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Original Article

Calibration and evaluation of new irrigated rice cultivars in the SimulArroz model[1]

Calibração e avaliação de novas cultivares de arroz irrigado no modelo SimulArroz

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HIGHLIGHTS:

Adding irrigated rice cultivars to the SimulArroz model is vital to improve the robustness of new genetics and environments.
Calibrations predicted adequate growth, development, and yield for the 'BRS Catiana' and 'BRS Pampa' cultivars.
The SimulArroz model can also estimate phenological stages and grain yield in tropical conditions in Brazil.

ABSTRACT: Given genetical coefficients need to be calibrated for the most important cultivars on the market, new cultivars must be added to models such as SimulArroz. Thus, the aim of this study was to calibrate and evaluate the SimulArroz model for two new irrigated rice cultivars. The experiments were conducted in the municipality of Goianira in Goiás state during four growing seasons (2014/15, 2015/16, 2016/17, 2017/18) and in Rio Grande do Sul state in the municipalities of Alegrete (2015/16), Cachoeirinha (2015/ 16), Capão do Leão (2016/17, 2017/18), Santa Vitória do Palmar (2017/18) and Uruguaiana (2014/15, 2015/16). A randomized block design was used, with four replicates in Rio Grande do Sul and sowing plots in Goianira. The BRS Catiana and BRS Pampa cultivars were used and the Haun stage (HS), phenology, shoot dry matter biomass and yield were evaluated. The root mean square error (RMSE) for above-ground dry matter ranged from 51.7 to 577 g m^{-2}, and for yield, the normalized root mean square error (NRMSE) ranged from 24 to 32% and 22 to 35% for the potential and high technological levels, respectively. The SimulArroz model was able to satisfactorily predict the growth, development, and yield of the BRS Catiana and BRS Pampa cultivars, increasing their area of application, including the tropical region of Brazil.

Key words: *Oryza sativa* L., modeling, new cultivars, phenology

RESUMO: Os coeficientes genéticos precisam ser calibrados para as cultivares mais representativas do mercado, portanto, é necessário adicionar novas cultivares a modelos como o SimulArroz. Portanto, o objetivo deste estudo foi calibrar e avaliar o modelo SimulArroz para duas novas cultivares de arroz irrigado. Os experimentos foram conduzidos no município de Goianira em Goiás durante quatro safras (2014/15, 2015/16, 2016/17, 2017/18) e no Rio Grande do Sul nos municípios de Alegrete (2015/16), Cachoeirinha (2015/16), Capão do Leão (2016/17, 2017/18), Santa Vitória do Palmar (2017/18) e Uruguaiana (2014/15, 2015/16). O delineamento utilizado foi o de blocos casualizados, com quatro repetições no Rio Grande do Sul e com parcelas de semeadura em Goianira. Foram utilizadas as cultivares BRS Catiana e BRS Pampa, sendo avaliadas o estádio Haun (HS), fenologia, biomassa de matéria seca da parte aérea e produtividade. A raiz do erro quadrático médio (RMSE) para matéria seca aérea variou de 51,7 a 577 g m^{-2}, e para produtividade, a raiz do erro quadrático médio normalizado (NRMSE) variou de 24 a 32% e 22 a 35% para o potencial e alto nível tecnológico, respectivamente. O modelo SimulArroz foi capaz de prever satisfatoriamente o crescimento, desenvolvimento e produtividade para as cultivares BRS Catiana e BRS Pampa, aumentando sua área de aplicação e abrangendo também a região tropical do Brasil.

Palavras-chave: *Oryza sativa* L., modelagem, novas cultivares, fenologia

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Introduction

World rice (*Oryza sativa* L.) production has remained constant (785 million tons) over the last five years (USDA, 2023). In Brazil, the subtropical region is the largest producer of irrigated rice, while the tropical region accounts for 10% of national rice production, with an average yield of 6.4 Mg ha^{-1} (CONAB, 2023). Rice production in this region is essential for the food chain due to the important nutritional and energy value of this grain, favoring logistics and supply (Utumi et al., 2016). The growing demand for this cereal has prompted breeding programs to focus mainly on the development of higher-yielding cultivars (De Oliveira et al., 2020).

Tropical rice yields are lower due to less solar radiation and management difficulties, especially with regard to irrigation, high temperatures and diseases (e.g. rice blast) (Meus et al., 2020). Modeling is an essential tool to reduce the crop management productivity gap, since models reliably estimate the timing of a given stage, thereby improving management practices, and maximizing resource use.

In rice, SimulArroz is a process-based model developed and calibrated for irrigated rice cultivation conditions in Rio Grande do Sul state (RS). This tool estimates grain yield considering different technological levels, atmospheric CO_2 concentration and sowing times, and performs similarly to the ORIZA1 model, with the advantage of having fewer coefficients to calibrate (Duarte Junior et al., 2021). Furthermore, SimulArroz has been used in practical applications, such as rice yield forecasting and agricultural climate risk zoning for irrigated rice in RS (Silva et al., 2016; Steinmetz et al., 2019).

Calibrated and validated agricultural models are fundamental to direct research and decision-making in the development of public policies (Choruma et al., 2019). New rice cultivars are constantly being introduced and to date, the SimulArroz model has been calibrated and tested only for subtropical cultivars and environmental conditions (Ribas et al., 2016; 2017) As such, this study aimed to calibrate and evaluate the SimulArroz model for two new irrigated rice cultivars.

Material and Methods

Field experiments were conducted at six sites in Rio Grande do Sul (RS) and one in Goiás (GO), Brazil. In Goiás, the experiments were conducted by EMBRAPA Arroz e Feijão in Goianira (16° 29′ 45″ S; 49° 25′ 33″ W and altitude of 757 m); and in Rio Grande do Sul, at the research station of the Rio Grandense Rice Institute (IRGA) in Cachoeirinha (29° 57′ 3″ S; 51° 5′ 38″ W and altitude of 10 m) and the EMBRAPA research stations of Clima Temperado in Capão do Leão (31° 45′ 46″ S; 52° 29′ 2″ W and altitude of 21 m), Uruguaiana (29° 45′ 18″ S; 57° 5′ 16″ W and altitude of 66 m), Santa Maria (29° 41′ 2″ S; 53° 48′ 25″ W and altitude of 115 m), Alegrete (29° 47′ 2″ S; 55° 47′ 28″ W and altitude of 102 m), and Santa Vitória do Palmar (33° 31′ 8″ S; 53° 22′ 4″ W and altitude of 23 m). The two cultivars used in this study were 'BRS Pampa', an early-cycle cultivar with high yield potential, released in 2011 by EMBRAPA, and 'BRS Catiana', a medium-cycle cultivar with high yields in tropical and subtropical environments, released in 2016 by EMBRAPA (Rangel et al., 2019). These two cultivars are grown in commercial fields and are representative of irrigated rice production in Brazil (EMBRAPA, 2014).

In the experiments carried out in Cachoeirinha/RS, each plot measured 20 m by 13 m with a randomized block design, and to obtain grain yield, 20 m² were harvested from each plot and cultivar. In Goianira/GO, the experiments were performed in seeding rows using dry planting, and only the 2014/2015 growing season experiment used transplanting. For the 2016/2017 and 2017/2018 growing seasons in Goianira, different plot irrigation treatments were applied. The irrigation methods used were ICC (the traditional flooded irrigation performed throughout the cycle), SSC (a condition close to saturated soil above field capacity and below saturated soil), IIF (intermittent irrigation until flowering and after flooding, whereby irrigation is performed in the lack of or decreased irrigation depth), and IIC (intermittent irrigation throughout the cycle). The experiments conducted in Capão do Leão, Uruguaiana, Alegrete, and Santa Vitória do Palmar were Value for Cultivation and Use (VCU). A randomized block design with four replications was used. The plots consisted of nine 5-m-long rows, spaced 0.175 m apart.

Four plants were marked with colored tags one week after emergence in each experimental plot to better identify them throughout the crop cycle. The plants were assessed twice a week or every three days until leaf collar formation, depending on the experiment. The number of leaves on the main stem was determined according to the Haun scale (HS) (Haun, 1973).

The emergence date was established when at least 50% of the plants were above ground level. Assessments were carried out every 1 m in each plot until the number of plants stabilized. In R1 (panicle differentiation), plants were assessed when 50% of them reached this stage, by sampling ten plants in each plot using the destructive method. The 50% criterion s was also used to determine stages R4 (flowering or anthesis) and R9 (complete maturity of the panicle grains). Dry matter (DM) was collected by separating green leaves, senescent leaves, stems, and panicles in all experiments. After separation, the material was dried at 60 °C.

The SimulArroz model has several submodels that describe different development, growth, and grain yield processes (Rosa et al., 2015). The leaf appearance and phenology submodels are the "clock" model, and the growth submodel describes daily dry matter accumulation and partitioning.

To estimate LARmax 1.2 (maximum emergence rate of the first and second leaves) of the two cultivars, the least squares method was used, which consists of minimizing the difference between observed and simulated values. Next, the evolution of phenology was calibrated, using the DVS method. The sum total thermal (STT) was estimated for each developmental stage from sowing until emergence (STTEM), emergence to panicle differentiation (STTVG), panicle differentiation to anthesis (STTRP) and anthesis to physiological maturity (STTEG).

The two rice cultivars used exhibit similar growth habits (semi-dwarf indica genotypes), such as the cultivars in version 1.1 of the SimulArroz model (Duarte Junior et al., 2021), and only the leaf appearance and phenology submodels were

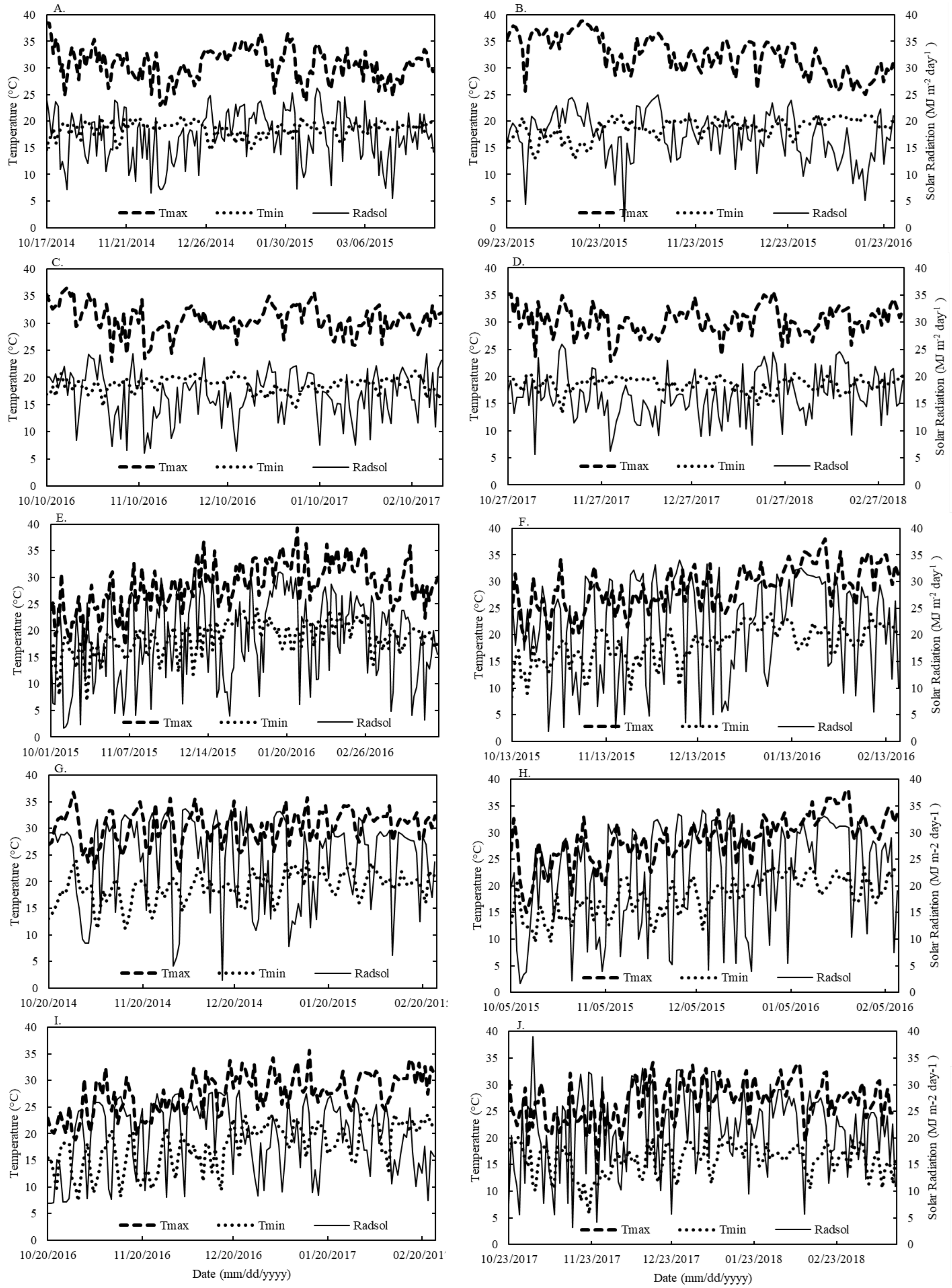


Figure 1. Minimum (Tmin) and maximum air temperature (Tmax) and incident solar radiation (Radsol) in each growing season for the irrigated rice experiment, in Goianira (A), (B), (C) and (D), Cachoeirinha (E), Alegrete (F), Uruguaiana (G) and (H), Capão do Leão (I) and (J)

calibrated. Calibration used the Haun Stage (Table 1) and phenology data from the experiments in Cachoeirinha/RS in the 2015/16 growing season, with a cross-validation approach (Table 2).

To calculate phenological progress in SimulArroz, that is, the developmental stage (DVS), the following equation was used:

$$DVS = \frac{STa}{STT}$$

where STa is the accumulated daily thermal sum (°C day) and STT the total thermal sum (°C day) to complete the phase. STa is calculated by (Streck et al., 2008):

$$STa = (T - Tb)1day \text{ when } Tb < T \leq Tot \text{ and if } T < Tb \text{ then } TTa = 0$$

$$STa = [(TB - T)(Tot - Tb)/(TB - Tot)]1day \text{ when } Tot < T \leq TB\text{, and if } T > TB \text{ then } STa = 0$$

where Tb, Tot, and TB are the lower basal, optimal and upper basal cardinal temperatures, respectively. These cardinal temperatures will vary according to the developmental stage during the crop cycle, with Tb =11, Tot = 30 and TB = 40°C for the sowing - emergence and emergence - panicle differentiation stages, Tb = 15°C, Tot = 25°C and TB = 35°C for panicle differentiation – anthesis, and Tb = 15°C, Tot = 23°C and TB = 35°C for anthesis -physiological maturity (Streck et al., 2011). STT is calculated by STT = ∑Sta.

The performance of the SimulArroz model for the two rice cultivars was similar to that of the other field experiments in RS and GO, which are independent data. The following statistics were used to evaluate the SimulArroz model: root mean square error (RMSE) (Janssen & Heuberger, 1995): RMSE = $[\sum(Si-Oi)^2/n]$ 0.5 , where Si are the simulated values, Oi the observed values and n the number of comments. The normalized RMSEn was calculated using the following equation (Janssen & Heuberger, 1995): RMSEn=100.RMSE/ O, where O is the average of the observed values. The "dw" index was calculated by (Borges & Mendiondo, 2007, Samboranha et al., 2013): dw = $1 - \sum(Si - Oi)^2 / [(|Si - O|) + (|Oi - O|)]^2$. The r value was calculated by (Borges & Mendiondo, 2007, Samboranha et al., 2013): r = $\sum(Oi - \bar{O})(Si - S)\{[\sum(Oi - \bar{O})^2][\sum(Si - S)^2]\}^{0.5}$, where Si are the simulated values, S the mean of the simulated values, Oi the observed values and Ō the mean of the observed values.

Results and Discussion

The genetic coefficients of the leaf appearance and phenology submodels for the two new rice cultivars in the SimulArroz model are presented in Table 3. The $LAR_{max1.2}$ (maximum emergence rate of the first and second leaves) is higher for 'BRS Catiana' and lower for 'BRS Pampa', indicating a higher leaf emergence rate for the former. The thermal time for the sowing-emergence stage was similar in both cultivars. For the vegetative stage, 'BRS Catiana' required a longer thermal time. In general, cultivars with longer vegetative stages produce a leaf area for longer periods, thereby favoring greater photoassimilate accumulation in the stem, which can then be translocated to grain filling. The total thermal time of the cultivar cycles were 1038 and 913 °C days for 'BRS Catiana'

Table 1. Rice cultivars, locations, and sowing dates of the irrigated rice experiments used to calibrate and evaluate leaf emission in the SimulArroz model (independent data)

Cultivar	Calibration				Evaluation			
	Location	Sowing date	Anthesis date	Maturity date	Location	Sowing date	Anthesis date	Maturity date
'BRS Catiana'	Cachoeirinha	12/03/2015	03/02/2016	04/07/2016	Uruguaiana	09/21/2019	-	-
					Santa Maria	01/08/2020	-	-
'BRS Pampa'	Cachoeirinha	11/09/2015	02/01/2016	03/03/2016	Cachoeirinha	10/01/2015	01/12/2016	02/05/2016

Table 2. Rice cultivars, locations, and sowing dates of the irrigated rice experiments used to calibrate and evaluate the SimulArroz model

Cultivar	Calibration				Evaluation			
	Location	Sowing date	Anthesis date	Maturity date	Location	Sowing date	Anthesis date	Maturity date
BRS Catiana	Goianira	27/10/2017			Goianira	10/17/2014	01/30/2015	02/27/2015
						11/28/2014	03/10/2015	04/08/2015
						10/10/2016	01/17/2017	02/20/2017
						09/23/2015	12/22/2015	01/26/2026
						10/27/2017	02/03/2018	03/07/2018
BRS Pampa	Cachoeirinha	11/09/2015	02/01/2016	03/03/2016	Cachoeirinha	10/01/2015	01/12/2016	02/05/2016
						12/03/2015	02/22/2016	03/27/2016
					Capão do Leão	10/20/2016	01/26/2017	02/24/2017
						10/23/2017	01/27/2018	02/27/2018
						11/01/2017	02/04/2018	03/05/2018
						10/28/2017	02/04/2018	03/03/2018
						11/08/2017	02/09/2018	03/17/2018
					Alegrete	10/13/2015	01/18/2016	02/20/2016
					Uruguaiana	10/20/2014	01/19/2015	02/21/2015
						10/05/2015	01/14/2016	02/16/2016
					Santa Vitória do Palmar	11/21/2017	02/21/2018	03/25/2018

Table 3. Calibrated genetic coefficients of leaf appearance and phenology in the SimulArroz model for two irrigated rice cultivars

Coefficient[1]	Unit	Cultivars	
		'BRS Catiana'	'BRS Pampa'
LARmax1.2	Leaves day	0.37	0.27
STTEM	°C day	110.61	88.90
STTVG	°C day	718.90	596.30
STTRP	°C day	115.00	107.50
STTEG	°C day	93.50	120.60

[1]$LAR_{max1.2}$ - Maximum emergence rate between the first and second leaves (leaves day); GD – Degrees day (°C day); STTEM - The total heat sum needed to complete the emergence stage; STTVG - The total heat sum needed to complete the vegetative-panicle differentiation stage; STTRP - The total heat sum required to complete the panicle-anthesis differentiation stage; STTEG - The total heat sum needed to complete the anthesis-physiological maturity stage

and 'BRS Pampa', respectively, indicating a difference in cycle length between the two cultivars in the vegetative period.

The predicted HS had an RMSE between 0.4 and 0.7 leaves on the main stem (Table 4). The highest RMSE occurred in 'BRS Catiana' in Uruguaiana. Similar results were reported by Streck et al. (2008), who observed an RMSE range between 0.6 and 0.9 leaves and Ribas et al. (2017), who found a range between 0.6 and 1.9 leaves for conventional and hybrid cultivars, respectively. The BIAS index ranged from -0.032 to 0.031, indicating good model accuracy. Based on these findings, the SimulArroz model satisfactorily simulates the number of leaves in both cultivars.

For the phenology of 'BRS Pampa', the RMSE varied from 5.8 to 7.9 days (Table 5). The BIAS index was negative at all locations for 'BRS Pampa', indicating slight underestimation of the model for the experiments. For the phenology of 'BRS Catiana', the RMSE ranged from 4.6 to 9.1 days, and the best model performance in terms of predicting the phenological stages occurred under the experimental conditions of Goianira/GO (Table 5), where this cultivar is one of the most produced. Pooling of all developmental stages and cultivars showed that the average RMSE varied from 5.2 to 7.1 days. These values are close to the 3 to 8-day RMSE reported by Ribas et al. (2020) when validating the 'IRGA 424 RI', 'Puitá INTA CL', and 'Guri INTA CL' cultivars in the SimulArroz model. The SimulArroz model also revealed an RMSE of 4.9 to10 days in the calibration of the IRGA 424 cultivar for Argentina (Meus et al., 2022). In Italy, Mongiano et al. (2019) found an RMSE

Table 4. Statistical indices for evaluating the performance of the SimulArroz model in simulating the Haun stage for two irrigated rice cultivars in Santa Maria, Uruguaiana, and Cachoeirinha in the 2015/2016 and 2019/2020 growing seasons

Location	Indices	'BRS Catiana'	'BRS Pampa'
Santa Maria	RMSE	0.47	-
	BIAS	0.03	-
	AI	0.99	-
	r	0.98	-
Uruguaiana	RMSE	0.79	-
	BIAS	0.03	-
	AI	0.77	-
	r	1.00	-
Cachoeirinha	RMSE	-	0.43
	BIAS	-	0.03
	AI	-	0.99
	r	-	0.99

RMSE - Root mean square error (leaves on the main stem); BIAS - BIAS index; AI - agreement index, r - Pearson's correlation coefficient

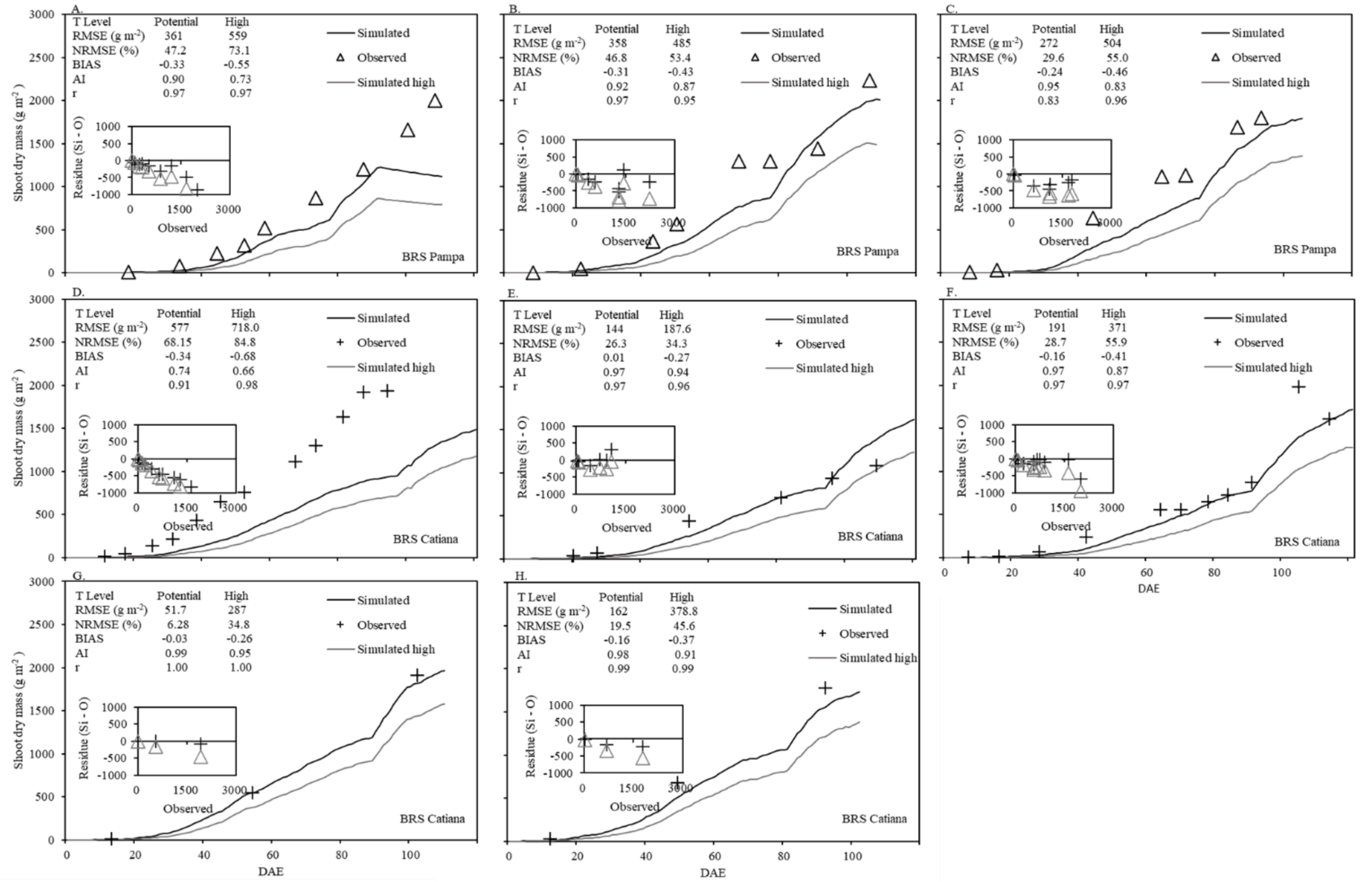
Table 5. Statistical indices of SimulArroz performance in simulating panicle differentiation (R1), anthesis (R4), and complete maturity of panicle grains (R9) for the 'BRS Catiana' and 'BRS Pampa' cultivars in Alegrete, Cachoeirinha, Capão do Leão, Santa Vitória do Palmar, Uruguaiana, and Goianira

Location	Indices[1]	'BRS Catiana'	'BRS Pampa'
Uruguaiana	RMSE	-	5.83
	BIAS	-	-0.6
	AI	-	0.99
	r	-	0.99
Alegrete	RMSE	-	7.87
	BIAS	-	-0.08
	AI	-	0.99
	r	-	0.99
Cachoeirinha	RMSE	9.12	5.96
	BIAS	0.12	-0.06
	AI	0.99	0.99
	r	0.99	0.99
Capão do Leão	RMSE	-	7.79
	BIAS	-	-0.06
	AI	-	0.99
	r	-	0.99
Goianira	RMSE	4.64	-
	BIAS	-0.01	-
	AI	0.99	-
	r	0.99	-
Santa Vitória do Palmar	RMSE	-	6.62
	BIAS	-	-0.05
	AI	-	0.99
	r	-	1
All locations	RMSE	5.26	7.13
	BIAS	0.01	-0.06
	AI	0.99	0.99
	r	0.99	0.99

[1]RMSE - Root mean square error (days); BIAS - BIAS index; AI - agreement index; r - Pearson's correlation coefficient

between 5.5 to 7.1 days for the R1 and R9 stages using the WOFOST_GT model. With the Oryza2000 model, the RMSE ranged from 3 to 10 days between flowering and physiological maturity (Van Oort et al., 2011).

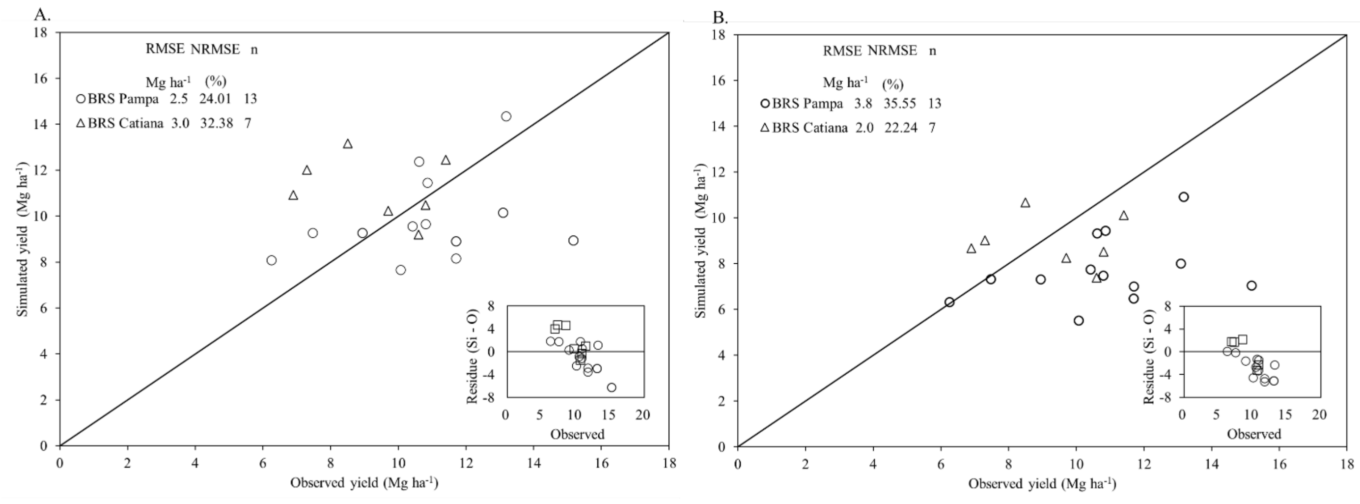
Knowing and understanding plant growth and DM accumulation in the different plant organs is essential to estimate yield using process-based models (Meus et al., 2020). Thus, plant DM production was validated at two technological levels (potential and high) in the SimulArroz model (Ribas et al., 2020). The highest RMSE for above-ground dry matter was found for 'BRS Catiana' in the 2015/2016 growing season in Goianira/GO, namely, 577 g m^{-2} in the potential technological level and 718 g m^{-2} for its high technological counterpart (Figure 2). The greater difference between observed and simulated data for the 2015/2016 growing season also occurred for grain yield, which is attributed to soil variability in the experimental area. The best SimulArroz model performance occurred in the 2016/2017 and 2017/2018 growing seasons, with RMSE below 200 g m^{-2} for the potential level and NRMSE below 30% (Figure 2). The above-ground DM was similar to that of Ribas et al. (2020), who found an NRMSE of 30% for 'Guri INTA CL' and 38% for 'IRGA 424 RI'. A comparison between the simulated and experimental data at the potential and high technological levels indicates the SimulArroz sensitivity for different production environments. In general, the model was able to estimate DM production dynamics in different environments.



The insets in each panel are the residuals (simulated-observed) versus the observed values and model performance (RMSE - Root mean square error (days); NRMSE – Normalized root mean square error BIAS - BIAS index; AI - agreement index; r - Pearson's correlation coefficient). Black lines represent simulation with the SimulArroz model at the potential technological level and the gray lines at a high technological level

Figure 2. Observed (dots) and simulated (solid lines) above-ground dry matter (DM) using the SimulArroz model for the 'BRS Pampa' in Cachoeirinha/RS (A, B, and C) and 'BRS Catiana' in Goianira (D, E, and F) and Cachoeirinha/RS (G and H) as a function of days after emergence (DAE)

The yield of the SimulArroz model (Table 2) was assessed by running it in four locations in RS (Alegrete, Cachoeirinha, Capão do Leão, and Uruguaiana) using 'BRS Pampa' and two locations (Cachoeirinha and Goianira) for 'BRS Catiana'. In the model at the potential technological level, RMSE ranged from 2.5 to 3.0 Mg ha^{-1} and NRMSE from 24.01('BRS Pampa') to 32.38% ('BRS Catiana') (Figure 3A). For the simulations at the high technology level, a better representation of the simulated yields was observed with 'BRS Catiana', with RMSE of 2.0 Mg ha^{-1} and NRMSE of 22.24% (Figure 3B). Arumugam



RMSE - Root mean square error (days); NRMSE - Normalized root mean square error; Si - Yield simulated by the model; O - Observed yield in the experiments

Figure 3. Simulated and observed yield for two rice cultivars ('BRS Catiana' and 'BRS Pampa') in Alegrete/RS, Uruguaiana/RS, Capão do Leão/RS, and Cachoeirinha using 'BRS Pampa' and Cachoeirinha/RS and Goianira/RS for 'BRS Catiana'. The observed data were obtained in experiments in five growing seasons (2014/2015, 2015/2016, 2016/2017, 2017/2018, and 2018/2019). Simulated data represent the potential (A) and high (B) technological levels of the SimulArroz model

et al. (2020) reported NRMSE above 35% for yield with the Ceres-Rice/DSSAT model in India. In China, Tang et al. (2009) noted differences between observed and simulated yields using the RiceGrow and ORYZA2000 models, with yields ranging from 0.6 to 9.6 and 5.7 to 10.9 Mg ha^{-1}, respectively. Given the data obtained here, the SimulArroz model satisfactorily simulates grain yields.

The particularities of the Brazilian tropical environment do not favor productive potential comparable with the southernmost areas of the country. One of the issues that most hampers high yields is the amount of solar radiation that reaches these areas, as demonstrated by meteorological data (Figure 1). Low solar radiation reduces the number of reproductive drains in the reproductive stage (Liu et al., 2014), and in the grain-filling stage increases the number of empty grains per panicle and favors a lower grain weight (Wang et al., 2013).

According to meteorological data, the highest temperatures for the experiments in this study occurred mainly in Goianira in the 2015/16 harvest. Temperature directly affects crop development throughout the cycle. In the grain-filling stage, high temperatures accelerate the filling rate, thereby compromising the panicle-filling process, resulting in lower grain weight and yield (Liu et al., 2013). These situations explain lower grain yields in Goianira than in Rio Grande do Sul, highlighting the importance of calibrating new cultivars in the SimulArroz model, with new updates as new genetics are launched onto the Brazilian rice market.

Conclusions

1. The SimulArroz model was calibrated and evaluated to simulate the number of leaves on the main stem, phenology, above-ground dry matter, and yield for two new cultivars.

2. The model satisfactorily predicted the grain growth, development, and yield of the 'BRS Catiana' and 'BRS Pampa' cultivars, increasing their area of application, including the tropical region of Brazil.

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