



ISSN 1678-3921

Journal homepage: www.embrapa.br/pabFor manuscript submission and journal contents, access: www.scielo.br/pab

Crop Science/ Original Article

Introducing rice yield loss caused by weed competition into the SimulArroz model




Abstract – The objective of this work was to model weedy rice (*Oryza sativa*) and barnyard grass (*Echinochloa* spp.) competition with flood-irrigated rice, introducing it as a submodule into the SimulArroz model. The competition of both weeds with irrigated rice was modeled using the rectangular hyperbola equation. The “i” and “a” coefficients of the rectangular hyperbola for each of these weeds were obtained from the literature and from field experiments carried out in the state of Rio Grande do Sul, Brazil. In SimulArroz, yield loss was applied to penalize yield in all three technological levels (high, medium, and low) of physiological maturity. For weedy rice, the coefficient values of i_{mean} for the high, medium, and low technological levels were 1.04, 1.50, and 3.57 respectively, and, for barnyard grass, 4.70, 10.49, and 15.51 respectively. Coefficient “a” was 100 for weedy rice, and a_{mean} values for barnyard grass were 101.63, 104.92, and 96.88 for the high, medium, and low levels, respectively. The yield loss approach was suitable to model the competition of weedy rice and barnyard grass with irrigated rice. The submodule yield loss caused by the competition of weedy rice and barnyard grass with irrigated rice improves the predictive capacity of the SimulArroz model.

Index terms: *Oryza sativa*, barnyard grass, modeling, weedy rice, yield loss.

Introdução da perda de produtividade de arroz pela competição com plantas daninhas no modelo SimulArroz

Resumo – O objetivo deste trabalho foi modelar a competição de arroz-daninho (*Oryza sativa*) e capim-arroz (*Echinochloa* spp.) com o arroz irrigado por inundação e introduzi-la como um submodelo no modelo SimulArroz. A competição das duas ervas daninhas com o arroz irrigado foi modelada com o uso da equação da hipérbole retangular. Os coeficientes “i” e “a” da hipérbole retangular referentes a cada erva foram obtidos na literatura e em experimentos de campo conduzidos no Rio Grande do Sul. No SimulArroz, a perda de produtividade foi aplicada para penalizar a produtividade nos três níveis tecnológicos (alto, médio e baixo) para maturidade fisiológica. Para o arroz-daninho, os valores do coeficiente $i_{\text{médio}}$, para os níveis tecnológicos alto, médio e baixo, foram 1,04, 1,50 e 3,57, respectivamente, e, para o capim-arroz, foram 4,70, 10,49 e 15,51, respectivamente. O coeficiente “a” foi 100 para o arroz-daninho, e o $a_{\text{médio}}$, para o capim-arroz, foi 101,63, 104,92, 96,88 para os níveis tecnológicos alto, médio e baixo, respectivamente. A abordagem de perda de produtividade foi adequada para modelar a competição de arroz-daninho e capim-arroz com o arroz irrigado. O submodelo de perda de produtividade pela competição de arroz-daninho e capim-arroz com o arroz irrigado melhora a capacidade preditiva do modelo SimulArroz.

Termos para indexação: *Oryza sativa*, capim-arroz, modelagem, arroz-daninho, perda de produtividade.

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Received
April 14, 2019

Accepted
October 23, 2019

How to cite

RICHTER, G.L.; STRECK, N.A.; JUNIOR ZANON, A.; ULGUIM, A. da R.; KRUSE, N.D.; SANTOS, G.A. de A. dos; CERA, J.C.; RIBAS, G.G.; DUARTE JUNIOR, A.J.; PILECCO, I.B. Introducing rice yield loss caused by weed competition into the SimulArroz model. *Pesquisa Agropecuária Brasileira*, v.54, e01418, 2019. DOI: <https://doi.org/10.1590/S1678-3921.pab2019.v54.01418>.



Introduction

Brazil is the first largest rice (*Oryza sativa* L.) producer in the world outside Asia (FAO, 2019), and has an annual production of around 11 tons. The state of Rio Grande do Sul is the largest rice producer in Brazil, and accounts for 70% of the national production (Conab, 2019) on 1.1 million hectare of flood-irrigated system (Conab, 2019). An analysis of the rice time series from 2012 to 2018 in Rio Grande do Sul shows a steady increase in yield of up to 8.0 Mg ha⁻¹, but this value is below the best yields obtained by farmers in the state, which is of 12 Mg ha⁻¹ (Ribas et al., 2016). One of the major factors causing the gap between average state yield and best yield is the unsatisfactory weed control (Rubin et al., 2014).

Weeds are the main causes of biotic stress in agricultural crops, because they compete for resources (solar radiation, water and nutrients) with the crop of economic interest (Agostinetto et al., 2007; Olajumoke et al., 2016). The most important rice weeds are those which belong to the same family (Poaceae), mainly weedy rice (*Oryza sativa*) and barnyard grass (*Echinochloa* spp.). Weedy rice belongs to the same species as cultivated rice, is characterized as its main weed (Olajumoke et al., 2016), and limits the increase in rice yield in Rio Grande do Sul (Rubin et al., 2014). Barnyard grass is also reportedly one of the most important weeds worldwide (Aminpanah et al., 2012). Well adapted to survive in flooded environments, it shows high infestation levels in paddy rice fields in Rio Grande do Sul. Yield losses in rice due to weedy rice and barnyard grass have been reported to vary from less than 1 to up to 30% of losses (Agostinetto et al., 2004; Galon et al., 2007).

The weed competition model that best biologically explains crop yield losses due to weed competition is the rectangular hyperbola (Cousens, 1985; Moon et al., 2011; Mamun, 2014). According to this approach, crop yield losses at low weed densities (when interspecific crop–weed competition predominates) show linear responses (Adati et al., 2006). As weed density increases, intraspecific competition increases, leading to a nonlinear response with a decreasing yield-loss rate, so that in crops showing very high weed density, yield loss approaches its maximum when competition among weed individuals begins (Adati et al., 2006). The rectangular hyperbola has two empirical coefficients,

“i” and “a”, which must be estimated from observation data collected in field experiments (Adati et al., 2006).

The use of submodels, such as weed competition submodels, into crop-based models, such as Oryza2000 (Li et al., 2017), InfoCrop (Aggarwal et al., 2006), RiceGrow (Tang et al., 2009) and SimulArroz (Ribas et al., 2017), increases the applicability of the models to yield simulations. SimulArroz is a process-based model that simulates growth, development, and yield of irrigated rice on a daily time step. This model differs from the others for having been adapted for cultivars grown under flood irrigation system in the state of Rio Grande do Sul (Walter et al., 2012; Ribas et al., 2017). Grain yield and yield components are calculated by equations described in the InfoCrop (Aggarwal et al., 2006) and Oryza2000 (Li et al., 2017) models, specifically calibrated for the most used cultivars in flooded rice systems in Southern Brazil.

Phenology is calculated in SimulArroz by the thermal time approach (°C day), using the lower and upper basal (temperatures below and above which plant development is negligible, respectively) and optimum temperatures (at which the development rate is maximum) (Streck et al., 2011). The dry matter production is calculated through the radiation use efficiency (RUE) and the leaf area index (LAI), in which RUE is described as a function based on cardinal temperatures. The daily dry matter production is partitioned among roots, leaves, stems and panicles, according to developmental stage and cultivar. The LAI is calculated using the dry matter sent to the leaves (g m² per day) and the specific leaf area (m² g⁻¹) varies according to cultivar and developmental stage.

The current version of the SimulArroz model is not equipped with a module that simulates weed–crop competition and its effect on rice yield. Instead, biotic factors that affect rice yield are assembled empirically in SimulArroz into three “technological levels” (high, medium, and low) of farms. In a farm with high technological level, weed control is assumed to be well done and thus to cause negligible effect on rice yield; in a farm with low technological level, weed control is unsatisfactory and there is high loss in rice yield, due to weed competition, and farming is not economically viable. The medium technological level is intermediate between the two levels above (Walter et al., 2012). This empirical approach has enabled to reproduce the technological level of famers at a county and state

level, so that the SimulArroz model was used for redefining the Agroclimatic Zoning of rice in the state for the first time in history (Brasil, 2018). However, on a farm level, there is clearly a need to introduce a more process-based approach that can depict on-farm variability in weed control.

The objective of this work was to model weedy rice and barnyard grass competition with irrigated rice, introducing it as a submodule into the SimulArroz model.

Materials and Methods

The weed competition effect on irrigated rice yield was modeled using the yield loss approach (Adati et al., 2006) and the rectangular hyperbola (Cousens, 1985) with equations:

$$Y_L = (iD)(1+\beta D)^{-1} \quad (1)$$

$$\beta = ia^{-1} \quad (2)$$

Weed density was used as predictive variable. Weedy rice and barnyard grass were used in this study, as they are the most important weeds in irrigated rice crops. Y_L is the yield loss, in percentage, related to the control treatment (without weed competition); D is the weed density in plants per square meter; i is the yield loss, in percentage, of rice grains per unit of weed when weed density approaches zero; a is the yield loss, in percentage, of rice grains when weed density approaches infinity; and β is the weed's competitiveness (Cousens, 1985; Mamun, 2014).

The i and a coefficients of the rectangular hyperbola model for each of the weed species were obtained from studies carried out in the state of Rio Grande do Sul and published in the literature (Tables 1 and 2). In addition, the inverse of the competitiveness of each weed was calculated, which represents the density of weeds that reduces yield by 50%. This parameter facilitates the understanding of the competition for

Table 1. Coefficient i (for yield loss, in percentage, of rice (*Oryza sativa*) grains per unit of weed when weed density approaches zero) and coefficient a (for yield loss, in percentage, of rice grains when weed density approaches infinity) of the rectangular hyperbola equation ($Y_L = (iD)(1+\beta D)^{-1}$) for weedy rice (*Oryza sativa*) in the rice crop.

Coefficient i	Coefficient a	Cultivar	Level	Reference
0.25	100	IRGA 417	High	Agostinetto et al. (2005a)
0.49	100	IRGA 417	High	Fleck et al. (2004)
0.50	100	BR-IRGA 409	High	Fleck et al. (2004)
0.51	100	BR-IRGA 409	Low	Agostinetto et al. (2005b)
0.63	100	BRS-38 Ligeirinho	High	Fleck et al. (2004)
0.70	100	BRS-38 Ligeirinho	Medium	Fleck et al. (2004)
0.72	100	BRS-38 Ligeirinho	Medium	Fleck et al. (2004)
0.75	100	BRS-38 Ligeirinho	High	Fleck et al. (2004)
0.77	100	BR-IRGA 409	Medium	Agostinetto et al. (2005a)
0.77	100	BR-IRGA 409	Medium	Fleck et al. (2004)
0.94	100	BR-IRGA 409	Low	Agostinetto et al. (2005b)
0.97	100	IRGA 417	Low	Agostinetto et al. (2005b)
1.23	100	BRS-38 Ligeirinho	High	Agostinetto et al. (2005b)
1.25	100	IRGA 417	High	Agostinetto et al. (2005b)
1.25	100	IRGA 417	High	Agostinetto et al. (2005b)
1.25	100	BR-IRGA 409	High	Agostinetto et al. (2005b)
1.25	100	IRGA 417	Medium	Agostinetto et al. (2005a)
1.30	100	BR-IRGA 409	High	Agostinetto et al. (2005b)
1.37	100	IRGA 417	High	Agostinetto et al. (2005b)
1.50	100	BRS-38 Ligeirinho	Medium	Agostinetto et al. (2005b)
1.51	100	IRGA 417	Low	Agostinetto et al. (2005b)
1.54	100	BRS-38 Ligeirinho	High	Agostinetto et al. (2005b)
1.67	100	IRGA 417	High	Agostinetto et al. (2005a)
1.74	100	BR-IRGA 409	Medium	Agostinetto et al. (2005b)
1.95	100	IRGA 417	Medium	Agostinetto et al. (2005b)
4.07	100	IRGA 417	Medium	Agostinetto et al. (2005a)
4.81	100	IRGA 417	Low	Agostinetto et al. (2005a)
12.65	100	IRGA 417	Low	Agostinetto et al. (2005a)

different rectangular hyperbolas (Cousens, 1985; Mamun, 2014):

$$s = 1\beta^{-1} \quad (3)$$

The module of yield loss due to weeds was introduced into the SimulArroz model to penalize yield at each of the three technological levels on the day of physiological maturity. The assumption was that competition occurs from the period prior to interference (PPI) up until physiological maturity, regardless of the technological level chosen. The source code for SimulArroz is available in Fortran, and the necessary measures for coupling equation 1 into the model were made. For this reason, the rectangular hyperbolas in Tables 1 and 2 were classified according to technological level (high, medium, and low). Crops with high technological level follow the principles of Project 10+ (Menezes et al., 2012), such as high fertilization, onset of flooded irrigation at V3 and a plant density of 200 plants per square meter. As low technological level were considered the experimental treatments with reduced use and incorrect application of fertilization, greater plant line spacing, delay in the onset of flooded irrigation and lack of application of pesticides at the right time. The medium level is intermediate between the high and low levels. After

classification, the average values of i_{mean} and a_{mean} were calculated for each weed species and technological level.

As independent data to test the model, four experiments were conducted in a completely randomized design for evaluating weed density and rice yield for both weeds; with one unit by combination of factors, the different densities functioned as repetitions and provided variance for the statistical analyses performed using the nonlinear model proposed by Cousens (1985).

For the weedy rice, two experiments were conducted in commercial farm fields during the 2016/2017 growing season in São João do Polêsine and Santa Maria, in Rio Grande do Sul, and were subjected to the farmer's management practices. Those two areas were chosen due to their historical weedy rice infestation.

To test the effect of barnyard grass on irrigated rice yield, two field experiments were carried out at Estação Experimental do Arroz in Instituto Rio Grandense de Arroz (IRGA), located in the municipality of Cachoeirinha, also in the state of Rio Grande do Sul, during the 2016/2017 growing season. Plant density of the weeds was defined when the rice plants were at the V3-V4 stage; using plastic cups or pieces of paper, barnyard plants were protected against the cyhalofop-

Table 2. Coefficient i (for yield loss, in percentage, of rice (*Oryza sativa*) grains per unit of weed when weed density approaches zero) and coefficient a (for yield loss, in percentage, of rice grains when weed density approaches infinity) of the rectangular hyperbola equation ($Y_L = (iD)/(1+\beta D)^{-1}$) for barnyard grass (*Echinochloa* spp.) in the rice crop.

Coefficient i	Coefficient a	Cultivar	Level	Reference
1,134	100.00	IRGA 424 RI	High	Beck et al. (2017)
1,1715	100.00	Guri INTA CL	High	Beck et al. (2017)
4.62	107.30	BRS Pelotas	High	Agostinetto et al. (2010)
4.71	107.10	IRGA 417	High	Galon et al. (2007)
6.01	98.97	BRS Pelotas	Low	Agostinetto et al. (2010)
7.22	112.50	IRGA 416	Medium	Galon et al. (2007)
8.14	96.30	BRS Pelotas	High	Agostinetto et al. (2010)
8.40	99.09	BRS Pelotas	High	Agostinetto et al. (2007)
9.79	108.30	IRGA 421	Medium	Galon et al. (2007)
10.40	104.30	BRS Pelotas	Medium	Agostinetto et al. (2007)
11.25	97.41	BRS Pelotas	Low	Agostinetto et al. (2007)
11.38	96.19	BRS Atlanta	Medium	Galon et al. (2007)
13.67	101.10	BRS Fronteira	Medium	Galon et al. (2007)
29.27	94.27	AVAXI	Low	Galon et al. (2007)

butyl herbicide commercial product applied at a dose of 1.5 L ha⁻¹.

Sites, weed, sowing date, cultivar, fertilizer, and technological levels used in each experiment for weedy rice and barnyard grass are listed in Table 3. Weed density evaluations for all experiments were carried out in nine-row plots with 0.17-m and 6.0-m-long spacing, by counting the individuals in a 0.5-m² area subdivided into two sites for each plot, and randomly selected. The yield was quantified using the harvested plots, and the grains obtained were corrected to a 13% moisture rate. The yield loss of the weed plots was calculated in relation to the plots maintained without infestation.

The observed data were compared with the values estimated by the SimulArroz model using the competition module for both weeds, with i_{mean} and a_{mean} for the weed and the technological level for all four conducted experiments. The performance was evaluated using statistics: root mean square error (RMSE), normalized root mean square error (RMSEn), BIAS index (Samboranza et al., 2013), modified index of agreement (dw) (Willmott et al., 1985), and Nash-Sutcliffe efficiency coefficient (COE) (Nash & Sutcliffe, 1970).

Results and Discussion

The i_{mean} values for high, medium and low technological levels were 1.04, 1.50, and 3.57, respectively (Table 4). Lower values of i_{mean} for the high technological level mean that the unit loss (yield loss of one weedy rice per square meter) is lower when management is better carried out by farmers (Agostinetto et al., 2004, 2007). Differently, in the experiments or treatments classified as low technological level, the i_{mean} coefficient was greater, which may be related to the emergence of the weed before the crop, or may be due to the lower environmental carrying capacity, defined as the environment's capacity for supporting lower plant density.

According to the inverse of the competitiveness indicators (Mamun, 2014), the weed density per square meter that causes 50% yield loss was 96, 67, and 28 plants per square meter for the high, medium, and low technological levels, respectively (Table 4). These values confirm that the environmental carrying capacity at the low technological level is significantly lower than at the other levels. The amount of resources limits the increase in density to higher levels, since the crop increases its ability to compete with weed in

Table 3. Sites, type of weed, sowing date, rice (*Oryza sativa*) cultivar, fertilizer, and technological levels in the four experiments used for validation.

Site	Weed ⁽¹⁾	Sowing date	Cultivar	Fertilizer (kg ha ⁻¹)	Technological level
Santa Maria	Weedy rice	11/6/2016	PUTÁ INTA CL	250 5-15-20 N-P ₂ O-K ₂ O ₅ and 150 urea	High
São João do Polêsine	Weedy rice	11/25/2016	IRGA 424 RI	200 5-15-20 N-P ₂ O-K ₂ O ₅ and 100 of urea	Medium
Cachoeirinha	Barnyard grass	11/23/2016	IRGA 424 RI	Maximum recommended	High
Cachoeirinha	Barnyard grass	11/23/2016	GURI INTA CL	Maximum recommended	High

⁽¹⁾Weedy rice, *Oryza sativa*; and barnyard grass, *Echinochloa* spp.

Table 4. Classification of the i_{mean} and a_{mean} coefficients of the rectangular hyperbola, with their respective values of competitiveness (β) and the density per square meter that causes a 50% yield loss (s) in the three technological levels for both weeds.

Technological level	Coefficient i_{mean}	Coefficient a_{mean}	β	s
Weedy rice (<i>Oryza sativa</i>)				
High	1.04	100.00	0.0104	96
Medium	1.50	100.00	0.0150	67
Low	3.57	100.00	0.0357	28
Barnyard grass (<i>Echinochloa</i> spp.)				
High	4.70	101.63	0.0462	22
Medium	10.49	104.92	0.1000	10
Low	15.51	96.88	0.1601	6

environments with greater availability of resources, thus reducing yield loss by increasing its density (Agostinetto et al., 2013). Density initially increases freely, then its increase rate reduces to the extent of the resources that are becoming insufficient to sustain it; it stabilizes near the upper limit, since for the low technological level this upper limit may be much lower than that of the other two technological levels (Agostinetto et al., 2013).

The validation of the SimulArroz model using the yield loss submodule performed satisfactorily, and the RMSE values were lower than 2,433 kg ha⁻¹ (Table 5). These values are close to the 2,134 kg ha⁻¹ reported by Rosa et al. (2015). RMSEn values are below those reported by Silva et al. (2016), which ranged from 12.7 to 79.7%; when compared with the 23.0 and 34.6% values obtained in the present study, they indicate that the yield loss submodule improved the simulation. The dw index, BIAS and COE coefficient show that the SimulArroz model with the weed competition module performed better for Santa Maria than for São João de Polêsine. A poorer performance of the model in São João do Polêsine may be related to the cultivar x technological level interaction. The IRGA 424 RI cultivar has a high tillering capacity, which renders it highly competitive with weeds, even under an intermediate technological level such as that of the farm in São João do Polêsine, where the yield loss for a range of about 30 to 90 weedy rice plants per square meter was not greater than 40%, compared with more than 50% yield loss simulated by the model (Figure 1).

For barnyard grass, the classification of the rectangular hyperbola coefficients was similar to that observed for weedy rice (Table 4), but with higher values, due to the grass' greater competitiveness,

faster growth, taller characteristic, and more efficient C4 metabolism (Tironi et al., 2009; Olajumoke et al., 2016). For the high, medium and low technological levels, the values of i_{mean} were 4.70, 10.49 and 15.51 respectively, and for the a_{mean} coefficient, 101.63, 104.92, and 96.88 respectively.

The unit loss (yield loss caused by one barnyard grass per square meter) increased considerably along with the reduction in technological level, at a much higher rate than that of weedy rice. This is because the environment supports fewer barnyard grass plants, that is, the environmental carrying capacity is much smaller for the barnyard grass and there are less resources available for its population to increase (Agostinetto et al., 2010, 2013). The rice yield loss caused by a barnyard grass plant per square meter under low technological level reached 15.51% and may reach close to 600 kg ha⁻¹ (Table 4).

Considering the i_{mean} value found in the present study under low technological level, a barnyard grass plant per square meter can lead to a yield loss of around 15%, which shows lower competitiveness with rice cultivation in this situation. Based on the inverse competitiveness β (s) at the different technological levels, it was observed that the barnyard grass density per square meter that promotes 50% yield loss is always lower than that observed in weedy rice; the values for barnyard grass were 22, 10, and 6 plants per square meter for the high, medium, and low levels respectively (Table 4). These values confirm the low environmental carrying capacity for barnyard grass; even under the high technological level the density is lower than under the low technological level for the weedy rice, due to its fast growth, taller characteristic, and C4 metabolism (Olajumoke et al., 2016).

Table 5. Performance of the SimulArroz model with the yield loss module for weed competition with rice (*Oryza sativa*)⁽¹⁾.

Location /Cultivar	RMSE	RMSEn	dw	Bias	COE
Weedy rice (<i>Oryza sativa</i>)					
Santa Maria/PUITÁ INTA CL	1,047	23.0	0.916	0.098	0.608
São João do Polêsine/IRGA 424 RI	2,433	34.6	0.614	-0.285	0.290
Barnyard grass (<i>Echinochloa</i> spp.)					
Cachoeirinha/IRGA 424 RI	1,492	18.9	0.965	-0.029	0.855
Cachoeirinha/GURI INTA CL	1,558	24.5	0.969	-0.101	0.839

⁽¹⁾RMSE, root mean square error; RMSEn, normalized root mean square error; dw, modified index of agreement; Bias, bias index; and COE, Nash-Sutcliffe efficiency coefficient.

The performance of the SimulArroz model with the yield loss submodule was better for barnyard grass than for weedy rice; it's RMSE values were below 1,558 kg ha⁻¹, and RMSE values, below 24.5% (Table 5). The dw and COE statistics indicate that the model has good accuracy and the BIAS index tended to underestimate yield, since the values for both weeds were negative.

Overall, the performance of the SimulArroz model in simulating the weed–crop competition in a wide range of weed densities in the field (both in experiments and in farms) was good. Very few crop simulation models

consider weed–crop competition to affect crop yield, and those that consider do so empirically. For instance, the Decision Support System for Agrotechnology Transfer does not have a weed-competition module, and the user can only choose weed control by herbicides when running a simulation (Hoogenboom, 2010). The SimulArroz model now has a module that can help consultants and farmers to understand how two of the major weeds affect rice yield and use this information for decision making.

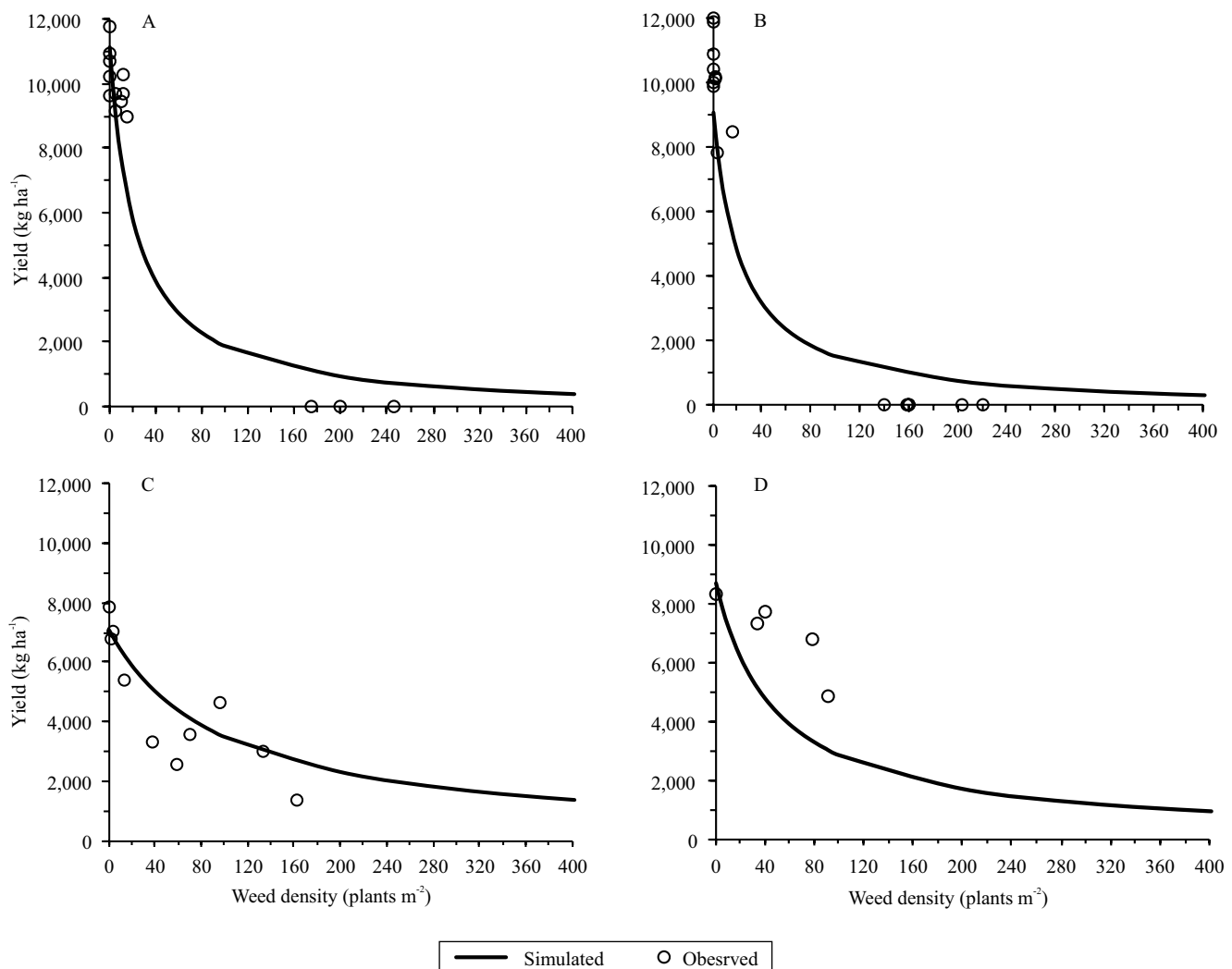


Figure 1. Irrigated rice (*Oryza sativa*) yield as a function of barnyard grass (*Echinochloa* spp.) in the experiment carried out with the IRGA 424 RI (A) and GURI INTA CL (B) cultivars in the municipality of Cachoeirinha, in the state of Rio Grande do Sul, Brazil, and in the experiments with weedy rice and the PUITÁ INTA CL cultivar in Santa Maria (C), and with IRGA 424 RI in São João do Polêsine (D), also in the state of Rio Grande do Sul.

Conclusions

1. The yield loss approach is suitable to model the weed-crop competition between weedy rice (*Oryza sativa*) and barnyard grass (*Echinochloa* spp.) with irrigated rice.

2. A yield loss submodule of the competition between weedy rice and barnyard grass with irrigated rice crops improves the SimulArroz model's predictive capacity.

Acknowledgments

To Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes), for scholarships awarded.

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