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Number of leaves and phenology of rice hybrids simulated by the SimulArroz model

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ABSTRACT

Process-based-models can predict leaf and reproductive development of agricultural crops. The objective of this study was to calibrate and evaluate the SimulArroz model in simulating the number of leaves on the main culm and the phenology of three hybrid rice cultivars in Rio Grande do Sul, Brazil. Field experiments were conducted in Santa Maria, Cachoeirinha, Uruguaiana and Santa Vitória do Palmar, in Rio Grande do Sul state, in two growing seasons. Observations were made to determine the number of leaves in the main culm through the Haun scale and the phenology of three hybrid cultivars (PRIME CL, INOV CL and QM 1010 CL) and a conventional rice cultivar used as a control (IRGA 424). The calibration of the SimulArroz model was efficient for simulating the number of leaves and phenology as a function of the sowing date and maturity group of three hybrid rice cultivars in Rio Grande do Sul.

Palavras-chave:

Oryza sativa
escala de Haun
soma térmica

Número de folhas e fenologia de híbridos de arroz simulado pelo modelo SimulArroz

RESUMO

Modelos matemáticos baseado em processos podem prever o desenvolvimento folhar e reprodutivo de cultivos agrícolas. Objetivou-se, com este trabalho, calibrar e avaliar o modelo SimulArroz em simular o número de folhas e a fenologia de três cultivares de arroz híbrido no Rio Grande do Sul. Foram conduzidos experimentos de campo em Santa Maria, Cachoeirinha, Uruguaiana e Santa Vitória do Palmar, no Rio Grande do Sul, em dois anos agrícolas. Foram realizadas observações para determinar o número de folhas do colmo principal através da escala da Haun e a fenologia de três cultivares híbridas (PRIME CL, INOV CL e QM 1010 CL) e uma convencional de arroz usada como testemunha (IRGA 424). A calibração do modelo SimulArroz utilizada foi eficiente em simular o número de folhas e a fenologia em função da época de semeadura e do grupo de maturação de três cultivares híbridas de arroz irrigado no Rio Grande do Sul.



INTRODUCTION

Brazil is the ninth largest rice producer in the world (USDA, 2016). The Brazilian production is approximately 12 Mt and the South region is responsible for 76%, while the state of Rio Grande do Sul (RS) is the largest producer, with 70% of the national production (CONAB, 2016). Annually, the RS state cultivates 1.1 million ha with irrigated rice; thus, it is one of the crops that represent a significant part of the gross national product, generated by the agricultural sector (CONAB, 2016). Hybrid cultivars are the most productive, for producing more per unit of area, due to the heterosis (Cantrell, 2003), which allows to reach yields 20 to 30% higher than those of conventional cultivars (Li & Yuan 2000; Coimbra et al., 2006).

In the agricultural sector, for reliability and applicability, there is the necessity to develop models adapted and tested in different environments (Streck et al., 2008; 2011). After tested, the agricultural models have multiple applications, because they can predict growth, development and yield of the crop as a function of the meteorological conditions during the growth season (Shin et al., 2006; 2010). The SimulArroz model is a dynamic ecophysiological process-based model that simulates growth, development and yield of irrigated rice. This model differs from the others for having been adapted for cultivars in the flood irrigation system in RS (Streck et al., 2011; Walter et al., 2012). The SimulArroz model contains a "biological clock" that controls growth and development by calculating the production of leaves and the phenology of the crop (Streck et al., 2008; 2011). In the current version of the SimulArroz (version 1.0), there is no option for hybrids, which is a limitation, as hybrid rice has been cultivated in RS since 2002 and currently has an area of approximately 68 thousand ha (IRGA, 2015). This study aimed to calibrate and evaluate the SimulArroz model in simulating the number of leaves and phenology of three hybrid rice cultivars in Rio Grande do Sul.

MATERIAL AND METHODS

Experiments were conducted in Santa Maria (29° 43' S, 53° 43' W), from October 2013 to February 2014 and from October 2014 to March 2015, at the research stations of the Rice Institute of Rio Grande do Sul (IRGA) of Cachoeirinha (29° 57' S, 51° 5' W), Uruguaiana (29° 32' S, 53° 20' W) and Santa Vitória do Palmar (33° 50' S, 57° 4' W) in RS, from October 2014 to March 2015.

The sowing dates of the experiments encompassed the period recommended for the crop in RS (early September until mid December) (Table 1). The density was 40 kg ha⁻¹ for the hybrids PRIME CL and QM 1010 CL, and 50 kg ha⁻¹ for INOV CL, due to the genetic characteristic of lower tillering (Peske et al., 2004). Besides the hybrids, a conventional cultivar was also used at the density of 100 kg ha⁻¹ as a control (Table 1). The conventional cultivar IRGA 424 (medium maturity group) was selected because it is recommended for all rice-growing regions of RS and also for showing higher yield among the conventional cultivars, because its productive potential is close to that of hybrid cultivars (SOSBAI, 2014).

The spacing between rows was 0.17 m in all locations. The size of the plot for each cultivar was 17 x 17 m in Santa Maria,

Table 1. Rice hybrids, locations and sowing dates of the experiments of flood-irrigated rice used for the calibration and evaluation (independent data) of the submodels of leaf appearance and phenology in SimulArroz model

Hybrid ⁽¹⁾	Calibration		Evaluation	
	Location	Sowing date	Location	Sowing date
PRIME CL	Uruguaiana	Oct 24, 2014	Santa Vitória do Palmar	Oct 21, 2014
			Cachoeirinha	Oct 27, 2014
INOV CL	Santa Maria	Dec 03, 2013	Santa Maria	Oct 28, 2014
			Santa Vitória do Palmar	Oct 21, 2014
			Cachoeirinha	Oct 27, 2014
QM 1010 CL	Santa Maria	Dec 03, 2013	Santa Maria	Oct 28, 2014
			Santa Vitória do Palmar	Oct 21, 2014
			Cachoeirinha	Oct 27, 2014

⁽¹⁾INOV CL and PRIME CL - Early cycle (106 to 120 d); QM 1010 CL - Medium cycle (121 to 135 d)

1.57 x 47 m in Cachoeirinha, 1.53 x 5 m in Santa Vitória do Palmar and in Uruguaiana. The experimental design in Santa Vitória do Palmar and in Uruguaiana was randomized blocks with 4 replicates. In Santa Maria and Cachoeirinha, there was no experimental design and samplings were performed according to the methodology described by Gabriel et al. (2014).

Leaf production and phenology were weekly evaluated (in Santa Maria and Cachoeirinha) and biweekly evaluated in the other locations in plants that were identified in the V2/V3 stage of the scale of Counce et al. (2000). These plants were evaluated for number of leaves in the main culm through the Haun scale, HS (Haun, 1973), which is calculated as follows:

$$HS = NL + \frac{L_{last}}{L_{pnult}} \quad (1)$$

where:

HS - number of leaves in the main culm;

NL - number of expanded leaves in the main culm;

L_{last} - length of the last leaf (without the formed collar); and,

L_{pnult} - length of the penultimate leaf (last one with formed collar), both in centimeters (cm).

Panicle differentiation (R1) was determined through the destructive sampling of 10 plants and the R1 date occurred when 50% of the plants were in this development stage. Marked plants were observed to identify the dates in which 50% of the plants were in anthesis (R4) and physiological maturity (R9) (Counce et al., 2000).

The daily rate of leaf production in the main culm in the SimlArroz model was calculated according to Streck et al. (2003):

$$LAR = LAR_{max1,2} f(T) f(C) \quad (2)$$

where:

LAR - leaf appearance rate (leaves d⁻¹);

$LAR_{max1,2}$ - maximum rate of appearance of the first and second leaves (leaves d⁻¹);

$f(T)$ - LAR response function with respect to air temperature, with cardinal temperatures for leaf production equal to 11 °C (Ellis et al., 1993; Infeld et al., 1998), 26 °C (Ellis et al., 1993) and 40 °C (Gao et al., 1992), respectively; and,

$f(C)$ - chronology function that causes LAR to decrease, from the third leaf on.

The cumulative number of leaves, represented by the Haun scale, is calculated as:

$$HS = \sum LAR \quad (3)$$

where:

HS - Haun stage (leaves in the main culm).

For the calculation of the progress of the phenology in SimulArroz, the development stage of the crop (DVS) was daily calculated as:

$$DVS = \frac{DTT}{TT} \quad (4)$$

where:

DTT - daily thermal time (°C day); and,

TT - total thermal time (°C day) to complete the stage.

The DTT is calculated according to Streck et al. (2011):

$$DTT = (T_{mean} - T_b) \cdot 1 \text{ day} \quad \text{if } T_b \leq T_{mean} \leq T_{opt} \quad (5)$$

$$DTT = (T_B - T_{mean}) \cdot \frac{(T_{opt} - T_b)}{(T_B - T_{opt})} \cdot 1 \text{ day} \quad \text{if } T_{opt} \leq T_{mean} \leq T_B \quad (6)$$

$$DTT = 0 \quad \text{if } T_{mean} < T_b \text{ or } T_{mean} > T_B \quad (7)$$

where:

T_b - lower base temperature;

T_{opt} - optimum temperature;

T_B - upper base temperature; and,

T_{mean} - mean daily air temperature.

The T_b , T_{opt} , and T_B vary according to the developmental phase, being $T_b = 11$ °C, $T_{opt} = 30$ °C and $T_B = 40$ °C for the Sowing-Emergence and Emergence-Panicle Differentiation Phases, $T_b = 15$ °C, $T_{opt} = 25$ °C and $T_B = 35$ °C for the Panicle Differentiation-Anthesis phase, and $T_b = 15$ °C, $T_{opt} = 23$ °C e $T_B = 35$ °C for the Anthesis-Physiological Maturity phase (Streck et al., 2011).

$$TT = \sum DTT \quad (8)$$

The DVS is -1 at sowing, zero at emergence, 0.65 at panicle differentiation (R1), 1 at anthesis (R4) and 2 at physiological maturity (R9).

The calibration of both submodels consisted in estimating the values of $LAR_{max1,2}$ (Eq. 2) and TTS (Eq. 10) for each hybrid, with data of experiments in Table 1. Both submodels were evaluated with independent data (Table 1).

Simulations were performed with the SimulArroz model for the cultivar IRGA 424, already available in the version 1.0, in order to compare the performance of the model in the

simulation of the hybrids with the conventional cultivar. The parameters of both submodels for the cultivar IRGA 424 in the SimulArroz model are: $LAR_{max1,2} = 0.347$ leaves d^{-1} , $TTEM = 50.0$ °C day, $TTVG = 644.3$ °C day, $TTRP = 153.0$ °C day, $TTEG = 112.78$ °C day.

The performance of both submodels in the SimulArroz model was evaluated using the following statistics: Root-mean-square error (RMSE), BIAS index, agreement index (dw) and Pearson's correlation coefficient (r).

RMSE was calculated according to Janssen & Heuberger (1995):

$$RMSE = \left[\frac{\sum (S_i - O_i)^2}{n} \right]^{0.5} \quad (9)$$

BIAS was calculated according to Samboranha et al. (2013):

$$BIAS = \frac{\sum S_i - \sum O_i}{\sum O_i} \quad (10)$$

The "dw" index was calculated according to Borges & Mendiondo (2007) and Samboranha et al. (2013):

$$d_w = 1 - \frac{\sum (S_i - O_i)^2}{\left[(\sum |S_i - \bar{O}|) + (\sum |O_i - \bar{O}|) \right]^2} \quad (11)$$

The "r" coefficient was calculated according to Borges & Mendiondo (2007) and Samboranha et al. (2013):

$$r = \frac{\sum (O_i - \bar{O})(S_i - S)}{\left[\left[\sum (O_i - \bar{O})^2 \right] \left[\sum (S_i - S)^2 \right] \right]^{0.5}} \quad (12)$$

where:

S_i - simulated values;

S - mean of simulated values;

O_i - observed values;

\bar{O} - mean of observed values; and

n - number of observations.

RESULTS AND DISCUSSION

The maximum appearance rate of the first and second leaves ($LAR_{max1,2}$) is higher in the hybrid with medium cycle (QM 1010 CL) and lower in that of early cycle (PRIME CL), indicating lower speed of leaf production in PRIME CL in comparison to the other two hybrids. The total thermal sum necessary to complete the Sowing-Emergence stage is similar in the three hybrids. The duration of the Emergence-Panicle Differentiation stage is shorter in the early hybrids, especially PRIME CL. For the hybrid cultivars, the vegetative stage is the one with highest influence on the duration of the total cycle (Table 2), regardless of the maturity group.

The simulation of the HS of the hybrids in the different locations showed RMSE from 0.5 to 1.9 leaves in the main

Table 2. Parameters of the submodels of leaf production and phenology in the SimulArroz model calibrated for three rice hybrids

Parameter	Unit	Hybrids		
		PRIME CL	INOV CL	QM 1010 CL
LAR _{max 1,2}	Leaves day ⁻¹	0.268	0.376	0.397
TTEM	°C day	50.0	51.4	51.4
TTVG	°C day	394.8	557.6	643
TTRP	°C day	175.3	145.9	142.2
TTEG	°C day	128.6	116.8	117.2

LAR_{max 1,2} - Maximum rate of appearance of the first and second leaves (leaves d⁻¹); TTEM - Total thermal time necessary to complete the Sowing-Emergence phase (°C day); TTVG - Total thermal time necessary to complete the Emergence-Panicle Differentiation phase (°C day); TTRP - Total thermal time necessary to complete the Panicle Differentiation-Anthesis phase (°C day); TTEG - Total thermal time necessary to complete the Anthesis-Physiological Maturity phase (°C day)

stem, close to the values found for maize (0.8 leaves) (Streck et al., 2010) and lower than that found for cassava (3.2 leaves) (Samboranza et al., 2013) using the model of Wang and Engel. The BIAS index varied from -0.03 to 0.45, indicating a slight underestimation of the model. The dw index and the correlation coefficient were high for all hybrids (above 0.89). Considering all locations, the RMSE of the hybrids varied from 0.6 to 1.4 leaves (Figure 1A). Comparing the statistics of the hybrids with those of the IRGA 424 (Table 3 and Figure 1A), it is noticed that the SimulArroz model simulates well the number of leaves, represented by the HS, in the three hybrids. The final leaf number (FLN) in the main culm, which is intrinsically solved (Streck et al., 2003), showed a RMSE of 1.1 leaves, being slightly higher than that reported for wheat (0.55 leaves) (He et al., 2012), using a nonlinear model, thus emphasizing to continue the efforts to improve the simulation of FNL. The other statistics (Figure 1B) indicate a very good performance in the model for this variable.

The RMSE of the cultivar IRGA 424 was close to those of the hybrids for the phenology, and the simulation of R1, R4 and R9 varied from 3.6 to 8.1 days between both locations. Considering all locations, the RMSE was equal to 4.2, 4.7 and 5.9 d (Table 4).

These values (Table 4) are lower than those described for wheat (12.6 days) and barley (11.5 days) using nine simulation models (APES-ACE, CROPSYST, DAISY, DSSAT-CERES, FASSETT, HERMES, MONICA, STICKS and WOFOST) (Rotter et al., 2012), confirming the better performance of the model used in the present study.

The hypothesis for the delay of the simulated emergence can be related to three factors, which are not considered in the model: (i) sowing depth, (ii) soil temperature (the model uses air temperature to estimate emergence) and (iii) rainfall from sowing to emergence, which can alter soil temperature and create an anoxic environment, which decreases the germination speed. Running the model from the observed emergence date, the RMSE is equal to 7.2, 4.8 and 4.6 days for R1, R4 and R9, respectively.

Figure 2 shows an application of the SimulArroz model to describe the Genotype x Environment interaction on the duration of the development cycle (Sowing to R9), of the three rice hybrid cultivars, on four sowing dates, in four locations of RS. The shortest duration of the development cycle occurred for the sowings in the months of November and December, due to the higher air temperature, which caused the thermal accumulation for each development stage to be faster, except

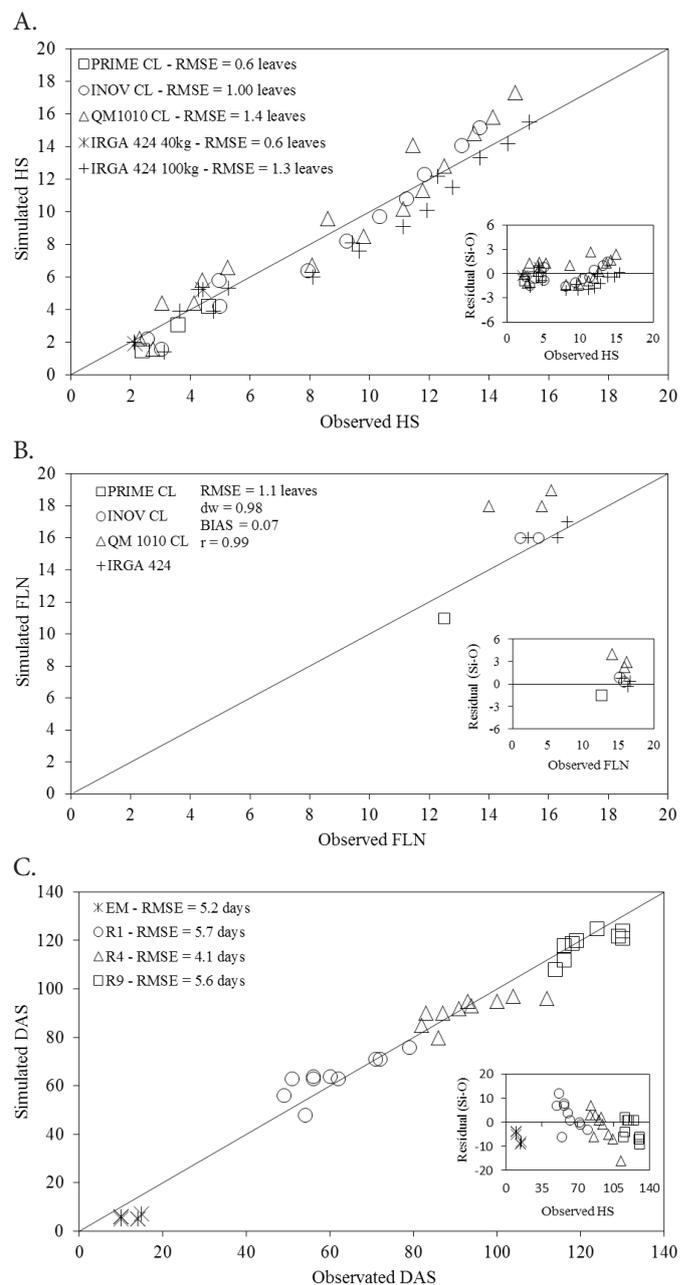


Figure 1. Number of leaves per plant on the main culm - HS (A), final leaf number in the main culm - FLN (B) and days after sowing (DAS) of the stages of emergence-EM (C), panicle differentiation (R1), anthesis (R4) and physiological maturity (R9) observed and simulated with the SimulArroz model for three hybrids (PRIME CL, INOV CL and QM 1010 CL) and one conventional cultivar (IRGA 424) of irrigated rice in Rio Grande do Sul in the 2014/2015 growing season

in Uruguaiiana, where QM 1010 CL showed the longest duration of the cycle for the sowing on December 25 (Figure 2). Among the locations, the duration of the cycle was longer in Santa Vitória do Palmar (sowing on September 25) and in Uruguaiiana (sowing on December 25). In these two locations, due to the geographic position, the lower temperature in the spring (Santa Vitória do Palmar) and in the autumn (Uruguaiiana) determined the lower daily rate of development and, consequently, prolongation of the cycle. Considering all locations and sowing dates, the cycle varied from 121 to 96 days for PRIME CL, 127 to 102 days for INOV CL and 134

Table 3. Performance of the SimulArroz model in simulating the Haun stage on the main culm of three hybrids and one cultivar (IRGA 424) of irrigated rice in four locations of Rio Grande do Sul, during the 2014/2015 crop season

Location	Statistics	Hybrids			IRGA 424
		PRIME CL	INOV CL	QM1010 CL	
Santa Maria	RMSE	-	1.1	1.3	1.5
	BIAS	-	-0.03	0.01	-0.12
	Dw	-	0.98	0.98	0.97
	R	-	0.99	0.98	0.99
Cachoeirinha	RMSE	0.7	0.7	1.0	1.2
	BIAS	-0.18	0.07	0.19	0.15
	Dw	0.93	0.95	0.89	0.97
	R	1.00	1.00	1.00	1.00
Uruguaiana	RMSE	-	-	1.9	0.8
	BIAS	-	-	0.20	-0.05
	Dw	-	-	0.90	0.98
	R	-	-	0.99	0.98
Santa Vitória do Palmar	RMSE	0.5	-	1.4	0.3
	BIAS	-0.13	-	0.45	0.07
	Dw	-	-	-	-
	R	-	-	-	-

RMSE - Root-mean-square error, BIAS - BIAS index; DW - Agreement index; R - Pearson's correlation coefficient (r); The hybrid cultivars PRIME CL and INOV CL were not evaluated in these locations; In Santa Vitória do Palmar, dw and r were not determined because of the lower number of observed data

to 108 days for QM 1010 CL, which are consistent with the duration of the cycles of these three hybrids in the technical recommendations for the rice crop in RS, equal to 110, 120 and 135 days, respectively (SOSBAI, 2014).

Table 4. Performance of the SimulArroz model in simulating the date of emergence, panicle differentiation (R1), anthesis (R4) and physiological maturity (R9) of three hybrids and one cultivar (IRGA 424) of irrigated rice in four locations of Rio Grande do Sul, during the 2014/2015 crop season

Location	Statistics	Hybrids			IRGA 424
		PRIME CL	INOV CL	QM1010 CL	
Santa Maria	RMSE	-	5.0	8.1	4.1
	BIAS	-	0.02	0.08	0.03
	dw	-	1.00	0.97	0.99
	r	-	1.00	1.00	1.00
Cachoeirinha	RMSE	3.6	3.6	4.9	4.1
	BIAS	-0.05	-0.05	-0.04	-0.05
	dw	1.00	1.00	1.00	1.00
	r	1.00	1.00	1.00	1.00
Uruguaiana	RMSE	-	-	5.8	6.1
	BIAS	-	-	-0.04	0.01
	dw	-	-	1.00	0.99
	r	-	-	0.99	0.99
Santa Vitória do Palmar	RMSE	5.6	-	4.7	5.4
	BIAS	-0.08	-	-0.06	-0.06
	dw	0.99	-	1.00	1.00
	r	1.00	-	1.00	1.00
All locations	RMSE	4.7	4.2	5.9	4.9
	BIAS	-0.07	0.01	-0.02	-0.02
	dw	1.00	1.00	0.99	1.00
	r	1.00	0.99	0.99	0.99

RMSE - Root-mean-square error; BIAS - BIAS index; dw - Agreement index; r - Pearson's correlation coefficient; The hybrid cultivars PRIME CL and INOV CL were not evaluated in these locations

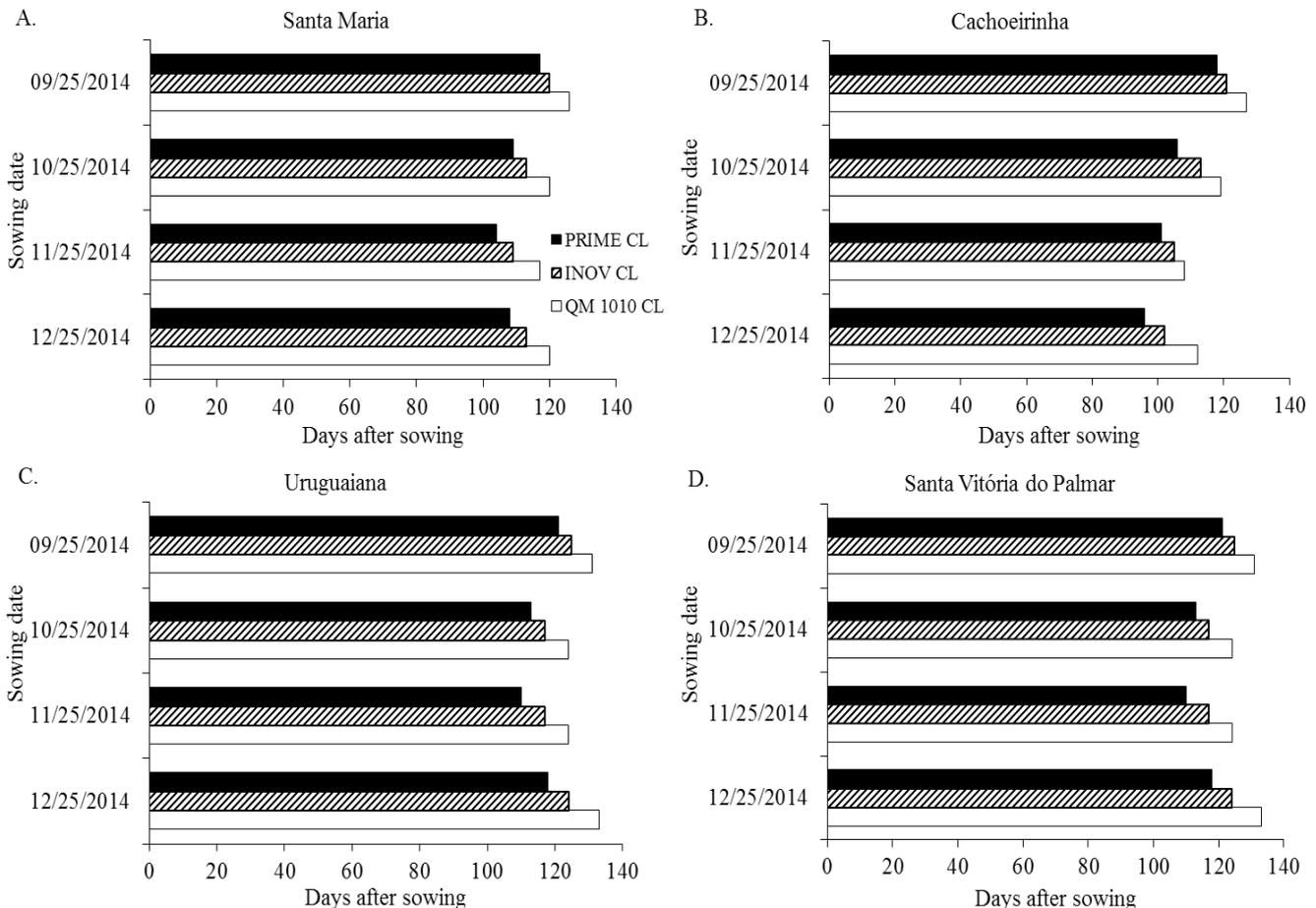


Figure 2. Development cycle duration (Sowing to R9) for three hybrid cultivars of irrigated rice, INOV CL, PRIME CL and QM 1010 CL, on four sowing dates, in Santa Maria (A), Cachoeirinha (B), Uruguaiana (C) and Santa Vitória do Palmar (D), RS, simulated with the SimulArroz model

CONCLUSIONS

1. The calibration approach of the SimulArroz model is efficient to simulate the number of leaves in the main culm and phenology of three hybrid cultivars of irrigated rice in Rio Grande do Sul.

2. The SimulArroz model captures the effect of sowing period on the hybrid cultivars and the stage from sowing to panicle differentiation has the highest influence on the duration of the total cycle.

3. The SimulArroz model is sensitive to the maximum leaf appearance rate, which varies with the maturity group, being higher in all cultivars of medium cycle.

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