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Is the current version of model ORYZA2000 able to encounter the multi-level stakeholders' demand for on-farm decision making?

Debjyoti Majumder*[1], Lalu Das[1], Rajan Bhatt[2], Vishnu D. Rajput*[3] and Tatiana Minkina[3]

[1]Department of Agricultural Meteorology and Physics, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia-741252, India
[2]Punjab Agricultural University-Krishi Vigyan Kendra Amritsar- 143601, Punjab, India
[3]Academy of Biology and Biotechnology, Southern Federal University, Rostov-on-Don, Russia

ABSTRACT

The ORYZA2000 model, developed by the International Rice Research Institute (IRRI) and Wageningen University, is a sophisticated tool for accurately predicting rice growth cycles and development under varying conditions. It excels in replicating field-level crop growth through meticulous calibration and validation across different agroecological settings worldwide. Operating on a daily time step, the model computes plant organ dynamics at different phenological stages by calculating rate variables for each time step and integrating state variables over the entire crop-growing period. ORYZA2000's applications extend to simulating agronomic management practices such as optimal fertilizer application, water management, and crop planning without the need for extensive field data. While it is commonly used to evaluate the impact of changing climate factors on rice yields, such as future rainfall patterns, temperature shifts, and elevated CO_2 levels, the model currently lacks flexibility in assessing factors like pest and disease damage, remote sensing applications, extreme weather events, and diverse crop varieties within a single simulation run. Despite these limitations, the ORYZA 2000 model remains a valuable tool for assessing management practices and forecasting rice production under evolving climatic conditions based on the latest CMIP6 climate model projections. Efforts to enhance the model's versatility in handling a broader range of factors are essential for its continued relevance and utility in rice crop research and planning.

Keywords: *Crop Yield Estimation, Crop simulation model, Nitrogen dynamics, ORYZA2000, Climate Change, On farm Trial*

Introduction

Approximately fifty percent of the global population, especially those who reside in Asia and the majority of emerging nations including India, rice (*Oryza sativa* L.) are the most important type of cereal grain. At least90% of the global paddy productivity i.e 674 million tonnes in 2008—was produced and eaten in Asia, where 611 million tons of that totals were produced [1]. After China, India is the country with the second-highest population and produces the most rice globally. With a productivity of 3.57 $tonsha^{-1}$, India produces roughly 152.6 million tonnes on 42.5 million ha [2].Global food security heavily relies on rice production which is mostly dependent on the irrigation facility and availability of lowland areas. Rice production is challenged by freshwater scarcity, water pollution, and international rivalry for water utilization [3] under climate warming and weather extremes. A significant barrier to increased agricultural productivity has been found as the depletion of soil fertility. In addition, projected climate change information mostly the amplified rise of global earth surface temperature (1.5 to 5.8°C at end of 21st century) is highly alarming to rice production although last century's rise of averaged earth surface temperature (~0.84°C during 1886-2012) was not impacted the rise production adversely. There is indeed no other alternative to assess rice production under future climate change scenarios is to employ crop simulation models that are process-based. To boost yields in the rainfed rice environment, a variety of management techniques have been proposed [4]. For example, alteration of sowing dates along with a suitable combination of using optimum level of solar radiation, temperature and rainfall may enhance rice production [5]. A recent study [6] emphasized that the use of crop simulation models in the computing lab to understand the real science for the growth and development of rice crop, may help the agronomists to improve their knowledge to manage the crop under stressful situations in the field level. The following four main methodologies are now used by crop growth modeling to assess the dry matter accumulation: (a) The light utilization efficiency (LUE): The Light Interception and Utilization (LINTUL) idea of model is the foundation for the LUE method. It makes use of the linear connection between the quantity of biomass produced and the amount of radiation absorbed by crop canopy grown with abundant water and nutrients but free of pests, diseases, and weeds,(c) The radiation use efficiency (RUE): This model, which is based on processes and is often employed in the CERES model [7], and (d) The water-driven development accelerator which is based on Steduto's re-elaboration of the biomass water productivity idea [8] in the AQUACROP model.

Normally, crop growth simulators and models are employed to forecast crop performance under different environmental conditions for day to day on farm decision making and future agricultural planning for different nations particularly developing countries where crop performance are constrained by several biotic and abiotic factors [9]. It can also be used to assess the yield and yield components under climate change conditions. Indirectly, it will help to explore different mitigation and adaptation options for coping with this variability and

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Corresponding Author: **Debjyoti Majumder & Vishnu D. Rajput*

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change [10]. Several studies using crop simulation models and field experiment data have investigated the impact of climate change on crop productivity [11]. Among several available eco-physiological crop simulation models, ORYZA 2000 is the recent generation modified version of an ideal, nitrogen-limited, water-limited, and nitrogen-water-limited conditions, the Oryza1 model simulates lowland, upland, and aerobic rice growth and development [12]. It has been calibrated and confirmed for roughly 18 prevalent rice species in 15 locations around Asia. The present paper attempts to highlight all aspects of Oryza models starting from its wide range of success stories to its limited applications for day-to-day crop management to different policy making and decision-taking by the multi-level stakeholders. Apart, this paper will also highlight the possibility of its operational use for on-farm agricultural planning after incorporating several untold issues. Lastly, the contents of the papers will provide a proper guideline on how to develop strong knowledge by eliminating some confusion of model development and applications in different aspects of research. This will also help for model developers how to improve the existing version of the model by incorporating several unsolved burning issues of recent times through different modules.

Methodology

To discover any information on the investigations carried out utilizing the ORYZA 2000 model, a comprehensive search of the literature was undertaken. Searches on PubMed, Mendeley, Google Scholar, and Research Gate were done to locate pertinent scholarly studies. Keywords such as ORYZA 2000, crop modeling, predicted rice yield, water scheduling, and rice's impact on climate change were combined. There were no dates on the published literature. Only reports or publications with English abstracts that were written were considered for this attempt. The full-text papers of the selected research were downloaded, and after that, their abstracts were examined and their titles were critically assessed. To locate more relevant works, we carefully perused the bibliography of the collected material.

Background and evolution/model chronology and working principles

ORYZA2000, a FORTRAN-based model, simulates lowland rice growth by integrating the FSE system with weather data (WEATHER), utilities (TTUTIL), and specific programming rules. Version 3.0 expands on previous versions to simulate single and multiple rice crops, incorporating irrigation, nitrogen management, soil dynamics, organic fertilizer impacts, temperature variations, plant density, root growth, climate stresses, and greenhouse gas emissions (CO_2, methane). The model calculates daily dry matter and phenological changes, integrating rates over time, and computes CO_2 assimilation and net daily growth. Biomass allocation to roots, leaves, stems, and panicles is determined, with leaf area expanding exponentially until canopy closure, then linearly. Nitrogen requirements for each organ are assessed based on soil availability, adjusting leaf area dynamics according to actual and potential leaf nitrogen concentrations [9,12-13]. ORYZA models simulate rice crop development under diverse production scenarios.

1. Potential production: Adequate nutrients and water, with growth influenced solely by varietal characteristics and environmental factors (solar radiation and temperature).

2. Water-limited production: Moisture stress limits development despite sufficient nutrients.

3. Nitrogen-deficit production: Nitrogen deficiency impacts growth for part of the season, a common issue globally.

4. Nitrogen and water-limited production: Both nitrogen and water are insufficient, restricting growth.

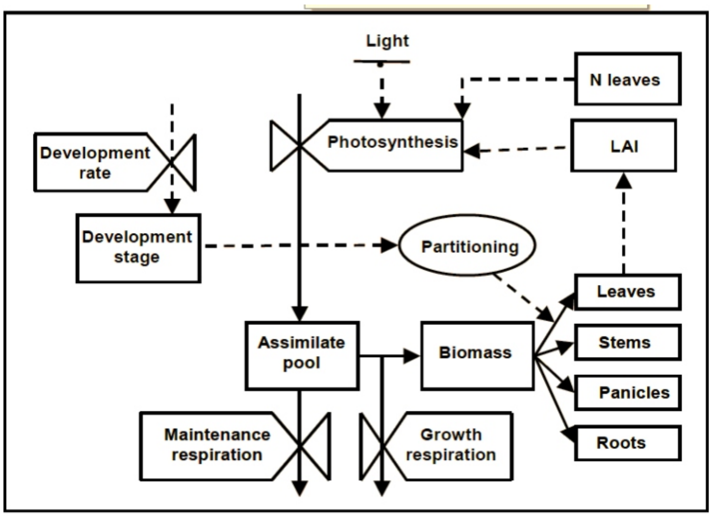

Fig 1: *An illustration of the ORYZA1 model in a prospective manufacturing scenario. Valves represent rates, circles represent intermediate variables, and boxes represent state variables. Information flows are represented by dotted lines, whereas material flows are represented by solid lines.*

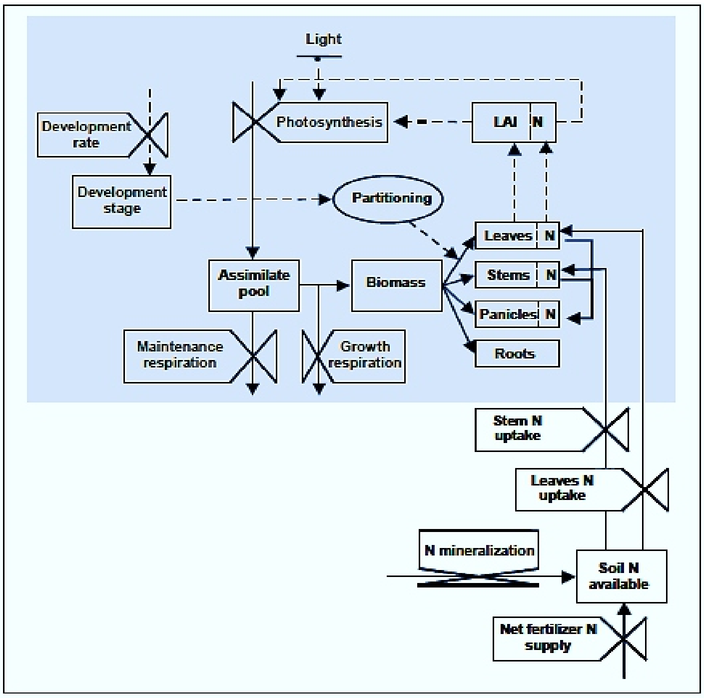

Fig 2: *ORYZA1 (grey region) and its connections to the nitrogen balancing subroutines for the case of nitrogen-limited production*

Paradigm shifting from version 2.13 to version 3.0

Updates to the model (Fig. 3.0) were created, and versions 1.0 through 2.13 of ORYZA2000 provide accurate simulations of rice development in lowland settings. Fresh modules/ systems introduced (black boxes), additional routines (grey boxes), and revised iterations of previous routines (double-frame boxes) were all created and included in ORYZA (v3).

Calibration of the ORYZA2000 model

The assessment of dynamic simulation models involves verification, calibration, and validation. Calibration is essential to reduce discrepancies between observed and simulated outcomes. This iterative process adjusts model parameters until the model accurately represents the real system, accounting for variations in crop phenology and growth.

Two effective calibration methods are:

1. Extensive calibration: Requires field trials with optimal management, where weather, soil, and management data are season-specific. Crop growth data from similar locations can be used if local trials are unavailable [14].

2. Phenology-based simple calibration: Adjusts model parameters until simulated physiological maturity matches actual maturity dates using local meteorological and agronomic data. Flowering dates are calibrated using general guidelines or published data [15].

ORYZA2000 divides the rice life cycle into four phenological stages: vegetative (DVRJ), photoperiod-sensitive (DVRI), panicle development (DVRP), and grain filling (DVRR). Calibration uses DRATES to calculate phenological development rates and PARAM to simulate growth parameters like leaf area, stem reserves, leaf death rates, specific leaf area, and partitioning of assimilates.

Evaluation of oryza2000 model

Model evaluation is crucial for ensuring accuracy and predicting future performance. It involves using test sets to assess predictive accuracy through holdout and cross-validation methods. Verification compares multiple outcomes for accuracy, while validation compares the model to the real system. This involves matching the model's implementation and data with the developer's conceptual description and specifications.

Under field test conditions, calibrated parameters (excluding treatment-dependent rates) are used to simulate each experiment. Graphical analysis and statistical calculations, such as absolute and normalized root mean squared error (RMSE) between simulated and measured values for total biomass, organ-specific biomass, crop N absorption, and organ-specific N intake, are recommended for performance evaluation [16].

RMSEa = $(1/n\ \Sigma(Yi - Xi)^2)^{0.5}$RMSEn = 100 x

$$(1+x)^n = \frac{\left(\frac{1}{n(Yi - Xi)2}\right)\ 0.5}{\sum \mathrm{Yi/Xi}}$$

Where Y is the mean value of the analyzed parameters over the field experiment replicates, and n is the total number of observations. Additionally, a Student's t-test of means (P (t)) is anticipated to be used for end-of-season variables under the assumption of unequal variance.

Generalized application of the model

Agronomic researchers, extension professionals, policymakers, farmers, the private sector, and educators use crop simulation models (CSM) as cost-effective tools for agronomic management, strategic interventions, real-time decision-making, and understanding research and policy impacts. The primary goal is to improve our understanding of crop development through mathematical equations. Comparing simulation results with actual data helps identify knowledge gaps, guiding further experiments. Once verified, models aid in analyzing field experiments and operational applications, particularly for predicting rice yield under different management techniques. Integrating CSM with remote sensing (RS) and geographic information systems (GIS) enhances performance and supports decision-making. Decision support systems (DSS) benefit farmers, extension agents, and policymakers by providing spatially variable inputs and expanding the applicability of simulation models (Fig. 3).

CSMs can evaluate experiment outcomes, extrapolate data, develop field management strategies, create DSS, assess climate change impacts, and estimate yields. ORYZA2000 can be used for sustainable crop production at the farm level[17, 18].

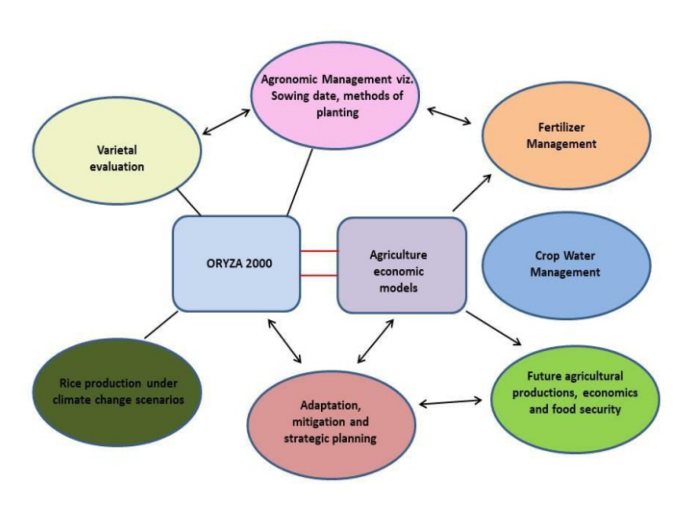

***Fig. 3**: Application of ORYZA2000 in an agricultural production system*

Extensive physiological evaluation of field tests

For assessing yield fluctuations due to LAI development, leaf N content, climate variability, and genotype characteristics, use ORYZA2000 in the "EXPERIMENT" simulation mode. It is crucial to take precise measurements of LAI and leaf N content during the growing season. Using LAI as an initial input helps ensure accuracy because the carbon-balance element of the model is better developed than the morphological portion [19]. If LAI is input directly, errors in morphological modeling won't impact early study findings. In the absence of field data, LAI can be modeled. Leaf N content data, either real or estimated, can be used in the model. The next step is to integrate the model with the entire nitrogen balance for tests with different nitrogen delivery schedules.

Estimation of crop performance under certain context

Applications of this type involve yield forecasting, yield gap analysis, and agroecological zone categorization. ORYZA2000's simulation mode should be set to "EXPLORATION" for these purposes. It can forecast yields under diverse environments and strategic approaches, including projected climate change scenarios. ORYZA2000 can handle changes in daily temperature without modifying meteorological data files. When used with the water-balance PADDY, it can determine the difference between potential and actual yields for rainfed crops and predict irrigation water needs [20-21].

Crop Breeding and Management Improvement

ORYZA2000 can optimize crop management factors like emergence date, plant densities, irrigation, and nutrient control specific to biophysical settings.

The simulation mode "EXPLORATION" was utilized to explore irrigation management options and assess potential rainfed rice yields in Jakenan, Indonesia [22]. ORYZA2000 enables the simulation of rice morphological and physiological changes, facilitating the identification of ideotypes tailored to different environments [23]. Crop growth models, parameterized for new cultivars through field trials, can predict the long-term yield stability of distinct cultivars under expected environmental conditions at a site [24].

Application-based studies of ORYZA2000

Agricultural yield assessment and calibration considering different sets of practices

The term "yield potential" (Yp) refers to the highest yield that can be produced in perfect circumstances, free from weeds, pests, diseases, water, nutrients, or other limits; the main ones are temperature and solar radiation [25]. It is difficult to find field experiments that come close to this maximum yield. By providing an alternate approach to Yp estimation, physiological crop models help to mitigate some of the challenges that come with conducting field research. More and more, these models are being used for a variety of tasks, such as forecasting the consequences of climate change [26], examining the results of management and policy adjustments [27] and evaluating yield gaps (Table 1).

Table 1. Model calibration, validation studies and implications of ORYZA 2000 models in various] agronomic management strategies.

Regions/Location and year of study of study	Objectives	Outcomes/ Suggestions	Authors
South-Central region of Chile	To examine future yield and the impact of N fertilizer on grain yield under projected weather patterns.	ORYZA2000 was realistic enough to replicate grain yield and crop N uptake at the end of the growing season. However, it was challenging to predict the season-long biomass and N uptake of certain organs. The propensity thus supports the need for dynamic N control in Chilean rice production, according to the simulation studies.	[28]
USA, (Multiple year raw data)	Estimation of potential yield (Yp) of irrigated rice for most popular rice cultivars of USA i.e M-206 and CXL745.	The Yp was having an agreement between 77-78%. The maximum Yp was found between 14.3-14.5tha^{-1}.	[29]
Heilongjiang province of China	To study potential impacts of CC and warming phenomenon on productivity of cold rice cultivars.	Between 2010 and 2050, the rice growing cycle might be cut by 4.7 and 5.8 days, respectively, while rice yields would increase by 11.9% and 7.9%, according to several CC scenarios. However, considering the impact of rising $CO_{2,}$ rice production in the area will be favourably impacted by CC.	[30-31]
Korea (1997-2004)	To validate the model for Korean rice cultivars and field circumstances by comparing real yield against the generated values for various management approaches and categories of rice.	A high degree of agreement with the measured data. But the model displayed substantial correlation for various transplanting dates and high yield data fluctuations. Model's photoperiod sensitivity needs to be precisely tuned.	[32]
Uzbekistan's Khorezm (2008-09)	To quantify the effects of expected increases in temperature and atmospheric CO_2 concentration on rice phenological development and crop productivity.	The planting date and rice grain production are closely related, according to simulations utilizing historical daily weather data. The ideal emergence dates for SD were June 25, June 5, and June 26 for MD and LD types, respectively. Both climate change scenarios could cause a 10-day delay in planting dates. As temperature and CO_2 concentration rose, so did productivity. However, planting rice earlier or later than the advised seeding dates significantly lowers the crop output and ascertainsproduction assurance.	[33]
Philippines and Thailand (2005-06)	To prioritize mitigation strategies targeted at increasing the yields of non-photoperiod-sensitive rice produced under rainfed circumstances and to assess the relative impact of yield-limiting parameters.	The present simulated yield gap in the fields of rainfed rice growers is 1.76 Mgha-1 (41%). Improving N-Management practises could dramatically reduce yield gaps by 1.48Mgha^{-1} (34%). The substantial production shortfall above the farmers' existing fertiliser level indicates a large possibility for yield growth through site- and timing-specific nutrient management.	[34]
Northern Iran (2008-09).	Calibration and validation of various crop growth and yield components.	According to the results, crop length varied depending on seedling maturity from 7 to 10 days. The length of the growth season, however, was consistently underestimated by the ORYZA2000 model. The normalised root mean square error (RMSEn) values varied from 4% to 6% for each phenological stage. Younger seedlings exceeded the measured value according to the simulation results, whereas older seedlings of short-duration types had the best fit. The trial results indicated that it may be possible to use the ORYZA2000 model as an additional research tool to determine the best strategies for increasing rice yield.	[35]

ORYZA2000 was validated under non-water-stressed rainfed lowlands, recommending the Ranjit variety to farmers with a yield increase of 0.65 Mg/ha due to enhanced nitrogen treatment response [36]. In separate validations, the model closely simulated physiological data for DRRH and Vikas varieties at the Directorate of Rice Research, Hyderabad [37]. In Iran, ORYZA2000 accurately predicted rice growth and yield across cultivars (Khazar, Ali Kazemi, Hashemi) under varying nitrogen levels, optimizing fertilizer use in Gilan province [38]. Eastern India research evaluated ORYZA1 and INFOCROP models' responses to CO_2 and temperature, showing varied yield projections [39]. In Northern Iran, ORYZA2000 simulations accurately predicted rice cultivar responses to nitrogen and salt stress [40]. Additionally, ORYZA2000 successfully simulated rice shrimp project sites, advising planting date adjustments for saline environments [41].

Water management and irrigation scheduling

Freshwater resources for irrigation are increasingly scarce due to urban and industrial demands, deteriorating infrastructure, and poor water quality. This underscores the need to boost rice output while conserving water (Table 2). Field studies are costly and labor-intensive for obtaining site-specific ecohydrological data over multiple years. ORYZA2000, combined with field data, offers detailed insights into system dynamics over time and space. Rice water productivity (WPET) ranges from 0.4 to 1.6 kg/m3 [41-42].

Table 2. Locations and crop specific water management and irrigation scheduling assessed through the ORYZA CSM.

Regions/Location and year of study of study	Parameters/Hypothesis	Outcomes	Authors
Between 1999 and 2002, Tuanlin, in the Dry Seasons- Chinese province of Hubei, and Los Banos, in the Philippines	Investigating how different irrigation techniques affect grain production, nitrogen (N) absorption and recovery, and the control of N on water productivity (grain production/evapotranspiration (ET)).	All of the biological yield parameters, as well as the field soil moisture conditions and soil water tension in the root Zone, which are components of the soil water balance after parameterization, were accurately simulated.	[43]
The two years multi-season of research (1999-2000) in Coimbatore, Tamil Nadu	To identify the critical growth to moisture stress that inevitably reduces crop productivity.	The approach can significantly dramatically boost production particularly compared to other water-saving irrigation techniques. To maximize water usage efficiency, a calibrated crop growth model and an optimization of algorithmic method are apparently needed.	[44]
China's Tuanlin province (2000–2002) and the Philippines' Muoz(2001) both had one dry season.	To compare several water-saving with continuous submergence (ponding)	Continuous submergence yielded a 4-6% lower yield than alternately submerged-non-submerged regimes. Other water-saving strategies reduced production. In comparison to continuous submersion, water-saving practices boosted water production in non-water-stressed settings.	[45]
Punjab, India	Examine the effects of water-related alternatives on rice growth and water use to improve the effectiveness of water utilization under irrigated environments.	Puddling more frequently did not have a significant impact on water productivity based on ET, although they did enhance water-based production significantly. This is true even if the WP for the continuous and two day intervals were not statistically significant.	[46]
North West India (1979-2010)	Building a model and analyzing the impact of water management on the water balance, soil moisture dynamics, and productivity and growth of rice crops.	Grain production, biomass, LAI, hydrogeological components, and soil water tension showed high agreement between simulated and actual results for irrigation ceilings ranging from continuous flooding (CF) to soil moisture stress.	[47]
Northeast China's Songnen Plain in 2018 and 2019	Assessing the potential for water savings with the use of conservation techniques to reduce water usage.	Comparison of the SWI, CTI, and TFI regimes to each other's water-saving modelling technique scenarios showed that each couldsave up to20-30% of irrigation water during times of drought.	[48]

Climate change studies

Rice production faces challenges from heat and cold-induced sterility now and in the future. Models determine optimal cultivation periods for rice with good yields, considering phenology and future climatic conditions across larger regions. Studies by Matthews et al. [41] project significant yield losses in parts of Asia due to increased heat sterility. Recent global assessments highlight varied climate change impacts, notably in dry regions like the Sahel and Pakistan [49], marked as high-risk areas in dark red. Initial versions of ORYZA2000 struggled to simulate yields accurately under extreme temperature conditions. Recent enhancements, based on current experiments, have improved its ability to model yields under normal conditions and calibrated phenology. However, the predecessor ORYZA1 model [40] showed limitations in yield simulation across multiple locations. Studies have indicated increasing water footprints (WF) at Kaifeng and Kunshan stations in China, with yearly average linear moving rates of 3.86 $m^3t^{-1}$and 2.62 m^3t^{-1}, respectively [50]. The blue water footprint is expected to increase significantly compared to the green water footprint in the future.

Future scope and Limitations

ORYZA2000 offers adaptability, transferability, and code portability advantages over commercial database applications. It effectively forecasts rice responses to significant weather fluctuations, relying heavily on precise weather data. This model primarily aims to predict commercial crop yields through strategic, practical, and predictive applications. Comparative studies with WOFOST and CERES models in Punjab, India, and Thailand highlight ORYZA2000's superior performance in simulating rice growth and grain production [51].

ORYZA2000 faces limitations due to its computational capacity and incomplete understanding of natural processes, particularly in estimating climate change impacts. Variations in user modeling proficiency and site-specific parameter inaccuracies further hinder its reliability. Root growth and soil property data are often less comprehensive than above-ground metrics, impacting model accuracy. Dependency on accurate weather data, particularly global radiation (Rs), restricts site-specific crop modeling. The model's approach to simulating cold sterility using cooling-degree days may oversimplify actual conditions, particularly in regions with high diurnal temperature variations. Studies suggest ORYZA1's tendency to over-predict under certain climatic scenarios, indicating ongoing challenges in refining model accuracy [20]. Integrating more comprehensive input data, including nutrients beyond nitrogen and water, is crucial for enhancing ORYZA2000's precision and applicability in diverse agricultural settings.

Conclusion

The growth and development of rice are realistically simulated by the ORYZA2000 rice model. Comparing the upgraded version, ORYZA2000 (v3), to v2.13, increases prediction confidence and broadens its usefulness. More realistic simulations of yield, biomass, leaf area, leaf N content, and soil water potential are made possible by improvements in soil temperature, root growth, and soil nutrient dynamics. Although ORYZA2000 (v3) requires average values for phenology parameters from several sites and contexts for wider applications, it operates effectively at various sizes and production scenarios. This limitation is anticipated to be addressed in future releases. All cultivar factors—aside from phenology—are included as genetic parameters and need to be carefully calibrated. The auto-calibration feature in the most recent version has simplified extensive calibration.

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Author Contributions

Data curation, D.M., L.D. and R.B., Investigation, D.M., L.D., and., Methodology, D. M, L.D and A.H., Supervision, L.D., Writing—original draft, D.M and L.D.,Writing—review & editing, L..D., R. B., V. D. R., T.M. and All authors have read and agreed to the published version of the manuscript.

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References

1. Food and Agriculture Organization of the United Nations, Trade and Markets Division (2020). *Food Outlook: Biannual Report on Global Food Markets, November 2020*. FAO Trade and Markets Division: Rome, 2020.

2. Food and Agriculture Organization of the United Nations (2013). *FAO Statistical Yearbook 2013*. Food & Agriculture Organic, 2013.

3. Postel, S. (2017). *Replenish: The Virtuous Cycle of Water and Prosperity*. Island Press: Washington, DC, 2017.

4. Fukai, S., Sittisuang, P., Chanphengsay, M. (1998). Increasing Production of Rainfed Lowland Rice in Drought Prone Environments: A Case Study in Thailand and Laos. *Plant Prod. Sci.*, 1, 75–82.

5. Tuong, T.P., Singh, A.K., Siopongco, J.D., Wade, L.J. (2000). Constraints to High Yield of Dry-Seeded Rice in the Rainy Season of a Humid Tropic Environment. *Plant Prod. Sci.*, 3(2), 164–172. https://doi.org/10.1626/pps.3.164.

6. Majumder, D., Das, L. (2018). Simulating the Yield Attributes of Boro Rice under Nitrogen and Irrigation Management at Mohanpur, West Bengal Using ORYZA2000. *J. Agromet.*, 20(1), 72–74. https://doi.org/10.54386/jam.v20i1.511.

7. Lizaso, J.I., Batchelor, W.D., Boote, K.J., Westgate, M.E., Rochette, P., Moreno-Sotomayor, A. (2005). Evaluating a Leaf-level Canopy Assimilation Model Linked to CERES-maize. *Agron. J.*, 97(3), 734–740. https://doi.org/10.2134/agronj2004.0172.

8. De Wit, C. (1958). Transpiration and Crop Yields. *Versl. Landbouwk. Onderz. Institute of Biological and Chemical Research on Field Crops and Herbage*, 64(6).

9. Van Keulen, H., Wolf, J. (1986). Modelling of Agricultural Production: Weather, Soils and Crops. Simulation Monographs. PUDOC.

10. Akponikpè, P.B.I., Mineta, J., Gérardc, B., Defournya, P., Bieldersa, C.L. (2011). Spatial Fields' Dispersion as a Farmer Strategy to Reduce Agro-Climatic Risk at the Household Level in Pearl Millet-Based Systems in the Sahel: A Modeling Perspective. *Agril. Forest Meteorol.*, 151, 215–227.

11. Peng, S., Huang, J., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X., Centeno, G.S., Khush, G.S., Cassman, K.G. (2004). Rice Yields Decline with Higher Night Temperature from Global Warming. *Proc. Natl. Acad. Sci. U. S. A.*, 101(27), 9971–9975. https://doi.org/10.1073/pnas.0403720101.

12. Bouman, B.A.M., Krop, M.J., Tuong, Y.P., Wopereis, M.C.S., Berge, H.F.M., Van Laar, H.H. (2001). ORYZA2000: Modelling Lowland Rice, Philippines. Wageningen, Netherlands.

13. van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z. (2013). Yield Gap Analysis with Local to Global Relevance—A Review. *Field Crops Res.*, 143, 4–17. https://doi.org/10.1016/j.fcr.2012.09.009.

14. Van Kraalingen, D.W.G. (1991). The FSE System for crop simulation. *Simulation Reports CABO-TT*, 23.

15. van Wart, J., Kersebaum, K.C., Peng, S., Milner, M., Cassman, K.G. (2013). Estimating Crop Yield Potential at Regional to National Scales. *Field Crops Res.*, 143, 34–43. https://doi.org/10.1016/j.fcr.2012.11.018.

16. Jing, Q., Bouman, B.A.M., Hengsdijk, H., Van Keulen, H., Cao, W. (2007). Exploring Options to Combine High Yields with High Nitrogen Use Efficiencies in Irrigated Rice in China. *Eur. J. Agron.*, 26(2), 166–177. https://doi.org/10.1016/j.eja.2006.09.005.

17. Dadhwal, V.K., Sehgal, V.K., Singh, R.P., Rajak, D.R. (2003). Wheat Yield Modelling Using Satellite Remote Sensing with Weather Data: Recent Indian Experience. *Mausam*, 54(1), 253–262.

18. Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T. (2003). The DSSAT Cropping System Model. *Eur. J. Agron.*, 18(3–4), 235–265. https://doi.org/10.1016/s1161-0301(02)00107-7.

19. Kropff, M.J., Cassman, K.G., Peng, S., Matthews, R.B., Setter, T.L. (1994). Quantitative Understanding of Yield Potential, Breaking the Yield Barrier, 21–38.

20. Matthews, R.B., Kropff, M.J., Horie, T., Bachelet, D. (1997). Simulating the Impact of Climate Change on Rice Production in Asia and Evaluating Options for Adaptation. *Agric. Syst.*, 54(3), 399–425. https://doi.org/10.1016/s0308-521x(95)00060-i.

21. Bouman, B.A.M. (2007). A Conceptual Framework for the Improvement of Crop Water Productivity at Different Spatial Scales. *Agric. Syst.*, 93(1–3), 43–60. https://doi.org/10.1016/j.agsy.2006.04.004.

22. Boling, S.D., Douglas, M.W., Shirley, R.B., Parsons, C.M., Koelkebeck, K.W. (2000). The Effects of Various Dietary Levels of Phytase and Available Phosphorus on Performance of Laying Hens. *Poult. Sci.*, 79(4), 535–538. https://doi.org/10.1093/ps/79.4.535.

23. Yin, X., Struik, P.C., Tang, J., Qi, C., Liu, T. (2005). Model Analysis of Flowering Phenology in Recombinant Inbred Lines of Barley. *J. Exp. Bot.*, 56(413), 959–965. https://doi.org/10.1093/jxb/eri089.

24. Palanisamy, S., Aggarwal, P.K., Thiyagarajan, T.M., Ranganathan, T.B., Nadu, T. (1994). Simulating yields and ranking of rice genotypes in multi-location trials. In *Applications of Systems Approach in Plant Breeding: Proceedings of the SARP Applications Workshop, Los Baños, Philippines*, pp. 91–95.

25. Evans, L.T., Fischer, R.A. (1999). Yield Potential: Its Definition, Measurement, and Significance. *Crop Sci.*, 39(6), 1544–1551. https://doi.org/10.2135/cropsci1999.3961544x.

26. Wang, W.G., Yu, Z.B., Wei, Z., Shao, Q.X., Zhang, Y.W., Luo, Y.F., Jiao, X.Y., Xu, J.Z. (2014). Responses of Rice Yield, Irrigation Water Requirement and Water Use Efficiency to Climate Change in China: Historical Simulation and Future projections. *Agric. Water Manag.*, 146, 249–261.

27. Amiri, E., Rezaei, M., Rezaei, E.E., Bannayan, M. (2014). Evaluation of Ceres-Rice, Aquacrop and Oryza2000 Models in Simulation of Rice yield Response to different Irrigation and Nitrogen Management Strategies. *J. Plant Nutr.*, 37(11), 1749–1769.

28. Artacho, P., Meza, F., Antonio Alcalde, J. (2011). Evaluation of the Oryza2000 Ricegrowth Model under Nitrogen-Limited Conditions in an Irrigated Mediterranean Environment. *Chil. J. Agric. Res.*, 71(1), 23–33.

29. Espea, M.B., Yangb, H., Cassmanb, K.G., Guilpartb, N., Sharifia, H., Linquist, B.A. (2016). Estimating Yield Potential in Temperate High-Yielding, Direct-Seeded US Rice Production Systems. *Field Crops Res.*, 193, 123–132.

30. Pu, L., Zhang, S., Yang, J., Chang, L., Xiao, X. (2020). Assessing the Impact of Climate Changes on the Potential Yields of Maize and Paddy Rice in Northeast China by 2050. *Theor. Appl. Climatol.*, 140(1–2), 167–182. https://doi.org/10.1007/s00704-019-03081-7.

31. Vaghefi, N., Shamsudin, M.N., Makmom, A., Bagheri, M. (2010). The Economic Impacts of Climate Change on the Rice Production in Malaysia. *Int. J. Agric. Res.*, 6(1), 67–74. https://doi.org/10.3923/ijar.2011.67.74.

32. Zhang, X., Lee, J.H., Abawi, Y., Kim, Y.H., McClymont, D., Kim, H.D. (2007). Testing the Simulation Capability of APSIM-ORYZA under Different Levels of Nitrogen Fertiliser and Transplanting Time Regimes in Korea. *Aust. J. Exp. Agric.*, 47(12), 1446. https://doi.org/10.1071/ea05363.

33. Devkota, K.P., Manschadi, A.M., Devkota, M., Lamers, J.P.A., Ruzibaev, E., Egamberdiev, O., Amiri, E., Vlek, P.L.G. (2013). Simulating the Impact of Climate Change on Rice Phenology and Grain Yield in Irrigated Drylands of Central Asia. *J. Appl. Meteorol. Climatol.*, 52(9), 2033–2050. https://doi.org/10.1175/jamc-d-12-0182.1.

34. Boling, A.A., Bouman, B.A.M., Tuong, T.P., Konboon, Y., Harnpichitvitaya, D. (2011). Yield Gap Analysis and the Effect of Nitrogen and Water on Photoperiod-Sensitive Jasmine Rice in North-East Thailand. *NJAS Wageningen J. Life Sci.*, 58(1–2), 11–19. https://doi.org/10.1016/j.njas.2010.05.001.

35. Larijani, B.A., Sarvestani, Z.T., Nematzadeh, G., Manschadi, A.M., Amiri, E. (2011). Simulating Phenology, Growth and Yield of Transplanted Rice at Different Seedling Ages in Northern Iran Using ORYZA2000. *Rice Sci.*, 18(4), 321–334. https://doi.org/10.1016/s1672-6308(12)60011-0.

36. Swain, D.K., Thomas, D. (2010). Climate Change Impact Assessment and Evaluation of Agro-Adaptation measures for Rice Production in Eastern India. *J. Environ. Inform.*, 16, 94–101.

37. Sailaja, B., Voleti, S.R., Gayatri, S., Subrahmanyam, D., Nagarjuna Kumar, R., Rao, R., Meera, S.N. (2015). Vulnerability of Rice Yields under Changed Climatic Conditions. *Int. J. Agric. Stat. Sci.*, 11(2), 523–526.

38. Azarpour, E., Moraditochaee, M., Bozorgi, H.R. (2014). Assessment Examine of the Modeling Ability of ORYZA2000 for Rice Cultivars in Guilan Province (Iran). *J. Biodiver. Environ. Sci.*, 4(2), 195–204.

39. Krishnan, P., Swain, D.K., Chandra Bhaskar, B., Nayak, S.K., Dash, R.N. (2007). Impact of Elevated CO2 and Temperature on Rice Yield and Methods of Adaptation as Evaluated by Crop Simulation Studies. *Agric. Ecosyst. Environ.*, 122(2), 233–242. https://doi.org/10.1016/j.agee.2007.01.019.

40. Tayefe, M., Amiri, E., Nasrollahzade, A., Hashemi, S.A. (2013). Testing the Modeling Capability of ORYZA2000 under Nitrogen Limit Conditions in Northern Iran. *Int. J. Biosci.*, 3(11), 1–7.

41. Tuong, T.P., Bouman, B.A.M. (2003). Rice Production in Water-Scarce Environments. In J. Kijne, R. Barker, D. Molden (Eds.), *Water productivity in agriculture: Limits and opportunities for improvement. Comprehensive assessment of water management in agriculture* (pp. 53–67). CABI Press: Wallingford, UK.

42. Babaeian, F., Delavar, M., Morid, S., Srinivasan, R. (2021). Robust Climate Change Adaptation Pathways in Agricultural Water Management. *Agric. Water Manag.*, 252=(106904), 106904. https://doi.org/10.1016/j.agwat.2021.106904.

43. Belder, P., Bouman, B.A.M., Spiertz, J.H.J. (2007). Exploring Options for Water Savings in Lowland Rice Using a Modelling Approach. *Agric. Syst.*, 92(1–3), 91–114. https://doi.org/10.1016/j.agsy.2006.03.001.

44. Soundharajan, B., Sudheer, K.P. (2009). Deficit Irrigation Management for Rice Using Crop Growth Simulation Model in an Optimization Framework. *Paddy Water Environ.*, 7(2), 135–149. https://doi.org/10.1007/s10333-009-0156-z.

45. Belder, P., Spiertz, J.H.J., Bouman, B.A.M., Lu, G., Tuong, T.P. (2005). Nitrogen Economy and Water Productivity of Lowland Rice under Water-Saving Irrigation. *Field Crops Res.*, 93(2–3), 169–185. https://doi.org/10.1016/j.fcr.2004.09.022.

46. Arora, V.K. (2006). Application of a Rice Growth and Water Balance Model in an Irrigated Semi-Arid Subtropical Environment. *Agric. Water Manag.*, 83(1–2), 51–57. https://doi.org/10.1016/j.agwat.2005.09.004.

47. Yadav, S., Li, E., Humphreys, G., Gill, S.S. (2011). Evaluation and Application of ORYZA2000 for Irrigation Scheduling of Puddled Transplanted Rice in Northwest India. *Field Crops Res.*, 122, 104–117.

48. Gao, Y., Xu, X., Sun, C., Ding, S., Huo, Z., Huang, G. (2021). Parameterization and Modeling of Paddy Rice (OryzaSativa L. Ssp. Japonica) Growth and Water Use in Cold Regions: Yield and Water-Saving Analysis. *Agric. Water Manag.*, 250, 106864. https://doi.org/10.1016/j.agwat.2021.106864.

49. Gourdji, S.M., Sibley, A.M., Lobell, D.B. (2013). Global Crop Exposure to Critical High Temperatures in the Reproductive Period: Historical Trends and Future Projections. *Environ. Res. Lett.*, 8(2), 024041. https://doi.org/10.1088/1748-9326/8/2/024041.

50. Zheng, J., Wang, W., Ding, Y., Liu, G., Xing, W., Cao, X., Chen, D. (2020). Assessment of Climate Change Impact on the Water Footprint in Rice Production: Historical Simulation and Future Projections at Two Representative Rice Cropping Sites of China. *Sci. Total Environ.*, 709, 136190. https://doi.org/10.1016/j.scitotenv.2019.136190.

51. Mukherjee, J., Singh, L., Bal, S.K., Singh, H. (2011). Comparative Evaluation of WOFOST and ORYZA2000 Models in Simulating Growth and Development of Rice (*Oryzasativa* L.) in Punjab. *J. Agromet.*, 13(2), 86–91.