Assessment of the CERES-Rice model for rice production in Ibadan, Nigeria

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Abstract: CERES-Rice model was used to simulate growth and yield of a new rice variety in Nigeria with the attention on rates of water application, one major factor that affects grain yield. The rates were full irrigation (100%ET), medium (75% ET), average (50% ET) and low (25% ET) irrigation treatments. The NEw RIce for AfriCA (acronym for NERICA) 2 variety was grown at IITA, Ibadan, Nigeria. Agronomic parameters such as plant height, root depth, canopy shading, Leaf Area Index (LAI), biomass and grain yield in relation to water use were obtained and compared with simulated values from CERES and the results were subjected to statistical analysis. The model predicted slightly higher values for biomass yield (13.74 t ha^{-1}), total yield (16.47 t ha^{-1}) and grain yield (2.63 t ha^{-1}) than the observed values of 8.17 t ha^{-1}, 10.58 t ha^{-1} and 2.41 t ha^{-1} respectively for NERICA 2 at 100% ET. There was no significant difference between the simulated and observed values of day 0 to flowering in the NERICA 2 (N2) variety. Highest values of most agronomic parameters were obtained at 100% ET and they were slightly lower than predicted. At 25% ET, prediction was very low when compared with the observed values which underlined the effect of limited water application rate. The result of ANOVA showed significant differences in biomass and grain yield, LAI, CS, plant height and root depth among treatments ($P < 0.05$). Recalibration and revalidation of CERES-rice model under nitrogen limiting and soil conditions is required to explore strategic management options to optimize resource-use efficiency and productivity.

Keywords: rice, CERES-Model, water, simulation, production, food security

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1 Introduction

Food security in the world is challenged by increasing food demand and threatened by declining water availability (Akinbile and Sangodoyin, 2011). Rice (*Oryza sativa L)* production which constitutes one of the most important staple foods for over half of the world's population is also not spared with the growing influence of global warming and attendant effects on production. Globally, it ranks third after wheat and maize in terms of production and in Nigeria, it is the sixth major crop in cultivated land area after sorghum, millet, cowpea, cassava and yam (Akinbile, 2010). Rice is one of the few crops grown nationwide and in all agro ecological zones from Sahel to the coastal swamps and could be cultivated in about 4.6 to 4.9 million ha of land in Nigeria, but the actual area under cultivation is only 1 million ha representing 22% of the total potential available area (Akinbile et al. 2007). Due to under utilization of available resources for rice production, Nigeria resulted to importation which rose from 7,000 t in 1960s to 657,000 t in 1990s (WARDA, 2003). Although, Nigeria is West Africa's largest producer of rice, producing an average of 3.2 million tons of paddy rice for the past 5 years (FAO, 2007) the country is also the World's second largest rice importer, spending over US$300 million on rice imports annually which rose to US$1 billion in 2010 (Sanusi, 2011). Despite research efforts to lift rice yields, there are gaps between biologically and climatically achievable potential yields at research stations and on farm (Guerra et al., 1998). Research addressing the issue of yield gaps and identifying factors

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responsible for those gaps are important for increasing food security and national revenue which in turn leads to increasing resource use efficiency and sustainability (Bouman, 2009). In an attempt to adapt to the effect of climate change on rice crop with particular reference to yield, the West Africa Rice Development Association (WARDA) developed new rice varieties called the New Rice for Africa (NERICA) by successfully carrying out cross-hybridization between the excellent traits of an Asian variety, *Oryza sativa L.,* which is high-yielding with hardy African rice variety, *Oryza glaberrima,* which is tolerant to diseases, drought and pests (WARDA, 2006). The product NERICA, therefore combines features of resistance to drought and pests with higher yields even with little irrigation or fertilizer. In addition, it contains more protein content than other types of rice (Akinbile et al., 2007).

Crop growth simulation models provide the means to qualify the effects of climate, soil and management on crop growth, productivity and sustainability of agricultural production (Nain and Kersebaum, 2007). These tools can reduce the need for expensive and time-consuming field trials and could be used to analyze yield gaps in various crops including rice (Pathak et al., 2005). There have been intensive efforts on studying rice production systems resulting in the development of several rice simulation models (Bouman and Tuong, 2001).

Recent advances of analysis through simulation using microcomputers enabled alternative strategies to be tested over several years and this allows the researchers to select optimum strategies for field testing. Hence, the objective of this study was to evaluate CERES-Rice model in the Decision Support System for Agro technology Transfer (DSSAT) with field data from selected rice research stations in Nigeria, for its applicability in determining appropriate technologies and their levels for rice production in this region.

2 Materials and methods

2.1 Field experimentation

Upland rice was planted at the farmyard of the International Institute of Tropical Agriculture, (IITA), Ibadan, Nigeria. IITA is located between latitude 3°54′ E and 7°30′ N, at elevation of 200 m above the mean sea level. It has an annual rainfall range of between 1,300 and 2,000 mm while its rainfall distribution pattern is bimodal. The annual mean temperature is 27.2℃ during dry season and 25.6℃ during rainy season (IITA, 2002). The experimental design was a Randomized Complete Block Design (RCBD) with four treatments. NERICA 2 was planted on all the plots and irrigation water was delivered through an overhead sprinkler systems. There were four treatments based on the level of irrigation water application. All the plots received water throughout the week but at varying ET irrigation rates. Plot A (first treatment) at 100% ET (i.e. full irrigation), plot B (second treatment) at 75% ET (i.e. medium irrigation), plot C, (third treatment) at 50% ET (i.e. average irrigation) and plot D (fourth treatment) at 25% ET (i.e. low irrigation). A controlled experiment to monitor the behaviour of rice on the field was carried in a lysimeter situated in a screen house located 50 m away from the field (Akinbile, 2009). The agronomic parameters such as plant height, root depth, leaf area index (LAI), canopy shading (CS) and associated post-harvest measurements such as biomass, grain and crop yields were measured while crop water use, actual evapotranspiration (ET) were determined by the method of Allen et al., (1998) as reported in (Akinbile and Sangodoyin, 2011; Akinbile, 2010).

2.2 Model description

There are several models been tested and validated but with various shortcomings. ORYZA2000 was until recently, one of the most advanced method and has been intensively tested. However, it is a single-crop model addressing crop growth, development and crop response to environmental constraints. It does not simulate crop rotations or carry-over effects although there is an increasing demand for the ability to simulate rice-based cropping systems (Gauch et al., 2003). Another model is the Agricultural Production System Simulator (APSIM), which was designed for the simulation of complex cropping systems and their management scenarios (Keating et al., 2003). System-related processes are available to any crop module through APSIM's infrastructure and generic crop libraries (Wang et al., 2007) greatly increasing the efficiency of model development by reducing redundancy and potential for error. Collaborative research efforts between Wageningen University, in the Netherlands, International Rice Research Institute (IRRI) and Agricultural Production System Research Unit (APSRU) have now resulted in the incorporation of ORYZA into the APSIM modelling framework. Crop modules in APSIM simulate crop phenology, leaf area development, biomass production, yield and nitrogen accumulation in response to environmental variables such as temperature, solar radiation, soil water and nitrogen supply (Wang et al., 2007). Rice-specific processes as simulated in ORYZA were implemented within APSIM. The CROPGRO, CERES and EPIC models, AUSCANE as well as many others have been used to quantify yield change resulting from global climate change. The water accounting rice model (WARM) was used within the crop yield forecasting system of the European Commission. WARM model was also used for the simulation of rice growth under flooded and un-flooded conditions in China and Italy. The WARM model simulates crop growth and development, floodwater effect on the vertical thermal profile, blast disease, and cold-shock induced spike let sterility during the pre-flowering period and hydrological peculiarities of paddy soils (Confalonieri et al., 2010).

The CERES-Rice model (Figure 1) emphasized the effects of management and the influence of soil properties on crop performance (Cheyglinted et al., 2001). The model was designed to predict the yield of crop varieties, soil water regimes and N level, as well as for alternative technology and new cropping sites. Yet a drawback has been its poor response to typhoons and incidence of pests. However, the CERES-Rice model could be an alternative tool to test the strategies at both research and farm levels. CERES-Rice model is a process based, management oriented model that could simulate the growth and development of rice as affected by varying levels of water and Nitrogen (Boutraa, 2010). CERES-Rice model has been evaluated for many tropical and sub-tropical locations across Asia and in temperate climates of Japan and Australia (Timsina and Humphreys, 2006). However, little or insufficient evaluation has been done in sub-Saharan Africa. The detailed explanation of the CERES-Rice model according to each of the three components is as shown below:

2.2.1 Phenology

The study was designed to record growing degree days (GDD) of N2 for the basic vegetative phase (P1), and from beginning of grain filling to physiological maturity (P5) in ℃ per day, and critical day length for flowering (P20) (measured in hours). To generate a photoperiod sensitivity coefficient (P2R) (i.e. the extent to which phenological development leading to panicle initiation is delayed, expressed as GDD measured in ℃ per day) for each hour increase in photoperiod above P20. It also included potential spikelet number coefficient (G1), single grain weight (G2, measured in grams) and tillering coefficient (G3). The temperature tolerance (G4) was given by the CERES-Rice model (Timsina and Humphreys, 2006). The P coefficients enable the model to predict events such as flowering and maturity and the G coefficients to predict the potential grain yield of a specific variety.

2.2.2 Nitrogen and water dynamics

The soil water balance was examined based on irrigation, precipitation, infiltration, evaporation while the nitrogen balance were examined in aspects of mineralization, leaching, ammonification, nitrification and denitrification for nitrogen balance. These processes were used in determining the deficiency factors such as rice phase development and growth processes for water and nitrogen (Nain and Kersebaum, 2007).

2.2.3 Growth components

The two modelling components used for the growth sub-model were plant and soil processes. The sub-components under plant processes were light interception, radiation use efficiency (RUE) or simply put as photosynthesis, respiration, dry matter allocation that was determined by growth stage and dry matter redistribution from stem and leaves which had carbohydrate pool. Others were root growth based on growth stage partitioning, distribution affected by depth and influence of water and nitrogen and solar radiation-induced transpiration.

The other sub-component were soil processes which involved the balance of water in the soil, the amount of surface water runoff, infiltration rate and the rate at which the water was redistributed in the soil. The nutrient processes which showed the transformation of nitrogen under upland condition, leaching, the nitrogen uptake, volatilization and denitrification (Nain and Kersebaum, 2007).

2.2.4 Output parameters

The output parameters comprising growth aspect was determined by the biomass production of the crop based on the light interception by the plant and conversion of the intercepted radiation to biomass. The conversion efficiency dependent on the leaf area index (LAI), growth stage, leaf weight, grain weight ET. The other output parameter considered was water which included average plant transpiration, evapotranspiration, maximum and minimum temperature. Flowering date, maturity, grain yield, panicle number and biomass data were the expected output from the simulation. Yield was the final output parameter.

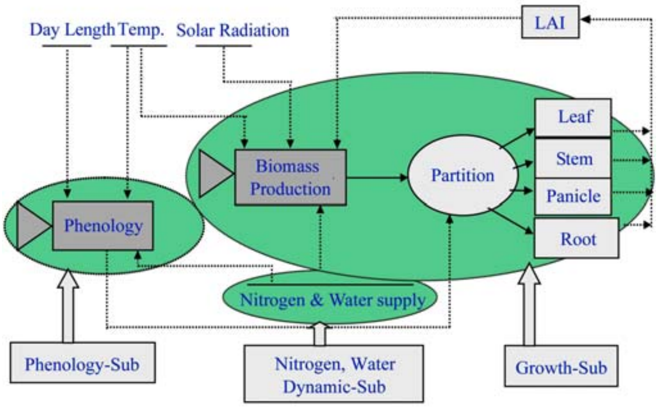


Figure 1 Schematic diagram of rice growth simulation model (CERES-Rice) (Cheyglinted et al., 2001).

2.3 Model calibration and evaluation

Calibration is the process of adjusting some model parameters to local conditions and it also obtains genetic coefficients for new cultivars used in modelling study. So the model was calibrated with the data collected during 2005 at the location that showed best performance in the field trials. To check the accuracy of the model simulation, it was run with the data recorded against the remaining treatments for the location during the year 2005. During this process, available data on grain yield, biomass yield and total crop yield was compared with simulated values.

2.4 Statistical analysis

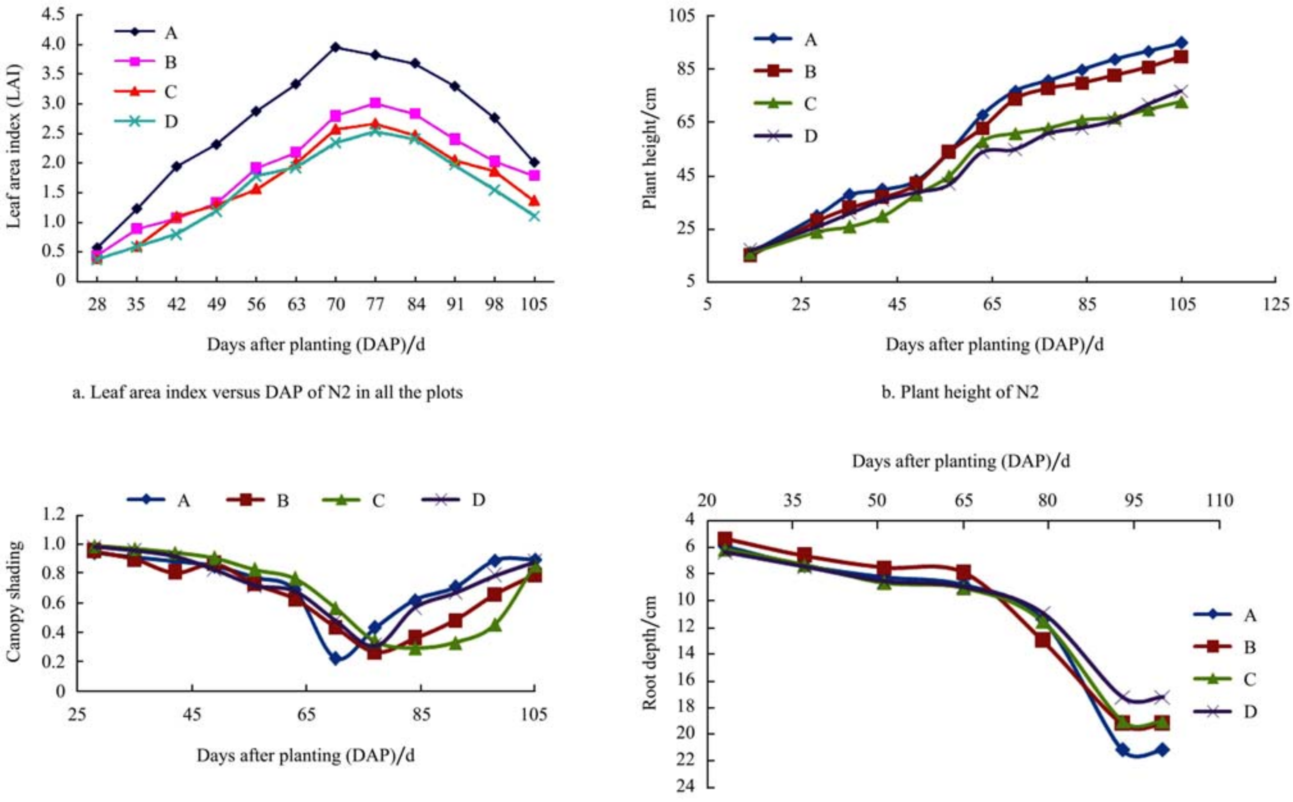
The statistical analyses tool used to determine the relationship between the simulated and observed values were the average error or bias, root mean square error (RMSE), standardized bias (R) and standardized mean square error (V). Test of goodness of fit was also used to compare the values. R^2 quantified the model's ability to reproduce the observed growth pattern. Negative deviations (Si-Ob>0) compensate positive deviations (Si-Ob<0) and vice versa. In contrast, V is a measure that reveals the model's tendency to over or underestimate field observations.

3 Results and discussion

The results of agronomic parameters of NERICA 2 with response to scheduled water application have been reported extensively in Akinbile and Sangodoyin (2011), Akinbile (2010) and Akinbile et al., (2007). The summary of the results (Table 1) indicated that the treatment A with 100% ET had most visible response in terms of higher values of LAI, CS, plant height, root depth, biomass and grain yields with respect to the crop water use while the behavioural responses of these parameters to water use at 25% ET (treatment D) was not encouraging. Hence, for optimum production of upland rice in Ibadan, Nigeria and with minimal water loss, treatment A was considered reasonable. Also, Figure 2 indicates the behavioural responses to irrigation scheduling of certain agronomic parameters such as LAI, CS, PH and RD of N2 throughout the growing period. LAI, plant height, canopy shading and root depth values of 3.95, 100 cm, 0.2 and 24 cm respectively in treatment A were the best for optimum rice growth. All these agreed with previous research works (Olaleye et al., 2004; Lafitte et al., 2007; Lafitte et al., 2004; Fujii et al., 2005) and have been reported in previous publications.

Table 1 Measured plant parameters (N2) after harvest from field experiment LSD ($P > 5\%$)

Crop Parameters	A	B	C	D
Plant height /cm	88.8	85.6	88.8	76.4
Root depth /cm	22.6	19.2	19.1	17.2
No. of leaves	11	9	11	8
No. of tillers	15	13	8	10
Leaf length /cm	36.89	35.94	32.30	29.46
Leaf width /cm	1.44	1.30	1.28	1.24
Panicle diameter /cm	3.92	3.76	4.50	3.34
Panicle length /mm	26.08	25.50	25.60	23.84



a. Leaf area index versus DAP of N2 in all the plots

b. Plant height of N2

c. Canopy shading for N2

d. Field

Figure 2 Experimental results of some agronomic (LAI, PH, CS & RD) parameters of N2 with days after planting (DAP)

3.1 Model validation

Simulated and observed values of total, grain and biomass yields of NERICA 2 variety at the time of harvest during 2005/2006 with variation of applied irrigation water are presented in Table 2. Results showed that predicted grain yields were much higher than the observed yields. A grain, biomass and total yield values of 2.63 t ha^{-1}, 13.74 t ha^{-1} and 16.47 t ha^{-1} were simulated by the CERES-Rice model which was slightly higher than observed field values of 2.41 t ha^{-1}, 8.17 t ha^{-1} and 10.58 t ha^{-1} respectively (Table 2). This may either mean that the model over-predicted grain and biomass yields due to model assumptions on soil water intake or the observed values were less than normal expected results, going by the weather and soil parameters input into the model. Using the statistical results to illustrate the findings, the difference in grain yields was not significant ($P<0.05$). Also, the estimated biomass yield was greater than the observed biomass yield. The Bias, *RMSE*, R^2 and V statistics showed that the difference between the measured and predicted grain yield (Table 2). The *RMSE*, BIAS R and V values of grain yield were 0.16, 0.06, 0.08 and 0.006 which showed minimum errors in the simulated and observed values. The same was valid for both leave and stem biomass and total aboveground biomass statistical values, indicating reasonable performance of the model under the present modelling scenario. Also, there was high variation between observed and predicted biomass yield when the model was tested for its performance under different timing of water application. The model overestimated biomass yield by 5.57 t ha^{-1} compared to observed values (Table 2). This may be due to the assumption of sunshine hours in place of extraterrestrial solar radiation which tend to increase photosynthesis and by extension biomass formation. These observations agreed with the results of Timsina and Humphreys (2006) and Akinbile and Sangodoyin (2010) respectively. Also, comparing the simulated and observed values in grain, biomass and total yields with respect to applied irrigation water, the coefficient R^2 values were excellent in all circumstances as shown in Figure 3, Figure 4 and Figure 5 respectively. All the R^2 values but one in the simulated grain yield were above 0.98 indicating good performance of the model and agreed with Cheyglinted et al., (2001).

Table 2 Observed and simulated yield values of N2 with statistical analyses results

Crop Parameters	N	SI	OB	SI-OB	R^2	RMSE	BIAS
Grain yield	4	2.63	2.41	0.22	0.99	0.16	0.06
Leaves and stem biomass	4	13.74	8.17	5.57	0.99	2.78	1.39
Total aboveground biomass	4	16.47	10.58	5.89	0.99	2.68	1.34

Note: SI- predicted value (t/ha); OB- observed value (t/ha); SI-OB- predicted value minus observed value; R^2- coefficient of determination; RMSE- root mean square error, N- number of observations.

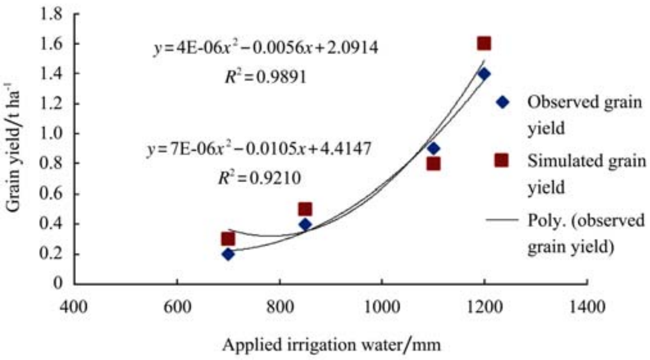


Figure 3 Comparison between observed and simulated total grain yield against applied irrigation water

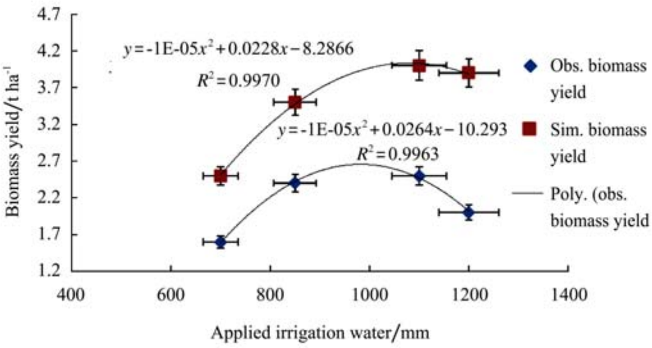


Figure 4 Comparison between observed and simulated biomass yield against applied irrigation water

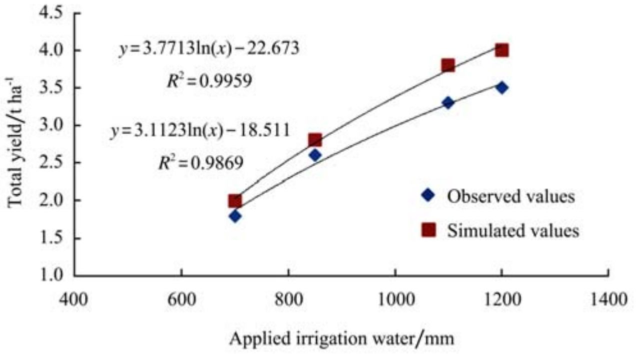


Figure 5 Comparison between observed and simulated biomass yield against applied irrigation water

4 Conclusion

CEREC-Rice model was used to simulate growth and yield of NERICA 2 variety in Ibadan, Nigeria for proper planning and efficient irrigation scheduling. Experimental values of N2 were obtained from the field experiment conducted at IITA to verify the workability of the model and authenticate its findings. The prediction by CERES-Rice model for grain and biomass yields were quite higher but reasonable for planning rice productivity, especially in Nigeria, going by the assumptions used which varied considerably when considered standard environmental conditions. Input parameters such as weather and crop parameters would also contribute to the performance of the model and therefore produce more reliable predictions under optimal water conditions. The variable performance of models, and in particular of CERES-Rice, highlights the importance of adaptation and evaluation in the environment of interest before applying them to evaluate different cropping management scenarios.

5 Recommendations

Re-calibration and modification to accommodate some local parameters are some improvements required to adequately achieve most acceptable predictions from the model. The effect of nitrogen in soil and water with respect to rice crop usage and by extension, model prediction is very germane and should be given serious consideration rather than mere assumptions. Further model validation is required under water and N limiting conditions before it can be used to explore management options and to increase resource use efficiency, such as stretching irrigation intervals and placement of N fertilizers for rice systems in Nigeria. Increase in rice yields could be guaranteed by improving crop management strategies hence, research needs to focus on increasing yield and resource-use efficiency. CERES-Rice model, in conjunction with socio-economic research, could be an effective approach for achieving this, but a dependable evaluation is required before models can be used to develop guidelines and policy for sustainable cropping systems.

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