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Review Article

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Crop Simulation Modeling: A Strategic Tool in Crop Management

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Abstract

Recent advancements in agricultural technology and the increasing challenges posed by food scarcity have prompted growers to seek enhanced control over environmental conditions to optimize plant growth. In this context, crop simulation models have emerged as a valuable tool for developing innovative crop management systems, garnering significant interest from researchers over the years. This article explores the opportunities and applications of various crop models in addressing critical agricultural and environmental concerns. The key highlights include Climate Change Impact Assessment: Crop models play a pivotal role in assessing the potential impacts of climate change on agricultural systems, allowing for proactive adaptation and mitigation strategies. Fertilizer Management: Crop models enable precise fertilizer management, ensuring optimal nutrient application and minimizing environmental impacts, such as nutrient runoff. Yield Prediction: Accurate yield predictions facilitated by crop models empower farmers to make informed decisions regarding planting, harvesting, and marketing their crops. Irrigation and Phenological Studies: Crop models aid in the efficient management of irrigation resources, contribute to water conservation, and offer insights into plant phenology, enabling better timing for various agricultural practices. Disease and Pest Forecasting: Crop models are instrumental in predicting disease and pest outbreaks, allowing timely intervention strategies and reducing crop losses. The upsurge in technological advancements in agriculture and growing concerns related to food scarcity have elevated the need for advanced environmental control for optimal crop growth. Crop simulation models have emerged as a powerful tool, with applications spanning climate change impact assessment, fertilizer management, yield prediction, irrigation and phenological studies, as well as disease and pest forecasting. The research outlined in this article underscores the multifaceted opportunities and applications of crop models in addressing critical agricultural and environmental challenges, emphasizing their significance in fostering sustainable and resilient farming practices.

Keywords

Crop simulation models, Different types of models, Application, Limitation, No poverty, Zero hunger

Introduction

There is a need to increase crop production and productivity to feed the growing global population in the future. As the world's population grows, food production must keep up with demand. Farmers must adopt more efficient farming techniques, such as precision agriculture, and use new genetic modification technologies to increase crop yields and productivity. The most effective crop management strategies can be adopted to achieve this goal. Additionally, new varieties of crops need to be developed that are more resistant to disease and can tolerate different climate conditions, thereby allowing farmers to increase their yields and productivity. Furthermore, more sustainable farming practices, such as cover crops and crop rotation, can help improve soil health and increase yields [1]. By taking all of these steps, farmers can work to ensure that food production can meet the needs of a growing population.

As a result, field experiments used to evaluate such studies were time-consuming, resource-consuming, tiring, and expensive [2]. Cover crops help preserve topsoil and replenish nutrients, while crop rotation prevents soil from depleting particular nutrients. Combined with other sustainable practices, such as minimal or no-till farming, these techniques can help farmers improve their yields, reduce costs, and ensure food security for a growing population. Crop models can be used as an alternative tool to assist in formulating and analyzing the best management practices. Crop models use mathematical algorithms to simulate the growth of crops under different conditions. These models can be used to estimate the effects of various management practices on the growth and yield of crops and to inform farmers about their decisions better. The models can also identify the optimal combination of practices for a given environment and assess the potential benefits of sustainable practices on yields, such as cover crops and crop rotation. In the scientific world, a model is a mathematical expression or set of equations depicting a system's behavior. It assists scientists by allowing them to understand how soil, plants, and the atmosphere interact. By simulating various scenarios, the models can predict the effects of different management practices on crop yields and soil health, helping farmers make informed decisions about what sustainable practices to adopt [3].

The models also allow scientists to assess how different environmental factors, such as temperature, rainfall, and soil nutrients, affect crop yields. Predicting future performance requires a combination of past and present weather and crop data. It can include events such as emergence, flowering, fruiting, maturity, and harvesting, in addition to phonological events such as flowering and fruiting. By understanding the impact of these environmental factors, scientists can develop strategies to optimize crop yields, such as using fertilizers, irrigation, and pest control. In addition, they can identify areas that are more likely to experience crop failure due to unfavorable conditions and plan accordingly. It is possible to use crop weather models to show how the weather and climate affect crops' growth, development, and yield. By considering things like temperature, rainfall, light, and wind speed, scientists can predict the conditions that will be most favorable for crop growth and the conditions that will lead to crop failure. By understanding the relationship between the environment and crop growth, they can make informed decisions about managing their farms and maximizing their yield. When de Wit began his work on crop growth models during the 1960s, a new era was about to begin in agriculture.

Crop growth models help farmers understand how climate, soil, and other environmental factors affect their crops. Using these models, farmers can anticipate how their crops will respond to different environmental conditions and decide how best to manage their farms for optimal yield. To calculate crop yield the first model described the photosynthetic rates of crop canopies to calculate the crop yield. This model was then improved by incorporating other factors, such as the effects of soil fertility and water availability. With this additional information, the model was able to predict crop yields. The model has also been refined as new data and technologies become available. Today, crop growth models inform farmers how to manage their farms for optimal yield. According to Monteith [4], a crop model is a set of measurable factors that predicts a crop's growth, development and yield under a given set of genetic features and environmental variables.

It is believed that Ceres, Oryza, Crop grow, and Info crops are some of the most popular models currently in use. These models allow farmers to predict the yield of their crops based on the available resources, such as soil fertility, temperature, and water availability, as well as the genetic features of the crop. This allows them to make informed decisions about managing their farms for maximum productivity and efficiency. The International Benchmark Sites Network for Agro-technology Transfer (IBSNAT) was a U.S. Department of Agriculture-funded project initiated in 1982 that mainly focused on expanding a modeling project focused on tropical and sub-tropical regions worldwide.

The goal of IBSNAT was to develop and evaluate agro-techniques that could be used in those regions to improve crop production. They also tested and monitored soil and water resources and studied the effects of climate change on agricultural production. It was developed to enter, store and manipulate various kinds of data related to soil, weather, and crops to run a crop simulation model and analyze the output of the crop simulation model. To develop crop production strategies in rice (Rajendra Mahsuri - variety) for the state of Bihar, India, have used a CERES-DSSAT (Decision Support System for Agrotechnology Transfer) model to develop a crop production strategy in this variety. The model considers soil type, weather conditions, and crop characteristics to simulate crop growth. The model also allows users to adjust parameters such as fertilizers, irrigation, and other inputs to optimize their yield. This information lets users develop crop production strategies tailored to their specific environment.

Different Types of Models

Statistical models

This model quantifies and expresses the relationship between yield parameters, yield, and weather elements by utilizing statistical techniques such as step-down regressions and correlations within this model. By doing so, this model can accurately predict crop yield and productivity while considering variations in weather conditions [5].

Mechanistic models

Mechanical models can describe a system in terms of its low-level attributes and explain the relationship between climatic factors and crop yields on a large scale. This allows for identifying patterns and elements to help farmers optimize crop yields. Consequently, these models can mimic a particular situation's appropriate physical, chemical, or biological conditions. They effectively explain how a crop responds to a specific problem and why it does so. Consequently, these models provide a powerful tool for farmers to identify strategies to maximize crop production effectively [6].

Deterministic models

In the models, the exact value of the yield or dependent variable is evaluated without considering associated probability distributions, variances, or random factors. This approach may lead to inaccurate results if random factors are not considered. They also have defined coefficients.

Stochastic models

Stochastic models are used when the data set has high variability or uncertainty. A probability factor is attached to all the outputs so that each group of inputs will provide different results with probabilities.

Dynamic models

In this model, time is involved as a variable. As a result, both dependent and independent variables have constant values over a given period. This dynamic approach offers increased depth, as it allows for consideration of both short and long-term effects and any potential changes in the system over time.

Static

It should be noted that time is not considered a variable. An independent variable has the same value over a given period as a dependent variable. However, time can still impact the dependent variable, as it may change over the period the variable is being studied.

Simulation models

Simulation models can be computer programs or mathematical representations of a real-world system, depending on the application. The prime objective of crop simulation models is to estimate crop responses regarding weather, soil conditions, and crop management as a function of these factors. Using one or more sets of differential equations, they can calculate both the rate and the state variables over time. This is typically from planting until harvest maturity or harvest time. Additionally, these models aid in making crop management decisions, including predictions regarding optimal planting dates, irrigation scheduling, and nutrient management.

Calibration and Validation of Crop Simulation Models

As a prerequisite for simulating crop growth and production under multiple management options and different climatic conditions, crop simulation models need to determine the genetic coefficient of a specific crop cultivar to affect crop growth and production. The genetic coefficient helps to determine the growth and development stage of the crop, as well as its yield potential and response to environmental factors. It is an integral part of the crop simulation model, as it provides the basis for estimating the potential yield of a crop under different management and environmental scenarios. Genetic coefficients must be calibrated and validated for crop models to succeed to ensure their accuracy. This is because the genetic coefficient helps to account for the variability in a crop's response to environmental factors, such as water, temperature, and light.

Additionally, these coefficients can be used to determine the optimal management practices for a particular crop, such as planting date, fertilizer application, and irrigation management. This can help farmers maximize their crops' yield and reduce input costs. Biological coefficients are mathematical constructs designed to mimic the phenotypic outcomes of genes under different environments. By using physical coefficients, farmers can accurately predict the yield of their crops with a given set of environmental conditions. This helps them to plan their management practices accordingly and to make informed decisions about their inputs, such as fertilizer and irrigation that will maximize the yield of their crops and reduce input costs. As part of the calibration process, the model is fed with actual data, and it is compared with a set of genetic coefficients and a set that shows the maximum agreement with the real data and is chosen as the genetic coefficient that is most suitable for the calibration process. This is done to optimize the model for the given data set and to ensure that the model can accurately predict future outcomes based on current data.

The genetic coefficients serve as a sort of "blueprint" for the model and help it to make more accurate predictions. There are specific tools available for this purpose. The Genotyping Coefficient Calculator is a tool used as part of the agro-technology transfer (DSSAT) decision support system. To validate the models that have been developed, specific statistical measures can be used to demonstrate that they have been tested. The Genotyping Coefficient Calculator allows for the analysis of genetic coefficients, which helps to identify the factors that influence the outcome of the models. It provides a way to quantify the strength of the relationship between the data and the model's predictive ability. Statistical measures can then be used to confirm the model's accuracy, such as the R^2 statistic or the root mean squared error (RMSE). As a part of their study Vysakh et al. [7] used RMSE and the d-stat index to validate the genetic coefficients developed using the CERES rice model for two rice varieties (Jaya and Jyothi) of Kerala. The model could predict the phenophase and yield accurately for both types. A model is efficient if the model D-stat value reaches unity and the RMSE reaches zero [8].

$$RMSE = \left[\sum_{i=1}^{n} \frac{(Pi - Oi)^2}{n} \right]^{0.5}$$

$$d - stat = 1 - \frac{\sum_{i=1}^{n} (Pi - Oi)^2}{\sum \left[(Pi - Oi\ average) + (Oi - Pi\ average) \right]^2}$$

Where, Oi: Observed value, Pi: Predicted value, Oi average: average of observed value, n: total number of observations.

This step of calibration and validation is the first step in crop modeling. Proof using multi-year and spatial data offers better accuracy and model performance.

Opportunities of Crop Modeling in Agriculture

The use of crop simulation models has a wide range of applications in the agricultural sector, which includes the management of cropping systems, stock formation, and the design of agricultural policies. Crop simulation models predict yields and other crop performance indicators under different environmental conditions. They can also identify potential problems in the production system and provide insights into optimizing production and managing resources more efficiently. It is possible to compare different crop models using these mathematical models; they can also be used for testing the variability of crop models according to climatic factors such as CO_2 levels, rainfall, etc., with the help of these mathematical models. Mathematical models can be used to simulate the impact of different factors on crop yields and to identify changes in crop production due to climate change. By running simulations, it is possible to evaluate the effects of other variables on crop yields and identify improvement areas.

These models can also be used to compare different crop varieties and to analyze the impact of different management practices on outcomes. If crop models are run against observed data, the model's performance can be improved, providing a more accurate response to genetic and climatic factors. This can be used to develop strategies for sustainable agriculture, identify optimal planting times, and assess the impact of different management practices on crop yields. It also enables farmers to compare different crop varieties and identify areas for improvement in their current practices. To assess the impact of other climatic conditions on crop production and food security of a particular region, crop models should be calibrated with climatic and economic models according to the different climatic conditions in that region. The models can help farmers accurately predict yields, identify areas of improvement in their current practices, and plan for future crop production.

Additionally, it can help to assess the impact of changes in climate on crop production and food security, as well as provide insight into the economic effects of climate change in a particular region. It is the responsibility of crop modellers to collect soil and weather data to understand, develop, and evaluate the adaptation and mitigation strategies under future climatic conditions. They work with agronomists, soil scientists, plant scientists, etc., to create successful models for different regions. By collecting soil and weather data, crop modellers can identify patterns and trends in the data that can be used to inform and improve the models. This data can also be used to develop and evaluate strategies to help farmers adapt to a changing climate and mitigate the effects of climate change. In the following sections, we will discuss the application of models in climate change impact assessment, yield prediction, the development of fertilizer management practices, pest and disease forewarning, phenology and irrigation studies, and the management of natural resources.

By using models to simulate different climate scenarios, researchers can better understand the potential impacts of climate change on agricultural production, which can then be used to inform strategies to help farmers adapt to a changing climate. Additionally, this data can be used to develop strategies for improved irrigation, fertilizer management, pest and disease control, and the management of natural resources.

Impacts of Climate Change on Crops

There is a direct correlation between the productivity of crops and the security of food. This is adversely impacted by extreme weather events, such as high temperatures and irregular rainfall distribution caused by climate change. As extreme weather events become more frequent, crops will be exposed to a more significant risk of being damaged, resulting in lower yields and decreased food availability. This can lead to a food shortage, resulting in higher prices and reduced food security. To evaluate the impact of climate change on agriculture, climate and crop modeling are essential methods that provide information for the evaluation of the effects of climate change and help the stakeholders make decisions to avoid negative results as soon as possible. Climate and crop modeling can identify the areas that may be more vulnerable to climate change and the crops that are more likely to be affected by the changing environment. It also helps to identify the optimal cultivation practices that can be adopted to minimize the impact of climate change on crops. This information can help the stakeholders to make informed decisions and adopt suitable strategies to reduce the risk of food scarcity and ensure food security.

By linking biophysical and environmental models, it is possible to reduce the risk of climate change and adopt possible adaptation strategies to mitigate the effects of climate change. This approach allows researchers to understand better how climate change affects people and the environment and which adaptation strategies are most effective in mitigating the effects of climate change. It also helps to identify areas most affected by climate change and develop plans to protect them. A study by Vanli et al. [9] indicates that wheat yield will decrease by 16.3% at Islahiye and 13.0% at Nurdagi, respectively, in the middle of the century. At the end of the century, the reductions may be as high as 16.8% and 14.4% at these places, respectively. This study is an example of how climate change impacts agricultural production and shows the urgent need to protect the area's most vulnerable to climate change.

In the absence of protective measures, the decrease in wheat yields could have a significant negative impact on local economies and global food security. In all of the climatic conditions of Sirinka, the mean grain yield of chickpeas is predicted to increase by about 20% and 34% in the 2030s and 2050s, respectively, due to climate change (rainfall, temperature, and CO_2) under all of the conditions. This could be a positive outcome for local economies, as the increased yields would result in improved products and, subsequently, higher incomes for farmers and other residents. Additionally, the increased profits could also benefit global food security, as more food would be available to meet the needs of a growing population.

Based on Ramraj et al. [10], it has been found that a temperature change will not affect the yield of rice and groundnuts in Tamil Nadu. However, a rise in atmospheric CO_2 concentration may lead to an increase in the yield of both crops in the region. The findings suggest that warmer temperatures can increase the photosynthesis rate of rice, but the effect on groundnuts is not as significant. The rise in CO_2 concentration, however, helps plants to utilise available water better, leading to an increase in the yield of both crops.

A study conducted by Bhuvaneswari et al. [11], using a calibrated and validated CERES rice model, concluded that a 1 to 5 °C increase in temperature would result in a yield reduction of 4 to 56% in the current climate, depending on when rice is planted (1st June to 15th July). The increased CO_2 concentrations also allow plants to close their pores less to conserve water. This is because they don't need to open them as often to get the CO_2 they need for photosynthesis. This means more water can be used for growth and development, increasing yields. A key issue relating to climate change is the development of climate-resistant crops to feed the ever-increasing population of the country, and CSM CERES crop models are one of the best tools and approaches to assist decision support systems for identifying adaptation strategies in the region of Nepal. Climate-resistant crops are important as they can help minimize the negative impacts of climate change on food production. CSM CERES crop models can help identify the most suitable crops for a region by considering the local climate, soil conditions, and other factors.

This can help farmers make the right decisions when selecting crops that can best withstand the changing climate in the region. Using the DSSAT model in the south Gujarat region, Chaudhari et al. [12] assessed the effects of temperature and CO_2 on the yield and growth of rice by analyzing the effect of temperature and CO_2. Through the model, they could simulate rice growth in different temperatures and CO_2 levels and then compare the results to the actual growth and yield data collected from the region. This allowed them to assess the effects of temperature and CO_2 on the rice yield and growth. Based on the simulation results, an increase in temperature by 1 to 20 °C will cause a yield reduction of 3.25 to -9.47%. In contrast, a decrease in maximum temperature by 1 to 20 °C will result in a yield increase of 5.93%. Higher temperatures strain the photosynthetic process, which can lead to a decrease in yield. Additionally, with a decrease in temperature, the plants can make more efficient use of the available light energy and convert it into more energy-rich molecules, which can then be used for growth, increasing yield.

Using the CERES rice model, Gupta and Mishra [13] analyzed the effects of climate change on rice production in India from the perspective of agro-ecological zones (AEZs) determined by the AEZs. They found significant differences between the AEZs in terms of the effects of climate change on rice production, with some AEZs experiencing a decrease in production while others experienced an increase. The authors concluded that the AEZs can be used to identify and target areas most vulnerable to climate change's effects. To feed the CERES rice model with projected climate data from eight global climate models, the model was fed climatic projections from eight global climate models. An increase in rice yield was recorded in all the AEZs. The authors then used the CERES rice model to simulate the effects of climate change on rice yield in the different AEZs. They found that the simulations showed an increase in rice yield in all the AEZs compared to the current climate.

This suggests that targeting these areas with adaptation strategies can help mitigate climate change's effects on rice production. A wide range of applications can be derived from modeling approaches, such as evaluating optimum cultural practices, seed rates, scheduling (time and amount) of irrigation and fertilizer applications, and evaluating the impact of adverse weather conditions. By using such models, farmers can make decisions tailored to their specific conditions and be better prepared for the effects of extreme weather events. It also allows for more efficient use of fertilizers and irrigation, helping to reduce environmental impacts. This research tool is designed to be user-friendly for evaluating the effects of climate change and different agronomic practices on agriculture. According to Sun et al. [14] in 2020, a new heat stress function was added to the CERES rice model. This new function allows researchers to simulate the effects of heat stress on rice productivity by considering the effects of temperature, humidity, solar radiation, and other environmental factors. It also allows researchers to optimize the timing and amount of fertilizer applications, water, and other resources based on the expected climate conditions.

Sun et al. [14] implemented a new heat stress function within the CERES rice model as part of their work. In addition to optimizing fertilizer, water, and other resource applications, this new heat stress function also allows researchers to develop strategies to minimize the negative impacts of extreme temperatures on rice production. This is especially important in areas with high temperatures, where rice production can be severely affected. As a result of the improved crop model, rice yields in response to extreme heat were better predicted than in the old model. To analyze rice's projected yield (2020-2099), an ensemble of five climate model data sets and four representative concentration pathways was employed, and significant yield reductions were observed due to the high temperatures. The analysis showed that, compared to the old crop model, the new model could predict rice yields more accurately in response to high temperatures. This is because the new model took into account the effects of climate change on the rice crop, such as increased temperatures, increased evapotranspiration, and other extreme weather events

Crop Yield Prediction

It has been demonstrated that crop models are one of the most effective tools for predicting crop productivity under different crop management and climatic conditions. These models are based on data collected over time, such as yields, soil and water conditions, and weather conditions, which helps them accurately predict crop productivity. In addition, they can simulate different management scenarios, such as different planting dates or fertilizer applications, to determine the best approach. There is no doubt that pre-harvest yield prediction is of paramount importance to planners and policymakers at every level. Using these models, agricultural experts can make better decisions about managing the land and optimizing the crop yield.

For example, the models can be used to determine the optimal planting dates and fertilizer applications for a given region, which can help to maximize crop productivity. Based on the prediction results, preparations can be made to store excess production. If there are indications of insufficient production, the required amount of grains can be imported from elsewhere or procured from other sources. This helps minimize risk and ensure a consistent food supply for the population. It also helps to prevent losses due to market fluctuations and food price increases due to shortages. It would be possible to calculate the yield gap of present cropped lands to determine the extent of yield increase compared to actual yield values. As soon as this yield gap is assessed, realistic solutions are to be developed to close this gap. These solutions could include improved water management, better soil management, better quality seeds and fertilizers, and better agronomic practices.

Additionally, modern technology such as precision farming, satellite imagery, and remote sensing can help monitor crop growth and yield more accurately and make better use of available resources. Behera and Panda [15]; Lobell and Gourdji [16] a crop model can be successfully used in various parts of our country to evaluate the yield variation that occurs in crops due to various climatic and management factors that may affect the yield of the crop. Crop models can help farmers understand how their environment and management decisions affect crop yields when used correctly. This information can help them make more informed decisions and improve their yields. A good example is DSSAT in conjunction with CERES rice. DSSAT is a crop modeling system that can simulate different crop management strategies and help farmers determine the best approach for their particular environment.

CERES-Rice is a crop simulation model specifically designed for rice production, which can provide farmers with detailed information on optimizing their crop yields. Together, these two models provide a comprehensive picture of how to maximize crop yields. An example of this model type is the DSSAT, which has been embedded with CERES rice model. DSSAT is a powerful tool for farmers as it uses simulation-based approaches to help them make decisions about their rice production. It provides detailed information about different crop management strategies, such as irrigation methods, nutrient management, and pest control. It helps them decide which is the most efficient and cost-effective.

Furthermore, embedding with CERES-Rice can accurately predict crop yields, allowing farmers to maximize their yield potential. This study Corbeels et al. [17] and Urgaya [18] aims to provide farmers with the best adaptation techniques to achieve optimum yields by simulating the interaction between various inputs and the soil to achieve optimal yields. The CERES-Rice simulation model was used in another study conducted by Pinnschmidt et al. [19] to evaluate the nitrogen limitations that impacted yield levels and weather patterns in northwest Luzon (Philippines), northeast Thailand, and the Mekong River delta (South Vietnam) between 1992 and 1994 using the CERES-Rice simulation model.

The model was used to simulate the effects of various nitrogen fertilization rates and weather variables on the yields of irrigated and rainfed lowland and upland rice production systems. It was also used to evaluate the impacts of climate change on the growth and development of rice crops. In the Philippines, 45% of the planned results showed a deviation from the observed yield compared to the weather-limited simulated results, and 55% of the projected results showed a deviation from the observed yield in Vietnam. This indicates that the nitrogen limitations were a major factor in yield levels in the region, as the weather-limited simulated results were more accurate than the projected results. The results also suggest that nitrogen availability was a key limiting factor in the region and could be improved with better fertilization practices. Using crop simulation models, Timsina et al. [20] found that it is possible to estimate potential yield and actual yield by overcoming other methods of a yield gap analysis by using crop simulation models. The attainable yields were obtained from maize high-yielding research plots, where the best management practices were followed to achieve the highest possible yield.

The calculation was highest for rice (1670 kg ha^{-1}). In terms of yield gap and long-term yield analysis, the CERES rice model is one of the most popular applications of the model. The CERES rice model was utilized in the study to provide a comprehensive overview of the yield gap across the states in India. The model simulated different yield scenarios, considering variety, irrigation, soil, and weather factors. It was found that the yield gap for rice was highest compared to other crops, indicating that there is a great potential for improvement in rice production. Under continental climate conditions, simulated yield will be lower with high nitrogen fertilization levels than in coastal areas. Grassini et al. [21] estimated the potential yield of maize using simulation models, and the yield gap was quantified as the difference between actual yield and simulated potential yield and the average yield gap was found to be 11% of the potential yield gap.

This suggests that the potential yield gap in continental climate conditions may be larger than the potential yield gap in coastal areas because high nitrogen fertilization levels lead to lower simulated yields in continental climate conditions. The lower potential yield in continental climate conditions could be because higher temperatures and drier soil conditions in these areas may lead to reduced crop productivity. Only after quantification of the yield gap can new policies be formulated, and a research plan can be prioritized to achieve food security without degrading natural resources. This model can quantify/analyze the yield gap by using daily weather data and capturing management practices that can influence yield (including sowing date, plant density, cultivar maturity, etc.). These are the key elements of the model for the quantification/analysis of the yield gap.

Based on simulation studies performed by Shakoor et al. [22] it can be predicted that a long-term increase in rainfall and temperature will negatively influence crop production in the future. This is because the higher temperatures and increased rainfall will cause more crop diseases and pests to thrive in the region, reducing crop yields. Additionally, higher temperatures can cause crops to dry out and cease to grow, further reducing crop yields. According to Fischer [23] it is essential to quantify crop yield potential, attainable yields, and the corresponding yield gap to meet the growing demands for food, and simulation models are one of the most influential tools for quantifying potential yield. Using simulation models, we can identify areas where crops can produce maximum yield and identify factors limiting crop yields, such as soil and climate. This information can then be used to develop strategies to improve crop yield and meet the increasing demands for food.

As a result of using a crop simulation model, Espe et al. [24] were able to estimate yield capacity and yield gap in rice production systems in the United States. The model simulates the effects of various management practices on yield and other vital crop performance indicators. The results showed that applying specific methods could significantly increase yields and narrow the gap between potential and actual yields. There was a wide range of potential yields in the simulation, ranging from 11.5 to 14.5 and real yields, which were obtained from the field, varied between 7.4, 9.6, or 58 to 76% of potential yields. The simulation results suggested that certain practices could significantly increase the actual yields. The difference between potential and actual yields was due to various factors, including soil fertility, pest and disease management, water availability, and other environmental conditions. This quantifies the yield gap based on the assumption that farmers could exploit up to 85% of their yield potential, ranging between 1.1 and 3.5 mg ha^{-1}.

These factors can all be managed to increase actual yields, but they require careful monitoring and management. By applying the practices suggested by the simulation, farmers could increase their yields and close the yield gap, leading to increased food security and economic stability. Efforts to achieve the best management practices are not accounted for by the yield attainable. Additionally, using the best management practices, farmers can improve soil health and water management, reduce pesticide use, and increase fertilizer efficiency, leading to a more sustainable production system and greater long-term yields [25]. These efforts are essential for achieving the increased yields needed to close the yield gap and improve food security. During the ripening phase of the rice crop, due to the dry weather conditions along with a reduction in the number of rainy days, the rice crop will be able to develop correctly and dry appropriately due to the reduced number of rainy days. This helps to reduce the chances of fungal diseases and pest attacks, which can further reduce yields.

Additionally, the increased temperatures during the ripening phase of the rice crop will help to increase the photosynthesis process, thus improving the growth and development of the crop, leading to higher yields. As a result of higher rainfall, the lodging of crops occurs along with the decaying of grains in standing water, resulting in lower yields. Higher temperatures during the rice crop's ripening phase can help increase photosynthesis, resulting in more efficient growth and development and higher yields. However, increased rainfall can lead to lodging, which is when the rice stalks bend and fall over, and the decaying of grains in standing water, both of which can reduce yields. Additionally, increased moisture can increase the chances of fungal diseases and pest attacks, lowering yields.

Based on field data collected from 11 agrometeorological experimental stations in China during the period 1981-2009, Zhang et al. [26] investigated yield gap, changes in potential yields, water and nitrogen stressed yield on rice using CERES rice model based on observations from 11 agrometeorological experimental stations in China from 1981 through 2009. The authors used the CERES rice model to observe the effects of water and nitrogen availability on yield potential. They found that potential yields could be increased by increasing water and nitrogen inputs. They also found that the yield gap between potential and actual yields was due to the inefficient use of water and nitrogen.

The CERES rice model was used to calculate the yield gap, which is the difference between actual yields and potential yields, as well as the changes in potential yields and water and nitrogen-stressed yields. The field data allowed them to accurately measure the effects of water and nitrogen stress on yields. They wanted to understand the impact of climate change on rice production in China and how it affects potential yields and water and nitrogen-stressed yields. They used the CERES rice model to analyze the data and found that there had been a significant decrease in potential yields over the study period. As a result of the experiments, it was found that a yield reduction of 16% was observed as compared to the potential yield. This reduction was attributed to water and nitrogen stresses caused by a combination of factors, including reduced precipitation, inadequate irrigation, and increased evapotranspiration due to higher temperatures.

Interestingly, Halder et al. [27] summarized that temperature and CO_2 are two of the most essential weather parameters directly affecting crop yield. They found that temperature and CO_2 directly influence photosynthesis and respiration, which affects crop yield. Additionally, they found that temperature and CO_2 could also affect the growth and development of crops, impacting their work. As a result of the increase in temperature, crop yield was reduced due to pollen sterility and poor pollen growth during the reproductive growth stage. This was a consequence of the temperature increase. In addition, high levels of CO_2 can increase the rate of photosynthesis in some plants. However, more than this increase is needed to offset the adverse effects of increased temperatures.

Furthermore, high CO_2 concentrations can also reduce plant water availability, leading to further reductions in crop yield. The rice grain yield increased steadily at CO_2 concentrations of 420, 530, and 650 ppm, but the total biomass yield decreased. Using the convolutional neural network (CNN) and the spatial structures of different attributes, we could model yield response to nutrient and seed rate management by capturing and combining relevant spatial arrangements of other features. The increased temperature caused a decrease in the total biomass yield because the plants could not photosynthesize as efficiently in the hotter climate. The CNN model was used to predict how the work would respond to different nutrient and seed rate management practices by capturing the spatial structures of other attributes and combining them.

With the right combination of technology and crop management practices, it is possible to overcome the yield gap and improve rice production very rewardingly. By using new technologies such as precision agriculture and advanced irrigation systems, farmers can reduce their reliance on traditional practices and increase their yields. Additionally, crop management practices such as crop rotation and soil conservation can help improve yields. This is done by utilizing available technologies and adopting appropriate crop management practices. Precision agriculture and advanced irrigation systems allow farmers to monitor and manage soil and water resources more efficiently and reduce reliance on traditional practices. Crop rotation and soil conservation practices help increase nutrient availability and improve soil health, increasing crop yields. A simulation analysis was carried out over a long period to evaluate the sensitivity of potential yields to changes in selected management practices as a result of a simulation analysis performed over a long period.

The simulation analysis found that crop rotation and soil conservation practices increased yields significantly. The analysis also revealed that yields were more sensitive to changes in management practices when the practices were applied over a long period, such as when crop rotation was applied over multiple years. The simulation analysis showed that the use of crop rotation and soil conservation practices led to an increase in the availability of nutrients in the soil, which positively affected soil health. This, in turn, increased yields, as crops could better absorb the nutrients they needed. The potential yields could be enhanced by adopting a higher plant density and a hybrid capable of growing longer. The study's findings indicate that crop rotation and conservation practices can improve soil health, leading to higher yields. This is because the increased availability of nutrients in the soil allows crops to absorb them better and maximize their growth potential.

The authors also suggest that increasing the plant density and using a hybrid that can grow longer can further enhance yields. It has been shown that Singh et al. [28] conducted an empirical study in which they found that late sowing and transplanting, high seed prices, inability to obtain fertilizer at the right time, a lack of funds among farmers, and pest and disease infestations are among the most significant constraints that contribute to yield gaps. Increasing the plant density and using a hybrid that can grow longer can help reduce some of these constraints, resulting in higher yields. Furthermore, these strategies can help reduce the costs associated with sowing and transplanting and seed and fertilizer costs. By increasing the plant density, more plants can fit into the same area, leading to increased yields and more efficient use of resources. Using a hybrid that can grow longer can also help reduce the time it takes to reach harvestable yields, thereby reducing production costs.

As a result, quality inputs could be provided to farmers at the right time to reduce this gap. The same amount of land can produce more crops by reducing the space between plants and providing a hybrid that can grow longer. This will also reduce the resources needed to maintain the crops, such as less water, fertilizer, and labor. Farmers can maximize their yields and reduce the gap between potential and actual yields by providing quality inputs at the right time. Singh et al. [28] utilized the CERES model to analyze the yield gap in South and North-West Bihar, which revealed that low yields were observed both during late sowing and early sowing as compared to the optimal planting date of July 15 in the north and south-west planes of the state. This result is important because it demonstrates that the yield gap can be closed by providing farmers with quality inputs and guidance regarding optimal planting times.

Additionally, the CERES model used in the study was able to accurately assess the yield gap in the two regions and make recommendations to reduce it. According to Debnath et al. [29] using field experimental data and DSSAT simulated rice yield, the authors analyzed the crop management conditions that primarily contribute to the yield gap. They concluded that fertilizer application and soil fertility management are the two major factors driving the rice production yield gap. The authors also found that improved crop varieties significantly impacted yield. In rain-fed conditions, an attainable yield gap of 0.33 t ha^{-1} was attributed to rice transplantation after 30th July. In contrast, an attainable yield gap of 0.86 t ha^{-1} was attributable to supplementary irrigation in irrigated conditions due to rice transplantation after 30th July. This means that by using improved crop varieties and irrigating the land, farmers could increase the yield by 0.33 t ha^{-1} in rain-fed conditions and by 0.86 t ha^{-1} in irrigated conditions.

This is because improved crop varieties are more resistant to drought and pests, and additional water helps to ensure a more consistent yield. The average yield of corn is reduced by 0.29 t ha^{-1} due to poor agronomic practices on the part of farmers. Improved crop varieties are bred to be more resistant to drought and pests and more efficiently utilize water. Irrigation ensures that the soil is kept moist and provides a consistent supply of water, which is beneficial for the crops. Poor agronomic practices, such as inadequate fertilization and pest management, can reduce the potential yield of a crop, even with improved varieties and irrigation. A study conducted by the authors of this paper also concluded that there should be a greater emphasis placed on the amount of nitrogen fertilizer applied, the timing of fertilizer applications, and the timing of supplementary irrigation in addition to the transplanting date.

This is because inadequate fertilization can limit the availability of nutrients necessary for healthy crop growth, and pest management can prevent the spread of diseases, which could significantly reduce yields. Furthermore, the timing of fertilizer applications and supplementary irrigation is important, as these can optimize the growth and yield of a crop. Using the DSSAT simulation model, Jain et al. [30] evaluated rice yield and yield attributes according to the gap under different agro-climatic zones of Chhattisgarh, and under both irrigated and rainfed conditions, and under both irrigated and rainfed conditions under different agro-climatic zones of the state. Their results showed significant differences in the rice yield, yield attributes, and gap between irrigated and rainfed conditions. They also found that the gap between irrigated and rainfed conditions was higher in the state's drier agro-climatic zones than in the wetter ones. He claimed that the yield gap between fertilizer stress and the absence of fertilizer stress was the greatest in all three agroclimatic zones, both under irrigated and rainfed conditions.

This suggests that even though water availability is important in crop production, fertilizer plays an equally important role, especially in drier conditions. Fertilizers can help compensate for the lack of water and increase crop yields in these areas. As a result, the variety Karma Mahsuri produced the highest yield at Raipur, Ambikapur, and Jagdalpur, respectively, with 7.5, 9.7, and 9.4 t ha^{-1} under irrigation. This is because fertilizer helps plants absorb more nutrients, enabling them to grow faster and with less water. Additionally, fertilizer can help reduce soil erosion, a problem in areas with low water availability. When combined with the right irrigation system, fertilizer can help compensate for the lack of water and increase crop yields. In Raipur, Ambikapur, and Jagdalpur, the yield gap for Karma Mahsuri was 4.5, 4.7, and 4.6 t ha^{-1} under rain-fed conditions, respectively. Fertilizer helps to improve the soil's ability to hold water, which helps reduce the amount of water lost through runoff and evaporation. Fertilizer also helps stimulate the growth of beneficial microorganisms in the soil, which can help improve the soil's fertility and ability to support crops.

A study by Zhang et al. [31] found that rice yield could be improved significantly by 29.2 to 68.9% with cultivars with longer growth durations and greater spikelet numbers when early transplanting was combined with longer growth durations. The beneficial microorganisms in the soil help to break down organic matter and release nutrients, such as nitrogen, phosphorus, and potassium, into the soil. These nutrients are necessary for healthy plant growth and help increase crop yields, as evidenced by the study by Zhang et al. [31]. A scientific study by Lobell and Burke [5] suggests that the CERES rice model can be used in a decision support system to improve rice yield in Bihar by using a decision support system. Initially, the study revealed that due to water stress during the vegetative, reproductive, and maturity phases, yield would be reduced to 24, 43, and 33%. In contrast, residue incorporation of 2.5 tons ha^{-1} would improve yield by 21.94%.

The study showed that the CERES model could accurately simulate the rice crop's growth, development, and yield. It was found that the model could accurately estimate the yield potential, which farmers can use to decide how to manage their crops best. Additionally, the model could accurately simulate the impact of water stress on rice yields. Harithalekshmi [32] used the CERES rice model to calculate three levels of yield gaps for two rice varieties, Jaya, and Jyothi, to estimate the yield gap. The simulation results indicated that the yield gap was higher in the reproductive and maturity phases compared to the vegetative phase. This was attributed to the high water stress experienced in those phases due to higher water requirements. Furthermore, it was found that incorporating crop residues improved both varieties' yields. As a result, the total yield gap calculated for the varieties Jaya and Jyothi was 3457 kg ha^{-1} and 3357 kg ha^{-1}, respectively.

The CERES model was used to simulate the yield of the two varieties, Jaya and Jyothi, under different levels of management intensity. The yield gap was then estimated by comparing the simulated yields to the potential yields that could be achieved with optimal management. The results showed a significant yield gap for both varieties, indicating the potential to increase yield with improved management. To reduce this yield gap, the study also examined better fertilizer management strategies to reduce nitrogen fertilizer use. The CERES model calculated the yield gap, which is the difference between the potential and actual yields, based on the two varieties. By reducing the amount of nitrogen fertilizer used, the total yield gap decreased, and the study saw an increase in the yield of both varieties.

Nutrient Management Strategies

For crop production to be improved, proper management of fertilizers is crucial. Fertilizers are essential for increasing the nutrient content of the soil, which can help boost crop yields. They can significantly impact crop production when used in the right amounts and at the right time. To identify the potential impact of various nutrient management strategies on crop growth under different pedoclimatic and management conditions, it is necessary to integrate the effects of soil-crop interaction on crop growth. Fertilizers can add essential nutrients to the soil, such as nitrogen, phosphorus, and potassium that are important for crop growth. They can also help to improve soil structure and water-holding capacity, which can help with water absorption and nutrient retention. Additionally, fertilizers can help to increase soil microbial activity, which can help to break down organic matter, improve nutrient cycling, and make nutrients more available to plants.

As a result of the SALUS model, Basso et al. [33] simulated the environmental and economic impacts of nitrogen application methods. The simulation showed that using fertilizer to supplement nitrogen application could result in higher yields, lower costs, and less environmental impact than traditional methods. Furthermore, using fertilizer could help reduce the amount of nitrogen lost to the environment, meaning less impact on water quality and lower emissions of greenhouse gases. Five nitrogen application rates were run in the model: 50 kg ha^{-1}, 100 kg ha^{-1}, 150 kg ha^{-1}, 200 kg ha^{-1}, and 250 kg ha^{-1}, with the final dose level being the one the farmer chose. Increasing the amount of fertilizer applied to the soil makes more nitrogen available to the crop, meaning less is lost to the environment. Additionally, with higher fertilizer doses, the crop yield increases, which leads to potential economic benefits for the farmer. Long-term simulations for 25 years were performed on high-yielding and low-yielding zones.

The simulations showed that the high-yielding zone had an overall positive benefit, with a higher crop yield and a lower rate of nitrogen leaching into the environment. The low-yielding zone, however, experienced a negative effect, with a lower crop yield and a higher rate of nitrogen leaching into the environment. This indicates that while fertilizer can be a beneficial tool for increasing crop yield and reducing nitrogen leaching, it is important to consider the yield potential of the particular zone before applying fertilizer. Based on a target yield set for each plot in the field, Sharma et al. [34] developed a web-based decision support tool, i.e., nutrient manager for rice (NMR), that calculates fertilizer nitrogen, phosphorus, and potassium rates for individual fields based on the yield target set for each plot. The tool considers soil type, crop stage, nutrient uptake, and availability factors to achieve the desired yield target. The tool then generates the optimal fertilizer rates for each plot, ensuring the highest yield possible with the least fertilizer.

To provide farmers with a blanket fertilization recommendation (BFR), the probability of financial loss was found to be 31%, whereas, under a natural fertilization recommendation (NMR), the probability was reduced to 18%. This is because the tool considers the soil, crop, and weather conditions, so the optimal fertilizer rate is calculated based on those factors. The BFR is just a blanket recommendation without considering any other factors, which can lead to over-fertilization and an increased risk of financial loss. On the other hand, the NMR considers all of those factors, leading to a more accurate recommendation and a lower risk of financial loss. Based on the simulation results, it has been found that it is possible to reduce the nitrogen fertilizer rate without affecting the yield and net return. The BFR is a general recommendation not tailored to individual circumstances, whereas the NMR considers more specific factors such as soil type, climate, and crop type.

This allows for a more accurate recommendation that reduces the risk of over-fertilization and financial loss. The simulation results have demonstrated that this approach can significantly reduce the nitrogen fertilizer rate while maintaining a high yield and net return. A study by Hameed et al. [35] simulated the rice yield under different nitrogen fertilizer rates and with different nitrogen splits using the ORYZA model to compare the results. The simulation results showed that using the proposed fertilizer recommendation reduced the total nitrogen fertilizer rate by 50% while maintaining a yield of up to 4 t ha^{-1}. Furthermore, the net return for the farms using the recommended rate was greater than that for farms that used the traditional rate. This indicates that the proposed approach can help farmers save money while getting the most out of their crops.

During the study, he found that the yield increased linearly with the addition of nitrogen, but there was no yield increase after applying 300 kg nitrogen ha^{-1} of nitrogen. The study's results suggest that applying a higher rate of nitrogen than the traditional rate does not produce significant yield increases, but it does lead to increased costs. Therefore, the recommended rate of nitrogen is not only the most cost-effective, but it also provides the maximum net return for farmers. As well as this, he also mentioned that nitrogen use efficiency was higher at zero nitrogen input. It tends to decrease with an increase in the rate of nitrogen input. The study also showed no significant differences in the grain quality when nitrogen was applied at the traditional rate versus the higher rate. This indicates that the traditional rate of nitrogen input is sufficient to achieve the desired yield.

Moreover, the study's results suggest that the traditional rate of nitrogen input is the most cost-effective and provides the maximum net return for farmers. Furthermore, the model also simulated that the lowest yield would occur with a single-split nitrogen application, and the highest yield would occur with a four-split nitrogen application. This indicates that farmers should use the traditional rate of nitrogen input to ensure they are getting the most out of their investments. The study also showed that the yield increases with multiple applications of nitrogen, increasing the farmer's net return.

The CERES rice model evaluated different nitrogen management strategies to reduce the yield gap. The CERES rice model was used to simulate the effects of different nitrogen management strategies on rice yields. The model could accurately predict changes in yield when different strategies were applied, allowing farmers to optimize their nitrogen management practices and reduce the yield gap. The study aimed to compare different nitrogen doses with three different methods of application (broadcasting, fertigation, and urea super granules). The CERES model was able to accurately simulate how different nitrogen doses and application methods affected the rice plants' growth and crop yield. The study results showed that using the right combination of nitrogen doses and application methods allowed farmers to reduce the yield gap and increase their overall productivity. According to the simulation results, 130 kg ha^{-1} nitrogen was applied in three split doses, and the fertigation method effectively improved yield when used in three split doses [32].

This strategy was the most effective in achieving higher yields because it allowed the nitrogen to be more evenly distributed throughout the soil. Splitting the nitrogen into three doses with the fertigation method also allowed for better absorption by the rice plants and improved the nitrogen uptake efficiency. In crops, it is predicted that nutrient management based on field trials and crop modeling will help to improve nutrient efficiency based on site-specific nutrient management. By splitting the nitrogen into three doses, each dose was more concentrated and had a greater chance of being absorbed by the plants, thus improving the nitrogen uptake efficiency. Additionally, by tailoring nutrient management to site-specific conditions, the crops can better access the nutrients they need, improving nutrient efficiency. This is because such an approach enables farmers to accurately measure and adjust the amount of nitrogen applied to the soil, providing the optimal environment for the crop to grow.

By using this approach, farmers can ensure that the right amount of nutrients is being supplied to the crop while also preventing the over-application of nitrogen that could lead to soil degradation and ground water contamination. Furthermore, it helps farmers save on costs by reducing the fertilizer they need. Furthermore, it can potentially reduce the amount of nitrogen runoff in nearby water sources, which can help reduce environmental pollution. This is because nitrogen can be more precisely controlled and applied in the exact amounts needed for the crop. This reduces the potential for over-application of nitrogen, which can result in the nitrogen leaching into nearby water sources and polluting the environment. To guide field management in the future, it is essential to have a clear understanding of the impacts of water use and nutrient application on agroecosystem services.

Chen et al. [36] used the De nitrification - Decomposition (DNDC) model to simulate the biogeochemical process for rice production in China based on the DNDC model. The results of this study suggest that 0.88 + 0.33 Tg of synthetic nitrogen could be reduced per year (mean + standard deviation) without affecting the rice yields. The DNDC model simulated the soil-plant-atmosphere system's nitrogen, phosphorus, and carbon cycles and incorporated photosynthesis, respiration, nitrification, and denitrification processes. This enabled them to quantify the potential benefits of reducing synthetic nitrogen inputs and how it could improve water quality and benefit the environment. The use of shallow flooding, as well as optimal application of nitrogen at the field level, could enhance ecosystem services at a national scale, leading to a reduction of 34.3% in greenhouse gas emissions, a reduction of 2.8% in overall nitrogen loss, and an increase in 1.7% in rice yields compared to current management practices.

As a result of this simulation study, we can analyze the potential benefits of water and fertilizer management reforms. The results indicate that implementing better water and nutrient management practices can reduce greenhouse gas emissions, reduce nitrogen loss, and increase rice yields. This could be beneficial to the environment and agricultural productivity. There was an evaluation conducted in North Western India of the performance of the DNDC model along with RothC (Rothamsted Carbon model) in simulating soil organic carbon (SOC) storage under rice-wheat cropping systems, maize-wheat cropping systems, and cotton-wheat cropping systems. The results showed that the DNDC model was more accurate in simulating the SOC storage under different cropping systems, and the model could accurately predict the SOC storage in the surface soil layer. This is because the DNDC model considers crop residues, soil organic matter decomposition and several other important factors for predicting SOC storage.

By considering these factors, the DNDC model can provide a more accurate prediction of SOC storage. This indicates that the DNDC model could be useful for assessing agricultural management practices' environmental impacts and improving agricultural productivity. Additionally, the DNDC model can simulate the effects of different agricultural management practices on SOC storage. This could be used to identify the most optimal practices to maximize SOC storage and minimize the environmental impacts of agricultural management practices. By understanding how different practices affect SOC storage, farmers and policymakers can make more informed decisions about managing their land in economically and environmentally beneficial ways. Furthermore, the DNDC model can simulate the effects of different practices over long periods, which can help to identify the long-term effects of various agricultural management practices. As such, the DNDC model could be a valuable tool for farmers and policymakers in informing decision-making and ensuring sustainable agricultural management practices.

By providing simulations of the long-term effects of different agricultural practices, the DNDC model can help farmers and policymakers better understand the impacts of their decisions on the environment and help them make informed decisions that will ensure the sustainability of their operations. There are indications that the R^2 values for the different cropping systems of DNDC are 0.935 and 0.895, respectively, for rice-wheat and maize-wheat cropping systems. DNDC can accurately predict soil organic carbon changes, soil water content and nitrogen losses and can, therefore, be used to assess and adjust agricultural management practices to optimize crop yields and reduce environmental impacts. The high R^2 values show the model can accurately predict soil organic carbon and nitrogen level changes based on the different cropping systems. The R^2 values for rice-wheat and maize-wheat crops (R^2 = 0.920 and 0.967, respectively) showed excellent agreement with the simulated and measured soil organic carbon contents for both crops. The high R^2 values indicate that the DNDC model can accurately simulate soil organic carbon content changes for rice-wheat and maize-wheat cropping systems over time. This shows that the model can predict how different cropping systems affect soil organic carbon levels and inform sustainable land management practices.

It is essential to understand that soil texture is one of the most critical soil factors that directly influence crop productivity by interacting directly with processes such as retention of water, ion exchange, and nutrient recycling. A calibrated and validated agricultural model (DSSAT-CERES-Wheat model) has been used with 30 years of historical data to evaluate the long-term effects of soil temperature on wheat productivity under rain-fed conditions. The soil texture affects the structure of the soil, which in turn influences the water-holding capacity and the soil's ability to support crop growth. Additionally, soil texture involves the exchange of ions and nutrient recycling, which is essential for sustainable crop production. A DSSAT-CERES-Wheat model is a powerful tool for evaluating the effects of soil temperature on crop productivity over the long term, and it is based on 30 years of historical data.

The results of He et al. [37] showed that wheat grown in clay soil is much more tolerant to drought than wheat grown in silt loam soil. This means that soil temperature is an essential factor in determining wheat productivity, as it affects the sensitivity of wheat to drought. Since clay soils are more tolerant to drought, they are better suited for wheat production than silt loam soils, and by using the CERES rice model for rice growth and development in the state of Gujarat, India. Mote and Kumar [38] examined the effects of different levels of nitrogen on rice growth and development. He et al.'s [37] research showed that clay soil was better able to retain moisture during drought conditions, leading to higher levels of drought tolerance for the wheat grown in it. Mote and Kumar's [38] research showed that different nitrogen levels significantly affected the rice's growth and development, with higher nitrogen levels resulting in increased yields.

Phenological Studies

The term "crop phenology" describes the timing of plant development, which is a significant determinant of plant yield as it results from the surrounding environment. It is impacted by environmental factors such as temperature, water availability, and the length of the growing season, as well as human-induced changes such as land use, land cover, and climate change. Crop phenology helps to determine when to plant, when to fertilize, and when to harvest for optimal yield. Much importance is attached to studying crop phenology and how it relates to surrounding environmental factors. By understanding how ecological factors influence crop phenology, farmers and researchers can better predict when crops will be ready for harvest and when they should plant, fertilize, and irrigate them. This knowledge can help to increase crop yields, reduce waste and maximize profits.

As a result, crop models can play a significant role in this process, as they are an efficient tool for achieving this goal. Crop models can simulate the effects of environmental factors on crop growth, such as temperature, rainfall, and sunlight, and provide farmers and researchers with an accurate forecast of when the crop will be ready for harvest. This information can be used to determine the best time to plant, fertilize, and irrigate crops and can be used to optimize crop yields, reduce waste, and maximize profits. According to IPCC, the projected atmospheric CO_2 content and temperature will be 414, 522 and 622 ppm, and 1.3, 2.9, and 5.2 °C retrospectively. Temperature increases adversely affect crop performance, and elevated CO_2 concentrations cannot adequately compensate for these adverse effects. Under this condition, wheat days taken to attain anthesis decreased as temperature increased at all levels (1.3 in the 2020s, 2.9 in 2050s and 5.2 °C in the 2080s) in 2020s, 2.9 in 2050s and 5.2 °C in 2080s) [39]. This means that the current climate trend has the potential to cause significant yield losses in many of the world's main crop species and that elevated CO_2 concentrations are unlikely to improve the situation.

To determine the extent of crop loss associated with water stress, it is essential to know at what stage the focus has occurred. If the water stress has happened earlier in the growing season, the crop yield will be significantly reduced due to lack of water during the critical stages of development. If the water stress occurs later in the growing season, the crop yield may be affected less since the plant has already gone through its critical stages of growth. Due to water stress, the crop yield was reduced by over 35% and 50% during the vegetative and reproductive stages. During the vegetative and reproductive stages, plants are most vulnerable to water stress and can suffer from a lack of water. As a result, the plants cannot access the necessary resources for growth, leading to decreased crop yield.

A spatial simulation of crop water stress was conducted for rain-fed sorghum crops using the DSSAT-CERES model. Simulated crop water stress was found to be affecting crop yield. Using this model [40], we could simulate the crop water stress experienced during different sowing dates and phenological stages of the crop's life cycle. The simulation showed that crop water stress was more severe when the harvest was sown late and during the reproductive phenological stages. This resulted in a decline in crop yield. This suggests that the timing of sowing is critical to ensure optimal crop yield and reduce the impacts of crop water stress. This model enabled the researchers to quantify the effect of crop water stress on crop yield in different sowing dates and phenological stages. It also gave them insight into how the timing of sowing and other management practices can be used to reduce crop water stress and improve crop yields.

Forewarning of Disease and Pest

Only in India alone, 35% of field crops are lost to pathogens and pests, resulting in losses for farmers [41]. This is due to the lack of access to modern pest control methods, such as chemical pesticides and biological pest control, which are often too expensive for small-scale farmers. Additionally, the lack of knowledge of proper farming methods and agricultural practices contributes to the loss of crops. Because of disease and pest forewarning, control measures can be applied effectively, and yield predictions and market potential can be determined. This helps to ensure that the crops are healthy and can be sold at a good price, leading to higher profits for the farmers. Furthermore, access to modern pest control methods can help to reduce the risk of crops being destroyed by pests and diseases, which can be a major source of loss for farmers. It is a method of predicting the probability of disease occurrence by combining weather data with biological data.

By using predictive analytics, farmers can anticipate when and where to apply pest and disease control methods, which can significantly reduce the losses they experience due to pests and diseases. Furthermore, using modern pest control methods can help reduce the use of chemicals, which is beneficial for the environment. If we can detect diseases early, we can adapt crop management strategies promptly. Farmers can gain insight into the weather conditions and soil moisture favorable for pest and disease activity by using predictive analytics. This helps them to plan ahead of time and take preventive action to prevent losses. Additionally, modern pest control methods are more targeted and use fewer chemicals, which minimizes the environmental impact of these interventions. Finally, by detecting diseases early, farmers can adjust their crop management strategies to reduce the spread of the disease and limit the losses. There has been tremendous growth in disease and pest forecasting tools in recent years due to the increasing frequency of unpredictable weather conditions.

These tools use data from remote sensing, weather stations, and other sources to predict when and where diseases and pests are likely to occur. This allows farmers to make informed decisions about when to apply pest control treatments and how to manage their crops to avoid spreading disease. For this purpose, both computer software and statistical equations were used as part of the analysis. The data is then analyzed using algorithms to identify patterns and trends. This allows the software to predict where and when pests and diseases will likely occur. Farmers then use this information to decide how best to manage their crops and when to apply pest control measures. Continuous monitoring of microclimatic elements is involved in the development of this model.

Since the late 1960s, when single-species population dynamics models were developed, simulation models have been used in pest management to control pest populations. In the later stages of this study, population dynamics models were devised to study biotrophic interactions between pests and their natural enemies. It was done in the mid-80s to integrate crop growth simulation models with pest damage mechanisms. Still, this approach was described as a one-way analysis of crop-pest interactions because these models accounted for pest effects on crop growth without considering the reverse. Because of the interlinking of pest population dynamics models with crop growth simulation models in the 1990s, there was an emergence of a two-way approach to crop-pest interactions. The first computer-based simulation model for disease pest forecasting was EPIDEM for the early blight of potatoes and tomatoes.

Gohain et al. [40] used an artificial intelligence model and a cloud-based collaborative platform to identify plant disease tracking and forecast for farmers. Plant images were collected over seven months, and the artificial intelligence model, the CNN, was trained with these huge data sets. CNN model diagnosed the test images, and plant pathologists validated the results. This novel methodology achieved over 95% disease identification accuracy. Some diseases show visible symptoms only during the critical stages; an example of such a disease is the false smut of rice. This disease shows symptoms only after the emergence of a panicle. The application of crop models is highly effective for forecasting these models. Such studies were carried out in India to forecast false smut of rice in West Bengal. The novel methodology accurately identified this type of disease because it focused on developing crop models to detect the symptoms early. This allowed for early detection and intervention, which increased the accuracy of the disease identification.

The study in India successfully forecasted false smut of rice due to implementing these crop models. Three years of aerobiological data were analyzed, including pathogenic spore concentration over the rice canopy. The study results showed that the model was highly effective in forecasting the false smut of rice in the region. Furthermore, the model could accurately differentiate between false smut and similar diseases. This provides an effective way to identify the disease early and take preventative measures. The percentage disease index values were calculated using multiple regression models with the age of the plant, the pathogen concentration, and meteorological factors being incorporated into the models. The dependence of disease severity on weather variables varied over different seasons. In the dry season, the false smut severity depends on the age of the plants as well as pathogenic spore concentration. On the other hand, in the wet season, the false smut severity depends on the age of the plants, pathogenic spore concentration and temperature.

This indicates that temperature is a more important factor in determining false smut severity during the wet season than in the dry season. In the rainy season, severity depends upon spore concentration, relative humidity, and minimum temperature. Table 1 below is a summary of the models that have been used to simulate the forecasting of this false smut in rice. In the dry season, the age of the plants and spore concentration are the two key variables. In contrast, the variables are spore concentration, relative humidity, and minimum temperature in the rainy season. These variables are used to develop models to forecast the false smut severity in rice accurately.

Models in pest management are not limited to forecasting pest populations but also to providing solutions to issues such as selecting strategies and state selection in pest management. This is because these models simulate the effects of different designs on the environment and the pest species in question. By doing so, they can help identify the most effective strategy for controlling pest populations and guide how to implement them best. Simulating pest growth and dynamics and the risk of pest invasion is possible. The models can also be used to assess the impact of climate change on pest populations and identify areas at risk of attack. The simulations are also used to help identify areas most vulnerable to changes in environmental conditions and assess the risk of pest establishment and spread.

An example of such a model would be FRUTFLY, which has successfully predicted the emergence of fruit flies in the past [42]. FRUTFLY is a model that uses data on climate, soil and other environmental factors to predict the emergence of fruit flies. It can also be used to assess the impact of climate change on pest populations, identify areas at risk of invasion and assess the risk of pest establishment and spread. The following are a few examples of some of the various pest-forecasting models that have been developed around the world. Each model assumes that the environment is critical to pest growth and dynamics. By combining data on climate, land

Table 1: Models for the forecast of false smut disease of rice.

Crop season	Estimate	Significant cofactor	R^2 for the whole model	Step down equation	R^2 for the step-down model
Rabi	1.8701	Age and Spore	0.92	PDI = 1.870 + 0.0235 x Age + 0.5813 x Spore	0.91
Kharif	8.0248	Spore, Minimum Temperature and Relative humidity (RH)	0.91	PDI = 8.0248 + 0.3588 x Spore - 0.9911 x Tmin-0.3561 x RH	0.89

Table 2: Different forecasting models for pests.

Forecasting models	Parameters	Country	Insect	Ref.
Ordinal logistic model	Max temperature, Min temperature and RH	India	Whitefly, Pyrilla and Fruit fly	[43]
SOPRA	Air and Soil temperature	Switzerland	*Dysaphis plantaginea* and *Grapholitha lobarzeweski*	[44]
FLYPAST	Suction trap data	UK	*Aphis fabae*	[45]
NAPPFAST	Degree days and Cold temperature survival	USA	*Scirtothrips dorsalis*	[46]

use, and other factors, these models can accurately predict the probability of pest invasion and the size of the population. This information can inform pest management strategies and help prevent or reduce the impact of pest invasions (Table 2).

Natural Resource Management

Developing strategic and long-term plans is critical to managing natural resources sustainably and strategically. This way, resources can benefit all stakeholders while preserving the environment and ecosystem. Long-term planning is necessary to ensure that resources are managed in a way that is ecologically sound and economically viable. The effects of the different environmental, anthropogenic, and socioeconomic threats must be evaluated and quantified to formulate such plans. Proper planning needs to consider how resources can benefit all stakeholders in the short-term and long term-while also considering such plans' ecological, socioeconomic, and political implications. This will ensure that resources are managed efficiently and sustainably. Some advanced tools for making decisions, artificial intelligence, numerical environmental simulation models, remote sensing systems, etc., are advanced forms of decision support systems used for these purposes.

These decision support systems can help identify and assess the environmental impacts of resource management decisions and advise how to implement them best. This will ensure that resources are managed as efficiently and sustainably as possible while minimizing any negative environmental impacts. Compared with other methods of identifying data, this model has many advantages, including the ability to conserve resources, save time, and ease of use. This type of model also can provide accurate, real-time data that can be used to inform decision-making and help to create more efficient and effective processes. Moreover, it can help reduce the costs associated with traditional data collection methods and reduce the environmental impact of activities that require the use of resources. An important pre-requisite for managing coastal zones, particularly in areas where mangroves occupy a large proportion of the shoreline, is the quantification and forecasting of wave attenuation by mangroves. This is important because wave attenuation directly impacts coastal erosion and flooding.

By quantifying and forecasting wave attenuation, it is possible to manage the coastal zone better, reducing the risk of erosion and flooding and ultimately reducing the environmental impact. It should be noted that, even though the dynamic consequences of waves on mangroves are not taken into account in the current regional wave forecasting system, even though they should be [47], these effects must be taken into account. This is because the effects of waves on mangroves are complex, and if they are not taken into account, there could be serious consequences, such as erosion and loss of habitat. Furthermore, the effects can be unpredictable and could lead to unexpected economic and environmental losses. A model called MODFLOW 2000 was used to simulate the groundwater level for present and future climates (2019 to 2023) in the Midnapur district of West Bengal, India.

This model uses a combination of surface topography and hydrologic properties to predict the groundwater level in a region accurately. It considers precipitation, evaporation, and runoff to make an accurate prediction. There is no doubt that this study sheds light on the future state of groundwater and the necessity for adopting groundwater management strategies as soon as possible [48]. Additionally, the model was tested with historical data, and the results showed a high degree of accuracy, indicating that it could be a dependable tool for accurately predicting future groundwater levels in the area. This is especially important in areas where groundwater depletion is a major concern and where long-term management strategies need to be adopted to ensure the sustainable use of groundwater resources. It is a challenge for the agricultural sector to produce more crops with less water due to increased demands for water from other sectors. This means that farmers have to look for innovative ways to conserve water, such as using mulch, no-till farming, and efficient irrigation systems, as well as adopting more efficient crop varieties and water-saving technologies.

This will help them to use the limited water resources more efficiently and sustainably [49]. It is becoming increasingly difficult for the agricultural sector to produce more food with less water due to the increasing demand for irrigation water to produce more food, along with increased competition across water-using sectors. By using more efficient irrigation systems and better water management practices, farmers can reduce the amount of water needed to produce a given amount of food. This can help reduce the water needed for irrigation and the amount lost to evaporation, runoff, and seepage. The goal can only be achieved if proper strategies are used for water savings and more efficient water use. For example, farm-level water management and augmenting water use efficiency can be achieved using simulation models to achieve the goal. Changes in farming practices, such as crop rotation and reduced tillage, can also help reduce water usage and improve water retention in the soil. Furthermore, agricultural policies and regulations should be implemented to ensure water resources are managed sustainably.

Limitations of Crop Models

It is also essential to discuss the uncertainties associated with the crop models. Uncertainty is a critical factor in determining crop yield, so it is necessary to thoroughly analyze the potential outcomes of different models. The accuracy of the crop model depends on how well it has been calibrated and validated, as we mentioned earlier [50]. To ensure that the model is fit for purpose, it is essential to understand the sources of uncertainty and take measures to reduce them. This includes identifying and addressing any structural uncertainty and conducting sensitivity analyses to determine how much a change in an input variable will affect the model's output [51]. Because field data are rarely so precise, validation is a difficult task. It is essential to remember that the quality of the input data limits the performance of a model. To better understand the model's performance, it is necessary to compare the model results to actual field data to verify the accuracy of the model. This process also helps identify areas where the model may not correctly capture the real-world dynamics and can be used to identify data deficiencies that need to be addressed.

When the processes mentioned above are performed with sufficient data and are repeated regularly, it is possible to improve the accuracy of the above mentioned processes. This helps ensure the model is calibrated correctly and accurately reflects real-world dynamics. Furthermore, continuously monitoring the model's performance makes it possible to identify potential data deficiencies that could lead to inaccuracies. By correcting these deficiencies, the accuracy of the model can be improved [52]. CGM has had several occasions where it has not been able to produce accurate results because of the lack of understanding of the natural processes in conjunction with the limitations of computer power. Therefore, it is essential to constantly monitor the model's results to identify potential data deficiencies and address them to improve the model's accuracy. This can include the data, available computer power, and understanding natural processes to predict and model the results better. It has been observed that climate models cannot project changes in climate variability at a local scale in most cases. They can also not launch changes in the frequency of extreme weather events locally, such as storms and droughts.

Climate models cannot accurately capture the complex local interactions between land, water, and air at the regional scale required to predict these changes effectively. Additionally, they need to consider the natural variability of weather patterns locally [53]. It is essential to remember that crop models are not universal, and therefore, the modellers should choose one peculiar model based on their objective use [54]. This is because climate models cannot account for natural variabilities, such as changes in wind direction or rainfall amounts, which can significantly impact crop growth. Additionally, the local interactions between land, water, and air that occur at a regional scale, such as soil moisture levels, can also affect crop growth, and climate models are not designed to consider this. To gain a deeper understanding of these problems more and more scientific evaluations of these problems needed to be conducted to gain a better understanding of these problems. These complex local interactions require detailed data analysis and field trials to understand how they affect crop yields. This data can then be used to fine-tune climate models and provide a more accurate picture of how climate change will influence crop yields in a given area [55].

Conclusion

It is most straightforward to formulate and evaluate different crop management strategies with the help of crop simulation models, which provide a sustainable and easy way to do so. To achieve this objective, various models were used, such as statistical, dynamic, stochastic, static, and simulation models. Moreover, these models help identify the most appropriate and prosperous agricultural sector development strategies. These models can be used effectively for assessing the impact of climate change, formulating adaptation strategies, managing natural resources, predicting crop yield, and predicting pests and diseases. As a result, appropriate integration of these models can lead to the successful implementation of agricultural objectives and strategies, maximizing the positive impacts of climate change and ensuring sustainable use of resources.

By leveraging the effectiveness of these models, we can gain insights into the future and make informed decisions to mitigate climate change impacts, develop more sustainable solutions, and promote a healthier environment. Ideally, it would be ideal to calibrate and validate models before going for such an application to achieve the most accurate possible results. This can help ensure the models function correctly and optimize for the specific application, leading to more successful outcomes. Despite this, some technical and practical limitations need to be addressed. To address such problems and improve the results of the models, further research needs to be carried out. To ensure the quality and effectiveness of the models, it is essential to identify and address the technical and practical limitations through further research and development. Crop models are a precious tool for crop management studies because of their advantages in saving time, resources, and labor compared to other methods. These models also help optimize crop yield, which adds to their cost-efficiency.

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Conflict of Interest

None.

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