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Crop Modelling: Guiding Agriculture Towards Climate Change Mitigation and Adaptation

[1]**Rushali Katoch**✉, [1]Varun Parmar, [2]NK Sankhyan

Department of Soil Science, CSK HPKV, Palampur

[2]Principal Scientist, Soil Science and Registrar, Central University of Himachal Pradesh

✉ rushalikatoch19@gmail.com DOI : 10.5281/zenodo.17332290

Abstract

Climate change is among the greatest threats to global food security with agriculture both a major victim of and contributor to greenhouse gases (GHGs) emissions. Rising temperature, elevated CO_2 and rainfall variability directly affect crop yields, while indirect effects through pests, diseases and resource competition further complicate outcomes. To anticipate and mitigate these risks, crop models have become essential tools for integrating climate, soil and management variables into yield projections and adaptation planning. Various models are designed to assess climate change impacts, guide mitigation strategies and build resilient cropping systems. These models demonstrate climate – smart practices to reduce GHGs emission through soil, crop and livestock systems, including soil carbon management, optimized fertilizer use, methane reduction in rice and livestock feeding innovations, offering strong potential for agricultural mitigation as well as adaptation. However, challenges remain high due to high input data requirements, uncertainties in long – term projections and socio – economic barriers, thereby highlighting the importance of multi – scale, data driven approaches.

Keywords: crop models, climate change, mitigation, adaptation

Introduction

Food security and climate change are closely intertwined within the framework of Sustainable Development Goals (SDGs). The global challenge is straightforward that by 2050, the world must feed nearly 10 billion people, yet agricultural production systems face increasing stress from changing climate and resource degradation. Despite advances in food production since last decade, hunger and malnutrition remain widespread. As per FAO reports, nearly 800 million people are undernourished, 161 million children under five are stunted, 500 million people are obese and around 2 billion are deficient in essential micronutrients. FAO further projects that to meet the rising food demand of rapidly growing population, global food production must increase by at least 60% in the coming decades.

However, climate change is already undermining food security through rising temperature, erratic rainfall and increased frequency of extreme events. These impacts pose severe risks to ecosystems, agricultural productivity and rural livelihoods, making the task of ending hunger and malnutrition more complex. The COVID-19 pandemic further intensified these vulnerabilities, pushing the world further off track to achieve zero hunger by 2030. Currently, more than half of the world's undernourished population lives in Asia, one – third in Africa and a smaller proportion in Latin America and the Caribbean. India's food security situation reflects this global challenge. Although the country has achieved self sufficiency in food grain production, it ranked 68^{th} out of 113 nations in Global Food Security Index (2022). Malnutrition persists, while agricultural productivity is increasingly threatened by deteriorating soil health, declining water resources, pest outbreaks and climate variability. Extreme and episodic events have become more frequent in the past three decades, raising urgent concerns about sustainability. India's diverse agro-ecological regions demand context-specific assessment of climate impacts that integrate socio-economic and bio-physical factors alongside climatic variables.

Crop modelling emerges as a vital approach to address these challenges. Models such as InfoCrop, DSSAT, APSIM, ORYZA, AquaCrop, RothC and DNDC have been widely applied for evaluating climate change impacts, resource-use efficiency and yield forecasting. They also support the design of mitigation and adaptation strategies. Simulation studies using these models have shown differential yield responses to rising temperatures and provide insights into effective interventions. Recommended strategies include crop diversification, improved water and nutrient management, adoption of climate-resilient crop varieties and optimized agronomic practices. In addition, models help identify pathways to reduce GHGs emissions while sustaining production, contributing to both food security and environmental sustainability.

Climate change drivers and agricultural impacts

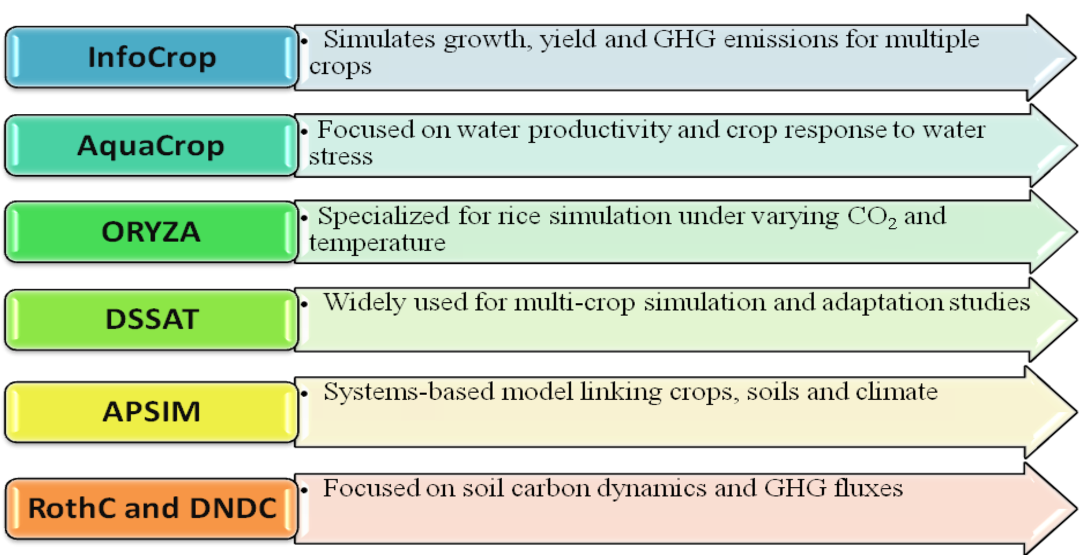
1. **Temperature rise:** Rising temperature increase heat stress, particularly during sensitive crop growth stages like flowering, thereby reducing yields. Fluctuating temperature also extend the survival and spread of pest and diseases, adding further risks to agriculture.
2. **Elevated CO_2:** Higher CO_2 levels can boost photosynthesis and water use efficiency in some crops, but these benefits are often reduced by nutrient dilution, heat stress and climate related constraints.
3. **Rainfall variability:** Unpredictable rainfall patterns cause both droughts and waterlogging, which damage soils, reduce nutrient availability and threaten rainfed farming systems.

4. **Extreme events and indirect impacts :** Floods, cyclones, landslides and storms directly harm crops, while indirect impacts include pest outbreaks, pollinator loss and soil erosion. These combined stresses can cause severe crop yield losses.

Role of crop models

A model can be understood as a simplified representation of a system, process or set of interactions that helps in explaining its overall behaviour (Wossen, 2019). In agriculture, crop models have emerged as mathematical tools that simulate plant growth and crop yields under diverse environmental and management practices, thereby predicting both the final harvest and key processes driving crop growth ((Hoogenboom *et al*. 2019). The crop models integrate physiological processes of plants with environmental and management factors, making them useful for understanding how climate, soil and farming practices influence crop productivity. Under the increasing pace of climate vulnerabilities, these serve as essential tools to project the potential impact of rising temperatures, variable rainfall and extreme events on crop productivity. By simulating future scenarios, the models not only quantify risks but also guide the development of suitable adaptation and mitigation strategies, making them highly relevant in the context of climate change.

Major crop models used in agriculture includes:



Mitigation and adaptation strategies identified by crop models

1. **Soil carbon sequestration and management:** Models like RothC and DNDC confirmed the potential of practices such as no – tillage, residue retention and use of biochar to increase soil organic carbon (SOC)

stocks. In Brazil, Lefebvre *et al*. (2020) used RothC model to assess biochar application in sugarcane fields, finding that incremental additions enhanced SOC stocks. Similarly, results from DNDC model showed that no – till practice along with addition of crop residues significantly increased SOC, particularly in degraded soils (Lembaid *et al*. 2021).

2. **Methane mitigation in rice:** Crop models have been used to assess irrigation and nutrient management options for reducing methane emissions in paddy fields. The practices like alternate wetting and drying or improved water management have shown strong potential to cut methane while sustaining rice productivity. Moura da Silva *et al*. (2025) evaluated DSSAT model to simulate rice yields and methane emissions, demonstrating its effectiveness in assessing irrigation strategies that conserve wate and lower GHG emissions in subtropical rice systems.
3. **Nitrous oxide reduction:** Nitrous oxide, with a global warming potential nearly 298 times higher than carbon dioxide, is largely driven by fertilizer use. Crop modelling studies indicated that practices such as nitrification inhibitors, slow – release fertilizers and nano – fertilizers can effectively reduce nitrous oxide emissions. By integrating nitrification inhibitor efficiency, the DNDC model reliably simulates nitrous oxide dynamics, supporting strategies to reduce emissions and mitigate climate change (Li *et al*. 2020).

Despite of their utility in agriculture, crop models also face limitations such as:

1. **High data requirement –** Accurate simulations demand detailed site – specific inputs *viz.*, long – term weather data, soil properties, crop phenology and management practices, which are often difficult to obtain.
2. **Uncertainty in projections –** model outcomes vary due to differences in model structures, assumptions and climate scenarios, leading to uncertainties in yields forecasts and climate impact assessments.
3. **Complex calibration and validation –** Reliable use of models depends on rigorous calibration and validation, which can be resource intensive and may limit their widespread application.
4. **Limited socioeconomic integration –** Most crop models emphasize biophysical processes but inadequately capture socio-economic drivers of agricultural decision making, reducing their utility in policy planning.

Conclusions and way forward

Crop modelling has emerged as a vital approach to understand and address the impact of climate change on agriculture. By simulating interactions between crops, climate, soil and management practices, these models provide valuable insights into yield responses, resource use efficiency and GHG mitigation strategies. They support the design of climate smart practices such as soil carbon management, improved water and nutrient use and optimized farming systems that sustain crop productivity while reducing emissions. However, the effectiveness of models depends on high quality long – term data, proper calibration and validation and its integrity with socio-economic considerations. Moving forward, a multi – scale modelling framework connecting field, regional and global data with digital tools (machine learning and remote sensing) will strengthen predictive capacity of crop models to guide sustainable agricultural policies and ensure food security under changing climate.

References

Hoogenboom G, Porter CH, Boote KJ, Shelia V, Wilkens PW, Singh U, White JW, et al., 2019. The DSSAT crop modeling ecosystem. In: Boote KJ, editor. Advances in crop modeling for a sustainable agriculture. Cambridge: Burleigh Dodds Science Publishing; p.173-216. https://doi.org/10.19103/AS.2019.0061.10

Lefebvre D, Williams A, Meersmans J, Kirk JD, Sohi S, Goglio P and Smith P., 2020. Modelling the potential for soil carbon sequestration using biochar from sugarcane residues in Brazil. *Scientific Reports* 10(1), 19479. https://doi.org/10.1038/s41598-020-76470-y

Lembaid I, Moussadek R, Mrabet R, Douaik A and Bouhaouss A., 2021. Modelling the effects of farming management practices on soil organic carbon stock under two tillage practices in a semi-arid region, Morocco. *Heliyon* 7, e05889. https://doi.org/10.1016/j.heliyon.2020.e05889

Li Y, Hussain Shah SH, Wang Y., 2020. Modelling of nitrification inhibitor and its effects on emissions of nitrous oxide (N_2O) in the UK. *Science of the Total Environment* 709, 136156. https://doi.org/10.1016/j.scitotenv.2019.136156

Moura da Silva EHF, Hoogenboom G, Boote KJ, Cuadra SV, Porter CH, Scivittaro WB, Steinmetz S, Pellegrino Cerri CE., 2025. Implications of water management on methane emissions and grain yield in paddy rice: A case study under subtropical conditions in Brazil using the CSM-CERES-Rice model. *Agricultural Water Management* 307, 109234. https://doi.org/10.1016/j.agwat.2024.109234

Wossen T., 2019. Role of crop modelling in scenario development analysis and developing strategic recommendation: a review. *International Journal of Scientific Research and Management* 7(1), 204-212. http://dx.doi.org/10.18535/ijsrm/v7i1.ah02