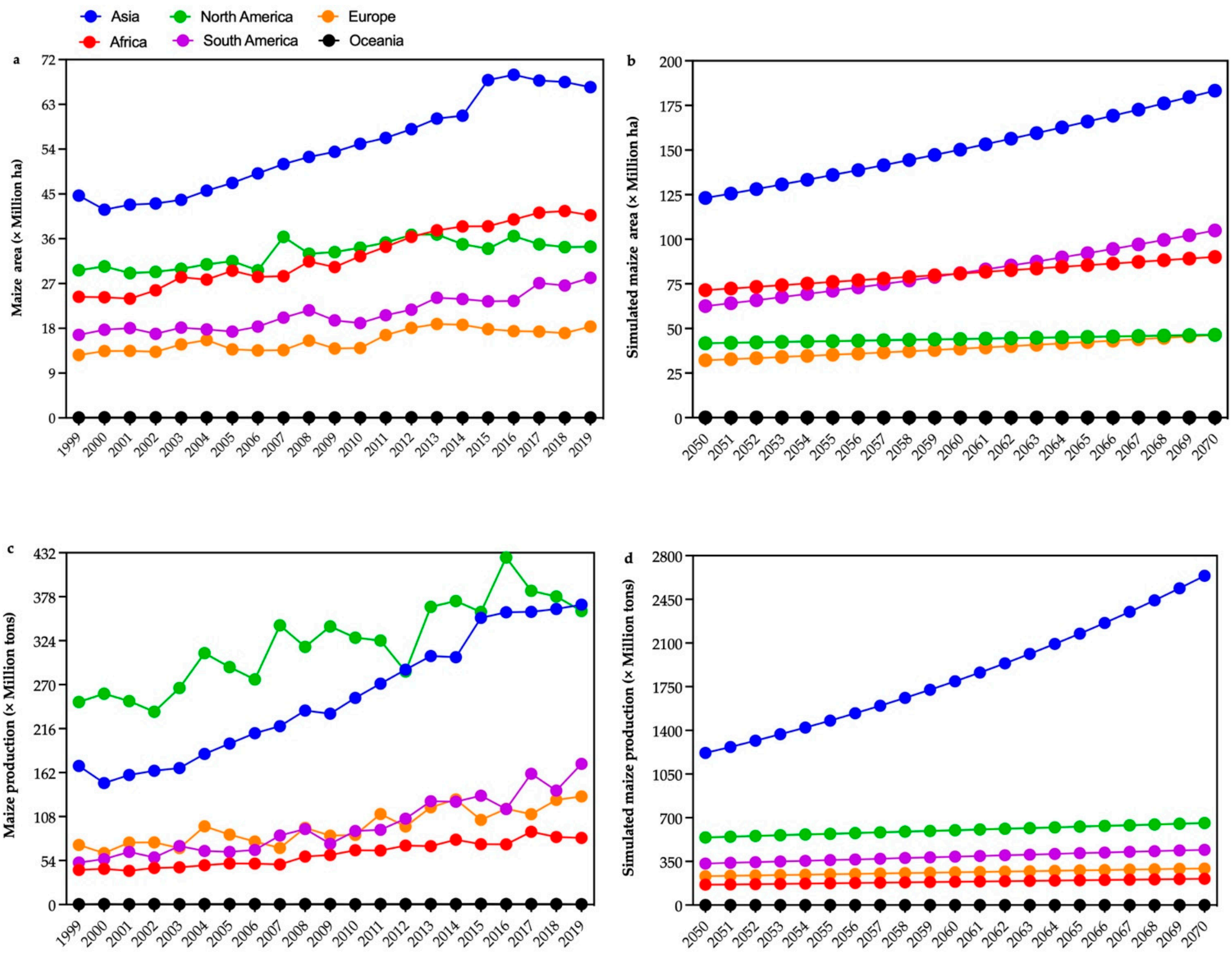

Figure 3. The trends of the maize (**a**) area, (**b**) simulated area, (**c**) production, and (**d**) simulated production across different continents of the world. Area of production was measured in million ha and the total production was measured in million tons. Data source: FAOSTAT [32]. Under the Eview 12 software [35], the autoregressive integrated moving average (ARIMA) model was used to generate the simulated data for both the crop area harvested and total production. For the comparison, we obtained recent data (for the period ranging from 1999–2019) and future simulated data (for the years ranging from 2050–2070). Data were visualized using GraphPad Prism version 9 (GraphPad Software, www.graphpad.com) (accessed on 1 August 2021).

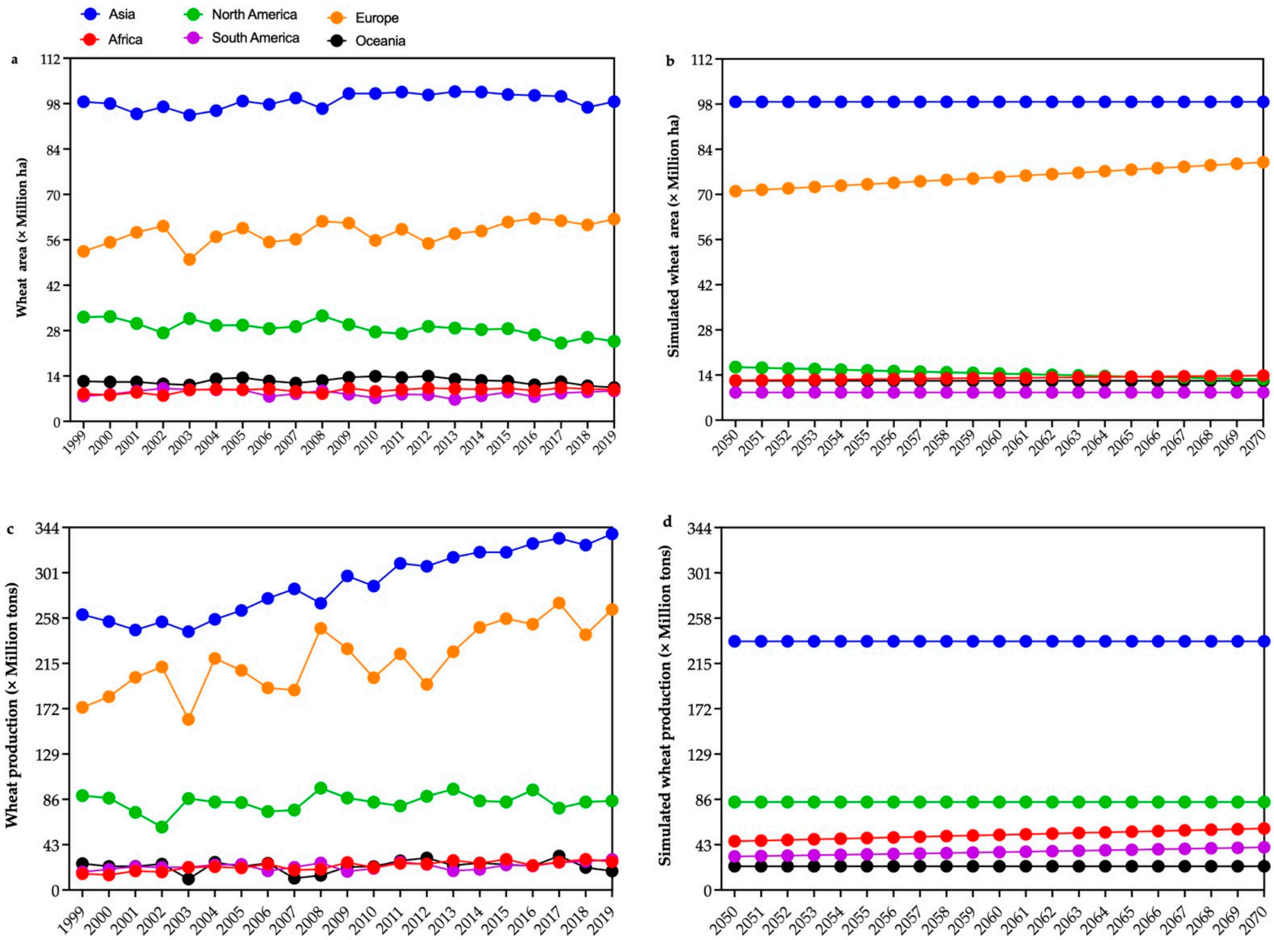

Figure 4. The trends of the wheat (**a**) area, (**b**) simulated area, (**c**) production, and (**d**) simulated production across different continents of the world. Area of production was measured in million ha and the total production was measured in million tons. Data source: FAOSTAT [32]. Under the Eview 12 software [35], the autoregressive integrated moving average (ARIMA) model was used to generate the simulated data for both the crop area harvested and total production. For the comparison, we obtained recent data (for the period ranging from 1999 to 2019) and future simulated data (for the years ranging from 2050 to 2070). Data were visualized using GraphPad Prism version 9 (GraphPad Software, www.graphpad.com) (accessed on 1 August 2021).

3. Significance and Requirements of Optimum Growing Conditions for the Top Three Cereals

Rice (*Oryza sativa* L.) is grown across 114 countries in the world, and over 50 countries produce over 100,000 tons per year. Rice, maize, and wheat are the main staple food for humans; however, rice is the most important food with respect to human nutrition and calorie intake because maize is used for purposes other than human consumption, such as, bioenergy feedstock. The export of rice is limited to only 5–6% worldwide because most of the rice grown is utilized in the countries from which it originates [36]. The description of the top three cereals is highlighted below.

3.1. Rice

Rice is the staple food for over 50% of the global population [37]. Approximately 90% of world's rice is produced (i.e., 11 countries in Asia) and consumed in Asia, and 11 countries in Asia contribute to ~87% of rice production, including China (28%), India (22%), Indonesia (10%), Bangladesh (7%), Vietnam (6%), Thailand (5%), Myanmar (4%), Philippines (2.5%), Japan (1.5%), Cambodia (1.3%), and Pakistan (1%) [37]. The export from 8 of these 11 countries in Asia constitutes about 35% of the global rice export, of which

China and India jointly constitute about 37% of the world's population and account for 49% of the world's rice production [33]. Therefore, the change in land-use patterns in Asian countries, especially China and India, will have a greater impact on rice production and global food security.

Rice is generally grown in flooded fields in over 95 countries in the world [38]. Rice requires a substantial amount of water for its optimum growth and development. The water input required for rice ranges from 500 to 829 mm depending upon the cultivars, growing conditions, and regions of its production (Table 2a). The optimum temperature for its growth ranges from 22–31 °C and needs 4–6 h of sunshine each day (Table 2a). Previous studies revealed that climatic conditions, particularly rainfall, irrigation, and temperature, can have a substantial effect on the yield of crops. The use of the continuous flooding method produced a higher rice yield (8.23 Mg ha^{-1}) compared to the rice grown using alternative wetting and drying irrigation systems (7.98 Mg ha^{-1}) (however, the difference was not significant) [39]. This was because rice used a total of 829 mm of irrigation water throughout the growing season in the "continuous flooding system" whereas, in the alternate ''wetting and drying system", rice only used a total of 757 mm of irrigation water [3].

The optimum soil pH required for rice growth ranged from 5.0–6.5. For growth, development, and its optimum yield, rice requires 90–120 kg, 30–40 kg, and 40–60 kg ha^{-1} of nitrogen, phosphorus, and potassium throughout its growing seasons. In addition, the use of pesticides is required in rice to protect the crop from spoilage (Table 2b).

3.2. Maize

Maize (*Zea mays* L.) is a wild grass of the Poaceae family. It is cultivated as a highland cereal and the main staple food crop in many developing countries in the world [40]. It is believed that maize was domesticated over 7000 years ago in Mexico and distributed rapidly throughout North and South America as a primary crop [41,42]. It is a third leading crop, after wheat and rice, in terms of its production [43]. Maize is considered a major crop for both human and animal consumption throughout the world. The nutrient content of maize is high, which contains 76–88% carbohydrates, 6–16% protein, 1.3% minerals, and 4–5.7% fats. Therefore, it is more nutritionally balanced and, agriculturally, small quantities of grain are used in livestock and poultry feed [44].

Maize is a warm-season crop that requires an optimum temperature range of 11–30 °C, with 6–7 h of sunshine per day (Table 2a). Wu et al. [17] used the pooled ordinary least squares (OLS) model from a long study (1979–2016) and resolved that an average temperature of 21.4 °C is required for maize growth and development. Rainfall requirements for maize were consistent from different studies; for example, 200–450 mm [45] and 571 mm [17] during the growing season. Maize is a C4 crop, so it is more water-efficient compared to C3 plants, such as rice and wheat. This is linked to the capacity of C4 plants that can fix carbon at high temperatures and low nitrogen levels due to their low transpiration rate. It has a life span of 90–110 days, depending on the weather conditions, such as the temperature and availability of rainfall (Table 2a). It prefers warm and silt loam soil, with a pH range of 5.8–7.0 (i.e., slightly acidic to neutral). An application of synthetic fertilizer is recommended to obtain optimum yields. The recommended dose of NPK for maize ranged 125–160, 55–80, and 85–110 kg ha^{-1}, respectively (Table 2b).

3.3. Wheat

Wheat is one of the most important food crops widely cultivated in many parts of the world. It provides a significant number of calories for about four billion people [46]. Based on the season of its growth, the wheat crop is classified as either spring wheat or winter wheat [47]. Spring wheat is usually planted between March and May and harvested between July and September. Spring wheat has a life cycle of about four months, which is considerably shorter than that of winter wheat, which takes approximately six months. Winter wheat is sown in October and November and harvested by June and July. Winter wheat sprouts before freezing occurs and stays dormant until the soil warms up in the spring. It requires around 3 weeks of cold temperature (i.e., −20 °C) before it flowers [3]. Results from a multi-crop and multi-climate model for wheat by the Agricultural Model Intercomparison and Improvement Project (AGMIP) revealed that estimated global wheat production will vary in the range of −2.3% to 7.0% under the 1.5 °C scenario, and −2.4% to 10.5% under the 2.0 °C scenario, compared with the baseline of 1980–2010, depending on the variations in local temperature, global atmospheric CO_2 concentration, and rainfall pattern, but irrespective of management change or wheat cultivars [48]. Therefore, it is imperative to implement measures, such as variations in the planting dates and irrigation management, developing heat and drought-resistant cultivars, improving storage capacity, and reducing trade barriers [49], which will help to acclimate to fluctuations in temperature and precipitation for improving food security.

Climate, soil, nutrient, and pesticide requirements for wheat growth and development are shown in Table 2a,b. The optimum temperature required for wheat growth is −3 to 23 °C, and its growing cycle ranges between 120 to 180 days, depending on spring and winter season cultivars. The wheat crop also requires 4 to 6 h of sunshine per day (Table 2a). It prefers sandy loam soils and the optimum pH range for wheat is between 5.5 to 6.5. Furthermore, nutrient requirements for wheat depend on its yield. However, for optimum production, it requires 70–200 kg of nitrogen, 20–40 kg of phosphorus, and 80–100 kg of potassium (Table 2b).

The overall impact of the agricultural system on carbon sequestration has been documented in various studies. For example, the positive effects of zero tillage (ZT) on crop production, water use efficiency, carbon sequestration, reducing heat stress in wheat, and reducing the cost associated during land preparation are well documented [50]. Conservation agriculture (CA) enhances system productivity and profitability, and reduces the negative effects of the environment with minimal soil disturbance and the inclusion of cover crops and diversified crop rotations [51]. This study also highlights the positive effects of CA on soil aggregation and total soil nitrogen accumulation compared to the conventional tillage (CT), which results in an increase in maize–wheat system productivity [51]. The positive effect of CA has been testified by another study that suggest that that CA-based agricultural management helps in carbon sequestration, as well as reverses the soil organic carbon loss under intensive cultivation [52–54]. CA with minimal tillage and precision nutrient management in the north-western Indo-Gangetic plains of India, reported an annual carbon-sequestration rate of 1.15 Mg C ha^{-1} $year^{-1}$ [55]. Similarly, the conversion of CT into NT can sequester about 0.43 Mg C ha^{-1} $year^{-1}$ of wheat cultivation [56], 0.57 Mg C ha^{-1} $year^{-1}$ in converting arable systems in no tillage systems globally [57], and 0.61 Mg C ha^{-1} $year^{-1}$ in Italy during fifteen years of NT in Mediterranean climate conditions [58].

Table 2. Suitable climatic conditions (i.e., rainfall, temperature, sunshine, and duration of growth) (**a**) and soil, fertilizer, and pesticide (**b**) requirements for the top three cereals are highlighted below.

(a) Climatic Conditions

Crops	Irrigation (mm)	Temperature (°C)	Sunshine (h/Day)	Duration of Growth (d)	Photosynthesis Pathway	References
Rice	500 to 60 (up to 829 mm [3])	22 to 31	4–6	90–120	C3	[39,59]
Wheat	60–90	−3 to 23	4–6	120–180	C3	[47,59]
Maize	200–450	11 to 30	6–7	90–110	C4	[44,59]

(b) Soil, Fertilizer, and Pesticide Requirements

Crops	Soil pH	Soil Type	N (kg/ha)	P (kg/ha)	K (kg/ha)	Pesticide	References
Rice	5.0–6.5	Flooded condition	90–120	30–40	40–60	Applied	[60,61]
Wheat	5.5–6.5	Sandy loam	70–200	20–40	80–100	Applied	[47,59,62,63]
Maize	5.8–7.0	Warm and silt loam	125–160	55–80	85–110	Applied	[44,45]

4. Greenhouse Gas Emissions and Global Warming Potential from Multiple Crops

Recent studies show that the global concentrations of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) are increasing rapidly, with the current levels being 40%, 20%, and 150% of pre-industrial age levels [3]. Greenhouse gas (GHG) emissions from agriculture are the major source of climate change, which contributes ~14% of anthropogenic GHG emissions via land-use change (~17%) [64]. At the global level, CO_2 emissions from human activities from different domains come from agriculture (43%), transportation (24%), industries (19%), and cities (14%). Similarly, methane (CH_4) gas is generated from animal husbandry (30%), rice plantation (22%), exploitation from oil deposits (17%), fires (11%), and waste decomposition (11%) [65]. Further, agricultural activities (particularly from cultivated lands) contributed to approximately 25% of CO_2, 50% of CH_4, and 70% of N_2O [66]. From a long-term perspective, GHG emissions from agricultural activities will have a significant impact on global temperature and climatic conditions [67]. A study from Loess Plateau of China revealed that net CO_2 emissions were reduced by 33.8% using no tillage (NT) (7.37 tons CO_2 equivalent ha^{-1} $year^{-1}$) compared with the emissions from conventional tillage (CT) (11.14 Mg CO_2 equivalent ha^{-1} $year^{-1}$) practices [68]. Another study reported a much higher carbon footprint of a 184.8 kg CO_2 equivalent from CT, compared to a 178.0 kg CO_2 equivalent from NT [69]. A greater carbon footprint from CT can be attributed to the higher amounts of mineral fertilizer used to produce a greater maize yield [70]. Further, an increase in the amounts of nitrogen (N) fertilization leads to a greater increase in GHG emissions from maize production [71]. Maize cultivation in the United States using the NT system with mineral fertilization can help to reduce GHG emissions by 6%, compared to CT with mineral fertilization [70].

Global warming potential (GWP) is an estimate used to evaluate the total quantity of heat that can be trapped in the atmosphere due to GHGs. The assessment of the global potential estimate is generally evaluated based on a 20- or 100-year duration, assuming that GHG has a higher thermal absorption rate and takes longer to decay, and it has a higher GWP [3].

A comprehensive meta-analysis of greenhouse gas (GHG) emissions of major cereal cropping systems and associated global warming potential (GWP) conducted by Linquist et al. [72], concludes that the GWP of CH_4 and N_2O emissions from rice (3757 kg CO_2 eq ha^{-1} $season^{-1}$) was much higher compared with wheat (662 kg CO_2 eq ha^{-1} $season^{-1}$) or maize (1399 kg CO_2 eq ha^{-1} $season^{-1}$). Further, they suggested that the yield scaled GWP was about 4 times greater for rice (657 kg CO_2 eq Mg^{-1}) compared with wheat (166 kg CO_2 eq Mg^{-1}) and maize (185 kg CO_2 eq Mg^{-1}). The higher GWP of emissions from the rice was mostly associated with CH_4 emissions that were not affected by the N input. An implementation of alternating wetting and drying techniques in rice, leads to a reduction in GWP and greenhouse gas intensity by 22% and 24%, respectively [73]. However, a report suggested that the GWP and carbon equivalent emission (CEE) of millet was the lowest, with the corresponding values of 3218 kg CO_2 eq ha^{-1} and 878 kg C ha^{-1}, respectively (Table 3). It can be recommended that millet is the better option to reduce the greenhouse gas emissions (reducing global warming) produced from agricultural operations because of its lowest GWP and lowest CEE amounts.

Table 3. Global warming potential and carbon equivalent emission of the top three cereal crops [74–81].

Crop	Global Warming Potential (kg CO_2 eq. ha^{-1})	Carbon Equivalent Emission (kg C ha^{-1})
Rice	2890–17,000	956–4600
Wheat	2000–18,000	545–4900
Maize	3427–17,600	935–4800
Millet	3218	878
Rice–Wheat *	7137–18,000	2000–4900
Wheat–Maize *	12,880–18,850	3512–5100

* Values represented are for the cropping system (2 seasons).

5. Cereal Crop Yield and Climate Change

Climate change is inevitable. Greenhouse gases (GHGs) are responsible for increasing the earth's temperature by trapping atmospheric gases, due to the thickening of the GHG layer and depleting the protective ozone layer [82]. With climate change, the yields of cereal crop have drastically changed in the long term [83]. For example, the impact of high temperatures on pollen viability, fertilization, and post-fertilization stages result in a sharp reduction in crop yield. The reduction in crop yield was associated with less time for photosynthesis and the accumulation of assimilates [83]. These trends can be attributed to an increase in the earth's temperature that has resulted in the expansion of dryland [84], desertification [85], flooding in the coastal regions [86], and other negative impacts on agricultural lands [87].

However, the relationship between the major three cereal crops' yield and temperature change, compared to the baseline climatology (based on the 1951–1980 average temperature of 15 °C), showed an increase in cereal yield with a marginal increase in the average temperature. A relationship between the cereal yield and temperature change showed that temperature change was positively correlated with the yields of rice, maize, and wheat, with the coefficient variation of 0.73, 0.80, and 0.76, respectively [32]. This change can be the result of escalated production in one region, while there is a sharp decline in production in different regions [88].

Previous studies have shown that the increasing temperature and variations in rainfall patterns have a significant impact on food production [89,90]. More evidence of low cereal production at any specific region as a result of climate change has been reported in several research articles. The use of different climate models in a rice research program in Thailand has predicted that rice production will decrease, due to an increase in temperature (approximately 3 °C) by the 2080s [91]. Soil biogeochemical processes can be altered by increasing the temperature, due to the variation in soil microbial composition, thereby influencing the soil sorption/desorption capacity [92]. These phenomena can lead to the accumulation of heavy metals in rice fields, resulting in a poor crop yield as well as a metal concentration in the grain [93]. Moreover, over the past century, the average global temperature has risen by 0.3 to 0.6 °C. This increase in temperature reduces the rice yield, due to the higher loss of carbon through increased respiration [94]. The flowers of the paddy also become sterile, disrupting the reproductive process of the plants, due to an increase in temperature. A simulated study conducted in different parts of Asia to observe the impact of atmospheric CO_2 levels on the productivity of rice, suggested that there will be a 4% reduction in the rice yield [95]. The same study also advised the growth of shorter maturing varieties with shorter ripening periods, to sustain its yield under climate change settings.

Global warming models predicted that a sharp increase in temperature (by 1.32 °C) would cause a decline in maize production (by 35%) in the northern region of China, compared with the productivity reported in 2008 [96]. Similarly, in the United States, global warming has resulted in maize yield reduction (by 2.5%) from 1970 to 1999. In addition to the temperature, irrigation also plays a vital role in maize production. The precipitation model projected a decline in maize production by 20 to 50%, based on the current emission situations [97]. Maize production was reduced by approximately 16.5% under non-irrigated conditions (10.68 tons ha^{-1}), compared to the well-irrigated conditions (12.44 tons ha^{-1}) [98]. A study performed in Africa, to evaluate the changes in maize yield with a 2 °C rise in temperature, and a 20% reduction in precipitation, reported a yield reduction by approximately 10% [99]. Another study reported the reduction in maize yield by 1% and 1.7% each day, when the crop was exposed to temperatures above 30 °C under rainfed and drought conditions, respectively [100]. This suggested that irrigation is vital for maintaining maize yield, which helps to withstand high temperature. A study revealed that maize pollen is sensitive to temperatures above 35 °C and loses its viability [101]. Moreover, extreme air temperatures are known to cause damage to tissues [102], and a higher accumulation of heat energy leads to yield loss [103].

Like rice and maize, wheat production will be severely affected by global climate change and extreme weather events, such as drought [3]. A study foresaw that there will be a decline in the wheat production in South Asia, by about 50% by 2050, which is approximately 7% of the global crop production [104]. The wetter winter resulting in waterlogging conditions can harm wheat production in the UK. Wheat is a temperature-sensitive species, so the weather conditions in western Europe, including the UK, are favorable for wheat production [105]. About 40% of the UK's arable land is used for wheat production [106]. It contributes to approximately 2% of the world's wheat production because of its high average yield of 8 tons ha^{-1}, compared to a world average yield of 3.5 tons ha^{-1} [107]. In Mexico, a projected decline in wheat yields by the 2050s has been reported [108], which can be the result of elevated CO_2 levels, with increased temperature and decreased rainfall. Demirhan [109] displayed that the wheat yield increased by 32.3 tons with a one-ppm increase in CO_2 emissions; however, the yield dropped by 90.4 million tons with a 1 °C rise in temperature. Studies also found a wide variation in wheat productivity in different regions or climatic conditions. A study suggested that the wheat yield in Northern China increased by 1–13%; however, a yield reduction of 1% to 10% was reported in southern China [110]. Moreover, irrigation plays a critical role in wheat productivity. Studies found that the wheat yield increased significantly under irrigated conditions compared with no irrigation, which can be due to the reason that irrigation increased "yield-attributing traits", such as tiller number, number of grains per spike, grain yield, and grain protein content [47].

At present, producers and economists around the world are worried about future food insecurity. The FAO data has shown that the "world cereal end stocks" declined from 860 million tons in 2017/18 to 817.5 million tons in 2021/22, which is projected to increase in 2022/23 [88]. The world cereal stock-to-use ratio has declined from 32.0 in 2017/18 to 29.2 in 2020/21, which, if this continues, can lead to a global cereal shortage in a few years. The World Food Program predicted that, by the end of the 2050s, countries, such as India, Myanmar, Egypt, Zambia, and Botswana, will have adverse food security. By the end of the 2080s, most of the countries in Asia and Africa will be food insecure countries due to the rise in temperatures and exhausting resources [111]. Studies suggested that climate change can cause a reduction in the yield of rice by 10–15% [112], maize by 34.6–35.4% [96], and wheat by 3.5–12.9% [113]. As previously reported, climate change can harm food production that triggered the rising in food prices by approximately 20% [114]. Global warming can cause an increase in the maize market price by 42–131%, by the 2050s. Similarly, a reduction in the yield of rice between 11–78%, and rice market prices are predicted to increase as a result of climate change [115]. Studies also advised that global warming and climate change tend make our food system unsustainable due to increasing food prices. This results in food insecurity issues in developing parts of the world, especially in Africa and Asia because they must spend a significant amount of their income on food [116]. Therefore, maintaining a food stability system is a great challenge and is inevitable to ensure sustainable food security.

6. Morphological, Physiological, and Biochemical Responses of Plants to Drought

Studies have shown that abiotic stresses (e.g., rainfall and temperature) have an adverse effect on a plant's morphological, biological, and biochemical mechanisms [1]. The optimum temperature for plant growth and development ranges between 10 to 35 °C. A minimal increase in temperature resulted in the deactivation of the ribulose-1,5 bisphosphate carboxylase-oxygenase (*Rubisco*) enzyme, which leads to the generation of xylulose -1,5-bisphosphate, an inhibitory compound. At an increased temperature, *Rubisco* did not work accurately because the *Rubisco* activase broke down and was unable to activate *Rubisco* [117]. Reduction in photosynthesis is attributed to the decrease in turgor pressure, stomatal closure, limited gas exchange, reduction in CO_2 assimilation, and impairment of photosynthetic apparatus, mainly PSI and PSII, and enhanced metabolite fluxes [118,119]. Water shortage in soils increases the salt concentration and decreases the water potential of the soil as compared to the plant cell. This results in a decrease in the turgor pressure and, therefore, delays cell development. Increased metabolite fluxes cause the formation of free radicals that delays development by stimulating oxidative stress inside the cell. The opening and closing of the stomata mainly balances water vapor loss and CO_2 uptake [120], and is greatly affected by the conditions inside or outside the cell, such as availability of light, CO_2, the leaf-to-air vapor pressure deficit (VPD), and plant growth regulators and ions [121–124]. Stomata closure lowers CO_2 assimilation, and the stomatal and mesophyll exchange increases the diffusive resistance and metabolic reaction that causes photodamage [125]. When the turgor pressure decreases in a plant, the cell accumulates osmolytes, such as glycine betaine, proline, organic compounds, polyols, and ions, for maintaining osmolarity, and pH to sustain life [126]. The impact of drought stress on various morphological, physiological, and other biological processes in the top three cereal crops is highlighted in Table 4.

Table 4. Impact of drought stress on morphological, physiological, and biological processes in the top three cereal crops.

Crop	Findings	References
Rice	Increase in leaf rolling, biomass and root traits severely affected, decrease in elongation and expansion growth, and number of tillers as well as physiological traits, i.e., photosynthesis, transpiration, leaf area index, and water use efficiency	[127]
Wheat	Exposure to drought at anthesis reduces fertility by increasing pollen sterility, number of tillers and kernels per ear, and ultimately reduced yield	[128]
	Decreased photosynthesis rate, transpiration rate, stomatal conductance, mesophyll conductance, photosynthetic pigment content, leaf area, dry weight, and relative water content	[129]
	Well water conditions lead to an increase in aerial biomass, root dry biomass, and root length. However, water stress studies found a negative correlation between aerial biomass and root dry biomass, root length, and root weight density	[130]
	Reduced photochemical quenching, the efficiency of PSII, and potential photosynthetic quantum conversion of leaves	[131]
	Decreased rate of photosynthetic gas exchange parameters, leaf water potential, and osmotic potential	[132]
	Increased ground dry matter and grain yield under well water conditions. However, foliar and grain carbon isotope discrimination decreased upon stress	[133]
Maize	Decreased plant height, stem diameter, leaf area, number of leaves per plant, cob length, and shoot fresh and dry weight per plant. Total biomass accumulation at silking, grain filling, and maturity, reduced by 37, 34, and 21%, respectively	[134]
Triticale, field bean, maize, and amaranth	Field bean and maize acclimatized more effectively compared to triticale and amaranth, due to the synthesis of phenolic compounds that act as photo protectors to avoid damage to PSII	[135]

7. Responses of the Plant Hormone in Abiotic Stresses

Phytohormones play an important role in stress response by modulating various signal transduction mechanisms under climate change. Abscisic acid (ABA), cytokinin (CK), gibberellic acid (GA), auxin, and ethylene are major phytohormones that play key roles in plant adaptation to drought stress [136]. ABA plays a major role in the regulation of stress responses by interacting with other hormones (Figure 5). ABA synthesized in roots and translocated to leaves, initiates plant adaptation to drought stress via stomata opening and closure, seed germination, and dormancy. During stress conditions, plant growth is severely reduced, and it increases the ABA concentration in cells. ABA accumulation during drought stress conditions controls transpiration and impedes stomatal disclosure [137]. However, if drought occurs at the reproductive stage, the great limitation is a reduction in carbon gain upon stomatal closure, and ABA-induced senescence [138]. There are certain ABA signaling genes, such as *OsNAP*, *OsNAC5*, and *DSM2*, that are responsible for improving plant yield under reproductive drought [139–143]. CKs are involved in delaying premature leaf senescence and death, a useful trait for increasing grain yield. An increase in the expression of isopentenyltransferase (IPT), a CK biosynthetic pathway gene, is involved in stress adaptation by delaying drought-induced senescence and increase crop yield [144,145]. A sharp decrease in the amounts of endogenous GA in plants, due to drought stress, leads to growth inhibition [146]. Auxin has a negative effect in the regulation of drought stress in plants. Similarly, ethylene is also the negative regulator of drought stress response by promoting leaf senescence, and reduces root growth and development, shoot and leaf expansion, and photosynthesis. Ethylene acts as signaling pathway in plant growth and weather conditions. Abiotic stresses, including water logging, high temperatures, salinity, frost, drought, nutrient deficiency, and heavy metal contact, moderate the biosynthesis of ethylene [147]. Furthermore, brassinosteroids, jasmonic acid (JA), salicylic acid (SA), and strigolactone are equally responsible in plant growth and development [148]. Thus, the overall drought stress response is regulated by the balanced combinations of different hormones that promote and inhibit the plant traits. For example, tillering in rice is the result of an interacting effect among three hormones, CK, auxin, and strigolactone (SL). CK promotes branching whereas the other two hormones impede branching, signifying that hormones interact and modulate each other's biosynthesis and responses, rather than acting individually [149]. Further, ABA plays a key role during plant adaptations to cold temperatures. Cold stress stimulates the synthesis of ABA, and the exogenous application of ABA improves the cold tolerance in plants [150]. However, CK is an antagonist to ABA, and the exposure of plants in drought stress conditions results in decreased levels of CK [151]. Similarly, an exogenous application of BR induces the expression of stress-related genes, thereby sustaining of photosynthesis activity, the accretion of osmoprotectants, the activation of antioxidant enzymes, and the induction of other hormone responses [152].

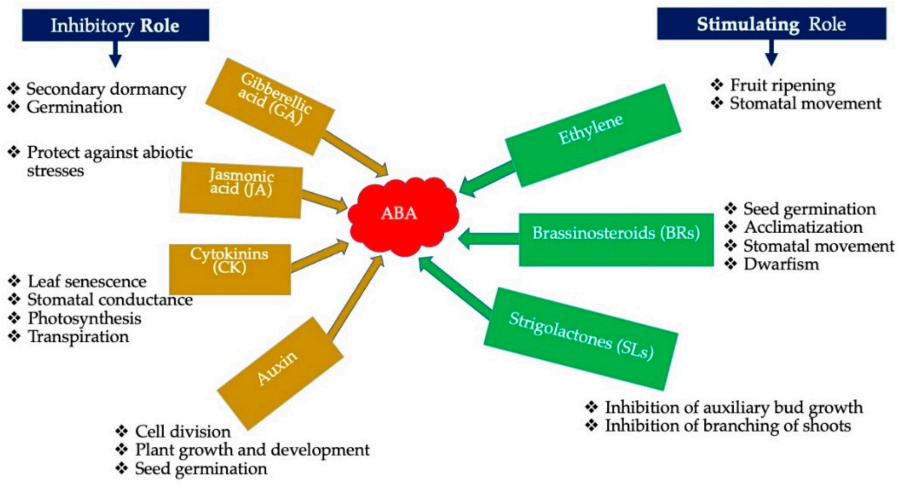

Figure 5. Hormonal crosstalk is related to different stresses. This was adapted from Raza et al. [1].

8. Strategies to Combat Climate Change and Increase Crop Yield

Alterations in the environmental conditions have a long-lasting effect on agriculture and food security in the world. Threats to food security and safety, due to weather conditions (e.g., variations in temperature and precipitation amounts), are not immediate and recent problems. Therefore, there is an urgent need to find strategies to cope with these weather variations. The approaches that are necessary for the crops to adapt to changing environmental stresses are described below.

8.1. Conventional Breeding Techniques

The stress responses to diverse abiotic factors are intertwined. Drought is a complex trait, and it is complicated to understand. Thus, the improvement of crops using hybridization and selection techniques is difficult to attain [153,154]. However, plant breeding reveals dynamic techniques in crop development under various abiotic stresses, by assisting plants to escape various stresses during the critical phase of plant growth, by developing stress-resistant cultivars [155]. Genetic divergence analysis is a crucial method for the development of new cultivars based on genetic distance and similarities. Genetic divergence analysis is applied in inbreeding, polymorphism, assessment, assortment, and recombination, to attain plant perfection [156,157]. Moreover, landraces are a crucial source for genetic studies. For example, wheat landraces that have been cultivated for thousands of years under different environmental conditions and stored in gene banks, present wider genetic diversity and provide a basis for stress adaptation because it contains cultivars adjustable to diverse environmental stress conditions [158]. Figure 6 demonstrates how genetic and genomic approaches are useful to develop the abiotic stress tolerance cultivars in cereal crops.

8.2. Modern Molecular Techniques and the Genomic Approach

Understanding the physiological, biochemical, and molecular mechanisms of plants in handling stress situations via modern molecular techniques and the genomics approach, and their engineering, provides a great potential for developing cultivars that are tolerant to stress [159]. Two groups of genes are involved in abiotic stress responses and tolerances. The first group includes genes that code for proteins, which are responsible for protecting cells from osmotic stress, late embryogenesis abundant (*LEA*) proteins, ferritin, lipid transfer proteins, water channels, and membrane transporters, and glutathione S-transferase (*GST*) and superoxide dismutase [160]. The second category includes genes performing regulatory functions, such as the signal transduction and activation of gene expression under stress; for example, transcription factors (*TFs*), protein phosphatases, protein kinases, and proteinases. Developing transgenic crops to improve stress tolerance involved engineering "single-action genes", which falls in the first category. However, engineering crops using a second category, such as TFs, improved the prospects of better stress tolerance because TFs can regulate several downstream stress-responsive genes [161–163].

Rapid advancements in genomics provide tools to find out the genetic basis of grain quality traits in cereals. For example, using a re-sequencing method in rice can improve its fragrance (*BADH2*, gene for fragrance in rice) and cooking temperature (*SSLLA*, starch biosynthesis gene). Similarly, RNA-seq in wheat improves the loaf volume (differentially expressed gene, *WBM*, encoding a small cysteine rich protein), wheat milling yield (encoding fasciclin-like arabinogalactan), and hardness (*PIN* genes) [164]. The resequencing of large-scale germplasm collection of 3010 diverse Asian cultivated rice genomes from the 3000 Rice Genomes Project, reported 29 million single nucleotide polymorphisms (SNPs), 2.4 million small indels, and over 90,000 structural variations between and within a population [165]. This study highlighted the use of the identified SNPs in the trait mapping analysis for highly heritable traits, such as grain length, grain width, bacterial blight resistance in rice [165]. Similarly, the resequencing of 278 maize inbred lines and greater variations in SNPs (27 million), indels (287,504), and copy number variations, can potentially be used as a selection index in future maize breeding programs [166]. Further, the genomic prediction was used to predict pearl millet hybrid performance, and the genome-wide association study (GWAS) predicted yield-associated traits in both irrigated and drought conditions [167]. Previous studies reported the use of SNPs in GWAS, and found the genomic regions and candidate genes for several agronomic traits; for example, abiotic stress tolerance in cereal crops, rice [168], pearl millet [169], barley [170], foxtail millet [171], sorghum [172], and several other crops [173,174].

Genomic technologies, implemented along with new methods of gene editing and genomic selection (GS), can accelerate the rate of genetic gains in crop breeding programs [173]. Therefore, employing these technologies will lower the breeding cycles along with breeding costs, whilst improving crop traits for adaptation to climate change and improving nutritional quality [175]. For example, cultivated barley (*Hordeum vulgare* L.) can be improved for drought tolerance by crossing it with its wild relative, *Hordeum spontaneum* L., which harbors alleles for drought tolerance [28,176]. For maize, drought tolerance can be achieved by using its wild relatives (teosinte), such as *Zea parviglumis* and *Tripsacum* [28,177]. Recent advances in gene-editing technologies, such as the CRISPR/Cas9 system, help to bridge the strong reproductive and genetic hurdles in gene transfer between cultivated crop species and crop wild relatives (CWRs) [178]. Millets can be used as a valuable genetic breeding tool. Foxtail millet harbors genes, alleles, and QTL for the genetic improvement of major cereal crops and bioenergy grasses [179,180].

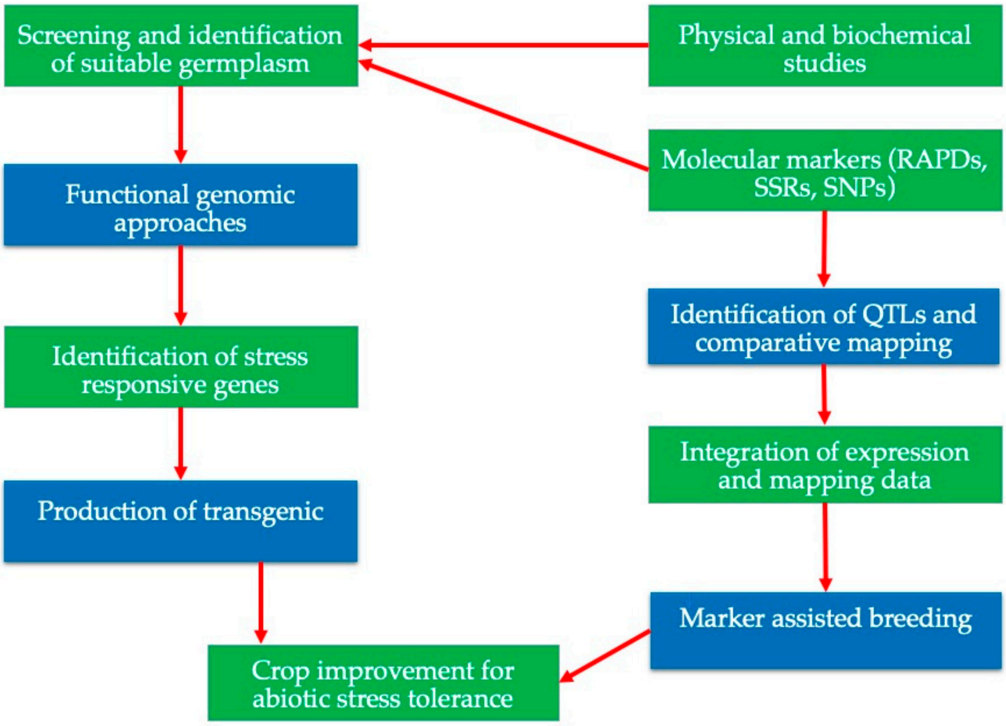

Figure 6. Integrated genetical and genomic approaches for abiotic stress tolerance in cereal crops, adopted from Lata and Shivhare [181]. For developing abiotic stress-tolerant crop plants, two key approaches, via which gene pools are identified through functional genomics approaches, can be implemented. The first approach is the identification of genes or quantitative trait loci (QTLs) conferring stress tolerance in the germplasm collection, the development of molecular markers, and their application in breeding programs, and the second approach is the introduction of a stress-responsive gene(s) into crops of interest via genetic engineering.

8.3. Agronomic Best Management (ABM) Approaches

Irrigation and fertilizer applications are vital for crop growth and development, and ultimately the yields of crops. However, some countries, particularly India, China, Mexico, and Pakistan, are facing water scarcity issues due to climate change, population growth, and the excessive use of fertilizers and chemicals [182]. A study reported that extreme weather events and global food demands are likely to cause a reduction in crop yield, including rice production, thereby threatening food security. Approximately 20% of irrigated areas in rice are predicted to suffer from physical water scarcity, by 2025. It is crucial to address and manage the water scarcity issues for achieving sustainable development goals and a cleaner production system [183]. One major strategy to improve water use efficiency and increase the crop yield is to use the drip irrigation system. A study conducted in California that evaluated the water use efficiency for diverse cultivation techniques, has found that the water use efficiency of the drip irrigation system was 88–90%, compared with that of sprinkle irrigation (70–90%) and surface irrigation (60–85%) [184]. Thus, using a drip irrigation system can save over 50% of water, and, at the same time, improve crop yields.

The drip irrigation system reduces water losses at conveyance and is highly effective. It is a water-saving and is less laborious in the time it takes during the watering process, than sprinkler irrigation system [50]. Alternating wetting and drying (AWD) is another viable option. A study reported that by implementing AWD techniques correctly, approximately 38% of the water demand for low land rice can be reduced without an adverse effect on the crop yield [185]. Using these techniques, the cost associated to water pumping and used fuel can be minimized and increase the farmers' income in developing countries, such as 17% in southern Vietnam, 32% in the Philippines, and 38% in Bangladesh [185]. An implementation of these cost effective techniques is crucial for rice cultivation because 30% of agricultural land devoted to cultivate irrigated rice consumed about 40% of irrigated water [186].

Likewise, studies have shown that the use of fertilizer improved the crop yield by 30–60% [187]. Nitrogen plays a key role in the regulation of the carbon cycle, which has a direct effect on the photosynthetic machinery of plants [188]. However, the excessive or under use of fertilizers has a negative effect on soil as well as the quality of cereal crops. Nutrient overload, for example N overuse, can lead to soil acidification, nitrogen leaching, and ammonia volatilization, which also contribute to adverse effects on environments [189]. A study conducted in China suggested that after 13 years of the production of crops, using excessive amounts of fertilizers resulted in a decline in soil pH to 4.3, causing a reduction in crop yields and their quality [190]. It is recommended to use a proper dose of fertilizers that can improve crop yields, but do not cause adverse environmental effects. However, nutrient deficiency, including th N_2 deficit condition, leads to stress conditions and activates the nutrient deprivation signal transduction. In nitrogen starvation conditions, plants use their stored nitrogen, as more than 50% of the leaf nitrogen is utilized in photosynthetic machinery; therefore, plants have to negotiate with the growth and yield [191]. In this situation, it is suggested to use diazotrophic bacteria that are abiotic stress tolerant and act as plant growth-promoting rhizobacteria (PGPR), to have a balanced nutrient flow between the plant–microbe–soil dynamic in stress conditions [192].

Likewise, other useful approaches for crop adaptability to climate change include changing/altering planting and harvesting time, planting cultivars with short life cycles, crop rotation, irrigation methods, and cropping schemes. The adjustment to sowing time, cultivating drought-resistant cultivars, and new crops are some of the useful strategies to minimize the negative feedbacks of climate change, and offer better adaptability options to crops for assuring food safety and security. The implementation of crop management techniques that enhance crop development under environmental stress conditions is another adaptation measure. Similarly, the choice of planting density, sowing time, and irrigation practices are vital techniques to combat weather stresses [1].

8.4. Cultivation of More Climate-Resilient Cereal Crops

Millet is a climate-smart crop containing a superior nutritive value compared with wheat and other major cereal crops, and is more resilient to climate stressors [193,194]. It also possesses a greater resilience to heat and drought, compared to wheat, rice, and maize [193]. Major morphological traits for climate resilience include small leaf area, short stature, thickened cell walls, and root systems [195]. It can be a great alternative to major cereal crops because of its adaptability to grow in marginal lands with limited soil water availability, poor soil fertility, high salt content, high temperature, and scant rainfall where major cereal crops perform very low [169]. Millet is a C4 crop that can fix carbon at a reduced transpiration rate compared with other cereal crops (C3 crop), such as rice and wheat [196]. CO_2 is found around ribulose-1,5 bisphosphate carboxylase-oxygenase (*Rubisco*), which suppresses ribulose-1,5-bisphosphate (RUBP) oxygenation and photorespiration [197]. *Rubisco* boosts the concentration of CO_2 in bundle sheath, and thus lowers photorespiration by around 80%, depending on the temperature and the catalytic activity of *Rubisco* in plants [198]. C3 has a high transpiration rate and therefore utilize a much higher amount of water compared to C4. Therefore, the yield reduction in C4 is much smaller compared with C3, due to its low moisture tolerance capacity. Since the *Rubisco* of C4 plants works at increased CO_2 levels, millets have enhanced photosynthetic rates at warm conditions, and have a water-use efficiency (WUE) and nitrogen-use efficiency (NUE) that is 1.5 to 4 times higher, compared to C3 photosynthesis [199,200]. Photo-respiration under elevated CO_2 and temperature in the atmosphere is much lower for C4 crops [199]. Additionally, the climate projection model suggests that the yields of C4 crops are predicted to increase by up to 38%, compared to the stagnant yields of C3 crops [201]. Further, the secondary benefits from C4 photosynthesis include improved growth and ecological enactment in warm temperatures, improved flexible allocation patterns of biomass, and reduced hydraulic conductivity per unit leaf area [200]. Considering the above-mentioned traits, millets can be the potential next-generation crops for research to explore the climate-resilient traits, and the information can be utilized for the improvement of major cereals [202].

9. Conclusions

Increasing drought leading to water stress in plants because of climate change is a major threat in reducing agricultural productivity, in the arid and semi-arid regions of the world. It imposes a major challenge to increasing crop production and environmental sustainability. The non-availability or/and less availability of water can lead to adverse effects on plant growth and development. The production of stress-tolerant crop varieties is necessary to immediately tackle the problem of climate change and to feed the ever-increasing world population, which is estimated to reach over 9 billion by the year 2050. There are continuing efforts to enhance crop production, globally. Conventional breeding approaches that include hybridization and selection techniques, did fail to further verify their potential due to signaling cascades and the complicated pathways involved. Therefore, advancements in approaches and the amalgamation of breeding, molecular markers, and genomic-based approaches, the cultivation of climate resilient crops, and the implementation of agronomic best management (ABM) practices, will help to introduce drought resistance in the crops and ultimately meet the objective of feeding the entire population of the world.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/earth3010004/s1. Table S1: Recent harvested area, and total production (1999–2019), and simulated harvested area and total production (2020–2070) of rice across different continents and the world. This also shows the recent average (1999–2019) and simulated average (2050–2070) area and total production, as well as the rate of change in production area and total production of rice in the world. Data source: FAOSTAT [32]. Under the Eview 12 software [35], the autoregressive integrated moving average (ARIMA) model was used to generate the simulated data for both the harvested crop area and total production. For the comparison, we obtained recent data (from 1999 to 2019) and the future simulated data (from 2050 to 2070). Table S2: Recent harvested area, and total production (1999–2019), and future harvested area and total production (2020–2070) of maize across different continents and the world. This also shows the recent average (1999–2019) and future average (2050–2070) area and total production, as well as the rate of change in production area and total production of maize in the world. Data source: FAOSTAT [32]. Under the Eview 12 software [35], the autoregressive integrated moving average (ARIMA) model was used to generate the simulated data for both the harvested crop area and total production. For the comparison, we obtained recent data (from 1999 to 2019) and the future simulated data (from 2050 to 2070). Table S3: Current harvested area, and total production (1999–2019), and simulated harvested area and total production (2020–2070) of wheat across different continents and the world. This also shows the current average (1999–2019) and simulated average (2050–2070) area and total production, as well as the rate of change in production area and total production of wheat in the world. Data source: FAOSTAT [32]. Under the Eview 12 software [35], the autoregressive integrated moving average (ARIMA) model was used to generate the simulated data for both the harvested crop area and total production. For the comparison, we obtained recent data (from 1999 to 2019) and the future simulated data (from 2050 to 2070). Figure S1: Average rice (**a**) area harvested (1999–2019), (**b**) simulated area (2050–2070), (**c**) production (1999–2019), and (**d**) simulated production (2050–2070) across different continents of the world. Area harvested and production were measured in hectares and tons, data source: FAOSTAT [32]. Under the Eview 12 software [35], the autoregressive integrated moving average (ARIMA) model was used to generate the simulated data for both the crop area harvested and total production. Maps were created by using ESRI ArcGIS Pro (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview) (Accessed on 1 November 2021). Figure S2: Average maize (**a**) area harvested (1999–2019), (**b**) simulated area (2050–2070), (**c**) production (1999–2019), and (**d**) simulated production (2050–2070) across different continents of the world. Area harvested and production were measured in hectares and t tons, data source: FAOSTAT [32]. Under the Eview 12 software [35], the autoregressive integrated moving average (ARIMA) model was used to generate the simulated data for both the crop area harvested and total production. Maps were created by using ESRI ArcGIS Pro (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview) (Accessed on 1 November 2021). Figure S3: Average wheat (**a**) area harvested (1999–2019), (**b**) simulated area (2050–2070), (**c**) production (1999–2019), and (**d**) simulated production (2050–2070) across different continents of the world. Area harvested and production were measured in hectares and tons, data source: FAOSTAT [32]. Under the Eview 12 software [35], the autoregressive integrated moving average (ARIMA) model was used to generate the simulated data for both the crop area harvested and total production. Maps were created by using ESRI ArcGIS Pro (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview) (Accessed on 1 November 2021).

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Abbreviations

GHGs: Greenhouse Gases; GWP: Global Warming Potential; CPMs: Climate Projection Models; IPCC: The Intergovernmental Panel on Climate Change; FAO: Food and Agriculture Organization; ha: Hectare; Mg: Megagram = 1000 kg.

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