Adaptability and stability of flood-irrigated rice cultivars released to the subtropical region of Brazil

Eduardo Anibele Streck[(1)], Ariano Martins de Magalhães Júnior[(2)], Paulo Ricardo Reis Fagundes[(2)], Gabriel Almeida Aguiar[(1)], Paulo Henrique Karling Facchinello[(1)] and Antônio Costa de Oliveira[(1)]

[(1)]Universidade Federal de Pelotas, Avenida Eliseu Maciel, s/nº, Caixa Postal 354, CEP 96010-610 Capão do Leão, RS, Brazil. E-mail: streck.eduardo@gmail.com, gabrielalmeidaaguiar@yahoo.com.br, phfacchinello@gmail.com, acostol@cgfufpel.org [(2)]Embrapa Clima Temperado, Rodovia BR-392, Km 78, 9º Distrito, Monte Bonito, Caixa Postal 321, CEP 96010-971 Pelotas, RS, Brazil. E-mail: ariano.martins@embrapa.br, paulo.fagundes@embrapa.br

Abstract – The objective of this work was to estimate the effects of genotype x environment interaction and the genetic potential of flood-irrigated rice cultivars, released between 1972 and 2017, for the state of Rio Grande do Sul, Brazil. The experiments were carried out in the field, in all agroclimatic regions of flood-irrigated rice crop in the state, between the 2005/2006 and 2015/2016 crop years, totaling 60 environments (trials), with 1,961 experimental units. Twenty-five cultivars of irrigated rice were evaluated for the traits grain yield, plant height, days to flowering, and whole grain quality after milling. The values of adaptability and stability were estimated with the aid of mixed models. The rice cultivars BRS Pampa, BRS Pampeira, and BRSCIRAD 302 showed simultaneously high-genotypic grain yield, adaptability, stability, good agronomic traits, and good whole-grain yield after milling. 'BRSCIRAD 302' and 'BRS Pampa' show high-yield stability and can be recommended for all rice cultivation regions of Rio Grande do Sul. 'BRS Pampeira' is responsive to environmental improvements and is indicated for high-technology conditions.

Index terms: *Oryza sativa*, genotype x environment interaction, mixed models, plant breeding, zoning of cultivars.

Adaptabilidade e estabilidade de cultivares de arroz irrigado por inundação lançadas para a região subtropical do Brasil

Resumo – O objetivo deste trabalho foi estimar os efeitos da interação genótipo x ambiente e o potencial genotípico de cultivares de arroz irrigado por inundação, lançadas entre 1972 e 2017, para o Rio Grande do Sul. Os experimentos foram realizados em campo, em todas as regiões agroclimáticas de cultivo de arroz irrigado por inundação do estado, entre os anos agrícolas de 2005/2006 e 2015/2016, no total de 60 ambientes, com 1.961 unidades experimentais. Vinte e cinco cultivares de arroz irrigado foram avaliadas quanto aos caracteres produtividade de grãos, altura de plantas, dias para o florescimento e qualidade de grãos inteiros após o beneficiamento. Os valores de adaptabilidade e estabilidade foram estimados por meio de modelos mistos. As cultivares de arroz BRS Pampa, BRS Pampeira e BRSCIRAD 302 apresentaram, simultaneamente, alta produtividade genotípica de grãos, adaptabilidade, estabilidade, bons atributos agronômicos e bom rendimento de grãos inteiros após o beneficiamento. 'BRSCIRAD 302' e 'BRS Pampa' apresentam alta estabilidade produtiva e podem ser recomendadas para cultivo em todas as regiões orizícolas do Rio Grande do Sul. 'BRS Pampeira' é responsiva às melhorias do ambiente e é indicada para condições de alta tecnologia.

Termos para indexação: *Oryza sativa*, interação genótipo x ambiente, modelos mistos, melhoramento genético, zoneamento de cultivares.

Introduction

Rice (*Oryza sativa* L.) is the dietary basis of half the world's population (Hao & Lin, 2010). In Brazil, flood-irrigated rice has a high-economic and social importance, and it is mainly produced in lowland areas. Rice in these areas shows high yields; however, there is a range of other agroclimatic regions, as well as technology uses. This generates diverse phenotypic responses of the genotype in the different regions, due to genotype x environment (GxE) interactions, which particularly affect the quantitative traits.

In order to obtain more precise estimates of GxE effects, it is necessary to conduct experiments in as many numbers of sites and years as possible, to evaluate the magnitude of the interactions and their possible impact on the selection and recommendation of cultivars (Silva et al., 2013). Therefore, for the cultivar maximum yield performance, it is necessary to carry out comparative tests in different environments, to determine yield, adaptability, and stability to different agroclimatic conditions. The knowledge of these environmental requirements and peculiarities of the main available cultivars allows of the selection of the most appropriate genotypes to each crop and growing condition. Thus, for cultivar recommendation, it is essential to determine the adaptability (broad or specific) and stability in each production region.

GxE can be studied by measures of adaptability and stability, which allows of a simple interpretation of a large dataset. In the context of mixed models, the harmonic mean of the relative performance of genetic values (MHPRVG) (Resende, 2007) has been shown to be one of the efficient alternatives for the simultaneous evaluation of genotypes for yield, adaptability, and stability, mainly when unbalanced data are produced (Balestre et al., 2010; Borges et al., 2010). This mixed model approach has been used efficiently in the analyses of numerous crops, such as sugarcane (Bastos et al., 2007), carrot (Silva et al., 2011), common beans (Torres et al., 2015), corn (Mendes et al., 2012; Faria et al., 2017), and rice (Colombari Filho et al., 2013).

Currently, the development of new high-yielding cultivars for different growing conditions (intrinsic conditions of planting, management, and climate) is one of the great challenges of breeders to attend the development requirements of technologies compatible with flood-irrigated rice. In this way, the plant breeding programs has developed numerous cultivars to meet the demand of various segments of cereal production chains. However, there is a lack of scientific information regarding the response of these flood-irrigated rice cultivars released in Rio Grande do Sul and their interactions with the growing environments.

The objective of this work was to estimate the effects of GxE and the genetic potential of flood-irrigated rice cultivars released between 1972 and 2017 for the state of Rio Grande do Sul, Brazil.

Materials and Methods

The experiment was carried out in all agroclimatic regions of flood-irrigated rice cultivation in the state of Rio Grande do Sul, which are: Fronteira Oeste, Campanha, Depressão Central, Planície Costeira Interna e Planície Costeira Externa, and Zona Sul. Twenty-five flood-irrigated rice cultivars released by the Embrapa breeding program for Southern Brazil, from 1972 to 2017, were used (Table 1). These cultivars were released over 46 years to meet the needs of the main production chain and their genetic constitutions that define the morphological traits, and purposes of use have changed over time.

The evaluations were evaluated in 60 environments, covering 1,961 experimental units. The number of sites in each of the 11 years of trial ranges from two to seven, depending on the availability of annual partnerships with companies and rural producers.

The experiment was carried out in randomized complete block design, with four replicates, for which the plots were composed of nine 5 m rows, spaced at 0.20 m between lines. The useful plot area was composed by the central 4 m lines of the seven internal ones, in order to exclude any incident effect on the border. Sowing was performed in conventional system, with one mechanical sowing of plots. The cultivation followed technical recommendations for flood-irrigated rice crop in Southern Brazil. The permanent flood irrigation system was used until the final maturation stage of the genotypes.

The following agronomic traits were evaluated: grain yield (kg ha^{-1}) adjusted to 13% humidity; plant height (cm) in the maturation stage, by measuring the length of the main tiller from the soil surface to the tip of panicles; number of days to flowering, measured by the number of days from emergence up to 50% of the panicles exposed; and the percentage of whole grains after milling, obtained by peeling and polishing of grains in a mini test device.

At first, the trials were grouped, considering each environment composed by a site in a given cultivation year. Not all the cultivars were evaluated in all the sites and cultivation years, since new cultivars were released over the evaluation period. Thus, the estimates of variance components were obtained by the residual maximum likelihood (REML) method, and the prediction of genetic values of each individual was performed with the best unbiased linear prediction procedure (Blup). The predicted values of the random effects (EBlup), associated to each of the genotypes, included a share allocated to the estimation of constant μp means (common average of cultivars without random genotypic deviations), and another share referring to the particular genotypic effects of each genotype.

The analyses were performed with the statistical software Selegen-REML/Blup (Resende, 2016), by which the variance components were obtained according to the linear mixed model

$$y_{ijkn} = \mu + g_i + b_{j(kn)} + l_k + a_n + gl_{ik} + ga_{in} + la_{kn} + gla_{ikn} + \varepsilon_{ijkn}$$

in which: y_{ijkn} is the observed value of the i^{th} genotype, in the j^{th} block, in the k^{th} environment, in the n^{th} harvest season; μ is the effect of the general mean; g_i is the random effect of genotype i; $b_{j(kn)}$ is the fixed effect of block j, inside site k, and year n; l_k is the random effect of site k; a_n is the random effect of year n; gl_{ik} is the random effect of the genotype x site interaction; ga_{in} is the random effect of the genotype x year interaction; la_{kn} is the random effect of the site x cultivation year interaction; gla_{ikn} is the random effect of the genotype x site x year interaction; and ε_{ijkn} is the error or experimental residue.

The statistical matrix used to estimate the harmonic mean of the relative performance of genetic values (MHPRVG) was obtained from the model $y = Xr + Zg + Wi + \varepsilon$, in which: y is the data vector; r is the block effect vector, considered as fixed, added to the general average; g is the genotypic effect vector, considered as random; i is the GxE (random) interaction effect vector; ε is the error or residue (random) vector; and X, Z, and W represent the incident matrices for these effects.

The harmonic mean of genetic values ($MHVG_i$) and the relative performance of the predicted genotypic values (PRVG) was obtained, respectively, by

Table 1. Flood-irrigated rice (*Oryza sativa*) cultivars used, with their respectively years of release, in the experimentation of 11 agricultural years, in different sites in the state of Rio Grande do Sul, Brazil.

Cultivar	Year	Crop year										
		2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	2015/2016
IAS 12-9 (Formosa)	1972											*
BR/IRGA 409[(1)]	1979	*	*	*	*	*	*	*	*	*	*	*
BR/IRGA 410	1980	*	*	*	*	*	*	*	*			*
BR/IRGA 411	1985											*
BR/IRGA 412	1986											*
BR/IRGA 413	1986											*
BR/IRGA 414[(1)]	1987											*
BRS 6 Chuí	1991	*	*	*	*	*						*
BRS 7 Taim	1991	*	*	*	*	*	*	*	*	*	*	*
BRS Ligeirinho	1995											*
BRS Agrisul	1995											*
BRS Bojuru	1997											*
BRS Atalanta	1999	*	*	*	*							*
BRS Firmeza	1999	*	*	*	*							*
BRS Pelota	2000	*	*	*	*	*						*
SCSBRS 113 - Tio Taka[(2)]	2004											*
BRS Fronteira	2005	*	*	*	*	*	*	*				*
BRS Querência	2005	*	*	*	*	*	*	*	*	*	*	*
BRSCIRAD 302[(3)]	2010						*					*
BRS Sinuelo CL	2010						*	*	*	*	*	*
BRS Pampa	2011						*	*	*	*	*	*
BRS 358	2015											*
BRS AG	2015											*
BRS Pampeira	2016									*	*	*
BRSCIRAD AH703 CL[(3)]	2017								*	*	*	*
Number of genotypes		9	9	9	9	7	8	7	7	7	7	25
Number of sites		2	6	7	7	6	3	5	6	7	4	7

[(1)]Cultivar released by Embrapa and IRGA (Instituto Rio Grandense do Arroz). [(2)]Cultivar released by Embrapa and Epagri (Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina). [(3)]Hybrid released by Embrapa and Cirad.

$$\mathrm{MHVG}_i = n\Big/\Big[\sum\nolimits_{j=1}^{n}\big(1/\mathrm{Vg}_{ij}\big)\Big] \text{ and}$$

$$\mathrm{PRVG}_i = (1/n)\times\Big[\sum\nolimits_{j=1}^{n}\big(\mathrm{Vg}_{ij}/\mu_i\big)\Big];$$

and the model which was considered simultaneously for yield, adaptability, and stability, obtained by harmonic mean of the relative performance of the genetic values (MHPRVG), was calculated by

$$\mathrm{MHPRVG}_i = n\Big/\sum\nolimits_{j=1}^{n}\big(1/\mathrm{PRVG}\big),$$

in which, n is the number of environments where the genotype i was evaluated; Vg_{ij} is the genotypic value of the genotype i in the environment j, expressed as the proportion of the average of this environment; and μ_j is the general mean of each environment j (Resende, 2016).

Results and Discussion

Grain yield, number of days to flowering, and plant height showed a large share of the total phenotypic variation ($\hat{\sigma}^2_f$) of genetic origin ($\hat{\sigma}^2_g$), which can be evidenced by the high estimated values of total genotypic effect and heritability ($\hat{h}^2_g$), even though these are considered traits of quantitative genetic inheritance (Table 2).

However, for the trait percentage of whole grains after milling, there was a high contribution of the GxE complex interaction (low-genotypic correlation between genotype x year x site) and low heritability. Grain quality traits are highly affected by the environment in the irrigated rice cropping (Cameron et al., 2008; Hakata et al., 2012; Lyman et al., 2013; Li et al., 2014; Xu et al., 2015).

In the comparative trials of cultivars, in order to have a good experimental reliability, the genetic and statistical approaches should show the proportion between the genetic and residual variations associated to the studied trait; therefore, the selective accuracy is the most indicated parameter (Resende & Duarte, 2007). Accuracies of 0.97, 0.98, 0.99, and 0.77 were observed for yield, cycle, height, and percentage of whole grains, respectively.

The high number of evaluated trials in different sites, during the 11 agricultural years, led to precise estimates of the genotypic value of the cultivars and of the GxE interaction effect. The presence of such interaction makes it difficult to recommend a single cultivar for all the producing environments; however, it allows of the recommendation of adapted cultivars to each environment. This accuracy can be verified by the estimates of the genetic and variance components (Table 2).

Based on the genotypic values and the measures of adaptability and stability obtained, the genetic potential for grain yield (G_i) of 'BRS Pampa' (9,837 kg ha^{-1}), 'BRSCIRAD 302' (9,247 kg ha^{-1}), 'BRS Pampeira' (9,216 kg ha^{-1}), and 'BRSCIRAD AH703 CL' (9,093 kg ha^{-1}) could be highlighted. These genotypes showed genetic potentials above 9,000 kg ha^{-1} (Table 3), and it should be noted that the predicted genetic values were validated by high accuracy.

Table 2. Estimates of variance components and genetic parameters for the traits grain yield (GY), days to flowering (DTF), plant height (PH), and percentage of whole grains after milling (WG) of 25 irrigate rice (*Oryza sativa*) cultivars, evaluated in 60 environments of the state of Rio Grande do Sul, Brazil[(1)].

Variance component[(1)]	Grain yield (kg ha^{-1})	DTF (days)	Plant height (cm)	WG (%)
$\hat{\sigma}^2_g$	1,787,804.963	75.644	39.733	4.704
$\hat{\sigma}^2_{ga}$	12,678.722	3.187	3.341	0.250
$\hat{\sigma}^2_{gl}$	273,379.473	0.622	0.620	0.111
$\hat{\sigma}^2_{gla}$	771,868.191	11.557	4.981	11.185
$\hat{\sigma}^2_e$	856,431.061	9.082	17.437	7.801
$\hat{\sigma}^2_f$	3,702,162.410	100.093	66.112	24.051
$\hat{h}^2_g$	0.483±0.040	0.756±0.060	0.601±0.050	0.196±0.030
$\hat{c}^2_{ga}$	0.003	0.032	0.051	0.010
$\hat{c}^2_{gl}$	0.074	0.006	0.009	0.005
$\hat{c}^2_{gla}$	0.208	0.115	0.075	0.465
$\hat{A}^c_g$	0.970	0.990	0.980	0.770
$\hat{r}_{gl}$	0.867	0.992	0.985	0.977
$\hat{r}_{ga}$	0.993	0.960	0.922	0.950
$\hat{r}_{gl\_a}$	0.868	0.992	0.986	0.978
$\hat{r}_{ga\_l}$	0.994	0.960	0.924	0.951
$\hat{r}_{gla}$	0.628	0.831	0.816	0.289
$\hat{\mu}$	7,718.2	89.0	94.2	60.6

[(1)] $\hat{\sigma}^2_g$, $\hat{\sigma}^2_{ga}$, $\hat{\sigma}^2_{gl}$, $\hat{\sigma}^2_{gla}$, $\hat{\sigma}^2_e$, $\hat{\sigma}^2_f$, are respectively the estimates of the genotypic variance, genotype x year interaction, genotype x site interaction, genotype x site x year interaction, residual variance and phenotypic individual; $\hat{h}^2_g$, estimate of the coefficient of heritability related to the individual plots of total genotypic effects; $\hat{c}^2_{ga}$ and $\hat{c}^2_{gl}$, respectively, estimates of coefficient of determination of the genotype x year interaction effects, and genotype x site interaction effects; $\hat{c}^2_{gla}$, estimate of the coefficient of heritability in the broad sense, at the level of averages of genotypes; $\hat{A}^c_g$, estimate of the accuracy of selection, at the level of averages of genotypes. The estimates $\hat{r}_{gl}$, $\hat{r}_{ga}$, $\hat{r}_{gl\_a}$, $\hat{r}_{ga\_l}$, $\hat{r}_{gla}$ are genotypic correlations respectively of: genotype x site; genotype x year; genotype x site with the year; genotype x year with the site; and of genotype x year x site; $\hat{\mu}$, estimate of general mean of the experiment.

As to the genotypic stability (MHVG), 'BR/IRGA 412', 'BRS Pampa', and 'BRS Agrisul' showed a stable behavior in the studied environments. The higher stability under conditions of environmental variations was obtained by 'BRSCIRAD 302' (Table 3), that is a hybrid released in 2010. This high-yield stability was expected because hybrids are less affected by adverse cultivation conditions. This was reported for 140 hybrid cultivars subjected to three levels of nitrogen (0, 60, and 120 kg ha^{-1}), in which positive heterosis for grain yield was observed, irrespectively of the tested environment (Young & Virmani, 1990).

Regarding the genotypic adaptability (PRVG), the cultivars that showed the highest genetic potential for yield were also considered more adapted to the cultivated regions in Rio Grande do Sul (Table 3). 'BRS Pampa', 'BRS Pampeira', 'BRSCIRAD AH703 CL', and 'BRSCIRAD 302' were quite productive and responsive to the cultivated conditions in Rio Grande do Sul.

The MHPRVG method, which is obtained by penalizing the genotypic instability effect and capitalizing by the favorable response of the genotype to the environment, allowed to discriminate the flood-irrigated rice cultivars considering, simultaneously, yield, genotypic adaptability, and stability (Table 3). Therefore, the outperformers were again 'BRS Pampa', 'BRS Pampeira', 'BRSCIRAD AH703 CL' and 'BRSCIRAD 302' that showed their greater potential for cultivation in lowland regions under flood-irrigated system. The high-yield potential of 'BRS Pampeira' had already been reported by Magalhães Júnior et al. (2017a).

The amplitude of fluctuation of genotypic responses, observed for each cultivar among environments, can be attributed to changes associated to cultivation years and sites within the year. The genetic parameters indicated three favorable and three unfavorable regions (Figure 1). The most favorable one was the Campanha region, with 10,389 kg ha^{-1} average yield,

Table 3. Predicted genotypic value ($\hat{G}_i$), selective accuracy ($\hat{r}_{\hat{g}g}$), genotypic stability (MHVG), genotypic adaptability (PRVG), and adaptability and stability of the genotypic values (MHPRVG), for the trait grain yield (kg ha^{-1}) of 25 irrigated rice (*Oryza sativa*) cultivars, evaluated in 60 environments in the state of Rio Grande do Sul, Brazil[1].

Cultivar	YL[1]	$\hat{r}_{\hat{g}g}$	Rº[2]	$\hat{G}_i$	Rº	MHVG	Rº	PRVG	Rº	MHPRVG
BRS Pampa	2011	0.97	1st	9837	3rd	9455	1st	1.302	1st	1.287
BRSCIRAD 302	2010	0.93	2nd	9247	1st	10280	4th	1.187	4th	1.177
BRS Pampeira	2016	0.96	3rd	9216	5th	8625	2nd	1.209	2nd	1.193
BRSCIRAD AH703 CL	2017	0.96	4th	9093	6th	8590	3rd	1.198	3rd	1.188
BR/IRGA 412	1986	0.91	5th	8783	2nd	9514	5th	1.144	5th	1.141
BRS 7 Taim	1991	0.97	6th	8641	9th	8322	6th	1.123	6th	1.117
BRS Pelota	2000	0.97	7th	8557	8th	8482	8th	1.108	8th	1.093
BRS Agrisul	1995	0.90	8th	8533	4th	9253	7th	1.113	7th	1.108
BR/IRGA 410	1980	0.97	9th	8377	12th	8070	9th	1.080	10th	1.070
BRS Fronteira	2005	0.97	10th	8280	11th	8122	11th	1.075	11th	1.066
BRS 358	2015	0.93	11th	8259	10th	8234	12th	1.074	9th	1.070
BRS Querência	2005	0.97	12th	8239	13th	7930	10th	1.075	12th	1.060
BR/IRGA 409	1979	0.97	13th	8185	14th	7909	13th	1.066	13th	1.060
BRS Sinuelo CL	2010	0.97	14th	8058	16th	7589	14th	1.056	14th	1.047
BR/IRGA 413	1986	0.91	15th	7963	7th	8563	15th	1.035	15th	1.026
BRS 6 Chuí	1991	0.97	16th	7779	15th	7806	16th	1.012	16th	1.002
BRS AG	2015	0.93	17th	7290	19th	6914	17th	0.935	17th	0.905
BR/IRGA 414	1987	0.90	18th	6765	17th	7273	18th	0.874	18th	0.872
IAS 12-9 (Formosa)	1972	0.91	19th	6689	18th	7005	20th	0.864	20th	0.839
BRS Firmeza	1999	0.96	20th	6672	20th	6538	19th	0.867	19th	0.845
BRS Bojuru	1997	0.91	21st	5958	21st	6273	21st	0.764	21st	0.753
SCSBRS 113 - Tio Taka	2004	0.88	22nd	5831	23rd	5826	23rd	0.733	23rd	0.710
BRS Atalanta	1999	0.96	23rd	5679	24th	5766	22nd	0.748	22nd	0.721
BR/IRGA 411	1985	0.91	24th	5574	22nd	5856	24th	0.715	24th	0.701
BRS Ligeirinho	1995	0.90	25th	5067	25th	5275	25th	0.649	25th	0.629

[1]YL, year of cultivar release. [2]Rº, ranking of the cultivars, according to the parameters of the analyses.

and an environmental index of +2,344 kg ha^{-1}; and the least favorable was the Depressão Central region, with an average yield of 6,752 kg ha^{-1}, and an environmental index of -1,293 kg ha^{-1}. Slightly different responses were reported in experiments performed in the regions Depressão Central, Fronteira Oeste, Planície Costeira Externa and Interna, and Zona Sul, showing average yields of 7,938, 9,774, 8,501, 8,314, and 9,759 kg ha^{-1}, respectively (Rosa et al., 2015). These contrasting results can be explained by the distinction in the group of evaluated cultivars in each study, which shows the importance of these GxE studies to define an agricultural zoning, with the purpose of recommending regionalized cultivars and selecting trial sites.

It is also important to verify the response as for the genotypic yield of cultivars in favorable and

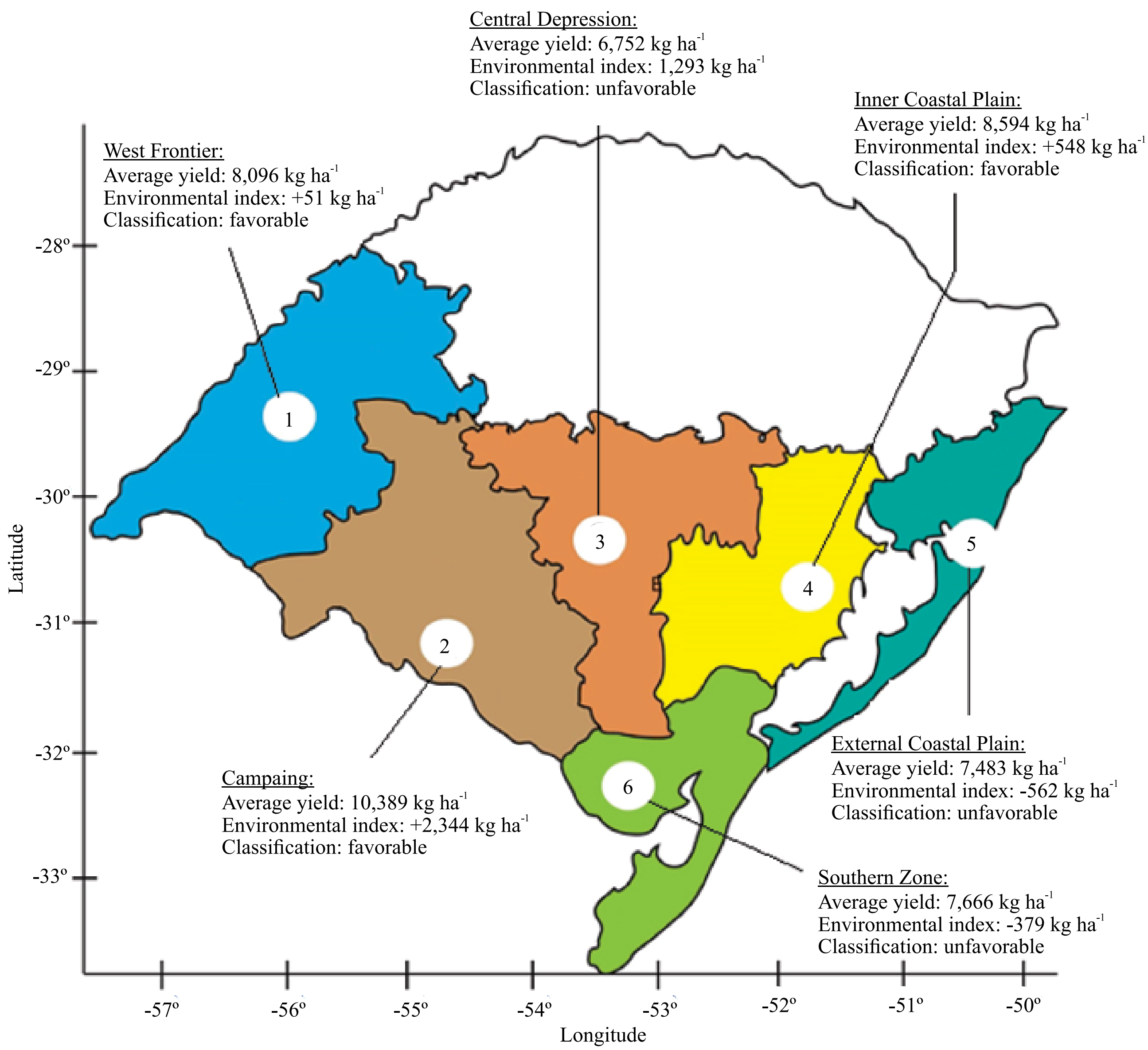

Figure 1. Average yield, environmental index, and classification of irrigated rice (*Oryza sativa*) cultivars conducted in 11 harvest seasons, in the six rice regions of the state of Rio Grande do Sul, Brazil.

unfavorable environmental conditions (Table 4). In favorable environments, three highly responsive cultivars stood out, with yields higher than 10,000 kg ha^{-1}: 'BRS Pampa' (10,593 kg ha^{-1}), 'BRS Pampeira' (10,423 kg ha^{-1}), and 'BRS Pelota' (10,105 kg ha^{-1}). Besides these, several others showed satisfactory yield potentials under favorable cultivation conditions, with general genotypic means of 8,667 kg ha^{-1}. However, in cultivation environments considered unfavorable, the genotypic mean of the cultivars was much lower (7,298 kg ha^{-1}), and only 'BRS Pampa' displayed yield above 9,000 kg ha^{-1}. This small difference in genotypic yield ($\Delta\hat{G}_i$), when different cultivated conditions were compared, shows the excellent yield capacity associated to a good stability of this cultivar regarding grain yield, which makes 'BRS Pampa' indicated for cultivation in all rice regions of the state.

Genotypic estimates of favorable agronomic attributes for rice improvement are displayed (Table 5). Among the cultivars released after the end of the 1970s, only 'BR/IRGA 411' and 'BRS AG' were taller than 100 cm. It should be noted that 'BRS AG' was developed and released recently for ethanol production or animal feed (Magalhães Júnior et al., 2017b).

The discovery of the *sd-1 gene*, responsible for the semidwarf rice, allowed breeders to include this phenotype (associated with other agronomic traits of interest) into flood-irrigated rice cultivars leading to increased yield potential, especially 'BR/IRGA 409' and 'BR/IRGA 410' in Rio Grande do Sul (Streck et al., 2017). In this context, it is verified that a large share of the cultivars released by the Embrapa breeding program, after the two mentioned ones, have aimed at lower-stature genotypes.

Table 4. Classification of the cultivars (Rº) according to the response of predicted genotypic values for grain yield (kg ha^{-1}) and the yield difference of each cultivar, on average, in favorable and unfavorable environmental conditions ($\Delta\hat{G}_i$) for 25 irrigated rice (*Oryza sativa*) cultivars in the state of Rio Grande do Sul, Brazil.

Cultivar	Rº	Favorable (kg ha^{-1})	Rº	Unfavorable (kg ha^{-1})	Rº	$\Delta\hat{G}_i$ (kg ha^{-1})
BRS Pampa	1st	10,593	1st	9,436	15th	1,157
BRS Pampeira	2nd	10,423	3rd	8,651	8th	1,772
BRS Pelota	3rd	10,105	6th	8,185	4th	1,920
BR/IRGA 410	4th	9,980	9th	7,946	2nd	2,033
BRS 7 Taim	5th	9,895	8th	8,109	7th	1,786
BRSCIRAD 302	6th	9,741	2º	8,971	23rd	771.0
BRS Querência	7th	9,600	14th	7,776	5th	1,824
BRSCIRAD AH703 CL	8th	9,595	4th	8,517	16th	1,078
BR/IRGA 412	9th	9,559	5th	8,488	17th	1,072
BRS Agrisul	10th	9,528	7th	8,159	14th	1,369
BRS Fronteira	11th	9,352	10th	7,873	11th	1,478
BR/IRGA 409	12th	9,272	13th	7,792	10th	1,480
BRS 6 Chuí	13th	9,097	16th	7,378	9th	1,719
BRS 358	14th	8,757	11th	7,844	20th	913.0
BRS Sinuelo CL	15th	8,546	12th	7,812	24th	734.0
BR/IRGA 413	16th	8,525	15th	7,728	21st	797.0
BRS Firmeza	17th	7,955	20th	6,136	6th	1,819
BR/IRGA 414	18th	7,824	19th	6,348	12th	1,476
BRS AG	19th	7,730	17th	6,959	22nd	771.0
BRS Atalanta	20th	7,587	23rd	5,204	1st	2,383
IAS 12-9 (Formosa)	21st	7,073	18th	6,496	25th	577.0
SCSBRS 113 - Tio Taka	22nd	6,999	24th	5,061	3rd	1,938
BRS Bojuru	23rd	6,605	21st	5,668	19th	937.0
BR/IRGA 411	24th	6,281	22th	5,260	18th	1,022
BRS Ligeirinho	25th	6,044	25th	4,656	13th	1,388
Average	-	8,667	-	7,298	-	1,368

As for the trait days to flowering (DTF), most of the released cultivars were observed as displaying cycles ranging from early (between 80 and 90 DTF) to medium (between 91 and 100 DTF). However, 'BRS Ligeirinho' and 'BRS Atalanta' display super-early cycles (<80 DTF), which puts them as alternatives to specific cultivation conditions. At the other extreme, 'SCSBRS 113 - Tio Taka', obtained by recurrent selection (Rangel et al., 2007), showed a very late cycle (>101 days to flowering) for the cultivation conditions of Rio Grande do Sul. This cultivar was developed and released specially for the State of Santa Catarina. The long cycle until flowering can explain the low-yield potential showed by this cultivar in the state of Rio Grande do Sul (Table 3). Rio Grande do Sul has a higher probability of low temperatures (Steinmetz et al., 2003) and low luminosity (Klering et al., 2008) at late February and early March.

Grain quality is also a widely considered parameter for the flood-irrigated rice improvement, as it determines the market value of the cereal. In this sense, the majority of the cultivars recently released by the breeding program have a high index of whole grains after milling, which is the main trait referring to rice industrial quality (Table 5). It should be noted that 'BRS Pampa', 'BRS Pampeira' and 'BRSCIRAD 302' which were outstanding for grain yield, also showed high-grain quality with, respectively, 62.19, 60.28 and 60.91% whole grains after milling.

Therefore, it can be considered that a wide range of flood-irrigated rice cultivars, developed by the Embrapa breeding program, shows good agronomic attributes for different cultivation conditions in the state of Rio Grande do Sul.

Table 5. Estimates of predicted genotypic values ($\hat{G}_i$) and selective accuracy ($\hat{r}_{\hat{g}g}$) for the traits number of days to flowering (DTF), plant height (PH), and percentage of whole grains after milling (WG) of 25 irrigated rice (*Oryza sativa*) cultivars, evaluated in 60 environments in the state of Rio Grande do Sul, Brazil.

Cultivar	Release	DTF (days)		Plant height (cm)		WG (%)	
		$\hat{G}_i$	$\hat{r}_{\hat{g}g}$	$\hat{G}_i$	$\hat{r}_{\hat{g}g}$	$\hat{G}_i$	$\hat{r}_{\hat{g}g}$
BRS Ligeirinho	1995	69	0.94	83.23	0.94	60.50	0.70
BRS Atalanta	1999	72	0.97	91.54	0.97	58.99	0.88
BR/IRGA 414	1987	81	0.94	92.72	0.94	62.40	0.73
BRS 6Chuí	1991	81	0.97	90.32	0.97	60.80	0.92
BRS Querência	2005	81	0.98	96.01	0.98	59.05	0.94
BRS Firmeza	1999	84	0.97	89.13	0.97	61.99	0.90
BRSCIRAD AH703 CL	2017	84	0.97	93.02	0.97	62.85	0.88
BRS Pampa	2011	85	0.97	95.33	0.97	62.19	0.92
BRS 358	2015	88	0.96	86.42	0.96	62.04	0.78
BRS Pelota	2000	89	0.97	95.58	0.97	60.51	0.92
BR/IRGA 410	1980	91	0.98	96.81	0.98	61.66	0.94
BRS Sinuelo CL	2010	91	0.97	86.51	0.97	61.45	0.92
BRSCIRAD 302	2010	91	0.96	98.31	0.96	60.91	0.82
BR/IRGA 411	1985	92	0.94	108.83	0.94	58.20	0.75
BRS AG	2015	92	0.96	109.50	0.96	56.21	0.78
BR/IRGA 412	1986	92	0.94	91.51	0.94	60.89	0.75
IAS 12-9 (Formosa)	1972	92	0.94	104.55	0.94	58.17	0.74
BRS 7 Taim	1991	92	0.98	89.60	0.98	61.14	0.94
BRS Agrisul	1995	93	0.94	94.03	0.94	56.91	0.75
BR/IRGA 413	1986	93	0.94	98.38	0.94	62.86	0.75
BRS Bojuru	1997	93	0.94	92.98	0.94	59.49	0.75
BR/IRGA 409	1979	94	0.98	93.95	0.98	62.49	0.94
BRS Fronteira	2005	94	0.97	95.08	0.97	63.32	0.93
BRS Pampeira	2016	99	0.97	96.07	0.97	60.28	0.88
SCSBRS 113 - Tio Taka	2004	114	0.94	86.05	0.94	61.16	0.70

Conclusions

1. 'BRS Pampa', 'BRS Pampeira', and 'BRSCIRAD 302' rice (*Oryza sativa*) show, simultaneously, high-genotypic grain yield, adaptability, stability, good agronomic attributes and good whole-grain yield after milling.

2. 'BRSCIRAD 302' and 'BRS Pampa' show high-yield stability, which makes them suitable for cultivation in all rice regions of Rio Grande do Sul; and 'BRS Pampeira' is a highly responsive cultivar to environmental improvements and is, therefore, indicated for high-technology conditions.

Acknowledgments

To Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes), for grants and fellowships; and to Embrapa Clima Temperado, for technical, scientific, and infrastructure support.

References

BALESTRE, M.; SANTOS, V.B. dos; SOARES, A.A.; REIS, M.S. Stability and adaptability of upland rice genotypes. **Crop Breeding and Applied Biotechnology**, v.10, p.357-363, 2010. DOI: 10.1590/S1984-70332010000400011.

BASTOS, I.T.; BARBOSA, M.H.P.; RESENDE, M.D.V. de; PETERNELLI, L.A.; SILVEIRA, L.C.I. da; DONDA, L.R.; FORTUNATO, A.A.; COSTA, P.M. de A.; FIGUEIREDO, I.C.R. de. Avaliação da interação genótipo x ambiente em cana-de-açúcar via modelos mistos. **Pesquisa Agropecuária Tropical**, v. 37, p.195-203, 2007.

BORGES, V.; SOARES, A.A.; REIS, M.S.; RESENDE, M.D.V.; CORNÉLIO, V.M.O.; LEITE, N.A.; VIEIRA, A.R. Desempenho genotípico de linhagens de arroz de terras altas utilizando metodologia de modelos mistos. **Bragantia**, v.69, p.833-841, 2010. DOI: 10.1590/S0006-87052010000400008.

CAMERON, D.K.; WANG, Y.J.; MOLDENHAUER, K.A. Comparison of physical and chemical properties of medium-grain rice cultivars grown in California and Arkansas. **Journal of Food Science**, v.73, p.c.72-78, 2008. DOI: 10.1111/j.1750-3841.2007.00631.x.

COLOMBARI FILHO, J.M.; RESENDE, M.D.V. de; MORAIS, O.P. de; CASTRO, A.P. de; GUIMARÃES, É.P.; PEREIRA, J.A.; UTUMI, M.M.; BRESEGHELLO, F. Upland rice breeding in Brazil: a simultaneous genotypic evaluation of stability, adaptability and grain yield. **Euphytica,** v.192, p.117-129, 2013. DOI: 10.1007/s10681-013-0922-2.

FARIA, S.V.; LUZ, L.S.; RODRIGUES, M.C.; CARNEIRO, J.E. de S.; CARNEIRO, P.C.S.; DELIMA, R.O. Adaptability and stability in commercial maize hybrids in the southeast of the State of Minas Gerais, Brazil. **Revista Ciência Agronômica**, v.48, p.347-357, 2017. DOI: 10.5935/1806-6690.20170040.

HAKATA, M.; KURODA, M.; MIYASHITA, T.; YAMAGUCHI, T.; KOJIMA, M.; SAKAKIBARA, H.; MITSUI T.; YAMAKAWA, H. Suppression of α-amylase genes improves quality of rice grain ripened under high temperature. **Plant Biotechnology Journal**, v.10, p.1110-1117, 2012. DOI: 10.1111/j.1467-7652.2012.00741.x.

HAO, W.; LIN, H.-X. Toward understanding genetic mechanisms of complex traits in rice. **Journal of Genetics and Genomics**, v.37, p.653-666, 2010. DOI: 10.1016/S1673-8527(09)60084-9.

KLERING, E.V.; FONTANA, D.C., BERLATO, M.A.; CARGNELUTTI FILHO, A. Modelagem agrometeorológica do rendimento de arroz irrigado no Rio Grande do Sul. **Pesquisa Agropecuária Brasileira**, v.43, p.549-558, 2008. DOI: 10.1590/S0100-204X2008000500001.

LI, Y.; FAN, C.; XING, Y.; YUN, P.; LUO, L.; YAN, B.; PENG, B.; XIE, W.; WANG, G.; LI, X.; XIAO, J.; XU, C.; HE, Y. Chalk5 encodes a vacuolar H^+-translocating pyrophosphatase influencing grain chalkiness in rice. **Nature Genetics**, v.46, p.398-404, 2014. DOI: 10.1038/ng.2923.

LYMAN, N.B.; JAGADISH, K.S.V.; NALLEY, L.L.; DIXON, B.L.; SIEBENMORGEN, T. Neglecting rice milling yield and quality underestimates economic losses from high-temperature stress. **PLoS ONE**, v.8, e72157, 2013. DOI: 10.1371/journal.pone.0072157.

MAGALHÃES JÚNIOR, A.M. de; MORAIS, O.P. de; FAGUNDES, P.R.R.; COLOMBARI FILHO, J.M.; FRANCO, D.F.; CORDEIRO, A.C.C.; PEREIRA, J.A.; RANGEL, P.H.N.; MOURA NETO, F.P.; STRECK, E.A.; AGUIAR, G.A.; FACCHINELLO, P.H.K. BRS Pampeira: new irrigated rice cultivar with high yield potential. **Crop Breeding and Applied Biotechnology**, v.17, p.78-83, 2017a. DOI: 10.1590/1984-70332017v17n1c13.

MAGALHÃES JÚNIOR, A.M.; FAGUNDES, P.R.R.; FRANCO, D.F.; MORAIS, O.P. de; SIQUEIRA, F.G.; STRECK, E.A.; AGUIAR, G.A.; FACCHINELLO, P.H.K. BRS AG: first cultivar of irrigated rice used for alcohol production or animal feed. **Crop Breeding and Applied Biotechnology**, v.17, p.72-77, 2017b. DOI: 10.1590/1984-70332017v17n1c12.

MENDES, F.F.; GUIMARÃES, L.J.M.; SOUZA, J.C.; GUIMARÃES, P.E.O.; PACHECO, C.A.P.; MACHADO, J.R. de A.; MEIRELLES, W.F.; SILVA, A.R. da; PARENTONI, S.N. Adaptability and stability of maize varieties using mixed model methodology. **Crop Breeding and Applied Biotechnology**, v.12, p.111-117, 2012. DOI: 10.1590/S1984-70332012000200003.

RANGEL, P.H.N.; BRONDANI, C.; MORAIS, O.P. de; SCHIOCCHET, M.A.; BORBA, T.C. de O.; RANGEL, P.N.; BRONDANI, R.P.V.; YOKOYAMA, S.; BACHA, R.E.; ISHY, T. Establishment of the irrigated rice cultivar SCSBRS Tio Taka by recurrent selection. **Crop Breeding and Applied Biotechnology**, v.7, p.103-110, 2007. DOI: 10.12702/1984-7033.v07n01a17.

RESENDE, M.D.V. de. Software Selegen-REML/BLUP: a useful tool for plant breeding. **Crop Breeding and Applied Biotechnology**, v.16, p.330-339, 2016. DOI: 10.1590/1984-70332016v16n4a49.

RESENDE, M.D.V. de; DUARTE, J.B. Precisão e controle de qualidade em experimentos de avaliação de cultivares. **Pesquisa Agropecuária Tropical**, v.37, p.182-194, 2007.

RESENDE, M.D.V. **Matemática e estatística na análise de experimentos e no melhoramento genético**. Colombo: Embrapa Florestas, 2007. 561p.

ROSA, H.T.; WALTER, L.C.; STRECK, N.A.; DE CARLI, C.; RIBAS, G.G.; MARCHESAN, E. Simulação do crescimento e produtividade de arroz no Rio Grande do Sul pelo modelo SimulArroz. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v.19, p.1159-1165, 2015. DOI: 10.1590/1807-1929/agriambi.v19n12p1159-1165.

SILVA, G.A.P.; CHIORATO, A.F.; GONÇALVES, J.G.R.; PERINA, E.F.; CARBONELL, S.A.M. Análise da adaptabilidade e estabilidade de produção em ensaios regionais de feijoeiro para o Estado de São Paulo. **Revista Ceres**, v.60, p.59-65, 2013. DOI: 10.1590/S0034-737X2013000100009.

SILVA, G.O. da; CARVALHO, A.D.F. de; VIEIRA, J.V.; BENIN, G. Verificação da adaptabilidade e estabilidade de populações de cenoura pelos métodos AMMI, GGE biplot e REML/BLUP. **Bragantia,** v.70, p.494-501, 2011. DOI: 10.1590/S0006-87052011005000003.

STEINMETZ, S.; ASSIS, F.N. de; BURIOL, G.A.; ESTEFANEL, V.; AMARAL, A.G.; FERREIRA, J.S.A. Mapeamento das probabilidades de ocorrência de temperaturas mínimas do ar, durante o período reprodutivo do arroz irrigado, no Estado do Rio Grande do Sul. **Revista Brasileira de Agrometeorologia**, v.11, p.169-179, 2003.

STRECK, E.A.; AGUIAR, G.A.; MAGALHÃES JÚNIOR, A.M. de; FACCHINELLO, P.H.K.; OLIVEIRA, A.C. de. Variabilidade fenotípica de genótipos de arroz irrigado via análise multivariada. **Revista Ciência Agronômica**, v.48, p.101-109, 2017. DOI: 10.5935/1806-6690.20170011.

TORRES, F.E.; TEODORO, P.E.; SAGRILO, E.; CECCON, G.; CORREA, A.M. Interação genótipo x ambiente em genótipos de feijão-caupi semiprostrado via modelos mistos. **Bragantia**, v.74, p.255-260, 2015. DOI: 10.1590/1678-4499.0099.

XU, Q.; CHEN, W.; XU, Z. Relationship between grain yield and quality in rice germplasms grown across different growing areas. **Breeding Science**, v.65, p.226-232, 2015. DOI: 10.1270/jsbbs.65.226.

YOUNG, J.; VIRMANI, S.S. Heterosis in rice over environments. **Euphytica**, v.51, p.87-93, 1990. DOI: 10.1007/BF00022896.

Received on March 22, 2017 and accepted on December 19, 2017