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Original article

Application of DSSAT crop simulation model to estimate the optimum dose of nitrogen fertilizer for the rice variety J-104

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ABSTRACT

The rice (*Oryza sativa* L.), is one of the cereals of greater production worldwide. Cuba is one of the highest consumer countries in Latin America; with values of around 72 kg per capita per year. So far, the national production only satisfies 50 % of the needs. In spite of the large amount of resources that are destined to the production of rice cultivation, the yields that are currently obtained do not satisfy the existing demand nor are economically justified. The present work was developed with the objective of applying the DSSAT crop simulation model to estimate the optimal nitrogen fertilizer dose based on the expected yield of the rice variety J-104. To calibrate the model, three experiments were evaluated in the Los Palacios Base Scientific Technological Unit, belonging to the National Institute of Agricultural

Sciences (INCA), in different sowing dates. For the simulation, the runs of the model were made for different doses of nitrogen, varying them from 150 to 200 kg ha^{-1}, with an interval of 10 kg ha^{-1} and the other parameters of the model were kept constant. The results show that the model is able to describe adequately the dependence of the yields with the level of nitrogen applied and the recommended dose to obtain the best yields.

Key words: calibration, simulation models, yield

INTRODUCTION

Rice (*Oryza sativa* L.), is one of the cereals with the highest production worldwide and, together with wheat, meat and fish, constitute the basis of human nutrition. The 75 % of the world population includes it in their daily food diet and may exceed, in some cases, the consumption of other cereals [1,2].

The Food and Agriculture Organization of the United Nations (FAO) reported that world production of this cereal in 2017 exceeded 0.6 % the previous year's campaign, reaching 503.9 million tons. World rice utilization is also to increase by 1.1 % forecast. Human consumption should represent the totality of this increase, and allow an increase in world consumption per capita to 53.7 kg [3].

Cuba is one of the highest consuming countries in Latin America; with values of around 72 kg per capita per year. So far, national production only meets 50 % of the needs and these are completed with imports [3].

Our country invests large sums in the import of this cereal for human consumption. The costs are getting higher and, in turn, they are difficult to acquire in the international market. That is why each area planted to rice cultivation must be obtained with high yields to satisfy the growing needs of the population with an efficient and rational use of resources.

Despite the large amount of resources that are destined to the production of the crop, the yields that are currently obtained do not satisfy the existing demand nor are they economically justified. In the country, rice cultivars have a yield potential that exceeds 7.0 t ha^{-1} [4]. However, despite the fact that in Cuba there are favorable climate and soil conditions for the growth and development of this cereal, in 2016 the yield did not exceed 3.7 t ha^{-1} [5].

As in other crops, nitrogen is the main limiting factor in rice production. Its availability is considered essential because it is a basic component in all organic molecules involved in plant growth and development. It promotes the rapid growth of the plant and increases the size of the leaves, the number of spikelets per panicle, the percentage of full spikelets and the protein content in the grain [6].

Today more than ever, increased food production depends on the prudent use of nitrogen. Furthermore, issues such as climate change, climate variability, soil and long-term carbon sequestration, effects on food security and environmental sustainability have become important aspects.

Knowing adequately the nitrogen dynamics in the different stages of development of the rice plant, to be able to elaborate cheaper and low environmental impact alternatives are aspects of special importance and should be a priority object of professional updating. The need for information in decision-making is becoming more crucial every day and there is a significant gap between the information that is needed and that traditionally generated through disciplinary research. For this purpose, a tool such as crop simulation models is very useful.

Ecophysiological based simulation models have been developed over the past 10 years for a significant number of crop systems. These are from other empirical models distinguished by their explicit representation of physical and biological processes such as photosynthesis, dry matter production, leaf area growth, plant development, nutrient cycling, and energy balance [7].

Crop simulation models have proven to be tools that allow evaluating available resources, evaluating a large number of plant-environment-management interactions and facilitating decision-making, quantifying production risk from a probability analysis taking historical series of daily climate data and soil characteristics [8]. The successful use of the culture model depends on the proper calibration of the models. The determination of the genetic coefficients of a cultivar can be obtained from the appropriate calibration of the model [9]. Crop models calibrated with cultivar parameters can be used to analyze and interpret different future scenarios due to modifications that may be proposed in crop management, changes in weather conditions or for yield forecasting, among other indicators [10].

DSSAT is a popular model of cultivation used in more than 100 countries for more than 20 years [7]. It is a microcomputer software package, which provides an interface for crop-soil simulation models, soil and climate data, and programs to evaluate management strategies.

For this reason, the objective of this work is to apply the DSSAT modeling tool to estimate the optimum dose of nitrogen fertilizer for the J-104 rice variety.

MATERIALS AND METHODS

Crop models have a working principle that goes from calibration, through validation, to simulation. To develop this research, the work was into two stages divided; the first to carry out the calibration of the model by obtaining the values of the genetic coefficients of the rice variety studied and the second to perform the simulations of the yield when using different nitrogen doses.

Calibration

To obtain the values of the genetic coefficients of the J-104 rice variety, data were taken from experiments carried out at the Los Palacios Base Scientific-Technological Unit (UCTB-LP), belonging to the National Institute of Agricultural Sciences; located in the southern plain of the Pinar del Río province (22° 44 'north latitude and 83° 45' west longitude, at 60 m a.s.l). Three planting dates were used corresponding to the cold or dry season, which in Cuba covers from November to February [11] (Table 1).

Table 1. Sowing dates used in the experiments

Nu	Cold or dry season (November-February)		
	Day	**Month**	**Year**
1	15	Enero	2004
2	2	Diciembre	2004
3	10	Febrero	2005

Source: Own elaboration

The medium-cycle variety J-104, which has a semi-dwarf indica plant type, was used. Its leaves are deep green in color, good initial vigor and high ability of tillering; it stands out for its high performance potential; for these reasons, it becomes a producer favorite.

The sowing was by broadcast carried out, with a norm of 120 kg ha^{-1} of seeds to ensure at least 320 plants per m^2. Experimental plots of 64 m^2 of surface and four replications were used.

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The phytotechnical work was as recommended in the Technical Instructions for the Cultivation of Rice carried out [11]. Water availability was throughout the crop cycle ensured. Pest and weed control were carried out effectively. Fertilization was by applying K_2O and P_2O_5 at the time of sowing carried out, at a rate of 60 kg ha^{-1} of both; 100 kg ha^{-1} of nitrogen was also applied, fractionated during the crop cycle, applying 25 % of the total in each fertilization. Triple superphosphate (46 % P_2O_5), potassium chloride (60 % K_2O) and urea (46 % N) were used as carriers [11].

Collection of data

The duration in days of the three phenological phases of the culture was evaluated in each experimental plot. The rice plant has three main vegetative phases: the vegetative phase, comprises the days elapsed from emergence to the cotton point; the reproductive phase, from the cotton point until the anthesis stage ends; and maturation, from anthesis to the maturity of the grain. Each phase was identified when more than 50 % of the experimental plot showed the characteristics of these stages.

The determination of the agricultural yield and its components (number of panicles per m^2, number of grains per panicle, percentage of empty grains and mass of 1000 grains) was carried out in each experimental plot. An area of 1 m^2 was taken, with two replications in each replica and the values were expressed in t ha^{-1}, at 14 % grain moisture. For panicles per m^2, the counting method was used in an area of 0.50 m^2, with four repetitions per plot. For the number of grains per panicle, 20 panicles were taken at random. These were shelled, the empty grains were separated from the filled ones and they were counted. For the mass of 1000 grains, two samples were taken per plot of 1000 filled grains, which were weighed on an analytical balance.

Preparation of input files

Six input files were created to run the CERES-Rice model inserted in DSSAT v4.6: file X, file A, file T, soil file, climate file and genetic coefficients file.

Files A and T stored the values of the physiological variables observed in the experiments and subsequently compared them with the values simulated by the model for calibration.

File X stored field conditions, experimental treatments and simulation options. Most of this file is the management data of crop production, separated into several sections.

The soil in the area where the experiments were carried out is classified as Hydromorphic Gley Nodular Ferruginous Petroleum, according to the Cuban Soil Classification 2015 (12).

For the preparation of the climate file, the values of the meteorological variables (maximum and minimum temperatures and daily rainfall) of the months in which the experiments were carried out, obtained from the Paso Real de San Diego Meteorological Station in Los Palacios, were used about 3 km from the experimental area.

Calibration of the model

The CERES – Rice model for DSSAT needs to be calibrated by obtaining eight genetic coefficients (P1, P2O, P2R, P5, G1, G2, G3 and G4). The P coefficients are those that consider phenological aspects of the crop, such as flowering and maturation. The G coefficients are to the potential yield of a specific variety related (13) (Table 2).

Table 2. Description of the CERES-Rice genetic coefficients

Coefficient	Definition
P1	Degrees days of accumulated heat from seedling emergence during which the rice plant does not respond to changes in the photoperiod.
P2O	Critical photoperiod or the longest duration of the day in which development occurs at maximum speed.
P2R	Degree to which the phasic development leading to the initiation of the panicle is for each hour of increase delayed in the photoperiod above P2O.
P5	Degrees days of accumulated heat from the beginning of grain filling until physiological maturity.
G1	Number of spikelets, potential estimated from the number of spikelets per gram of dry weight of the main culm in anthesis.
G2	Weight of a grain under ideal growing conditions, that is, light, water and non-limiting nutrients and absence of pests and diseases.
G3	Relative tillering coefficient when cultivating IR64 under ideal conditions.
G4	Temperature tolerance coefficient, usually 1.0 for varieties grown in normal environments.

Source: Own elaboration with information taken from (14)

The calculation of the degrees days of accumulated heat (GDCA) (Equation 1) was carried out taking into account the duration of the phenological phases reached by the crop on the different planting dates and the temperature records, by adding the degrees days heat (GDC) [15].

$$GDCA = \sum \frac{Tmax - Tmin}{2} - Tbase \quad [1]$$

where: *Tmax* is the maximum daily air temperature; *Tmin* is the minimum daily air temperature and *Tbase* is the base temperature in which the process of interest does not take place and in this case, it was taken at 9 ºC.

The coefficients were adjusted by the manual method of trial and error until the $RMSEn$ less than 5 % was achieved between the values observed in the experiments and those simulated by the model, on the dates of anthesis and physiological maturity, mass of 1000 grains and grain yield [14].

$RMSE$ and d-index were also calculated [16], with the following equations (Equations 2, 3 and 4):

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(Si - Oi)^2}{n}} \quad [2]$$

$$RMSEn = 100 * \frac{\sqrt{\sum_{i=1}^{n} \frac{(Si - Oi)^2}{n}}}{\overline{Ob}} \quad [3]$$

$$d = 1 - \frac{\sum_{i=1}^{n} (Si - Oi)^2}{\sum_{i=1}^{n} (|Si - \overline{Ob}| + |Oi - \overline{Ob}|)^2} \quad [4]$$

where: Si and Oi - simulated and observed values, n is the number of observations; if $\overline{Ob}$ – mean of the Oi values.

It is feasible to use the above equations, since $RMSE$ a useful tool to test the goodness of fit of simulation models and represents a global measure between observed and simulated values; the value closest to zero indicates good performance in the simulation [17].

RMSEn was used to give a percentage measure of the relative difference between simulated and observed values on anthesis and physiological maturity dates, 1000 grain mass, and grain yield. A simulation can be considered Excellent if the *RMSEn* is less than 10 %, Good if it is between 10 and 20 %, Reasonable if it is between 20 and 30 % and Bad if it is greater than 30 % (18). It is proposed that d must be close to one (16).

Simulation

To carry out the simulations, the file of the experiment carried out in January 2004 was, taken and entered into the seasonal analysis tool included in DSSAT. The sensitivity analysis of the grain yield to the application levels of nitrogen fertilizer was carried out creating six experiments where the fertilizer doses were varied from 150 to 200 kg ha^{-1} of nitrogen with an interval of 10 kg ha^{-1} of nitrogen and the other model parameters were kept constant as defined in the calibration.

For the simulation with the different nitrogen do5ses, the phenological phases of the fourth leaf, start of tillering, active tillering and cotton point were selected and the percentage of the fractionations were calculated from the dose recommended in the Technical Instructions for Rice (19) to obtain a yield of 6 t ha^{-1}.

The model run was performed to obtain the grain yield values for these experiments and they were compared to determine the best of them.

RESULTS AND DISCUSSION

Calibration

The values of the genetic coefficients that determine the vegetative and reproductive growth for the variety J-104 are presented in Table 3. These summarize, quantitatively, how a particular variety responds to environmental factors. The determined values are in the range of values described in the CERES-Rice User Manual (20).

Table 3. Values of the genetic coefficients for the variety J-104

P1 (ºC)	P2O (h)	P2R (ºC)	P5 (ºC)	G1 (spikelets per gram)	G2 (g)	G3	G4
600.0	10.00	200.4	350.5	45.11	0.025	1.00	1.129

Source: Own elaboration

Table 4 shows the comparison of the observed and simulated values, in terms of grain yield, 1000 grain mass, days before anthesis and days at maturation, as well as the indicators of goodness of fit of the model. The predicted grain yields were in agreement with those observed with $RMSE$ = 97.66 kg ha^{-1} and d = 0.98. Similar behavior had the values of the days before anthesis and the days at maturation with $RMSE$ = 5.32 days and 6.2 days respectively, with d = 0.66 and 0.87 respectively. It is valid to highlight that although d is below 0.9, there are authors who consider these values as satisfactory (4,14). In all the cases evaluated, the *RMSEn* behaved with values less than 10 %, which shows the excellence of the simulations carried out by the model.

Other authors reported a higher *RMSE* value (305.2 kg ha^{-1}), compared to that obtained in this investigation, for the yield of the LP-5 rice variety in the town of Los Palacios, Cuba (4). In Northwest India, the absolute *RMSE* for both anthesis and maturity was 6 days and the d-index was 0.72 and 0.96 for anthesis and maturity dates, respectively, that agrees with the results of this investigation (21).

Table 4. Goodness of fit indicators for yield, 1000 grain mass, days before anthesis and days at physiological maturation

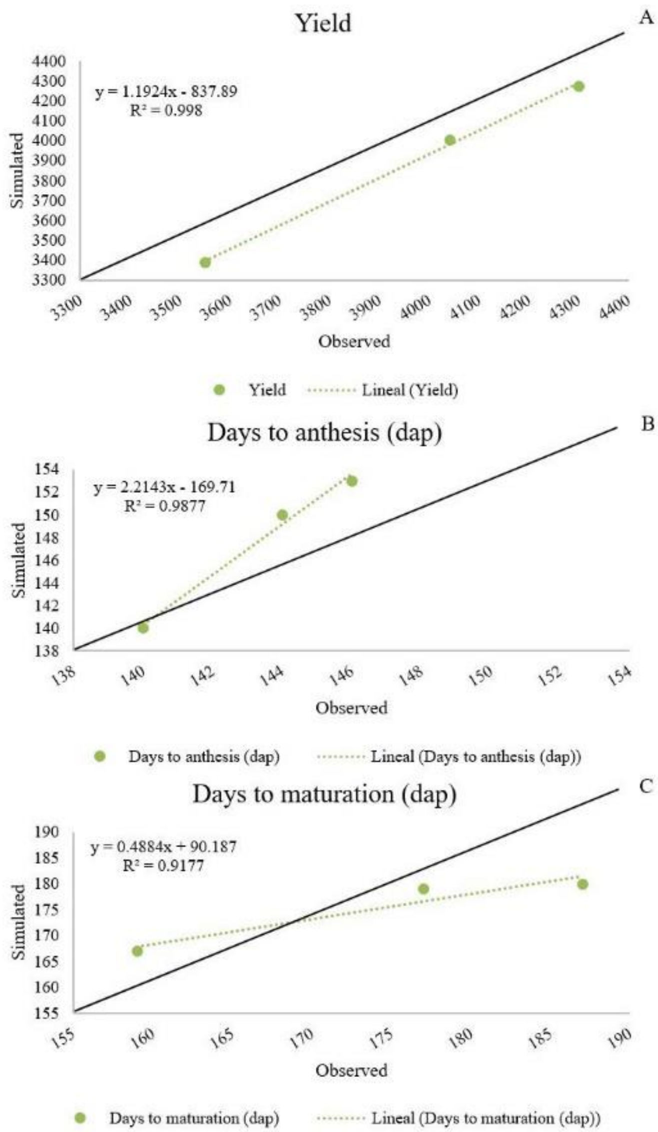
	Yield (kg ha^{-1})		**Mass of 1000 grains (g)**		**Days before la anthesis (dap)**		**Days to maturation (dap)**	
Experiment	Oi	Si	Oi	Si	Oi	Si	Oi	Si
January 2004	3550	3387	25.0	25.0	140	140	159	167
December 2004	4300	4274	25.0	25.0	144	150	177	179
February 2005	4042	4005	25.0	25.0	146	153	187	180
$\boldsymbol{RMSE}$		97.663		0		5.323		6.245
$\boldsymbol{RMSEn}$ (%)		2.46		0		3.71		3.58
D		0.98		-		0.66		0.871

Si Simulated values and Oi – observed values

Source: Own elaboration

Figure 1 shows the behavior of the observed and simulated values on the line (1: 1) and the determination coefficient (R^2). It can be seen that the models are of good fit since R^2> 90 % in all cases, which also confirms that the predicted values are very similar to those observed.

In general, the model underestimated the average yield obtained and overestimated the observed values for days before anthesis and days at maturation. These differences in the average estimates of the parameters studied are quite small and support the good statistical metrics presented in this study.



dap: days after planting

Source: Own elaboration

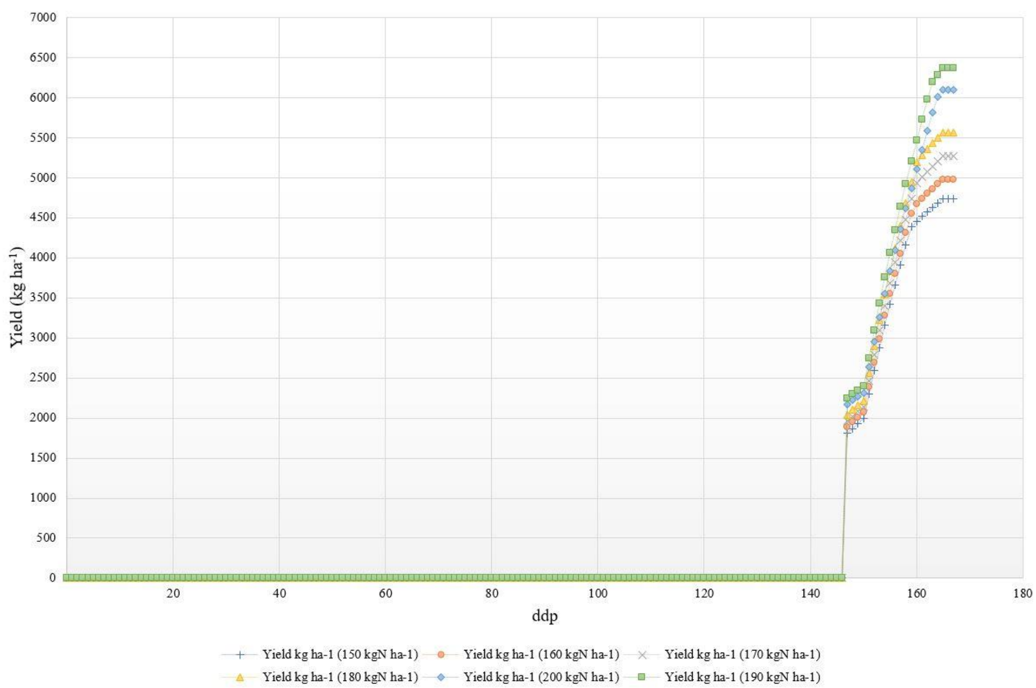
Figure 1. Behavior of the observed and simulated values for yield (a), days before anthesis (b) and days at maturation (c)

Therefore, the results of this study suggest that the DSSAT model can be used to calculate genetic coefficients with a considerable degree of precision to model the performance of the J-104 rice variety, in the dry season, and its physiological components in Cuba.

Simulation

Figure 2 shows the performance behavior of the variety J-104 rice for the six nitrogen doses used in the simulations. The highest yield value was obtained for the dose of 200 kg ha^{-1} of nitrogen with 6363 kg ha^{-1}, achieving an efficiency of 31.8 kg of rice per kg of nitrogen applied. This yield was 1627 kg ha^{-1} higher than the 150 kg ha^{-1} nitrogen variant, which achieved the lowest yield.

Therefore, the results of this study suggest that the model DSSAT can be used to calculate genetic coefficients with a considerable degree of precision to improve the yield of the J-104 rice variety, in the little rainy season and its physiological components in Cuba.



Source: Own elaboration

Figure 2. Simulated yield for the different nitrogen doses

Studies carried out show that the nitrogen level influences significantly the agricultural yield and its components, since the varieties IACuba28 and J-104 showed the highest response with the maximum applied level, 140 and 180 kg ha^{-1} of nitrogen in the wet and dry campaigns, respectively [22]. An optimal dose of 225 kg ha^{-1} of nitrogen has also been reported when adjusting a quadratic model, varying the doses from 0 to 300 kg ha^{-1} of nitrogen [6].

CONCLUSIONS

- Obtaining the genetic coefficients of the J-104 rice variety allowed us to establish that the DSSAT model can be used to model the performance of rice and its physiological components under Cuban conditions.
- The model is able to adequately describe the dependence of the yields with the applied nitrogen level; obtaining the highest yield when using the dose of 200 kg ha^{-1} of nitrogen.

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