TRENDS IN AGRICULTURE SCIENCE
ISSN:2583-7850

Popular Article
Domain: Agriculture Science
Vol 5 Issue 4, April 2026, 422-428

Crop Modeling for Climate Smart Modern Farming

K Kadinlungliu Pamai and Abdus Sattar
Department of Agronomy, Post Graduate College of Agriculture, Dr. Rajendra Prasad Central Agricultural University, Pusa.
Centre for Advanced Studies on Climate Change, Dr. Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar - 848125
Email: kalengtak@gmail.com
doi.org/10.5281/TrendsinAgriculture.19913582

Introduction

Climate change has emerged as one of the most significant challenges to modern agriculture, influencing crop growth, productivity, and sustainability through rising temperatures, erratic rainfall patterns, and increased climatic variability. Under such changing conditions, understanding and predicting crop responses has become essential for ensuring food security and promoting climate-smart modern farming. In this context, crop modeling has become an important scientific tool for simulating crop growth, development, and yield under diverse environmental and management scenarios by integrating knowledge from agronomy, meteorology, soil science, and computer science to represent the complex interactions among soil, plant, weather, and management practices using mathematical equations and simulation techniques (Kumar *et al*., 2024).

From a systems perspective, a crop production system is dynamic because its state changes over time, either continuously through gradual changes or discretely through rapid or sudden shifts. A model is a simplified representation of a real-world system, while simulation is the study of system behaviour over time using mathematical models. Crop modelling involves using these equations to represent, analyse, and predict system performance. Crop models consist of sets of equations that describe the behaviour of the crop system and function as computer programs that mimic crop growth and development. Dynamic crop growth simulation is an advanced technique that enables a quantitative understanding of how environmental factors and agronomic management practices influence crop growth and productivity. These models provide a mechanistic description of the processes governing crop growth, including physiological, meteorological, physical, and chemical processes. By adopting a systems approach, crop growth simulation models treat crops as dynamic entities whose state variables change over time in response to internal processes such as photosynthesis, respiration, transpiration, and nutrient uptake, as well as external factors such as weather and soil conditions. By updating key state variables such as biomass accumulation, leaf area index, and soil moisture on a daily time step, crop models can realistically mimic crop responses throughout the growing season. In climate-smart agriculture, these models play a crucial role in optimizing resource use, evaluating climate-related risks, forecasting yields, and developing adaptation and mitigation strategies. They allow farmers, researchers, and policymakers to evaluate "what-if" scenarios for planting dates, irrigation scheduling, fertilizer application, and varietal selection without the cost and risk of extensive field experimentation. Moreover, crop models support yield gap analysis and assessment of climate change impacts, thereby contributing to sustainable intensification and the development of resilient food systems under changing climatic conditions.

Basic Steps for Assessing Impacts of Climate Change

Defining Goals: Understanding the agricultural system and the objective of the study

↓

Defining System and Boundaries: Identify the crop field as the system

↓

Defining Key Variables: Categorizing variables as state, rate, driving and auxiliary

↓

Quantifying Relationships: Developing mathematical equations to express variable relationship

↓

Calibration/Validation: Adjusting the model using experimental data, then validating it

↓

Sensitivity analysis: Testing the model's response to changes in factors like temperature and rainfall

↓

Simplification: Making the model user-friendly

↓

Decision Support: Using the model in decision-making systems for crop management

Plate 1: Steps in Crop Modeling (Sattar et al.,2025)

Calibration and Validation of Simulation Models

Calibration of a simulation model is an essential step before applying it to any specific study area. This process involves adjusting model parameters based on results from detailed field experiments, particularly those related to varietal performance. Such experimental data help ensure that the model accurately represents crop growth and development under local conditions. Once calibrated, the model is tested through validation by comparing simulated outputs with observations from independent experiments conducted under different treatments and environmental conditions. Validation helps confirm the model's reliability and robustness in predicting crop performance across a range of conditions.

A successfully validated model can then be used with confidence to simulate crop responses and assess the impacts of various factors within a region. The model's performance is evaluated using statistical indices such as model bias error (MBE), root mean square error (RMSE), index of agreement (IA), and model efficiency (ME), among others.

Sensitivity Analysis

The aim of sensitivity analysis is:

- To determine how sensitive the output of a crop model is with respect to the inputs of the model, which are subject to uncertainty or variability.
- To identify which parameters, have a small or a significant influence on the output.
- To check that the model output behaves as expected when the input varies.

Input Data Requirement for Crop Models

Weather	Crop	Soil	Crop Management
Max. and Min temperature	Crop name	Soil layer thickness	Date of sowing
Solar Radiation	Variety	PH, EC, N, P, K	Irrigation
Rainfall	Crop Phenology	Soil Organic C	Fertilizer and Manure
RH	Leaf area index	Sand and clay %	Seed rate
Windspeed	1000 grain wt.	Soil texture	Crop residue
		Soil moisture	Depth of seeding
		Wilting point	
		Bulk Density	

Name of Popular Crop Growth Models

Crop Model	Developed by	References
DSSAT (Decision Support System for Agrotechnology Transfer)	USA	Jones et al., 2003
WOFOST (World Food Studies)	Netherland	Van Diepen et al., 1989

APSIM (Agricultural Production Systems SIMulator)	Australia	Keating et al., 2003
ORYZA	IRRI	Bouman et al., 2006
InfoCrop (Information on Crop)	IARI	Aggarwal et al., 2006

Why is Crop Modeling important today?

Crop modeling plays a crucial role in modern agriculture, particularly as farming systems face challenges such as declining soil fertility, unpredictable weather patterns, and the growing demand for sustainable use of natural resources. It provides a scientific basis for informed decision-making at the farm and policy levels.

Managing crops under stressful conditions: Crop models help predict how different crops respond to adverse conditions such as drought, heat stress, and poor soil quality. By simulating crop performance under these conditions, farmers can select suitable crops and adopt appropriate management practices to reduce yield losses.

Improved crop system management: Efficient crop management is essential for achieving higher productivity with minimal inputs. Crop modelling allows farmers and researchers to evaluate different management options, such as irrigation, fertilisation, and planting density, and to understand their effects on crop growth, yield, and resource use.

Assessment of weather-related risks: By integrating meteorological data, crop models can assess the potential impacts of climate variability on crop growth. This helps farmers to identify weather-related risks in advance and adopt strategies to minimize their negative effects on crop productivity.

Supporting investment and economic decisions: Crop models provide estimates of expected yields and economic returns under different scenarios. This information helps farmers make better investment decisions, optimize input use, lower production costs, and improve farm profitability.

Efficient use and conservation of resources: Sustainable agriculture depends on the efficient use of water, nutrients, and energy. Crop models help optimize these resources by identifying the most suitable crop varieties, planting times, and management practices for a given location, thereby reducing environmental impacts and conserving natural resources.

Determination of the optimum planting time: Crop modelling helps identify the best planting window by considering soil temperature, moisture conditions, and anticipated weather patterns. This allows farmers to synchronize planting with favourable conditions for crop establishment and growth.

How Crop Modeling Supports Modern Farming Technologies

Crop modelling has become an integral component of modern farming technologies, enabling the quantitative assessment of crop growth, development, and yield under varying environmental and management conditions. Crop weather and crop growth models integrate weather variables (temperature, rainfall, solar radiation), soil characteristics, crop genetic parameters, and management practices to simulate crop responses under both current and projected climate scenarios. The integration of crop models with weather forecasting enhances decision-making in modern agriculture by enabling timely adjustments to sowing dates, irrigation scheduling, fertiliser management, and varietal selection. By simulating crop performance under alternative climatic and management scenarios, models reduce uncertainty associated with climate risks such as heat stress, drought, and rainfall variability. Crop modeling further strengthens precision agriculture by improving resource-use efficiency. Simulation-based evaluation of management options enables optimization of water and nutrient inputs, thereby reducing production costs and environmental impacts while sustaining crop yields. The document emphasises that these modelling approaches offer a cost-effective alternative to extensive field experimentation, particularly for long-term climate impact assessments. Within digital and innovative agriculture frameworks, crop models serve as decision-support systems that enable "what-if" analyses and support climate-smart agricultural planning. Proper calibration and validation with experimental data enhance the reliability of model outputs, bridging the gap between research and field-level application. Overall, crop modelling supports modern farming technologies by improving predictive capabilities, promoting efficient resource management, and enabling climate-resilient, sustainable agricultural production systems.

Advantages of Crop Modelling

- Enables advanced prediction of crop growth and yield
- Enhances efficient utilisation of water, nutrients, and seed inputs
- Facilitates the identification of yield gaps between attainable and actual production
- Supports precision agriculture and site-specific management
- Assists in optimising planting density, irrigation scheduling, and fertiliser management
- Provides a tool for analysing field-level management scenarios
- Aids in developing adaptation strategies under climate change
- Promotes conservation of agricultural resources
- Supports climate-smart and sustainable crop production

Limitations of Crop Modelling

- Strong dependence on the accuracy and quality of input data
- Limited ability to represent spatial variability in soils and fields
- Uncertainty in climate projections affects model reliability
- Incomplete representation of complex biological and environmental processes
- Inadequate model validation under diverse field conditions
- Potential misuse or misinterpretation of model outputs
- High complexity of crop-soil-climate interactions
- Reduced model performance in highly heterogeneous environments

Future Scopes of Crop Models

The future of crop modelling is closely linked with advances in data science, digital agriculture, and climate-smart farming. Key future directions include:

- **Integration with Advanced Data Sources:** Crop models will increasingly integrate satellite-based remote sensing, GIS, and real-time weather data to improve the spatial and temporal accuracy of simulations and yield forecasts. The effectiveness of this approach has already been demonstrated: Sentinel-2-derived leaf area index (LAI) and soil moisture, when assimilated into the WOFOST crop model, increased wheat yield prediction accuracy, with R^2 improving from 0.41 to 0.76 and the average relative error decreasing to 3.17% (Wang *et al*. 2025). Such integration enables near-real-time monitoring and more reliable crop growth simulations.
- **AI and Machine Learning-Driven Model Enhancement:** Artificial intelligence and machine learning techniques will be utilised to refine model parameters, reduce uncertainty, and enhance prediction accuracy by leveraging large and diverse datasets. The integration of process-based crop models with machine learning, demonstrated for maize (corn) across the U.S. Corn Belt, has been shown to reduce yield prediction error by 7-27% and to improve predictive performance under extreme drought conditions by 22-43%, thereby highlighting its strong potential for climate-resilient, data driven crop modelling (Shahhosseini *et al*. 2021)
- **Precision Agriculture and Resource Optimization:** Future crop models will support site-specific management of inputs such as water, fertilisers, and energy, helping maximise productivity while minimising resource use and environmental impacts.
- **Climate-Resilient Crop Planning and Policy Support:** Enhanced models will play a crucial role in designing adaptation strategies for climate variability and change, supporting policymakers in developing resilient cropping systems and informed agricultural policies.
- **Location-Specific Model Development:** Crop models will be increasingly tailored to local agro-climatic conditions, soils, and management practices, allowing hyper-local recommendations for farmers.
- **Multi-Model and Ensemble Approaches:** Using multiple models together will help quantify and reduce uncertainty in predictions, providing more robust yield forecasts and risk assessments.
- **Automated and Collaborative Modeling Platforms:** Future crop modelling will move toward automated, interoperable, and globally collaborative systems, improving data sharing, transparency, and collective learning across regions.

Overall, these advancements will transform crop models into more responsive, accurate, and decision-oriented tools, strengthening agricultural forecasting, sustainability, and food security in the face of climate change and population growth.

Conclusion

Crop modelling has emerged as a crucial tool for climate-resilient contemporary agriculture amid escalating climate variability. Taking into account soil, weather, crop, and management characteristics, it helps to simulate crop development, production, and resource consumption. Accurately calibrated and validated models facilitate informed decision-making about planting schedules, irrigation, and fertilizer management. Crop models boost resource-use efficiency, support precision agriculture, and aid in yield gap and climate risk analysis. Despite limitations related to data quality and uncertainty, technological advancements are improving model performance. Integration with remote sensing, AI, and digital agriculture is strengthening predictive capability. Overall, crop modeling plays a crucial role in developing resilient, sustainable, and productive agricultural systems.

References:

Aggarwal, P. K., Kalra, N., Chander, S., & Pathak, H. (2006). InfoCrop: a dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. I. Model description. *Agricultural systems*, **89**(1), 1-25.

Bouman, B. A. M., & Van Laar, H. H. (2006). Description and evaluation of the rice growth model ORYZA2000 under nitrogen-limited conditions. *Agricultural Systems*, **87**(3), 249-273.

Jones, J. W., & Hoogenboom, G. (2003). Porter. *CH, Boote, KJ, Batchelor, WD, Hunt, LA, Wilkens, PW, Singh, U., Gijsman, AJ, Ritchie, JT*, 235-265.

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., ... & Smith, C. J. (2003). An overview of APSIM, a model designed for farming systems simulation. *European journal of agronomy*, **18**(3-4), 267-288.

Kumar, S., Mishra, A. C., & Kumar, A. The Role of Crop Modeling in Agricultural Sustainability.

Malunjkar, V. S., Kanade, S. G., Andhale, R. P., Kadam, S. A., Kumar, P., Gorantiwar, S. D., Shinde, M. G., Patil, R. H., Jadhav, J. D., & Ghadge, S. N. (2025). Crop Weather Modelling: Tools for Climate Smart Agriculture. Satish Serial Publishing House.

Sattar, A., Saha, S., & Jha, R. K. (2025). Crop modeling: Foundations, applications, methodologies, and limitations. In 75 Platinum Jubilee Annual Conference of Indian Society of Agricultural Statistics (ISAS). Data Revolution in Agriculture: Innovative Statistical and Computational methods for Viksit Bharat @ 2047, 39-52

Shahhosseini M, Hu G, Huber I and Archontoulis S V. 2021. Coupling machine learning and crop modeling improves crop yield prediction in the US Corn Belt. *Scientific reports* **11**(1): 1606.

Singh, A. K. (1994). Crop growth simulation models. *IASRI, New Delhi*, 497-509.

Van Diepen, C. V., Wolf, J. V., Van Keulen, H., & Rappoldt, C. (1989). WOFOST: a simulation model of crop production. *Soil use and management*, **5**(1), 16-24.

Wang D, Yang P and Fu J. 2025. Integrating Remote Sensing and Crop Modeling for Real-Time Yield Prediction in Wheat. *Field Crop* 8.