The Impact of Climate Change on Agricultural Productivity and Economic Stability

Abstract

The title of a review "The Impact of Climate Change on Agricultural Productivity and Economic Stability" explores the multifaceted effects of climate change on global agriculture and its subsequent economic implications. As climate change accelerates, altering precipitation patterns, increasing the frequency of extreme weather events, and shifting temperature zones, agricultural productivity faces significant challenges. These environmental changes can lead to reduced crop yields, altered growing seasons, and increased pest and disease pressures. The study examines how these impacts vary across different regions, particularly affecting vulnerable and low-income communities that rely heavily on agriculture for their livelihoods. Furthermore, it investigates the broader economic consequences, including food price volatility, reduced food security, and economic instability. By employing a combination of climate models, agricultural simulations, and economic analysis, the study aims to provide comprehensive insights into the urgent need for adaptive strategies and sustainable practices to mitigate the adverse effects of climate change on agriculture and economic stability.

Keywords: stability, changes, climate, disease, economics, productivity

Introduction

Food insecure regions, particularly those in Asia, are particularly vulnerable to the effects of climate change, which poses a substantial danger to agricultural productivity. The livelihoods of farmers have been significantly impacted by climate-related extremes such as drought, heat waves, irregular rainfall patterns, storms, floods, and the emergence of insect pests[1]. In the future, climate forecasts indicate that there will be a large increase in temperature as well as irregular rainfall with a higher intensity. However, there is a degree of unpredictability in the patterns of climate that may be used to anticipate climate extremes[2]. Pakistan is expected to have an increase in maximum temperature of 2.8 degrees Celsius and a rise in lowest temperature of 2.2 degrees Celsius over the middle of the century (2040-2069). In order to mitigate the negative consequences of climate change, it is necessary to maximize climate-smart and resilient agricultural methods and technologies in order to achieve sustainable levels of productivity[3]. In order to measure the impacts of climate change on rice and wheat crops and to create adaptation methods for the rice-wheat cropping system throughout the middle of the century (2040-2069), a case study was carried out. Adaptation technology, such as altering sowing time and planting density of crops, crop rotation with legumes, agroforestry, mixed livestock systems, climate resilient plants, livestock and fish breeds, farming of monogastric livestock, early warning systems and decision support systems, carbon sequestration, climate, water, energy, and soil smart technologies, and promotion of biodiversity have the potential to reduce the negative effects of climate change[4].

Floods, droughts, heat stress, cold waves, and storms are examples of climate-driven extremes that have large negative consequences on the agriculture sector in Asia, notably the rice-wheat cropping system. Climate variability and climate-driven extremes are also a major contributor to these impacts[5]. As a result of these changes, the protein content and grain yield of wheat have dropped, the growth season for crops has been shortened, and crop evapotranspiration has begun to occur. The increase in temperature has also had a detrimental impact on the qualitative characteristics of wheat crops, such as the starch percentages, sugars, and protein content of the wheat production[6].

Fig 1 & 2. Effect of draught stress on agriculture

The unpredictability of the climate and the practices of human management have both contributed to changes in agricultural phenology in China. Temperature increases have led to a rise in the number of aphids that have infested wheat fields, which has led to a decrease in production. There is a correlation between increased temperatures and greater amounts of carbon dioxide in rice production and illnesses that are associated with climate change. One example of this is Fusarium head blight[7].

Rice production in Asia has been significantly influenced by climatic variability, with floods, droughts, heat stress, and water shortages lowering rice output in South Asia and other regions of Asia. This effect has been particularly pronounced in South Asia. The germination of seeds is also hindered by high temperatures and a lack of available water, which results in a lack of stand establishment and vigour in the seedlings[8].

Under RCP 8.5, the unpredictability of the climate might diminish agriculture water production by 32 percent or 29 percent by the year 2080. The booting and anthesis development stages of rice are negatively impacted by high temperatures in China and Pakistan, which ultimately leads to a drop in yield because of the conditions. Different agricultural models, such as DSSAT and APSIM, have predicted that the yields of rice and wheat harvests may decrease by as much as 19 and 12 percent, respectively, by the year 2069[9].

Asia is facing substantial challenges in the areas of agriculture, cattle, forestry, fisheries, and aquaculture as a result of climate change issues. Because of the detrimental effects that climate change would have on the quality and quantity of pastures, it is anticipated that 35 million farmers in Asia will start raising cattle as their primary source of income by the year 2050[10]. Extreme weather conditions, such as heat waves, will result in an increase in the number of disease infestations, a decrease in milk output, and a decrease in reproductive rates in animals. The quantity and quality of pasture that is available to cattle may decrease as a result of heat stress, which will have an impact on the demand for goods derived from livestock[11].

Fig 3. Livestock sustainability

As a result of climate change, timber forests, which yield a variety of benefits including food, fiber, and medicines, are also under danger. A total of 300 million people in India rely on forests for their food needs, as well as forty percent of rural households and one-third of the country's animal population[12]. Forests in Bangladesh are more likely to be affected by natural disasters such as fires, storm surges, and elevations in sea level, coastal erosion, and landslides. The restoration of forests and the fulfilment of rising needs for food, fibre, and medicine both require the implementation of climate adaptation techniques[13].

Asia is also home to a sizable aquaculture sector, which accounts for 80 percent of the world's total production and 52 percent of the wild-caught fish. A number of climate extremes, including but not limited to unpredictable rainfall, drought, floods, heat stress, salinity, cyclones, ocean acidification, and higher sea levels, have their detrimental impact on aquaculture. The consequences of climate change on agriculture, cattle, forestry, fisheries, and aquaculture in Asia are discussed in this study. The research also highlights the problems, possibilities, and mitigation techniques that are associated with these impacts[14].

Impact and changes in climate

The long-term mean climate will undergo major changes, which will have significant ramifications for the production of food throughout the world and may necessitate continual adaptation. On the other hand, increases in year-to-year unpredictability and extreme weather events may pose bigger threats to the nation's capacity to provide adequate food supplies[15]. Throughout the course of agricultural history, some of the most significant decreases in crop output have been attributable to occurrences of unusually low precipitation. Even very little variations in the average yearly rainfall can have an effect on productivity. For example, a change in the amount of precipitation that falls during the growing season by one standard deviation is related with a change in production that can be as high as ten percent[16].

The geographical and temporal distribution of monsoon rainfall is of critical importance to the growth of the agricultural sector in India. Meteorological data indicate that heatwaves were more often throughout the course of the twentieth century. Although individual heatwaves cannot be traced to climate change, the change in the probability of a heatwave may be attributed to climate change[17]. There was a particularly severe climatic event that occurred in Europe during the summer of 2003. The average temperatures were 6 degrees Celsius higher than normal, and there was a shortfall of up to 300 millimeters of precipitation. There was a record crop output loss of 36% in Italy for maize that was planted in the Po valley, which was characterized by unusually high temperatures prevalent throughout the year. It has been calculated that the likelihood of seeing such summer temperatures in Europe is now fifty percent higher as a direct result of the climate change caused by human activity[18].

The geographical location had a significant role in determining the criteria of what defines severe weather. It is possible that farming may adapt to increases in severe temperature occurrences in many locations by shifting to techniques that are currently utilized in warmer climates, such as cultivating crops that are more resistant of the extreme temperatures[19]. However, in areas where farming is practiced on the verge of crucial thresholds, increases in high heat or drought may change the local climate into a condition that has never been seen by humans in the past. This makes it impossible to determine the extent to which adaptation will be feasible[20].

Fig 4. Climate smart agriculture

In nations across Europe, crop yields may have been influenced by recent increases in climatic variability from about the middle of the 1980s. This may have caused more inter-annual variability in wheat yields compared to previous years. Even crops grown in mid-latitudes might be negatively affected by extremely high temperatures if adaption measures are not taken[21, 22]. It is possible for crop reactions to changes in growing circumstances to be nonlinear, to display threshold responses, and to be vulnerable to combinations of stress factors that have an effect on the crop's growth, development, and final output.

Alterations in temperature extremes over a short period of time can be quite dangerous, particularly if they occur at the same time as important phases of development. It is possible for crop reactions to changes in growing circumstances to be nonlinear, to display threshold responses, and to be vulnerable to combinations of stress factors that have an effect on the crop's growth, development, and final output[23].

There are many distinct definitions of drought, each of which reflects a different point of view. Drought is a worldwide phenomenon that has an impact on the agriculture industry. The significance of drought rests in the effects it has, and because of this, definitions ought to be region-specific as well as impact- or application-specific for those who make decisions. Agricultural drought, hydrological drought, socio-economic drought, and meteorological drought are the four primary forms of drought[24].

Since the 1960s, there has been an increase in the percentage of land that has been impacted by drought around the world. This change has occurred in the regions that have been planted for important crops such as wheat, barley, maize, rice, sorghum, and soy bean. There has also been a rise in the global mean PDSI, and simulations of climate models show that the observed drying trend in PDSI may have been caused by anthropogenic increases in the concentrations of greenhouse gases and aerosols[25].

In the context of pre-industrial settings, the 20th percentile of the PDSI distribution across time is the threshold that is used to characterize drought. There will be around twenty percent of the land surface that is considered to be in a drought state at any given moment. On the other hand, the circumstances in a place that is generally moist but is experiencing drought may nonetheless be less dry than those in another region that is dry under normally occurring conditions[26].

Fig 5. Burning of forest tree species

Taking a baseline of the long-term trend in yield and comparing it with actual yearly yields, Li et al. (2009) establish a yield reduction rate (YRR) that is related to climatic variability. This YRR is defined by comparing the baseline yield with the actual yields[27, 28]. It has been suggested by them that a linear link between YRR and a drought risk index that is derived from the PDSI may account for sixty to seventy-five percent of the observed YRRs. It is possible that the effects of dryness will cancel out the advantages of higher temperatures and longer seasons that have been observed in mid- to high-latitudes[29]. It was hypothesized by Alcamo et al. (2007) that a drop in agricultural output in certain parts of Russia may be compensated for by an increase in production in other regions, which would result in very minor average changes. On the other hand, their findings suggest that the frequency of food production deficits might increase by a factor of two in several of the primary crop growing regions in the 2020s and by a factor of three in the twentieth century[30].

There is also the possibility that heavy rainfall and floods will have an effect on food production. This can result in waterlogging of the soil, anaerobicity, decreased plant development, delayed farming activities, and adapted agricultural gear. A decreased grain quality, sprouting in the ear, and fungal disease infections of the grain were all associated with the heavy rainfall that occurred in the month of August. As the climate continues to warm, it appears that the fraction of total rainfall that falls during heavy rainfall events is increasing, and it is anticipated that this tendency will continue for the foreseeable future[31].

Climate change impact on crops

When it comes to the world food supply, crops cultivated in the United States are extremely important since they account for roughly 25 percent of all grains. Crop yields may be strongly impacted by a variety of factors, including fluctuations in temperature, atmospheric carbon dioxide (CO2), and harsh weather[32]. It is dependent on the crop's ideal temperature for growth and reproduction as to how the effect of increasing temperature will manifest itself. The warming of certain regions may be beneficial to crops that are traditionally cultivated there or may enable farmers to switch to crops that are produced in warmer regions. On the other hand, yields will decrease if the greater temperature for a crop is higher than the optimal temperature for that crop. Increasing levels of carbon dioxide (CO2) can have an impact on crop yields, and there are some laboratory research that show that increased CO2 levels might stimulate plant growth[33]. There are, however, additional elements that might potentially counterbalance these potential gains in production. These considerations include fluctuating temperatures, ozone, and water and nutrient restrictions. It is possible, for instance, that improvements in yield will be diminished or reversed if the temperature of a crop is higher than the ideal level, if there is insufficient water and nutrients available, and so on[34].

There is a correlation between increased severe temperatures and precipitation and the inability of crops to thrive. Severe weather events, such as floods and droughts, can cause damage to crops and reduce harvests. There is a possibility that dealing with drought may become difficult in regions where the rising summer temperatures lead the soils to grow drier. Increasing the amount of irrigation may also be challenging in certain locations[35].

Temperatures that are higher, climates that are wetter, and increasing amounts of carbon dioxide promote the growth of weeds, pests, and fungus. Every year, farmers in the United States spend more than eleven billion dollars combating weeds, which are plants that compete with crops for light, water, and nutrients[36]. There is a high probability that the ranges and distributions of weeds and pests may expand as a result of climate change, which may result in the emergence of new challenges for crops that were not previously affected. The increase in carbon dioxide levels can encourage the development of plants, but it also lowers the nutritional content of the majority of food crops, which poses a possible risk to human health[37].

Impact of climate change on livestock and fisheries

A number of severe dangers, such as heat waves, drought, parasites, and illnesses, are being brought about by climate change, which is affecting cattle. Temperature stress makes a person more susceptible to sickness, lowers their fertility, and reduces the amount of milk they produce. Due to the fact that drought affects the amount of high-quality fodder that is available to grazing animals, it poses a potential danger to pasture and feed supplies[38]. It is possible that climate change could also lead to an increase in the incidence of illnesses and parasites that afflict livestock. This is because milder winters and earlier springs would make it easier for some infections to thrive within animals[39]. In order to preserve the health of cattle in reaction to climate-induced changes in pests, parasites, and microorganisms, it is anticipated that potential adjustments in veterinary practices will be implemented. These changes may include an increased usage of parasiticides and other therapies for animal health. This may result in an increase in the danger of pesticides entering the food chain or may lead to the development of pesticide resistance, which will have an impact on the distribution, consumption, and safety of goods derived from livestock and aquaculture[40].

While increases in carbon dioxide (CO_2) may lead to higher pasture output, they may also lead to a decline in the quality of the pastures. The production of plants that are used as feed for cattle can be increased by a rise in CO_2 levels; however, this may also result in a reduction in the nutritional content of some forages that are present in pasturelands[41].

Temperature and seasonal shifts have the potential to influence the timing of reproduction and migration, which can result in significant reductions in the number of salmon stocks. Additionally, as a result of increases in carbon dioxide (CO_2) levels in the atmosphere, the seas of the world are showing signs of becoming more acidic. Shellfish might be harmed by this acidity because it could damage their shells, which are generated by extracting calcium from saltwater. Additionally, this acidification could undermine the structures of delicate ecosystems, which are dependent on certain fish and shellfish[42].

Direct effects of climate change on crop output

Through impacts on pests and disease, rising atmospheric CO_2 and climate change might indirectly affect crops. Aphids and weevil larvae are among the pests that benefit from higher CO_2; higher temperatures lower overwintering mortality, therefore allowing earlier and maybe more extensive distribution[43]. By effects of warmth or drought on crop resistance to certain illnesses and by increased pathogenicity of organisms resulting from environmental stress, climate change may potentially influence pathogens and disease. Disease affecting oilseed rape may expand to further northern areas and become more severe within its current distribution during the next ten to twenty years Variability of the climate might also be important as it influences the magnitude and predictability of outbreaks[44].

For agriculture, remote climatic changes are vital as irrigated agricultural land accounts for less than one-fifth of all planted lands yet generates between 40 and 45 percent of the global food production. Often taken from rivers dependent on far-off climatic conditions, including the Nile in Egypt, water for irrigation is taken from in other rivers, like the Nile, which would help agriculture, climate change might boost flow all year round[45]. In some catchments, such as the Ganges, however, the rise in run-off results in a corresponding rise in monsoon peak flow. Inadequate peak season flow storage might cause water shortage that would lower agricultural output even with general yearly water availability rise. Peak flow increases might also harm agriculture fields by flooding[46].

Changing patterns of snow cover drastically affect how water is stored and released in places where snow melt predominately controls river flow. If run-off can be stored during periods of excess to be used later in the growing season, then extra river-flow can help agriculture. Few rivers now have enough storage to handle significant run-off seasonal fluctuations[47].

Mountain glaciers feed major rivers like the Indus and Ganges, which account for around one-sixth of the world's population right now. These regions are expected to see notable population increase, which might affect food output. Globally, glaciers are shrinking; the main driver of retreat is warming. Initially increasing river-flow, melting glaciers will improve seasonality, therefore raising flood danger. Glacial retreat is predicted to be accelerated over long terms, which would finally cause run-off to decrease[48].

With about 15,000 glaciers in the Himalayas and 46,377 glaciers overall in western China, the Chinese Glacier Inventory classified these glaciers hold 12,000 km3 of pure water, about. Climate change may make the Indus and Ganges progressively seasonal rivers, stopping to flow during the dry season. This combination with a growing population indicates that future water shortage in the area would be projected to becoming more severe[49].

A warmer climate's unavoidable result from thermal expansion of ocean water and land ice melting is mean sea-level rise. This can finally lead to coastal land flooding, particularly in areas where there is quite limited or non-existent capacity for introduction or modification of sea defences. Where low-lying coastal agriculture exists in tandem with significant sea-level rise, crop output is most susceptible. Though the worst effects may not be visible for many centuries due to the time needed to melt big ice sheets and allow warmth to reach into the deep ocean, increases in mean sea level threaten to flood agricultural fields and salinize groundwater in the next decades to centuries[50].

Melt of the main ice sheets would cause potential sea-level rise of 5 m for West Antarctic Ice Sheet (WAIS), 60 m for East Antarctic Ice Sheet (EAIS), and 7 m for Greenland Ice Sheet (GIS). Though somewhat improbable, a maximum geostatic sea-level increase of around 2 m by 2100 is physically conceivable. Even in cases when land is not permanently lost, short-lived storm surges can inflict significant destruction[51].

<u>Prospects in the age of climate change for farming</u>

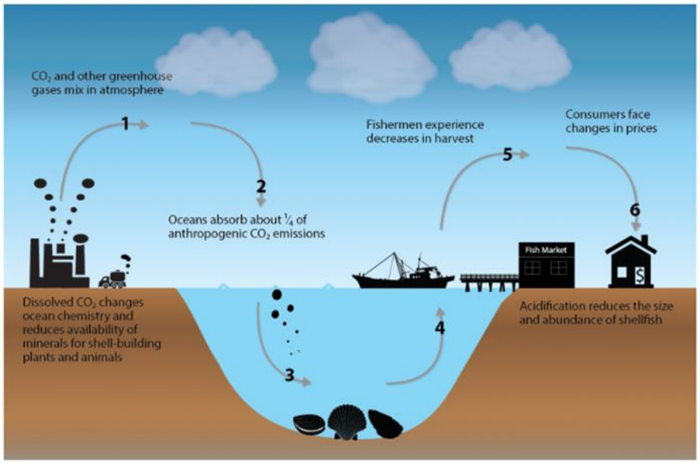
Agricultural production is much influenced by climate variability, which calls for the creation of adaptation plans and technologies to lessen its negative consequences. Resilient and climate-wise friendly agriculture methods can assist to guarantee sustained output and food security. Since it reduces harmful consequences of climate change for sustainable development, adaptation is the greatest approach to manage unpredictability and change in the climate. Defensive adaptation and innovative technology help to lower the unpredictable and negative effects of climate on agricultural output[52].

Common problems in underdeveloped nations that point to the need of mitigating and adapting strategies to maintain output are poverty, food insecurity, and declining agricultural production. Food security is the main factor determining the success of adaptation and mitigating both at the national and regional levels[53]. Promoting sustainability and productivity depends much on combining mitigating and adapting techniques, which presents a huge difficulty. Integration of land, water, forest biodiversity, cattle, and aquaculture helps one to build and diverse climate resilient agricultural production systems[54].

Major obstacles for the evolution of adapting and mitigating strategies are the decrease in greenhouse gas (GHG) emissions from agriculture under marginal conditions and the increased food production[55]. Essential is controlling agricultural practices that result in GHG emissions, including chemical fertilizer use and CH4 emissions from systems of cattle and rice farming. Minimizing tillage, lowering soil erosions, controlling soil acidity, and using crop rotation help to restore carbon from soil[56].

To thrive under difficult climatic conditions, creation of climate-resilient breeds of plants and animals with increased growth rates and reduced GHG emissions should be done. Especially for cattle, concentrating more on creative research and development for climate-resilient breeds is very vital[57].

Figure 1. Ocean Acidification Impact Pathway for Shellfish



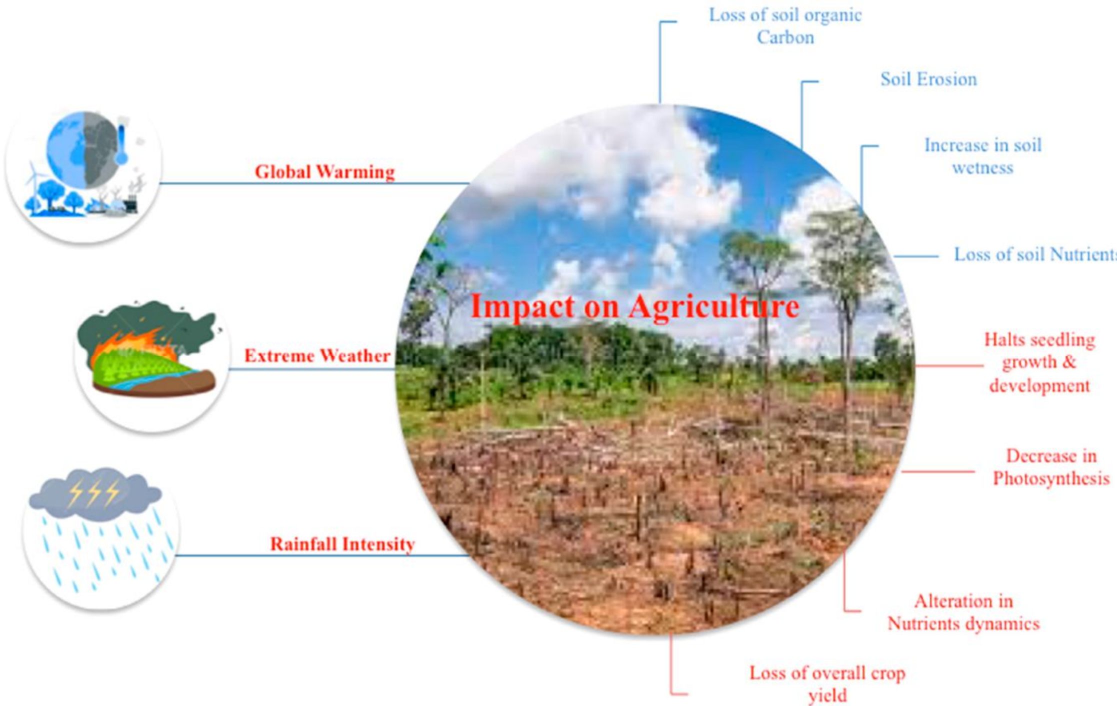


Fig 6. Different impacts on agriculture

Reducing and adjusting to the extreme consequences of climate variability and change can be much aided by ICT and decision support systems. Early warnings regarding natural catastrophes can come from early warning systems and autonomous weather stations, therefore supporting farmers' attempts to reduce negative consequences on ecosystems[58]. Furthermore helping to reduce and adapt to the negative impacts of climate change on agricultural production include geographical information systems, wireless sensor networks, mobile technology, web-based applications, satellite technology, and UAV[59]. Minimizing the negative consequences of climatic variability depends critically on crop management and cropping system adaptability. These approaches comprise dependable water collecting and conservation methods, punctual irrigation water application, and water conservation by means of varying irrigation volume. Significant beneficial impact comes from crop-specific management techniques include changing sowing timings, crop rotation, intercropping, crop diversification and intensification[60].

Sustainable production depends on adaptation efforts including soil, water, and crop preservation rather than substituting new energy crops. Well farm management and changing input utilization, fertilizer rates, and drought-resistant cultivars are therefore necessary. Furthermore included should be crops with climate resilience genetic features to guarantee sustainable output[61].

Sustainable livestock production methods combine rice fields for both rice and fish output, agricultural production, and rearing of animals. Activities connected to cattle adaptation techniques vary in pasture rates, rotation, grazing times, animal and fodder species variety, and combined production of both crops and cattle[62]. Sustainable cattle production should coincide with additional feeds, balanced diet management, better waste management techniques, and integration with agroforestry in evolving climatic conditions.

Important for sustained agricultural output also are soil management and carbon sequestration[63]. Under future climate change situations, selection of more drought-resistant genotypes and simultaneous plantation of hardwood and softwood species is regarded as adaptive adjustments in forest management. Rotation times should be connected with timber growth and harvesting patterns; plantation in landscape patterns should help to lower shifting and burning of forest tree species under climate-smart settings[64]. Adaptation techniques in agroforestry—including tree cover outside the woods, boosting forest carbon stores, protecting biodiversity, and thus lowering risks by preserving soil health sustainability—can help to mitigate effects of climate change[65].

Additionally with chances for sustainable economic output are fisheries and aquaculture. Measures should be conducted to find regions where local produce reacts favourably to changes in climatic circumstances thereby strengthening the adaptive potential of underprivileged rural farmers. One should understand the necessity of developing the climate-smart ability of rural people and other areas to reduce the negative effects of climate change[66].

Through newly adapted aquaculture techniques like agroforestry, combining aquaculture with agriculture offers more benefits to salty soils in locations with flooded conditions and excess water. Aquaculture and artificial stocking involve the water storage and irrigation system, therefore improving food security and living conditions. To guarantee the viability of agriculture, fisheries, and aquaculture in the face of climate change, then, adaption plans and strategies are needed[67].

Table 1. summarizing various technologies in agriculture that help combat climate change [88, 89, 90, 91, 92]:

Technology	**Description**	**Benefits**
Precision Farming	Uses GPS, sensors, and data analytics to optimize field-level management.	Reduces waste, improves yield, minimizes environmental impact.
Drought-Resistant Crops	Genetically modified or selectively bred crops to withstand drought conditions.	Ensures crop survival and yield in arid conditions.
Vertical Farming	Growing crops in stacked layers, often using controlled environments.	Saves space, reduces water usage, minimizes transportation emissions.
Climate-Smart Irrigation	Advanced irrigation systems like drip or sprinkler systems tailored to weather patterns.	Conserves water, enhances efficiency, reduces energy use.
Renewable Energy	Solar panels, wind turbines, and	Reduces reliance on fossil fuels,

Sources	biogas systems for powering farms.	lowers greenhouse gas emissions.
No-Till Farming	Avoiding ploughing to maintain soil structure and carbon sequestration.	Prevents soil erosion, improves soil health, retains carbon.
Agroforestry	Integrating trees and shrubs into crop and livestock systems.	Enhances biodiversity, sequesters carbon, and improves resilience.
Biopesticides and Biofertilizers	Using natural organisms and substances to manage pests and enhance soil fertility.	Reduces chemical use, promotes sustainable farming practices.
Smart Greenhouses	Controlled environment agriculture using sensors and automation.	Increases efficiency, reduces water and energy consumption, extends growing seasons.
Artificial Intelligence (AI)	AI-driven tools for predictive analytics, crop monitoring, and decision support.	Optimizes resource use, improves productivity, anticipates and mitigates risks.

Table 2. The effects of climate change on agricultural crops[93, 94, 95, 96, 97]:

Climate Change Factor	**Effect on Agricultural Crops**	**Examples**
Temperature Increase	Alters growing seasons, reduces yields, and increases heat stress.	Reduced wheat yield, premature ripening of fruits.
Changes in Precipitation Patterns	Causes droughts or flooding, impacting water availability and soil moisture.	Drought stress on corn, waterlogged rice fields.
Increased CO2 Levels	Can enhance photosynthesis but may reduce nutritional quality of crops.	Faster growth of soybeans but lower protein content.
Extreme Weather Events	Increases the frequency of storms, floods, and heatwaves, damaging crops.	Crop loss from hurricanes, heatwaves harming vegetable crops.
Pest and Disease Pressure	Expands the range and lifecycle of pests and diseases, affecting crop health.	Spread of locusts in new regions, increased fungal infections in cereals.
Sea Level Rise	Leads to saltwater intrusion in coastal agricultural lands.	Salinization of rice paddies, reduced productivity of coastal crops.
Soil Degradation	Accelerates erosion and nutrient depletion, reducing soil fertility.	Loss of topsoil in maize fields, decreased organic matter in soils.
Shifts in Pollinator Populations	Affects crop pollination success due to changes in pollinator behaviour and populations.	Reduced fruit set in orchards, decline in pollinated vegetable crops.
Variability in Growing Seasons	Causes uncertainty in planting and harvest times, affecting crop cycles.	Unpredictable wheat harvest, disrupted planting schedules for vegetables.

Table 3. Specific crops and the effects of climate change on them[98, 99,100,101]:

Crop	Effect of Climate Change	Examples/Details
Wheat	Reduced yields, heat stress, altered growing seasons	Lower yields in regions like India and Australia; early ripening
Rice	Flooding, drought stress, salinization	Increased flooding in Southeast Asia; drought in South Asia
Corn (Maize)	Drought stress, heat stress, reduced pollination	Reduced yields in the U.S. Midwest; poor kernel set
Soybeans	Increased CO2 levels, drought stress, nutrient quality reduction	Faster growth but lower protein content; drought impacts in Brazil
Coffee	Temperature increase, altered growing regions, pest pressure	Suitable growing areas shifting; increased coffee borer infestation
Grapes	Temperature increase, altered growing seasons, drought stress	Earlier harvests; reduced quality in wine regions like France
Cotton	Heat stress, drought stress, pest pressure	Reduced fiber quality; increased pest attacks in India
Potatoes	Temperature increase, drought stress, disease pressure	Reduced tuber quality; late blight outbreaks in Europe
Sugarcane	Drought stress, temperature increase	Lower yields in Brazil and India; reduced sugar content
Apples	Temperature fluctuations, frost damage, altered growing seasons	Frost damage during bloom; shifting suitable growing regions
Coffee	Temperature increase, altered growing regions, pest pressure	Shifting suitable growing regions; increased pest infestations
Tea	Temperature increase, altered growing regions, water scarcity	Reduced quality in traditional areas like India; shifting production areas
Cocoa	Temperature increase, altered precipitation patterns, disease pressure	Decreased yields in West Africa; increased black pod disease
Barley	Drought stress, temperature increase, heat stress	Reduced malting quality; lower yields in Europe
Bananas	Increased CO2 levels, altered precipitation patterns, disease pressure	Increased growth but higher disease susceptibility; shifting growing regions

Fig 7. A way Forward towards Sustainable agriculture and Cleaner Environment

<u>Mitigating the effects of climate change on agriculture:</u>

1. Adopt Climate-Smart Agriculture Practices

- **Conservation Agriculture**: Implement practices like no-till farming, cover cropping, and crop rotation to improve soil structure, enhance organic matter, and increase carbon sequestration. These practices reduce soil erosion, maintain soil moisture, and improve overall soil health [68].
- **Agroforestry**: Integrate trees and shrubs into agricultural landscapes. This practice enhances biodiversity, provides shade and windbreaks, improves soil fertility through leaf litter, and sequesters carbon. Agroforestry systems can also offer additional income through the production of fruits, nuts, and timber [69].
- **Sustainable Water Management**: Employ efficient irrigation systems such as drip or sprinkler irrigation to optimize water use. Implement rainwater harvesting and water storage systems to capture and store rainwater for dry periods. Use practices like contour bunding and check dams to conserve soil moisture and recharge groundwater [70].

2. Develop and Use Drought-Resistant Crop Varieties

- **Genetic Engineering and Selective Breeding**: Invest in the development of crop varieties that are more resistant to drought, heat, and pests through genetic modification and traditional breeding techniques. These crops can maintain higher yields under adverse conditions [71].
- **Seed Banks**: Preserve diverse genetic resources in seed banks to ensure the availability of resilient crop varieties. Seed banks act as a repository of genetic diversity, which is crucial for developing new varieties adapted to changing climates [72].

3. Improve Soil Health

- **Organic Farming**: Use organic fertilizers, compost, and green manure to maintain and enhance soil fertility. Organic farming practices promote soil biodiversity and structure, which are essential for healthy crop growth [73].
- **Soil Conservation Techniques**: Implement measures to prevent soil erosion, such as terracing, contour farming, and maintaining vegetation cover. These practices reduce runoff, retain soil nutrients, and improve water infiltration [74].

4. Promote Renewable Energy in Agriculture

- **Solar and Wind Power**: Install solar panels and wind turbines on farms to generate renewable energy. This reduces dependence on fossil fuels and lowers greenhouse gas emissions. Solar-powered irrigation systems and windmills can also be used for water pumping [75].
- **Biogas**: Use animal waste and crop residues to produce biogas for cooking, heating, and electricity generation. Biogas systems reduce methane emissions from manure and provide a sustainable energy source.

5. Implement Integrated Pest Management (IPM)

- **Biopesticides and Natural Predators**: Reduce chemical pesticide use by employing biopesticides and encouraging natural predators of pests. This approach minimizes environmental impact and promotes sustainable pest control [76].
- **Crop Diversification**: Diversify crops to disrupt pest and disease cycles. Planting a variety of crops reduces the likelihood of large-scale pest infestations and improves resilience to climate variability [77].

6. Enhance Data and Monitoring Systems

- **Precision Agriculture**: Use GPS, sensors, and data analytics to optimize field-level management. Precision agriculture allows farmers to apply inputs like water, fertilizers, and pesticides more efficiently, reducing waste and environmental impact.
- **Climate Prediction Models**: Utilize advanced climate models to predict weather patterns and plan agricultural activities accordingly. Accurate forecasts enable farmers to make informed decisions about planting, irrigation, and harvesting [78].

7. Strengthen Agricultural Policies and Support Systems

- **Subsidies and Incentives**: Provide financial support for farmers adopting sustainable practices. Governments can offer subsidies, tax incentives, and grants to encourage the transition to climate-smart agriculture [79].
- **Insurance Schemes**: Develop crop insurance schemes to protect farmers against climate-induced losses. Insurance can provide financial stability and encourage investment in resilient farming practices [80].

8. Invest in Agricultural Research and Development

- **Innovation Hubs**: Establish research centres focused on developing climate-resilient agricultural technologies and practices. These hubs can facilitate knowledge exchange and innovation [81].

- **Public-Private Partnerships**: Foster collaborations between governments, the private sector, and research institutions to drive advancements in agricultural sustainability. Joint efforts can accelerate the development and dissemination of new technologies [82].

9. Educate and Train Farmers

- **Extension Services**: Provide training and resources on sustainable farming practices and climate adaptation strategies. Extension services can offer technical support, workshops, and field demonstrations to help farmers implement new techniques [83].
- **Community Engagement**: Involve local communities in planning and implementing climate-resilient agricultural initiatives. Engaging farmers and community members ensures that strategies are tailored to local conditions and gain broader acceptance [84].

10. Promote Sustainable Supply Chains

- **Fair Trade Practices**: Ensure fair prices and market access for farmers practicing sustainable agriculture. Fair trade practices support the livelihoods of smallholder farmers and promote social equity [85].
- **Sustainable Certification**: Encourage adoption of certification schemes that promote environmental and social sustainability. Certification labels can provide market recognition for sustainably produced products and incentivize farmers to adopt best practices [86, 87].

Conclusion

In conclusion, the impact of climate change on agricultural productivity and economic stability is profound and multifaceted. As climate change continues to disrupt weather patterns, increase the frequency of extreme weather events, and alter ecosystems, agricultural systems worldwide face unprecedented challenges. Reduced crop yields, increased pest and disease pressure, and shifting growing seasons directly threaten food security and the livelihoods of millions of farmers, particularly in vulnerable and low-income regions. These agricultural disruptions have cascading effects on economic stability, leading to food price volatility, reduced income for farming communities, and broader economic insecurity. To address these challenges, it is imperative to adopt adaptive strategies and sustainable agricultural practices that enhance resilience and mitigate adverse effects. This includes investing in climate-smart technologies, promoting sustainable land and water management, and supporting research and innovation in crop resilience. Collaborative efforts at local, national, and global levels are essential to safeguard agricultural productivity and ensure economic stability in the face of a changing climate.

References

1. Adhikari, S., Keshav, C. A., Barlaya, G., Rathod, R., Mandal, R. N., Ikmail, S., et al. (2018). Adaptation and mitigation strategies of climate change impact in freshwater aquaculture in some states of India. *J. Fisheries Sci*. 12, 16–21. doi: 10.21767/1307-234X.1000142

2. AgMIP (2013). *The Coordinated Climate-Crop Modeling Project C3MP: An Initiative of the Agricultural Model Inter Comparison and Improvement Project. C3 MP Protocols and Procedures*. London.

3. Ahmad, S., Abbas, G., Ahmed, M., Fatima, Z., Anjum, M. A., Rasul, G., et al. (2019). Climate warming and management impact on the change of phenology of the rice-wheat cropping system in Punjab, Pakistan. *Field Crops Res*. 230, 46–61. doi: 10.1016/j.fcr.2018.10.008

4. Allen, C. D., Breshears, D. D., and McDowellm, N. G. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*. 6, 1–55. doi: 10.1890/ES15-00203.1

5. Antle, J. M., Stoorvogel, J. J., and Valdivia, R. O. (2014). New parsimonious simulation methods and tools to assess futurefood and environmental security of farm populations. *Philos. Trans. Soc. Biol. Sci*. 369, 2012–2028. doi: 10.1098/rstb.2012.0280

6. Arehart, J. H., Hart, J., Pomponi, F., and D'Amico, B. (2021). Carbon sequestration and storage in the built environment. *Sustain. Prod. Consum*. 27, 1047–1063. doi: 10.1016/j.spc.2021.02.028

7. Azad, N., Behmanesh, J., Rezaverdinejad, V., and Tayfeh, R. H. (2018). Climate change impacts modeling on winter wheat yield under full and deficit irrigation in Myandoab-Iran. *Arch. Agron. Soil Sci*. 64, 731–746. doi: 10.1080/03650340.2017.1373187

8. Bailey-Serres, J., Parker, J. E., Ainsworth, E. A., Oldroyd, G. E., and Schroeder, J. I. (2018). Genetic strategies for improving crop yields. *Nature* 575, 109–118. doi: 10.1038/s41586-019-1679-0

9. Balamurugan, B., Tejaswi, V., Priya, K., Sasikala, R., Karuthadurai, T., Ramamoorthy, M., et al. (2018). Effect of global warming on livestock production and reproduction: an overview. *Res. Rev*. 6, 12–18.

10. Bao, Y., Wang, F., Tong, S., Na, L., Han, A., Zhang, J., et al. (2019). Effect of drought on outbreaks of major forest pests, pine caterpillars (*Dendrolimus* spp.), in Shandong Province, China. *Forests* 10, 264–272. doi: 10.3390/f10030264

11. Boonwichai, S., Shrestha, S., Babel, M. S., Weesakul, S., and Datta, A. (2019). Evaluation of climate change impacts and adaptation strategies on rainfed rice production in Songkhram River Basin, Thailand. *Sci. Total Environ*. 652, 189–201. doi: 10.1016/j.scitotenv.2018.10.201

12. Cai, Y., Bandara, J. S., and Newth, D. A. (2016). Framework for integrated assessment of food production economics in South Asia under climate change. *Environ. Model. Software* 75, 459–497. doi: 10.1016/j.envsoft.2015.10.024

13. Challinor, A. J., Muller, C., Asseng, S., Deva, C., Nicklin, K. J., Wallach, D., et al. (2018). Improving the use of crop models for risk assessment and climate change adaptation. *Agric. Sys*. 159, 296–306. doi: 10.1016/j.agsy.2017.07.010

14. Chen, H., Liang, Z., Liu, Y., Jiang, Q., and Xie, S. (2018). Effects of drought and flood on crop production in China across 1949–2015: spatial heterogeneity analysis with Bayesian hierarchical modeling. *Natural Hazards* 92, 525–541. doi: 10.1007/s11069-018-3216-0.

15. Chun, J. A., Li, S., Wang, Q., Lee, W. S., Lee, E. J., Horstmann, N., et al. (2016). Assessing rice productivity and adaptation strategies for Southeast Asia under climate change through multi-scale crop modeling. *Agric. Sys*. 143, 14–21. doi: 10.1016/j.agsy.2015.12.001

16. Clair, S. B. S., and Lynch, J. P. (2010). The opening of Pandora's Box: climate change impacts on soil fertility and crop nutrition in developing countries. *Plant Soil*. 335, 101–115. doi: 10.1007/s11104-010-0328-z

17. Dagar, J. C., and Yadav, R. K. (2017). Climate resilient approaches for enhancing productivity of saline agriculture. *J. Soil Salinity Water Qual*. 9, 9–21.

18. Das, S. K. (2018). Impact of climate change (heat stress) on livestock: adaptation and mitigation strategies for sustainable production. *Agric. Rev*. 39, 35–42. doi: 10.18805/ag.R-1777

19. Din, M. S. U., Mubeen, M., Hussain, S., Ahmad, A., Hussain, N., Ali, M. A., et al. (2022). "World nations priorities on climate change and food security," in *Building Climate Resilience in Agriculture* (Cham: Springer), 365–384. doi: 10.1007/978-3-030-79408-8_22

20. Downing, M. M. R., Nejadhashemi, A. P., Harrigan, T., and Woznicki, S. A. (2017). Climate change and livestock: impacts, adaptation, and mitigation. *Climate Risk Manag*. 16, 145–163. doi: 10.1016/j.crm.2017.02.001

21. Dubey, A., Malla, M. A., Khan, F., Chowdhary, K., Yadav, S., Kumar, A., et al. (2019). Soil microbiome: a key player for conservation of soil health under changing climate. *Biodive. Conserv*. 28, 2405–2429. doi: 10.1007/s10531-019-01760-5

22. Ebi, K. L., and Loladze, I. (2019). Elevated atmospheric CO_2 concentrations and climate change will affect our food's quality and quantity. *Lancet Planetary Health* 3, 283–284. doi: 10.1016/S2542-5196(19)30108-1

23. Ewert, F., Rötter, R. P., Bindi, M., Webber, H., Trnka, M., Kersebaum, K. C., et al. (2015). Crop modelling for integrated assessment of risk to food production from climate change. *Environ. Model Soft*. 26, 287–303. doi: 10.1016/j.envsoft.2014.12.003

24. Fahad, S., Bajwa, A. A., Nazir, U., Anjum, S. A., Farooq, A., Zohaib, A., et al. (2017). Crop production under drought and heat stress: plant responses and management options. *Fron. Plant Sci*. 9, 1147. doi: 10.3389/fpls.2017.01147

25. FAO (2016). *The Impact of Disasters on Agriculture: Addressing the Information Gap*. Rome, 19.

26. FAO IFAD, and WFP. (2015). *The State of Food Insecurity in the World: Meeting the 2015 International Hunger Targets: Taking Stock of Uneven Progress. FAO, IFAD and WFP*. Rome: FAO.

27. Garcia-Franco, N., Hobley, E., Hübner, R., and Wiesmeier, M. (2018). Climate-smart soil management in semiarid regions. *Soil Manag. Climate Change* 12, 349–368. doi: 10.1016/B978-0-12-812128-3.00023-9

28. Garlock, T., Asche, F., Anderson, J., Ceballos-Concha, A., Love, D. C., Osmundsen, T. C., et al. (2022). Aquaculture: the missing contributor in the food security agenda. *Global Food Sec*. 32, 100620. doi: 10.1016/j.gfs.2022.100620

29. Garnett, T. (2011). Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? *Food Policy* 36, S23–S32. doi: 10.1016/j.foodpol.2010.10.010

30. Geng, X., Wang, F., Ren, W., and Hao, Z. (2019). Climate change impacts on winter wheat yield in Northern China. *Adv. Meteorol*. 4, 11–12. doi: 10.1155/2019/2767018

31. Ghaffar, A., Habib, M. H. R., Ahmad, S., Ahmad, I., Khan, M. A., Hussain, J., et al. (2022). *Adaptations in Cropping System and Pattern for Sustainable Crops Production under Climate Change Scenarios*. (Boca Raton, FL: CRC Press), 10. doi: 10.1201/9781003286417-1

32. Gouldson, A., Colenbrander, S., Sudmant, A., Papargyropoulou, E., Kerr, N., McAnulla, F., et al. (2016). Cities and climate change mitigation: economic opportunities and governance challenges in Asia. *Cities* 54, 11–19. doi: 10.1016/j.cities.2015.10.010

33. Habeeb, A. A., Gad, A. E., and Atta, A. M. (2018). Temperature-humidity indices as indicators to heat stress of climatic conditions with relation to production and reproduction of farm animals. *Int. J. Biotechnol. Recent Adv*. 1, 35–50. doi: 10.18689/ijbr-1000107

34. Handisyde, N., Telfer, T. C., and Ross, L. G. (2017). Vulnerability of aquaculture-related livelihoods to changing climate at the global scale. *Fish Fisheries* 18, 466–488. doi: 10.1111/faf.12186

35. Hassen, A., Talore, D. G., Tesfamariam, E. H., Friend, M. A., and Mpanza, T. D. E. (2017). Potential use of forage-legume intercropping technologies to adapt to climate-change impacts on mixed crop-livestock systems in Africa: a review. *Regional Environ. Change* 68, 1713–1724 doi: 10.1007/s10113-017-1131-7

36. Havlik, P., Valin, H., Mosnier, A., Obersteiner, M., Baker, J. S., Herrero, M., et al. (2013). Crop productivity and the global livestock sector: implications for land use change and greenhouse gas emissions. *Am. J. Agric. Econ*. 95, 442–448. doi: 10.1093/ajae/aas085

37. Henderson, B. B., Gerber, P. J., Hilinski, T. E., Falcucci, A., Ojima, D. S., Salvatore, M., et al. (2015). Greenhouse gas mitigation potential of the world's grazing lands: modeling soil carbon and nitrogen fluxes of mitigation practices. *Agric. Ecosyst. Environ*. 207, 91–100. doi: 10.1016/j.agee.2015.03.029

38. Hisano, M., Searle, E. B., and Chen, H. Y. (2018). Biodiversity as a solution to mitigate climate change impacts on the functioning of forest ecosystems. *Biol. Rev*. 93, 439–456. doi: 10.1111/brv.12351

39. Hoogenboom, G., Jones, J. W., Wilkens, P. W., Porter, C. H., Boote, K. J., Hunt, L. A., et al. (2015). *Decision Support System for Agrotechnology Transfer (DSSAT). Version 4.6*. Prosser, WA: DSSAT Foundation.

40. Hussain, J., Khaliq, T., Ahmad, A., Akhter, J., and Asseng, S. (2018). Wheat responses to climate change and its adaptations: a focus on arid and semi-arid environment. *Int. J. Environ. Res.* 12, 117–126. doi: 10.1007/s41742-018-0074-2

41. Iannella, M., De Simone, W., D'Alessandro, P., and Biondi, M. (2021). Climate change favours connectivity between virus-bearing pest and rice cultivations in sub-Saharan Africa, depressing local economies. *PeerJ*. 9, e12387. doi: 10.7717/peerj.12387

42. Imam, N., Hossain, M. K., and Saha, T. R. (2017). “Potentials and challenges of using ICT for climate change adaptation: a study of vulnerable community in riverine islands of bangladesh,” in *Catalyzing Development Through ICT Adoption*, eds H. Kaur, E. Lechman, and A. Marszk (Cham: Springer), 89–110. doi: 10.1007/978-3-319-56523-1_7

43. IPCC (2019). *Global warming of 1.5°C. Summary for Policy Makers. Switzerland: World Meteorological Organization, United Nations Environment Program, and Intergovernmental Panel on Climate Change*. Bern.

44. Islam, M. S., and Haq, M. E. (2018). Vulnerability of aquaculture-based fish production systems to the impacts of climate change: insights from Inland Waters in Bangladesh. *Bangladesh I* 6, 67–97. doi: 10.1007/978-3-319-26357-1_3

45. Jhariya, M. K., Yadav, D. K., Banerjee, A., Raj, A., and Meena, R. S. (2019). Sustainable forestry under changing climate. *Sustain. Agric. Forest. Environ Manag*. 24, 285–326. doi: 10.1007/978-981-13-6830-1_9

46. Karanasios, S. T. A. N. (2011). *New and Emergent ICTs and Climate Change in Developing Countries*. Manchester: Center for Development Informatics, Institute for Development Policy and Management, SED, University of Manchester.

47. Karmakar, S., Purkait, S., Das, A., Samanta, R., and Kumar, K. (2018). Climate change and Inland fisheries: impact and mitigation strategies. *J. Exp. Zool. Ind*. 21, 329–335. Avaiable online at: https://www.researchgate.net/publication/323546601_CLIMATE_CHANGE_AND_INLAND_FISHERIES_IMPACT_AND_MITIGATION_STRATEGIES

48. Keating, B. A., Carberry, P. S., Hammer, G. L., and Probert, M. E. (2003). An overview of APSIM a model designed for farming systems simulation. *Eur. J. Agron*. 18, 267–288. doi: 10.1016/S1161-0301(02)00108-9

49. Kheir, A. M., El Baroudy, A., Aiad, M. A., Zoghdan, M. G., El-Aziz, M. A. A., Ali, M. G., et al. (2019). Impacts of rising temperature, carbon dioxide concentration and sea level on wheat production in North Nile delta. *Sci. Total Environ*. 651, 3161–3173. doi: 10.1016/j.scitotenv.2018.10.209

50. Kolstrom, M., Lindner, M., Vilen, T., Maroschek, M., Seidl, R., Lexer, M. J., et al. (2011). Reviewing the science and implementation of climate change adaptation measures in European forestry. *Forest* 2, 961–982. doi: 10.3390/f2040961

51. Kumar, V. S., Kumar, R. P., Harikrishna, C. H., and Rani, M. S. (2018). Effect of heat stress on production and reproduction performance of buffaloes-a review. *Pharma Innov*. 7, 629–633. Available online at: https://www.thepharmajournal.com/archives/2018/vol7issue4/PartJ/7-3-162-175.pdf

52. Kurukulasuriya, P., and Rosenthal, S. (2003). *Climate Change and Agriculture: A Review of Impacts and Adaptations. Climate Change Series Paper No. 91*. Washington, DC: World Bank.

53. Lal, R. (2007). Carbon management in agricultural soils. *Mitig. Adapt. Strateg. Glob. Chang*. 12, 303–322. doi: 10.1007/s11027-006-9036-7

54. Lam, V. W., Chavanich, S., Djoundourian, S., Dupont, S., Gaill, F., Holzer, G., et al. (2019). Dealing with the effects of ocean acidification on coral reefs in the Indian Ocean and Asia. *Reg. Stud. Marine Sci.* 100, 560–570. doi: 10.1016/j.rsma.2019.100560

55. Liang, C., Xian, W., and Pauly, D. (2018). Impacts of ocean warming on China's fisheries catches: an application of “mean temperature of the catch” concept. *Front. Mar. Sci*. 6, 5–26. doi: 10.3389/fmars.2018.00026

56. Lima, V. P., de Lima, R. A. F., Joner, F., Siddique, I., Raes, N., and Ter Steege, H. (2022). Climate change threatens native potential agroforestry plant species in Brazil. *Sci. Rep.* 12, 1–14. doi: 10.1038/s41598-022-06234-3

57. Liu, Y., Chen, Q., Ge, Q., Dai, J., Qin, Y., Dai, L., et al. (2018). Modelling the impacts of climate change and crop management on phenological trends of spring and winter wheat in China. *Agric. For. Meteorol.* 248, 518–526. doi: 10.1016/j.agrformet.2017.09.008

58. Lv, Z., Liu, X., Cao, W., and Zhu, Y. (2013). Climate change impacts on regional winter wheat production in main wheat production regions of China. *Agric. For. Meteorol.* 171, 234–248. doi: 10.1016/j.agrformet.2012.12.008

59. Lybbert, T. J., and Sumner, D. A. (2012). Agricultural technologies for climate change in developing countries: policy options for innovation and technology diffusion. *Food Policy* 37, 114–123. doi: 10.1016/j.foodpol.2011.11.001

60. Ma, Q., Zhang, J., Sun, C., Zhang, F., Wu, R., and Wu, L. (2018). Drought characteristics and prediction during pasture growing season in Xilingol grassland, northern China. *Theo. App. Climatol.* 133, 165–178. doi: 10.1007/s00704-017-2150-5

61. Mbow, C., Smith, P., Skole, D., Duguma, L., and Bustamante, M. (2014). Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Curr. Opin. Environ. Sustain.* 6, 8–14. doi: 10.1016/j.cosust.2013.09.002

62. Meena, R. K., Verma, T. P., Yadav, R. P., Mahapatra, S. K., Surya, J. N., Singh, D., et al. (2019). Local perceptions and adaptation of indigenous communities to climate change: Evidences from High Mountain Pangi valley of Indian Himalayas. *Ind. J. Trad. Knowl.* 11, 876–888. Available online at: https://www.researchgate.net/publication/343818597_Local_perceptions_and_adaptation_of_indigenous_communities_to_climate_change_Evidences_from_High_Mountain_Pangi_valley_of_Indian_Himalaya

63. Meera, S. N., Balaji, V., Muthuraman, P., Sailaja, B., and Dixit, S. (2012). Changing roles of agricultural extension: harnessing information and communication technology (ICT) for adapting to stresses envisaged under climate change. *Crop Stress Manag*. 16, 585–605. doi: 10.1007/978-94-007-2220-0_19

64. Moreira, S. L., Pires, C. V., Marcatti, G. E., Santos, R. H., Imbuzeiro, H. M., and Fernandes, R. B. (2018). Intercropping of coffee with the palm tree, macauba, can mitigate climate change effects. *Agric. Forest. Meteorol*. 265, 379–390. doi: 10.1016/j.agrformet.2018.03.026

65. Mottaleb, K. A., Rejesus, R. M., Murty, M. V. R., Mohanty, S., and Li, T. (2017). Benefits of the development and dissemination of climate-smart rice: ex ante impact assessment of drought-tolerant rice in South Asia. *Miti. Adap. Strat. Global Change* 22, 879–901. doi: 10.1007/s11027-016-9705-0

66. Nasi, W., Amin, A., and Fahad, S. (2018). Future risk assessment byestimating historical heat wave trends with projected heat accumulation using SimCLIM climate model in Pakistan. *Atmos. Res*. 205, 118–133. doi: 10.1016/j.atmosres.2018.01.009

67. Nguyen, N. H. (2015). Genetic improvement for important farmed aquaculture species with a reference to carp, tilapia and prawns in Asia: achievements, lessons and challenges. *Fish Fisheries* 17:483–506 doi: 10.1111/faf.12122

68. Nizam, H. A., Zaman, K., Khan, K. B., Batool, R., Khurshid, M. A., Shoukry, A. M., et al. (2020). Achieving environmental sustainability through information technology:"Digital Pakistan" initiative for green development. *Environ. Sci. Poll. Res*. 2, 1–16. doi: 10.1007/s11356-020-07683-x

69. Ogello, E. O., Mlingi, F. T., Nyonje, B. M., Charo-Karisa, H., and Munguti, J. M. (2013). Can integrated livestock-fish culture be a solution to East Afircan's food insecurity a review. *Afr. J. Food Agric. Nut. Develop*. 13, 8058–8078. doi: 10.18697/ajfand.59.12920

70. Paricha, A. M. P., Sethi, K. C., Gupta, V., Pathak, A., and Chhotray, S. K. (2017). Soil water conservation for microcatchment water harvesting systems. *J. Soil Sci. Plant Nutri*. 8, 55–59.

71. Pineiro, G., Paruelo, J. M., Oesterheld, M., and Jobbagy, E. G. (2010). Pathways of grazing effects on soil organic carbon and nitrogen. *Range Ecol. Manag*. 63, 109–119. doi: 10.2111/08-255.1

72. Poonam, A., Saha, S., Nayak, P. K., Sinhababu, D. P., Sahu, P. K., Satapathy, B. S., et al. (2019). Rice-fish integrated farming systems for eastern India. *J. Integrat. Agric*. 6, 77–86. Available online at: https://www.semanticscholar.org/paper/Rice-Fish-Integrated-Farming-Systems-for-Eastern-Poonam-Saha/43040f2fe84dab3be27fd48785f040351278f25d

73. Population of Asia (2019). *Demographics: Density Ratios, Growth Rate, Clock, Rate of Men to Woman*. Available online at: www. population of.net (accessed June 2, 2019).

74. Prein, M. (2002). Integration of aquaculture into crop–animal systems in Asia. *Agric. Syst*. 71, 127–146. doi: 10.1016/S0308-521X(01)00040-3

75. Quyen, N. H., Duong, T. H., Yen, B. T., and Sebastian, L. (2018). *Impact of climate change on future rice production in the Mekong River Delta. Miti. Adap. Strat. Global Change.12, 55–59*. Available online at: https://hdl.handle.net/10568/99563

76. Rahman, M. H. U., Ahmad, A., Wang, X., Wajid, A., Nasim, W., Hussain, M., et al. (2018). Multi-model projections of future climate and climate change impacts uncertainty assessment for cotton production in Pakistan. *Agric. Forest Meteorol*. 253, 94–113. doi: 10.1016/j.agrformet.2018.02.008

77. Rakszegi, M., Darko, E., Lovegrove, A., Molnár, I., Lang, L., Bed,o, Z., et al. (2019). Drought stress affects the protein and dietary fiber content of wholemeal wheat flour in wheat/Aegilops addition lines. *PLoS ONE* 14, e0211892. doi: 10.1371/journal.pone.0211892

78. Raman, H., Uppal, R. K., and Raman, R. (2019). Genetic solutions to improve resilience of canola to climate change. *Genomic Designing Climate-Smart Oilseed Crops* 8, 75–131. doi: 10.1007/978-3-319-93536-2_2

79. Renaudeau, D., Collin, A., Yahav, S., De Basilio, V., Gourdine, J. L., and Collier, R. J. (2012). Adaptation to hot climate and strategies to alleviate heat stress in livestock production. *Animal* 6, 707–728. doi: 10.1017/S1751731111002448

80. Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., and Boote, K. J. (2013). The agricultural model inter comparison and improvement project (AgMIP): protocols and pilot studies. *Agric. For. Meteorol.* 170, 166–182. doi: 10.1016/j.agrformet.2012.09.011

81. Ruane, A. C., Cecil, L. D., Horton, R. M., Gordon, R., McCollum, R., Brown, D., et al. (2013). Climate change impact uncertainties for maize in Panama: farm information, climate projections, and yield sensitivities. *Agric. For. Meteorol.* 170, 132–145. doi: 10.1016/j.agrformet.2011.10.015

82. Ruane, A. C., Goldberg, R., and Chryssanthacopoulos, J. (2015). Climate forcing datasets for agricultural modeling: merged products for gap-filling and historical climate series estimation. *Agric. Meteorol.* 200, 233–248. doi: 10.1016/j.agrformet.2014.09.016

83. Runkle, B. R., SuvocCarev, K., Reba, M. L., Reavis, C. W., Smith, S. F., Chiu, Y. L., et al. (2018). Methane emission reductions from the alternate wetting and drying of rice fields detected using the eddy covariance method. *Environ. Sci. Technol.* 53, 671–681. doi: 10.1021/acs.est.8b05535

84. Sangareswari, M., Balasubramanian, A., Palanikumaran, B., and Aswini, D. (2018). Carbon sequestration potential of a few selected tree species in Coimbatore District, Tamil Nadu. *Adv. Res.* 2, 1–7. doi: 10.9734/AIR/2018/39676

85. Sarkar, U. K., and Borah, B. C. (2018). Flood plain wetland fisheries of India: with special reference to impact of climate change. *Wetlands Ecol. Manag*. 26, 1–15. doi: 10.1007/s11273-017-9559-6

86. Seddon, N., Turner, B., Berry, P., Chausson, A., and Girardin, C. A. (2018). *Why Nature-Based Solutions to Climate Change Must Be Grounded in Sound Biodiversity Science* (England: Nature Climate Change), 65. doi: 10.20944/preprints201812.0077.v1

87. Shafiq, F., Nadeem, A., Ahsan, K., and Siddiq, M. (2014). Role of ICT in climate change monitoring: a review study of ICT based climate change Monitoring services. *Res. J. Recent Sci.* 3, 123–130. doi: 10.4236/ajcc.2018.72010

88. Smith, P., and Olesen, J. E. (2010). Synergies between the mitigation of, and adaptation to, climate change in agriculture. *J. Agric. Sci.* 148, 543–552. doi: 10.1017/S0021859610000341

89. Sohag, A. A. M., Tahjib-Ul-Arif, M., Brestic, M., Afrin, S., Sakil, M. A., Hossain, M. T., et al. (2020). Exogenous salicylic acid and hydrogen peroxide attenuate drought stress in rice. *Plant, Soil Environ*. 66, 7–13. doi: 10.17221/472/2019-PSE

90. Suryadi, F. X. (2020). *Soil and Water Management Strategies for Tidal Lowlands in Indonesia*. Boca Raton, FL: CRC Press. doi: 10.1201/9780429333231

91. Tan, B. T., Fam, P. S., Firdaus, R. R., Tan, M. L., and Gunaratne, M. S. (2021). Impact of climate change on rice yield in Malaysia: a panel data analysis. *Agric*. 11, 569. doi: 10.3390/agriculture11060569

92. Ullah, A., Ahmad, I., and Ahmad, A. (2019). Assessing climate change impacts on pearl millet under arid and semi-arid environments usingCSM-CERES-Millet model. *Environ. Sci. Pollut. Res*. 26, 6745–6757. doi: 10.1007/s11356-018-3925-7

93. UNO (2015). *World Population Prospective. The 2015 Revision, Volume II: Demographic Profiles. New York, NY: United Nations Department of Economic and Social Affairs, 21–27*. Available online at: https://www.un.org/development/desa/pd/content/world-population-prospects-2015-revision-volume-ii-demographic-profiles

94. Wasaya, A., Yasir, T. A., Sarwar, N., Mubeen, K., Rajendran, K., Hadifa, A., et al. (2022). "Climate change and global rice security," in *Modern Techniques of Rice Crop Production* (Singapore: Springer), 13–26. doi: 10.1007/978-981-16-4955-4_2

95. Williams, P. A., Crespo, O., and Abu, M. (2019). Adapting to changing climate through improving adaptive capacity at the local level–the case of smallholder horticultural producers in Ghana. *Climate Risk Manag*. 23,124–135. doi: 10.1016/j.crm.2018.12.004

96. World Bank (2018). World BankOpen Data. Available online at: https://data.worldbank.org/.com (accessed January, 2021).

97. Xiong, D. P., Shi, P. L., Zhang, X. Z., and Zou, C. B. (2016). Effects of grazing exclusion on carbon sequestration and plant diversity in grasslands of China: a meta-analysis. *Ecol. Eng*. 94, 647–655. doi: 10.1016/j.ecoleng.2016.06.124

98. Yadav, S. S., and Lal, R. (2018). Vulnerability of women to climate change in arid and semi-arid regions: the case of India and South Asia. *J. Arid Environ*. 149, 4–17. doi: 10.1016/j.jaridenv.2017.08.001

99. Yu, H., Zhang, Q., Sun, P., and Song, C. (2018). Impact of droughts on winter wheat yield in different growth stages during 2001–2016 in Eastern China. *Int. J. Disaster Risk Sci*. 9, 376–391. doi: 10.1007/s13753-018-0187-4

100. Zafar, S. A., Hameed, A., Nawaz, M. A., Wei, M. A., Noor, M. A., and Hussain, M. (2018). Mechanisms and molecular approaches for heat tolerance in rice (*Oryza sativa* L.) under climate change scenario. *J. Integrative Agric*. 17, 726–738. doi: 10.1016/S2095-3119(17)61718-0

101. Zahra, N., Wahid, A., Hafeez, M. B., Ullah, A., Siddique, K. H. M., and Farooq, M. (2021). Grain development in wheat under combined heat and drought stress: Plant responses and management. *Environ. Experi. Bot.* 188, 104517. doi: 10.1016/j.envexpbot.2021.104517