Review Article

Assessing the impact of climate change on agricultural production using crop simulation model

Abstract

Crop simulation models are crucial in gaining valuable insights into the intricateinteractions between crops and their surroundings. They achieve this by simulatingdiverse scenarios and predicting the impacts of varying environmental conditions, such as temperature, rainfall, and soil quality. The resulting information enables assisting farmers in making wise choices about the best times to plant, fertilize, irrigate, harvest, and manage their crops, especially in the context of a changing climate. Moreover, crop simulation models that account for climate change factors can quantify the effect of climate change on crop production, and prioritize and evaluate adaptation measures at the farm level. As a result, Crop simulation modeling has the potential to revolutionize agriculture, leading it towards achieving the goals of sustainability.

Keywords: Crop simulation model; climate change; crop production; Adaptation; sustainability

1. INTRODUCTION

Water resources, food security, hydropower, human health, and the entire planet have already been negatively impacted by climate change.[1]The annual average GHG concentrations in the atmosphere in 2019 were 410 parts per million (ppm) of carbon dioxide (CO2), 1866 ppb of methane (CH4), and 332 ppb of nitrous oxide (N2O), according to the Intergovernmental Panel on Climate Change (IPCC, 2021).Meeting the food demand of the increasing global population while preserving the fragile ecosystem that is under threat due to the effects of climate change is among the major challenges of the present century[2].About 70% of the people in developing nations reside in rural areas, where agriculture is the main source of income. The majority of developing nations are found in lower latitudes (tropical dry and semi-arid regions), where the effects of climate change will be most pronounced and they have less potential for adaptation. Agriculture has a significant role in the economies of many emerging nations. However, as urban areas and industrial output expand, agriculture will eventually have to compete with them for limited water and land resources[3].Studies on the impacts of climate change and viable adaptation strategies are emerging as significant subjects of scientific concern. There is a need for a computerised statistical tool that can provide decision support due to the changing climate and weather factors. The integration of soil characteristics, climatic factors, and crop management techniques has become possible because to advancements in current science and technology[4]. Crop simulation models are one such instrument for next agricultural research [5].

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2. CROP MODEL

A model is a simplified description of a systemof an object, or an idea that is used to help people comprehend the real system or thing. Models are frequently included in mathematical equations to help with calculations or predictions [6]. A crop model can be described as a simple portrayal of a real crop. In the current context, a crop model can be defined as a computer programme thatwhen given the right set of input data, can be run iteratively for 'n' times to compute a number of pre-designed mathematical or statistical equations representing crop growth and environment relations and/or their interactions. Crop models can be viewed as systems research methods which assist in resolving issues with crop production.

2.1. CROP SIMULATION MODELS

Computer simulations model that use mathematics to represent real-world systems. Crop simulation models (CSM) major objective is to evaluate the agricultural productivity as a function of weather, soil characteristics, and crop management inputs.Plant growth and development are predicted by crop simulation models using physiological processes in connection to production-influencing factors such environmental factors and crop management techniques [7]. Crop models are frequently constructed around four key components (Fig. 1). To execute a crop model and simulation, collection of input data, known as a "Minimum Data Set," is required [8]. The site-specific meteorological data for the growing season, and ideally the full year, as well as information on the surface and profile features of the soil, as well as data on crop management from the experiment that was carried out to calibrate, are among the necessary data.The minimum meteorological information required is latitude and longitude of the weather station, daily values of incoming solar radiation (MJ/m^2/day), maximum and minimum daily air temperatures (°C), and daily total rainfall (mm). Soil data comprises details on the depths of the top and lower horizons (in centimetres), the amounts of sand, silt, and clay, bulk density, organic carbon, water pH, and number of roots. Management data includes planting dates, evaluation dates for soil prior to planting, planting density, and physiological processes to forecast plant growth and development in relation to production affecting elements like weather and crop management practises.

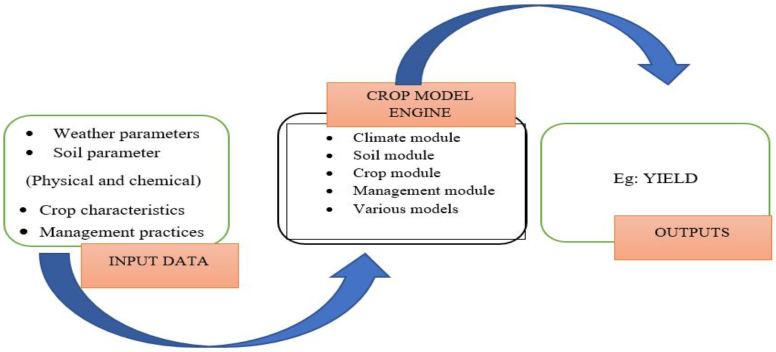

Fig. 1. Crop model components

3. CLIMATE OUTLOOKS AND CLIMATE MODELS

Climate forecasts is an accurate projection of the future climate based on a number of climatological correlations and IPCC radioactive forcing hypotheses.Global climate models (GCMs) and regional climate models (RCMs) are complex mathematical representations in three dimensions, which can illustrate how the atmosphere, land surface, oceans, and sea ice interact with one another [9]. GCMs are beneficialgears for modelling the important aspects of the current and future climate, despite the fact that they still have significant flaws [10]. Higher spatial resolution GCMs can simulate regional climates with reasonable accuracy, which enables climate scientists to assess the impact of climate change on agricultural productivity and better understand how it is affecting certain areas. Climate models must be used in conjunction with other modelling techniques to predict climate vulnerability as well as climate variables like temperature and rainfall.HadCM3 (Hadley Centre Climate Model 3) created the ATEAM (advanced terrestrial ecosystem analysis and modelling) frameworkutilizing the GCM to evaluate the sensitivity of climate change[11]. Based on historical climate data, [12] discussed climate variability and droughts in Australia and suggested some potential policy approaches to deal with the extreme climate variability. A innovative analytical method based on sound decision-making was devised by [13] in order to quantify the SRES scenarios (Special Report on Emissions Scenarios) produced using the scenario-axes technique for decision makers.

ROLE OF CLIMATE CHANGE IN AGRICULTURAL PRODUCTION AND CROP MODELING

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Earth temperature is expected to rise due to an increase in the concentration of carbon dioxide and other greenhouse gases.Any change in the global climate would have a huge influence on crop yields and productivity because weather changes are a key component of agricultural production. In addition, the rise in temperature in tropical and subtropical regions could nullify the positive impacts of carbon dioxide, leading to substantial reductions in crop yields and a surge in crop failures. By having a thorough understanding of the effects of climate change, scientists may be able to assist farmers in making crop management decisions, such as selecting crops, cultivars, sowing dates, and irrigation schedules, to reduce risks. Concern over the potential severe harm that climatic changes may do to both market and non-market sectors has grown in recent years. Farmers can adapt to climate change and decrease its consequences by changing farming practises, planting patterns, and utilising new technologies. In order to examine the potential impacts of climate change and climate variability on water use, crop models are used. This establishes a direct link between models, agro-meteorology, and societal issues.Since climate change deals with future challenges, general circulation models (GCMs) and crop simulation models provide a more scientific way to assessing the implications of climate change on agricultural production and global food security than previous surveys.Although Global Climate Models (GCMs) have limitations, it is advisable for the agricultural community worldwide to view both Crop Simulation Models (CSMs) and GCMs as more reliable and acceptable tools for generating weather data. This will assist in finding solutions for crop production in the face of climate change, especially in underdeveloped and developing nations.

3.1.THE ROAD AHEAD: OPPORTUNITIES FOR CROP SIMULATION MODELS IN AGRICULTURAL RESEARCH AND CLIMATE CHANGE

Crop simulation modelling offers a possibility to look into the possibilities of cultivars for new conditions without having to spend the money and time on expensive and time-consuming field tests. Crop models is an important toolsin decision-making, analysing the effects of climate change/variability and management practices on productivity and environmental performance of various cropping systems [14]. To make agriculture more productive and sustainable, this is done.Crop modelprovides a more efficient and economical substitute for investigating the impact of agricultural land management practices on crop productivity and the environment. It helps to identify the optimal management level required to achieve economically viable yields. [15] [16]. According to [17],models can give results that are reasonably accurate for creating agricultural land management strategies if they are calibrated and tested using trustworthy observable field data.For instance, [18] analyses and suggested that improved management practices like fertilizer application and water usage at the farm and plot level and have examined the efficacy of different agricultural land management practices under various climate change scenarios using crop models. Given that each model has modules created specifically for a specific crop, they can take into account the understanding of that crop physiology acquired over many years of field experiments and laborator. They also provide a useful means to explore how crops will react to climate change and different management scenarios[19]

3.2 LIMITATION IN USING CROP SIMULATION MODELS

The process of running a simulation mechanics model following input data entry may appear straightforward. However, there are many data accessibility and data quality scaling challenges from the data on global climate change to the plot scale, where these models usually function. Poor model performance, especially at the regional scale, has been demonstrated to be caused by the incorrect consideration of the factors and processes determining yield variability or by the aggregation of input data that may inconsistently reproduce the spatial variability of growing conditions, such as soils and climate, within a region [20, 21].Majority of simulation models, complete and accurate farm management, weather, and agricultural phenological data are required. [22] study, which also validated the EPIC model for use in western Africa, found that a scarcity of data made crop modelling difficult. Rice has been shown to be sensitive to seasonal rainfall, but it was also found to have a limited tolerance for severe water stress.The uncertainty in the model prediction and validation when taking into account a scenario with multiple-year calibration for several variables, such as plant biomass, leaf area index, and yield, is primarily caused by the poor quality of the input data (estimation of the impact of dry spells on grain output). Impact studies make use of information from the CSAG and CSIR scenarios, GCM outputs from the global Coupled Model Intercomparison Project (CMIP) archives, and RCM downscaled products from international centres. Rice has been shown to be sensitive to seasonal rainfall, but it was also found to have a limited tolerance for severe water stress. When considering a scenario with multiple-year calibration for several variables, such as plant biomass, leaf area index, and yield, the uncertainty in the model prediction and validation is mostly brought on by the poor quality of the input data (estimation of the influence of dry spells on grain output). Impact studies make use of information from the CSAG and CSIR scenarios, GCM outputs from the global Coupled Model Intercomparison Project (CMIP) archives, and RCM downscaled products from international centres. [23] This 'pick and mix' method of using climatic scenarios limits the ability to analyses and synthesize the findings of various impact studies. Poor access to the data required for model calibration and validation is another factor. There are more restrictions as a result of the user various decisions while calibrating, executing, and assessing models. The justification of these modelling decisions is frequently absent from crop-climate studies. [24]direct comparisons between research challenging. [25] claim that an overly complex model will require more parameters that can be restricted by data. Additionally, some parameters must be inferred as part of the calibration process because they cannot be observed directly. In order for the simulations to be consistently accurate, careful model selection, calibration, and evaluation of past performance are essential.

4.1. CLIMATE CHANGE IMPACTS ON CROP YIELD

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Crop models offer pragmatic means of forecasting the potential impact of future events on crop productivity. These models primarily concentrate on simulating crop responses to various dynamics, such as soil water, nutrients, and carbon. They represent crop growth processes with varying levels of complexity, simulate the influence of water scarcity on potential crop yields, and integrate the impact of management and climate. [26]. Agricultural Production Systems Simulator Model (APSIM) [27] and [28] are two examples. Decision Support System for Agrotechnology Transfer (DSSAT); Cropping Systems

Simulation Model (CropSyst) [29] .With the help of the crop models CROPGRO for major grain legumes, CERES for cereal crops, and SUBSTOR for plants with below-ground storage organs are included in DSSAT[30] ,as well as the Environmental Policy Integrated Climate (EPIC) [31] and CROPWAT/AquaCrop models from the Food and Agriculture Organisation of the United Nations[32], Simulateur multidiscplinaire pour Les Cultures Standard) [33], Many crop simulation models, including CERES-Maize (Crop Environment Resource Synthesis) [34], CERES-Wheat, SWAP (soil, water, atmosphere, plant), and InFoCrop[35] have been used to assess the potential effects of climate variability on crop production, particularly to analyses crop yield-climate sensitivity under various climate scenarios. A list of the crop growth models that were used to research how climate change affects crop yields are presented in Table 1.

Table 1. General Crop models for climate change impacts.

Crop model	Crop	Predicted Climatic impacts	References
CropSyst	Wheat	Rainfall and temperature	[81]
CERES-Rice	Rice	CO_2	[82]
SWAP	Rice	CO_2	[83]
InFoCrop	Rice	CO_2 and temperature	[84]
	Rice and wheat	Climate change	[85]
IBSNAT-ICASA	Cereal/soybean	Climate change	[86]
GLAM	Peanut	Climate uncertainty	[87]
SWAT	Maize	Climate vulnerability	[88]
CERES-Wheat	Wheat	CO_2 levels	[89]
CERES-Maize	Maize	Sustainable production	[90]
	Maize	Planting date and different weather	[91]

Studies on wheat productivity and climate change primarily concentrate on future CO_2 concentrations. [36] observed that while global warming may improve wheat crop yield in some locations, it may decrease productivity in areas with high temperatures in their discussion of how wheat can adjust to climate change in the Indo-Gangetic Plains for the year 2050. As a result, developing wheat germplasm that can withstand heat is essential to halting climate change. [37] utilisedCropSyst version-4 to forecast how climate change might affect wheat production in southeast Australia. According to their findings, the average wheat yield can be reduced by about 25% as a result of rising CO_2 levels. [38] utilised the CERES-wheat model to analyse the impacts of climate change on wheat output under four distinct scenarios, and they found that the CO2 effect continued to be a key factor in increasing crop productivity in the study area. Using the DSSAT 3.5 CERES-Wheat models, [39] investigated the effects of climate change on wheat output in Southern Australia for the 2080s. The findings indicate that wheat output will grow at all CO_2 levels and that drier areas are better suited for wheat farming, while they may yield wheat of inferior quality. One of the most significant crops in the world, maize yield, and climate change are hotly debated subjects. [40] studied the impact of climate change on rainfed maize yield and investigated using CERES-Maize crop model in combination with CCCM and GISS climate models and discovered that the GISS model can increase dry matter by 3.5–5.6 t/ha whereas the CCCM model can only increase it by 1.4–2.1 t/ha. [41] employed the Mann-Kendall to forecast agricultural sustainability in smallholders under several climatic scenarios in South Africa. The findings indicate that adding inorganic nitrogen and rainwater collection can, over time, boost agricultural productivity for smallholders. [42] investigated the impact of planting dates and different weather patterns on maize productivity in Brazil using CERES-Maize. According to the findings, a later planting date will result in a 55% reduction in average yield under rainfed conditions and a 21% reduction under irrigation settings.Furthermore, roughly 45 days prior to harvest, an accurate yield projection can be made. [43] used CERES-Maize to investigate maize cultivation under both precision irrigation and deficit irrigation techniques over a period of thirty years in Sofia, Bulgaria. According to the findings, the average productivity during moisture deficit season gives 60% lower than it would be under a soil moisture state that is sufficient.According to the study [44] on how the climate influences maize yield in the South African Limpopo Basin, both higher temperatures and more precipitation are good for crop productivity, with the latter being more important than the former. Results from the study by [45] [59] that used the ORYZAI and InFoCrop-rice models to examine the effects of elevated CO_2 and temperature on irrigated rice yield in eastern India show that increased CO_2 concentration can increase rice yield, which is dependent on the sterility of rice spikelets at increasing temperatures, timing of sowing, and genotype selection. In the key rice-producing regions of China, the CERES-Rice model was used to analyse the impacts of CO_2 levels on rice yield. According to the results, [46] rice yield will decrease if CO_2 is absent. [47], who used the GLAM (generic large-area model) to examine the effects of climatic uncertainty on peanut yield, the production of peanuts can increse by 10–30%. [48] estimated potential climate change in the major grain cereals and soybean crop yield using the IBSNAT, and suggested that as a result of climate change, there will likely be a boost in crop yields at mid and high latitudes, while a decline in yields is expected at lower latitudes. Using GCMs and the soybean crop simulator GLYCIM, [49] validated soybean yield prediction in the Mississippi Delta, providing a useful method to ascertain the general relationship between crop yields and climate change, including temperature, precipitation, and CO_2 concentration. [50] principally examined the effect of temperature on crop yield in India under the present (1961–1990) and future (2071-2100) climate projection scenarios. They did this by using the regional climate model PRECIS and the GLAM crop model. The results show that availability of irrigation water throughout the prolonged growth period, excessive temperatures have a negative influence on agricultural output. However, mean and high temperatures are not thought to be the key criteria which are utilized to determine crop yield. Depending on the area latitude and irrigation practices, different regions may likely suffer a boost or decline in crop productivity as a result of climate change. Crop production can be increased by both irrigation application and an increase in precipitation during crop growth. Because the growing season would be shortened due to climate change, the planting date must also be altered in order to enhance crop productivity. Climate change may shorten the length of crop rotation, therefore farmers must consider selecting appropriate crop cultivar,optimum sowing dates, fertilizer levels and other cultural practices when planting crops. The beneficial impacts of climate change on farming are linked to the elevated levels of CO2, longer growth periods in higher latitudes, and the conservation of mountainous ecosystems. Conversely, the harmful effects consist of a surge in pests and diseases, as well as soil degradation due to temperature fluctuations. To meet the demand for food of the growing population, researchers have had to create novel crop strains that can withstand the changing climate and soil erosion. Evaluating climate unpredictability is a crucial factor in predicting the variation in crop yields under future climate conditions

4.2 IMPACTS OF CLIMATECHANGE ON FOOD SECURITY

"Food security" has been defined by the Food and Agriculture Organization (FAO) as "a condition in which all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [51]. The studies that are now available, however, mainly concentrate on how climate change can alter food availability and hardly ever examine how this would affect the stability of the food supply. The area that can be planted with crops, such as in degraded soils, may rise in the meantime as a result of modified crop varieties that can tolerate extreme weather conditions including drought, waterlogging, salinity, and heat. This could enhance the amount of food that is available in the coming years. Climate change will have an influence on food quality because of increased temperatures and shortened agricultural growth cycles. In their investigation of the impacts of climate change on food security, [52] employed the HadCM3, SWAP, and water salinity basin model to simulate evapotranspiration and available water at the field size and assess the link between irrigation depth, crop area, and food quality.Expanding the cultivated land area is imperative to avert a decrease in food security and enhance the total grain production. [53] provided several recommendations for boosting agricultural production potential, including crop diversification and increasingrainfed and irrigated agriculture regions and evaluated the impacts of current and projected climatic scenarios on water availability and food security in the 2020 and 2070s.[54] came to the conclusion that while expanding crop area can boost food production, it will worsen food securityconversely, reducing irrigation water allocation and decreasing crop area can boost both environmental quantity and security. This was done by using the ADAPT and SWAP models to examine the effects of climate change on food quantity and security. [55] examine the potential impacts of climate change on the wheat crop cultivated in South Australia under different levels of CO_2 concentration, researchers combined integrated global climate models with DSSAT 3.5 CERES-Wheat. The findings indicated that although the drier areas would gain more from climate change scenarios than the wetter sites, the quality of the wheat grown there could suffer due to the drier settings. [56] examined China agricultural productivity and water management in order to analyses future food security in that country and around the world. They emphasized the need to consider these elements with population, ecology, energy, and climate. This is due to the fact that numerous uncertainties caused by climate change might affect how water resources are managed and other water-related issues.Food security is becoming increasingly significant to people all around the world. As a result of climate change, scientists continue to encounter serious problems with the supply and quality of food. The impact of CO_2 on food security in the context of a changing climate is a constant subject of research. Future research on the subject will need to take population, agricultural production, climate change, and water availability into account in order to evaluate food security thoroughly and methodically.

5.ADAPTATION AND MITIGATING CLIMATE RISKS IN AGRICULTURE: HARNESSING THE POWER OF CROP SIMULATION MODELS

5.1 Adaptation

Numerous regions of the world may experience significant issues due to impact of climate change, [57]. Crop modelling has been used to analyses the consequences of climate change and gauge potential adaptation methods [58].Adjusting irrigation, cultivars, nitrogen fertilizer intake, planting dates, and irrigation were some of these techniques[59] [60] [61] [62]. The adaptation strategies include: Shifting the planting dates for grains and oilseeds is frequently advised at the conclusion of the growing season if it does not indicate an increase in dryness. This may be required due to high temperatures and/or low rainfall associated with climate change that occur during the early part of the growing season in semi-arid places, or due to the potential for prolonged growing seasons as a result of higher temperatures that encourage growth during cooler months [63] [64]. Moving planting dates may, with considerable variation across all studies, enhanced yields by a median of 3–17%.Crop variety and planting schedule optimization appear to be an effective adaptation when coupled across tests, increasing yields by up to 23% in contrast to current management. As the effects of climate change persist [65] and particularly as the frequency of unpredictable weather patterns rises, the adaptability to plant different crops at different times depending on seasonal circumstances could become increasingly critical. Increased rainfall variability and drought [66] further highlight the need for these changes in cropping systems and management.Adjusting the plant population and nutrient management, shifting to crops that require less water due to rainfall and LGP variations, adopting site-specific cultivation practices [67]and increasing the variety of crops and cultivars in response to drought, soil salinity, or waterlogging are among the measures that can be taken.

Weather forecasts and shelter belts for microclimate modification [68] also assist in lowering production risks under a changing and changeable climate. Another strategy for agricultural systems to adapt to climate change is diversification of activities ([69] [70].Incorporating a variety of activities often involves engaging in higher-value ventures or those that enhance the efficiency of scarce resources, such as by increasing water usage efficiency, or to mitigate risk.[71][72]. In some cases, increased diversification outside of agriculture may be favored [73]. To ascertain the impacts of climate change on rice production, [74] statistically downscaled five general circulation models under RCP8.5 for Pakistani rice output in the middle of the century (2039-2069). The temperature increase will cause a 7.3% loss in rice yield, according to model projections. Several adaptation strategies were explored in the middle of the 20th century to combat this decline in rice output. Adaptive measures that involved augmenting the plant population, elevating nitrogen levels, and transplanting crops earlier resulted in 8.7% increase in rice yield for mid-century scenarios under RCP8.5.Using the bias-corrected RegCM4 output (DSSAT) model, Singh assessed the effects of agronomic adaptation choices on the rainfed rice yield gap for India for the baseline era (1981-2005) and two future periods (2016-2040 and 2026-2050).The results showed that altering the transplanting period (advanced by a fortnight), crop spacing (10 x 10 cm), and N-fertilizer application (140 kg/ha) was the most efficient method for closing the yield gap under the climate change scenario[75] .[76] examined on the impact of climate change variability on groundnut yields in the Anantapur district. Five GCMs (MPI-ESM-MR, MIROC5, CCSM4, HadGEM2-ES, and GFDL-ESM2M) were utilized to generate climate change projections based on RCP8.5, which indicated a rise in rainfall activity by 10.6% to 25% and warming by 1.4°C to 2.4°C. Using the CROPGRO-Peanut model, simulations revealed that implementing heat-tolerant cultivars, drought-tolerant cultivars, supplemental irrigation, and a combination of drought-tolerant cultivars and supplemental irrigation could enhance groundnut yields by an average of 1.0%, 5.0%, 14.4%, and 20.2%, respectively.Depending on the location, the relative geographical patterns of the benefits of adaptation choices varied, but the adoption of new cultivars with drought tolerance and one supplemental irrigation at 60 DAS enabled the biggest increases. Improvements in irrigation technologies, more effective water harvesting methods, and water-smart practises like deficit and drip irrigation can be made to prevent water logging and conserve soil and water [68] [77] [71] [78]. The previously mentioned adaptations could either significantly decline the negative effects of climate change or advantage from positive transformation, individually or together.

5.2.MITIGATION

Some agricultural management strategies, such as minimal tillage and leaving residues on the soil surface, can help increase productivity while requiring less fertilizer, while other strategies can help decrease fertilizer usage. These techniques will reduce emissions of greenhouse gases like CO_2 and N_2O because these gases depend a lot on soil organic carbon levels and the pace at which nitrogen fertilizer is added. [79] showed that the ideal amount of nitrogen fertilizer may be decreased by using crop modelling in conjunction with precision agricultural technologies, resulting in lower N_2O emissions.While using less fertilizer, some agricultural management techniques, such as limited tillage and leaving residues on the soil surface, can help enhance productivity. Other techniques can help reduce the need for fertilizers. Because the amounts of soil organic carbon and the rate at which nitrogen fertilizer is applied to the soil greatly affect the emissions of greenhouse gases like CO_2 and N_2O, these strategies will lower their emissions. [79] demonstrated that employing crop modelling in conjunction with precision agricultural technologies can reduce the optimal nitrogen fertilizer amount, resulting in lower N_2O emissions.

CONCLUSION

In order to anticipate the impacts of climate change, numerous climate models have been created. Models with greater spatial resolution can provide more precise estimations of the potential future climate scenarios, which is particularly advantageous when predicting their impact on agricultural yield and food security.The productivity of crops will have negative consequence by future climate change, particularly in tropical regions, jeopardizing the supply of food in these regions. Climate change has both direct and indirect effects on crop productivity. Climate variability and extremes are growing, while the average climate is changing. Fertilisation of CO_2 and the impact of ozone on vegetation are two effects of GHG emissions that are unrelated to climate change. Although a warmer climate could lead to reduced crop yields, developing countries located in tropical regions have the ability to counteract these negative effects by implementing more intensive agricultural practices and adapting to changes in the environment and climate. While other forms of adaptation strategies are important, this paper concentrates on methods of adapting at the field level. Crop models are versatile tools that can be utilized by academics, farmers, and policymakers across various agricultural scales, ranging from individual fields and farms to entire regions and the global community.An effective and validated model can be utilized for resource optimization, weather forecasting, yield analysis, mitigating climate change, and having knowledge of market policies. Overall, crop simulation models are an effective tool for enhancing agricultural sustainability and production in the face of mounting environmental demands. The significance of these models is only going to rise in the years to come as the global population keeps expanding and the effects of climate change become more obvious.

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