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ORIGINAL ARTICLE

Understanding nutrient competition between *Echinochloa* spp. and *Oryza sativa* L.

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Abstract

Weed competition in southern Brazil is one of the main limiting factors for *Oryza sativa* L. (flooded rice) yield. *Echinochloa* spp. (barnyardgrass) occurs at a high frequency. Although the potential for weed interference in this cereal is well known, there is little information available about the impact of nutrient competition on rice. Thus, this study aimed to evaluate the relationship between the increase of the barnyardgrass population and the development and nutrition of flooded rice plants at different stages of development. The treatments consisted of growing populations of barnyardgrass competing with the crop from stage V4, which were: 0, 1, 6, 13, 100 and 200 plants · m^{-2}. The experimental design was randomized blocks with two replications, and the experimental units were plots 1.53 m wide by 5 m long. Plant biomass, nutrient uptake and loss of productivity were determined with three replications. An increase in the barnyardgrass population reduced the dry mass of rice leaves and stems, regardless of the evaluation period and the vegetative or reproductive period. Barnyardgrass plants had a significant impact on the reduced grain yield of a flooded rice crop, mainly due to high nutrient competitiveness, especially N in the vegetative period and K in the reproductive period. Barnyardgrass caused a loss of yield by unit · m^{-2} of 1.13%. The competition for N between rice and barnyardgrass plants was higher in the vegetative period, while for K, Ca and Mg the highest competition occurred in the reproductive period.

Keywords: barnyardgrass, flooded rice, interference, mineral nutrition

Introduction

Weed interference with agricultural crops is a major cause of crop productivity loss, since there is competition for environmental resources such as water, light and nutrients (Agostinetto *et al*. 2008). In the flooded rice crop (*Oryza sativa* L.) between 46 and 60% yield reduction can occur depending on the competing population. It can reach 96% when control strategies are not employed (Chauhan and Johnson 2011). Among the main measures that can reduce the effect of crop competition with weeds is the adoption of cultural management practices, such as the use of more competitive cultivars (Chauhan 2012).

Mathematical models are widely used in several crops to evaluate weed competition and yield loss (Fleck *et al*. 2007). For this, we used various types of equations to predict the ecological behavior of crop and weed. The use of linear models can serve to evaluate plant morphological characters regarding competition with weeds (McDonald *et al*. 2010). In this sense, one of the main species that infests the cultivation of flooded rice is barnyardgrass (*Echinochloa* spp.). It belongs to the poaceae family and presents a C4 photosynthetic pathway, with high growth rates, and high competitive potential (Chauhan and Abugho 2013).

Due to the morphological and ecophysiological similarity of barnyardgrass with flooded rice, it occupies the same niche and, consequently, is highly competitive for the resources available in the environment (Agostinetto *et al.* 2008). In addition, weed resistance to herbicides occurs (Heap 2019). This makes it difficult to control and favors its occurrence in production areas. In rice cultivation, competition with barnyardgrass can lead to reduced height, leaf area and yield (Agostinetto *et al.* 2008; Galon *et al.* 2007; Rezaeieh *et al.* 2015).

Competition for nutrients is one of the main weed competition factors that most limits crop development (Cury *et al.* 2012). In southern Brazil, there are high levels of grain yield of flooded rice crop associated with the occurrence of soils poor in natural fertility, if there is poor soil is there low yield of rice especially with low levels of organic matter which has a lower nitrogen (N) supply capacity. Due to the low availability of phosphorus (P) and potassium (K), these main macronutrients are required via fertilization (Genro Junior *et al.* 2010). In this sense, weeds generally have a higher competitive nutrient absorption capacity than cultivated crops which can cause the cultivated plants to have low nutritional levels, generate physiological dysfunctions and consequently affect crop development and grain yield. However, there is little knowledge about the main macronutrients (N, P and K) and also the secondary macronutrients such as calcium (Ca) and magnesium (Mg) in rice plants that are most affected by competition with barnyardgrass.

Weedy rice (*Oryza sativa* L.) can take 63% of fertilized N to transform into biomass at a competition condition with flooded rice (Burgos *et al.* 2006). Moreover, competition with barnyardgrass reduced the biomass of different rice cultivars by around 30% (Agostinetto *et al.* 2008), confirming the competitiveness of weed. Therefore, the objective of the present study was to evaluate the relationship between the increase of the barnyardgrass population and the development and nutrition of flooded rice plants at different developmental stages.

Materials and Methods

Experimental design

The experiment was carried out during the 2016/17 crop season, at the Rice Experimental Station of the Rio Grande do Sul Rice Institute (EEA/IRGA), in Cachoeirinha (29°57'S, 51°5'W, and elevation 17 m), Rio Grande do Sul (RS), Brazil. The soil of the experimental area is classified as a Dystrophic Haplic Gleysol (Dos Santos *et al.* 2018). The local climate, as defined by the Köppen classification, is Cfa, characterized as humid subtropical with hot summers and no defined dry season (Kuinchtner and Buriol 2001). The experimental design used was randomized blocks with two replications. The experimental units were composed of nine 6 meter long rows with 17 cm spacing. The rice was grown in the conventional system. It was sown on November 23, 2016, at a density of 100 kg · ha^{-1}, using the cultivar IRGA 424 CL. The fertilization used was 166, 68 and 108 kg · ha^{-1} of N, P_2O_5 and K_2O, respectively. Phosphorus and potassium were applied at sowing and N was applied 16, 100 and 50 kg · ha^{-1} at sowing, and at the phenological stages of V3 and R0, respectively (Technical Meeting of Flooded Rice 2018).

The treatment consisted of growing populations of barnyardgrass based on the natural weed infestation present in the area: 0, 1, 6, 13, 100 and 200 plants · m^{-2}. The barnyardgrass populations were determined when the rice plants were in stage V4. The natural infestation in the area had a predominance of *Echinochloa crus-galli* (L.) Beauv. with a low presence of *E. colona* L. Cyhalofop-butyl at a dose of 152 g i.a. · ha^{-1} was applied to define the populations, and the barnyardgrass plants were protected from the different treatments with plastic cups in the smallest populations and brown wax paper in the largest populations (Westendorff *et al.* 2014). In the control treatment (zero plants of barnyardgrass · m^{-2}) the herbicide was applied over the total area. To control Cyperaceae plants present in the experimental area, the herbicide pyrazosulfurom-methyl (20 g i.a. · ha^{-1}) was applied to all experiments. Immediately after the herbicide application, nitrogen fertilization at 90 kg N · ha^{-1} was carried out and flood irrigation started.

Variables analyzed and data collection

The variables analyzed were dry matter of the aerial part (DMAP), nutritional composition of different plant parts and grain yield, characterized as three replications. The grain yield variable was expressed in kg · ha^{-1}, consisting of the harvesting result of the 3.06 m^2 plot useful area and grain moisture correction to 13%. Samples of both species were collected in an area of 0.25 m^2 at 43, 63 and 93 days after emergence (DAE), which coincided with the development stages V6, R1 and R4 (Counce *et al.* 2000). The samples were separated into leaves and stalks and then dried in an oven with forced air circulation at 60°C for 72 h, and later weighed on an analytical balance, and the data converted to Mg · ha^{-1}.

Dry samples of the aerial part of the plants were used to evaluate the nutritional composition of rice and barnyardgrass. For this purpose, acid digestion (sulfuric acid and hydrogen peroxide) of the plant tissue was performed and subsequently nitrogen was determined by micro Kjeldahl distillation and later titration. Phosphorus was determined by colorimetry, potassium by flame photometry while calcium and magnesium were determined by atomic absorption spectrophotometry (Tedesco *et al.* 1995). For the calculation of the nutrient amounts extracted from rice and barnyardgrass plants, the nutrient and dry matter contents in the different stages were considered, according to the equation:

$$ne = a.\,nc,$$

where: *ne* – the amount of nutrients extracted from kg · ha^{-1}; *a* – dry matter of the aerial part (DMAP); *nc* – the nutrient content in rice and barnyardgrass plants.

Experimental analysis

The DMAP and nutrient content data were adjusted by linear regression model using Sigma Plot 12.3 software (Systat INC, United Kingdom) according to the equation:

$$y = a + b.\,x,$$

where: *y* – DMAP (Mg · ha^{-1}) or *ne* (kg · ha^{-1}); *x* – the population of barnyardgrass; *a* – the intercept; *b* – the angular coefficient.

From the grain yield data the percentage losses were calculated in relation to the plots maintained without infestation (control) in a population of up to 200 plants · m^{-2}, according to the equation:

$$L = \frac{Ya - Yb}{Ta} \times 100\ [\%],$$

where: *L* – crop yield loss compared to control; *Ya* and *Yb* – crop yields without or with barnyardgrass, respectively.

The relationships between rice yield percentage losses and barnyardgrass population were calculated using the non-linear regression model derived from rectangular hyperbole, as proposed by Cousens (1985), as follows:

$$Y_L = (i.D)(1 + \beta.D)^{-1},$$

$$\beta = i.a^{-1},$$

where: Y_L – the yield loss in percentage related to control treatment (without weed competition); *D* – the barnyardgrass weed density in plants · m^{-2}; *i* – the yield loss in percentage of rice grains per unit of weed when weed density approaches zero; *a* – the yield loss in percentage of rice grains when the weed density approaches infinity; *β* – the competitiveness of the weed (Cousens 1985; Mamun 2014). In addition, the inverse of the *β* (*s*) was calculated, which represents the density of weeds that reduce yield by 50%, as described below:

$$s = 1.\beta^{-1}.$$

Data were adjusted to the model using the Proc Nlin procedure of SAS Software. For this procedure, the Gauss-Newton method was used, which, by successive interactions, estimated the values of the parameters in which the sum of the squares of the deviations from the observations in relation to the adjusted values was minimal (Ratkowsky 1983). The value of the *F* statistic ($p \le 0.05$) was used as a criterion for data analysis of the model. The acceptance criterion of the hyperbolic model was based on the highest value the coefficient of determination (R^2) and the lowest value of the mean square of the residue (*QMR*) (Westendorff *et al.* 2014). The graphics were generated using the Sigma Plot 10.0 program (Sigma Plot 2006).

Results

Leaf and stem dry matter accumulation and productivity as a function of competition

The results of univariate analysis of variance showed a significant difference for the analyzed variables. For the linear polynomial regression model there was an adjustment for the leaf and stem DMAP variables for the evaluated times, with a significance of parameter *b* for most curves, and coefficient of determination (R^2) between 0.50 and 0.95 (Table 1, Figs. 1 and 2). For the grain yield loss in relation to the control there was an adjustment to the rectangular hyperbole model.

Similar behavior for all evaluation periods was seen for DMAP in rice and barnyardgrass, whose increase in dry matter was observed for weed, whereas for the crop it decreased as the population of barnyardgrass plants increased by area. This result was confirmed by the value of the linear coefficient, which presented negative and positive signs for rice and barnyardgrass, respectively, for all equations, being significant in most cases.

For the DMAP of barnyardgrass leaves and stems at 63 and 93 DAE (Figs. 1A and B), respectively, no significance was found for the angular coefficient, which indicates the absence of a tendency of growth or decrease for these variables. The lower slope of the curve at 93 DAE was also observed for DMAP of barnyardgrass leaves, according to the increase of weed population by area (Fig. 1C).

Mineral nutrition of rice and barnyardgrass

Nutrient amounts extracted from both leaves and stems of rice plants were significantly impacted by the population increase of barnyardgrass plants per unit area. There was an increase in the amount of nutrients extracted by barnyardgrass and a linear reduction in the amount of nutrients extracted by flooded rice as competition increased (Tables 2–6; Figs. 4–7).

For N (Fig. 4 and Table 2), it was observed that the most intense competition for this element occurred in the vegetative period (43 DAE). The increment of barnyardgrass plant · m^{-2} meant a reduction

Table 1. Linear regression parameters of dry mass of aerial part (DMAP) of leaves and stems of rice in relation to the barnyardgrass population [plants · m^{-2}], 43, 63 and 93 days after emergence (DAE)

Species	Days after emergence	Parameters		
		a	*b*	R^2
Dry mass of leaves [Mg · ha^{-1}]				
Barnyardgrass	43	–0.095	0.0098**	0.91
Rice		1.623	–0.0068**	0.78
Barnyardgrass	63	0.6970	0.0060	0.11
Rice		3.5715	–0.0136*	0.55
Barnyardgrass	93	–0.019	0.0034*	0.71
Rice		3.6509	–0.0137**	0.93
Dry mass of leaves [Mg · ha^{-1}]				
Barnyardgrass	43	0.0522	0.0167**	0.95
Rice		0.9189	–0.0039**	0.75
Barnyardgrass	63	–0.3893	0.0316**	0.82
Rice		2.5456	–0.0099*	0.50
Barnyardgrass	93	0.0479	0.0194	0.51
Rice		5.525	–0.0217**	0.91

*p value below 0.05; **p value below 0.01

Table 2. Linear regression parameters of nitrogen nutritional content [kg · ha^{-1}] of leaves and stems of rice in relation to the barnyardgrass population [plants · m^{-2}], in 43, 63 and 93 days after emergence (DAE)

Species	Days after emergence	Parameters		
		a	*b*	R^2
Nitrogen in leaves [kg · ha^{-1}]				
Barnyardgrass	43	–4.26	0.34**	0.85
Rice		91.76	–0.48**	0.73
Barnyardgrass	63	1.24	0.14	0.78
Rice		106.10	–0.07	0.04
Barnyardgrass	93	0.04	0.02	0.56
Rice		75.73	–0.27*	0.77
Nitrogen in stems [kg · ha^{-1}]				
Barnyardgrass	43	–2.93	0.30**	0.89
Rice		29.64	–0.15**	0.62
Barnyardgrass	63	0.54	0.09**	0.61
Rice		45.16	–0.15	0.19
Barnyardgrass	93	0.08	–0.37**	0.75
Rice		66.11	–0.30*	0.34

*p value below 0.05; **p value below 0.01

of 0.48 and 0.15 kg N · ha^{-1} kg on leaves and stems in rice plants, respectively. Also, the uptake of 0.64 kg N · ha^{-1} in barnyardgrass plants demonstrated a broad N extraction capacity by this weed. At 93 DAE the reduction of total N extraction in rice was 0.27 0.30 kg N · ha^{-1} in leaves and stems, respectively. The greatest competition for N was possibly due to the low availability of N in soil with 1.2% organic matter, a recurring

Table 3. Linear regression parameters of phosphorus nutritional content [kg · ha^{-1}] of leaves and stems of rice in relation to the barnyardgrass population [plants · m^{-2}], 43, 63 and 93 days after emergence (DAE)

Species	Days after emergence	Parameters		
		a	*b*	R^2
	Phosphorus in leaves [kg · ha^{-1}]			
Barnyardgrass	43	0.001	0.11**	0.62
Rice		2.64	–0.01	0.09
Barnyardgrass	63	–0.02	0.002**	0.90
Rice		2.19	0.001	0.02
Barnyardgrass	93	ns	ns	ns
Rice		7.01	–0.03	0.05
	Phosphorus in stems [kg · ha^{-1}]			
Barnyardgrass	43	0.04	0.008**	0.82
Rice		0.66	–0.003	0.34
Barnyardgrass	63	–0.19	0.01**	0.87
Rice		1.95	–0.002	0.03
Barnyardgrass	93	0.05	0.004**	0.72
Rice		3.90	0.003	0.002

ns – non-fitted to a linear regression; **p* value below 0.05; ***p* value below 0.01

Table 4. Linear regression parameters of potassium nutritional content [kg · ha^{-1}] of leaves and stems of rice in relation to the barnyardgrass population [plants · m^{-2}], in 43, 63 and 93 days after emergence (DAE)

Species	Days after emergence	Parameters		
		a	*b*	R^2
	Potassium in leaves [kg · ha^{-1}]			
Barnyardgrass	43	–0.23	0.11**	0.79
Rice		39.47	–0.14*	0.30
Barnyardgrass	63	–0.89	0.09	0.90
Rice		98.18	–0.02	0.007
Barnyardgrass	93	0.06	0.01	0.80
Rice		83.95	–0.38	0.52
	Potassium in stems [kg · ha^{-1}]			
Barnyardgrass	43	–0.48	0.18**	0.92
Rice		25.29	–0.11**	0.48
Barnyardgrass	63	–0.89	0.09**	0.90
Rice		76.24	–0.12**	0.33
Barnyardgrass	93	1.1	0.14**	0.77
Rice		156.87	–0.68**	0.43

**p* value below 0.05; ***p* value below 0.01

condition in flooded rice cultivation soils in southern Brazil. Another hypothesis may be the early growth of barnyardgrass compared to rice plants, mainly because barnyardgrass has C4 metabolism which gives the plant rapid growth and greater nutrient extraction capacity.

It was observed that at 63 and 93 DAE, even with the increase of the barnyardgrass population, there was a reduction in the amounts of N extracted compared to 43 DAE (Figs. 4A and D). This may be associated with the translocation of this nutrient to the inflorescence

Table 5. Linear regression parameters of calcium nutritional content [kg · ha^{-1}] of leaves and stems of rice in relation to the barnyardgrass population [plants · m^{-2}], 43, 63 and 93 days after emergence (DAE)

Species	Days after emergence	Parameters		
		a	*b*	R^2
Calcium in leaves [kg · ha^{-1}]				
Barnyardgrass	43	0.02	0.02**	0.94
Rice		12.4	–0.05**	0.66
Barnyardgrass	63	–0.08	0.02*	0.76
Rice		7.92	0.06**	0.31
Barnyardgrass	93	0.29	0.008	0.58
Rice		34.2	–0.14**	0.37
Calcium in stems [kg · ha^{-1}]				
Barnyardgrass	43	0.93	0.02	0.26
Rice		4.75	–0.02*	0.38
Barnyardgrass	63	0.04	0.03**	0.75
Rice		7.90	–0.03**	0.41
Barnyardgrass	93	0.04	0.06	0.71
Rice		21.41	–0.08*	0.27

**p* value below 0.05; ***p* value below 0.01

Table 6. Linear regression parameters of magnesium nutritional content [kg · ha^{-1}] of leaves and stems of rice in relation to the barnyardgrass population [plants · m^{-2}], 43, 63 and 93 days after emergence (DAE)

Species	Days after emergence	Parameters		
		a	*b*	R^2
Magnesium in leaves [kg · ha^{-1}]				
Barnyardgrass	43	3.64	–0.01**	0.95
Rice		8.56	–0.03**	0.75
Barnyardgrass	63	5.15	0.002**	0.99
Rice		8.16	0.06**	0.41
Barnyardgrass	93	0.1	0.01**	0.76
Rice		21.39	0.09**	0.48
Magnesium in stems [kg · ha^{-1}]				
Barnyardgrass	43	0.26	0.01**	0.88
Rice		3.64	–0.01**	0.72
Barnyardgrass	63	–0.24	0.03**	0.81
Rice		5.14	0.002	0.004
Barnyardgrass	93	–0.05	0.08**	0.78
Rice		37.37	0.14**	0.45

**p* value below 0.05; ***p* value below 0.01

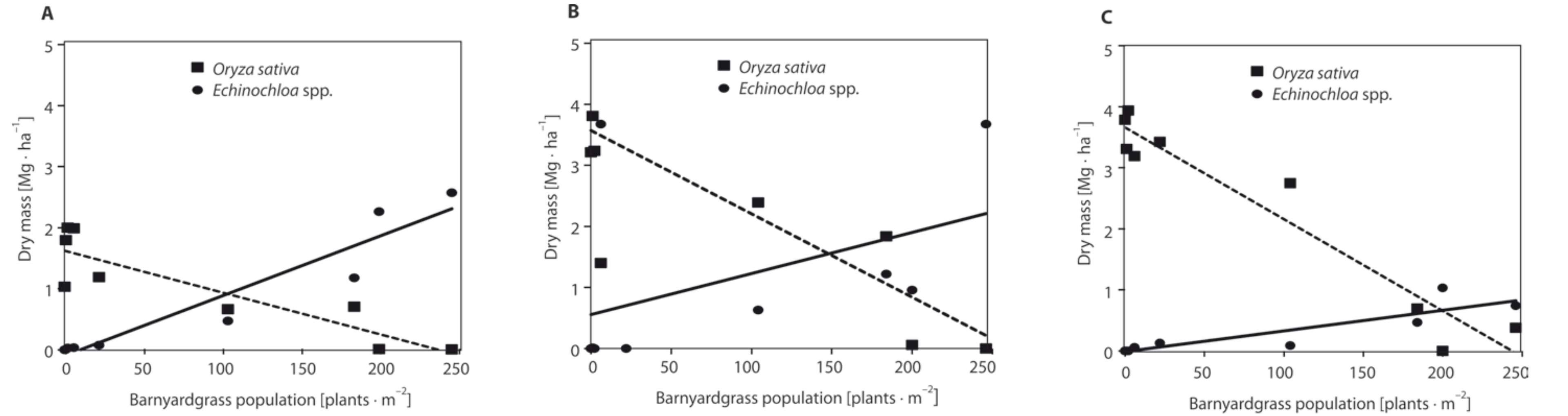

Fig. 1. Leaves dry mass aerial part of rice cultivar IRGA 424 CL in relation with the barnyardgrass population, in 43 (A), 63 (B) and 93 (C) days after emergence (DAE). The dotted and the solid lines represents the linear regression of *Oryza sativa* and *Echinochloa* spp., respectively

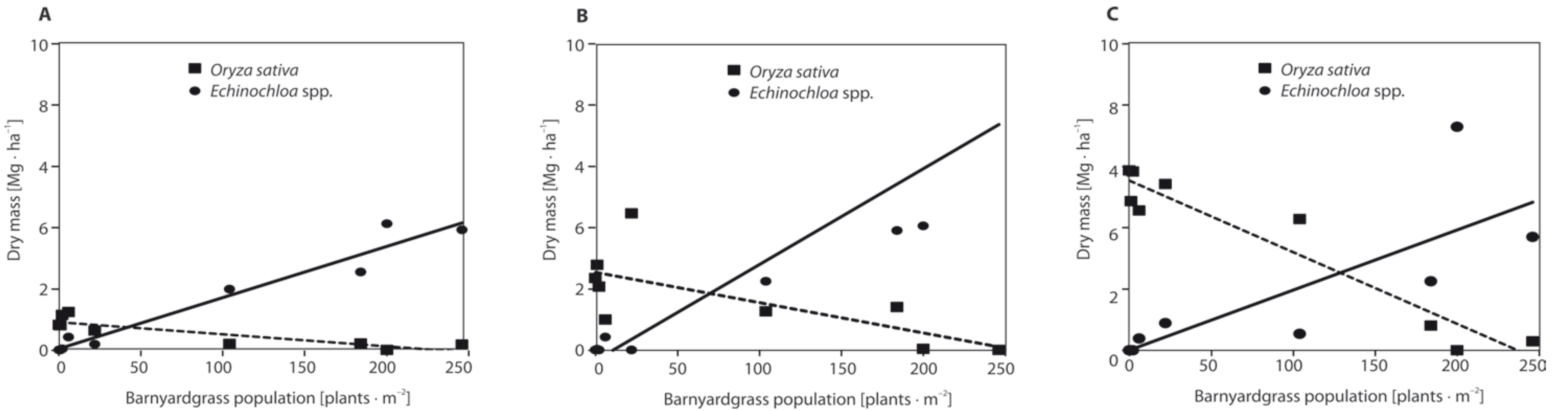

Fig. 2. Tillers dry mass aerial part of rice cultivar IRGA 424 CL in relation with the barnyardgrass population, in 43 (A), 63 (B) and 93 (C) days after emergence (DAE). The dotted and the solid lines represents the linear regression of *Oryza sativa* and *Echinochloa* spp., respectively

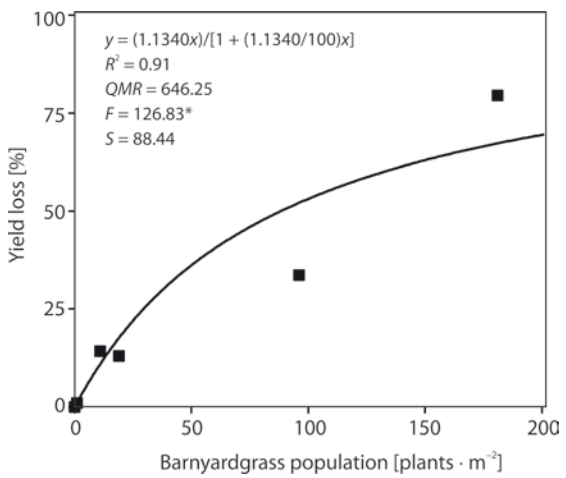

Fig. 3. Hyperbolic rectangular model of yield loss of a rice cultivar (IRGA 424 CL) in relation with the barnyardgrass population

and grain reserves at these more advanced stages. The amounts of P extracted from leaves and stems and rice were not affected by the population increase of barnyardgrass plants (Table 3 and Fig. 5). On the other hand, there was a significant increase of P extraction by barnyardgrass plants, not exceeding the extraction of 3 kg P · ha^{-1} in the largest weed population (Table 3 and Fig. 5), regardless of the evaluated season.

The amounts of K extracted by rice crops were significantly impacted at all times analyzed (Table 4 and Fig. 6). However, the greatest impact on the extraction of this nutrient was found at 93 DAE and in the population of 200 barnyardgrass plants · m^{-2} , where each weed represented a reduction of 0.38 kg K · ha^{-1} in leaves and 0.68 kg K · ha^{-1} in the stems (Table 4 and Figs. 6C and F), totaling a reduction of 1.06 kg K · ha^{-1} in rice plants. K can be considered the most impacted element in the population increase of barnyardgrass plants, mainly at 93 DAE (Figs. 6C and F). During this period, an extraction reduction of 1.071 kg K · ha^{-1} was observed for each barnyardgrass plant. However, no high K extraction was observed in any of the evaluated periods for barnyardgrass plants as it was at 43 DAE for N (Figs. 4A and D), where there was direct competition for N.

The amounts of Ca extracted by rice plants were more pronounced at the reproductive stage (93 DAE) (Table 3 and Fig. 7), and were similar to that observed for K. In this period, the reduction in Ca extraction by rice plants was 0.22 kg · ha^{-1} (0.14 kg Ca · ha^{-1} on leaves and 0.08 kg Ca · ha^{-1} on stems) per unit of barnyardgrass m^{-2} (Table 3 and Figs. 7C and F). At 43 and 63 DAE the reduction of Ca extraction by rice plants was also significant, however, to a lesser extent than at 93 DAE (Fig. 7). The amounts extracted from Mg by rice plants were also significantly impacted in the reproductive period (93 DAE) (Figs. 8C and F). The reduction in Mg extraction from the crop was 0.23 kg · ha^{-1} (0.09 kg Mg · ha^{-1} in leaves and 0.14 Mg · ha^{-1}) (Table 4 and Figs. 8C and F) per barnyardgrass unit per m^2 at 93 DAE. Mg losses by rice plants in the vegetative period (43 DAE) (Table 4 and Figs. 8A and D) were also significant, but to a lesser extent than at 93 DAE. Corroborating the dynamics in the other nutrients, the amounts of Ca and Mg extracted by rice plants were also reduced with the population increase of barnyardgrass plants, being more pronounced in the period at 93 DAE (Figs. 7C–D; 8C–D). However, the magnitude of the reduction of Ca and Mg extraction was smaller than N and K.

Discussion

Leaf and stem dry matter accumulation and productivity as a function of competition

This result may be due to intraspecific competition between plants and increased self-thinning to suit the environment in competition with other plants (Chu *et al.* 2010), thus leading to leaf senescence in this condition and reducing mass differences between different plant populations. In turn, it can be stated that the reduction in rice DMAP in all variables analyzed as weed population increase was due to the established competition, whose changes in morphological characteristics were due to weed interference in the crop. In a study evaluating the competitive ability of different rice cultivars with barnyardgrass in different plant populations, it was observed that the rice leaf area index and crop DMAP decreased when there was competition (Agostinetto *et al.* 2008). The presence of barnyardgrass reduced the number of panicles emitted by the crop, besides reducing the canopy DMAP, which may culminate in productivity loss (Chauan and Johnson 2010). In general, the observed data regarding DMAP reductions in rice crop leaves and stalks are in line with natural behavior to avoid shading and to seek light when in competition with weeds (Afifi and Swanton 2012), which can impact productivity.

For the analysis of productivity losses it was necessary to set the value of the parameter aof a rectangular hyperbole at 100%, considered as maximum productivity loss (Fig. 3). In this sense, it is important to highlight that the model was not able to estimate the total yield loss, probably due to the absence of larger barnyardgrass populations. The unit productivity loss value of parameter *i* was 1.13% productivity loss relative to the clean control, indicating a relatively low loss in the conduction conditions of the study (Fig. 2). This value was lower than in previous studies evaluating the barnyardgrass population, date of irrigation water intake and crop spacing, where it was established between 8.4 and 11.3% yield (Agostinetto *et al.* 2007; Agosti-

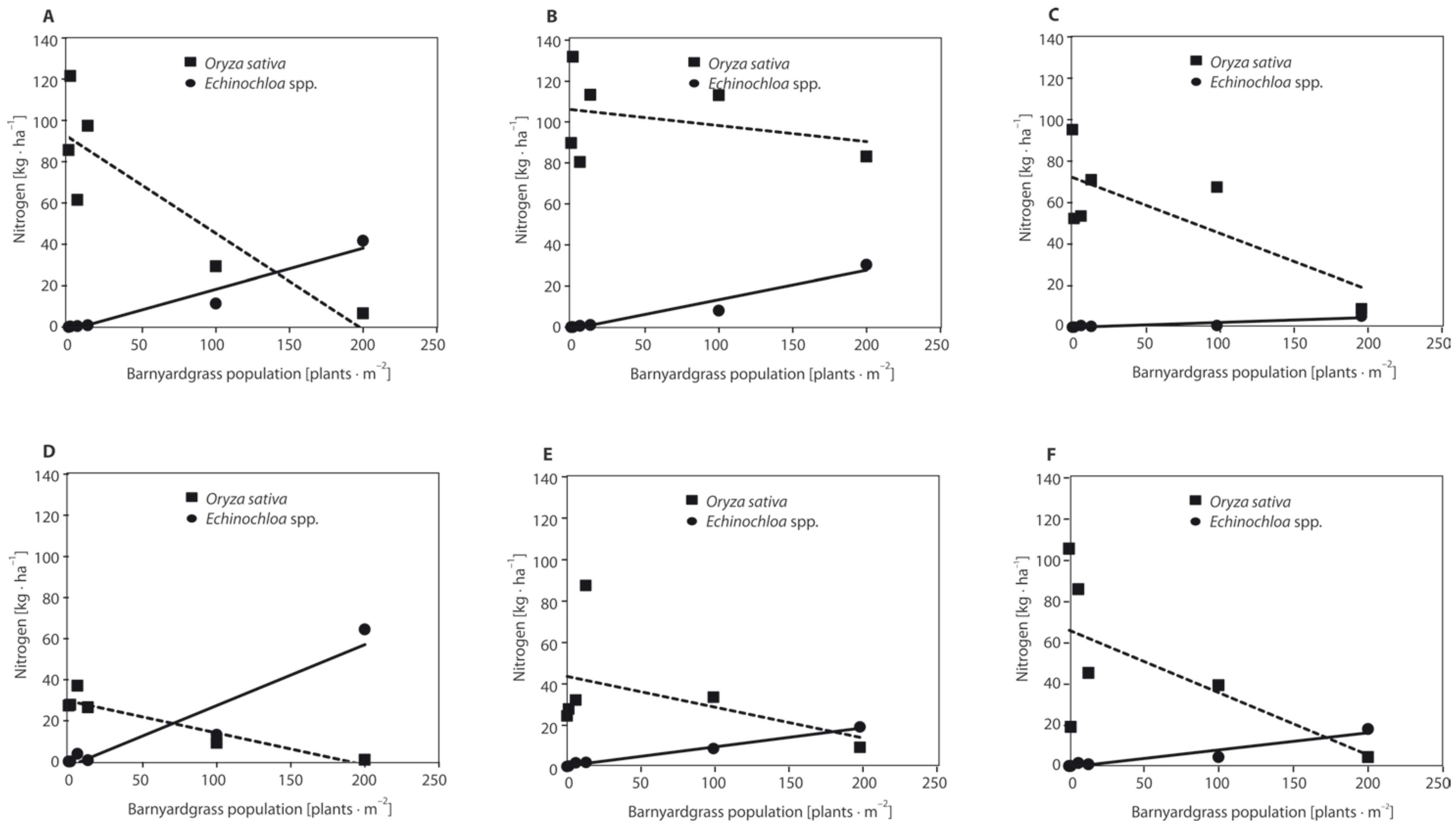

Fig. 4. Nitrogen extracted by the leaves (A, B, C) and tillers (D, E, F) of rice cultivar IRGA 424 CL and barnyardgrass at 43 (A, D), 63 (B, E), 93 (C, F) days after emergence relation with the barnyardgrass population. The dotted and the solid lines represents the linear regression of *Oryza sativa* and *Echinochloa* spp., respectively

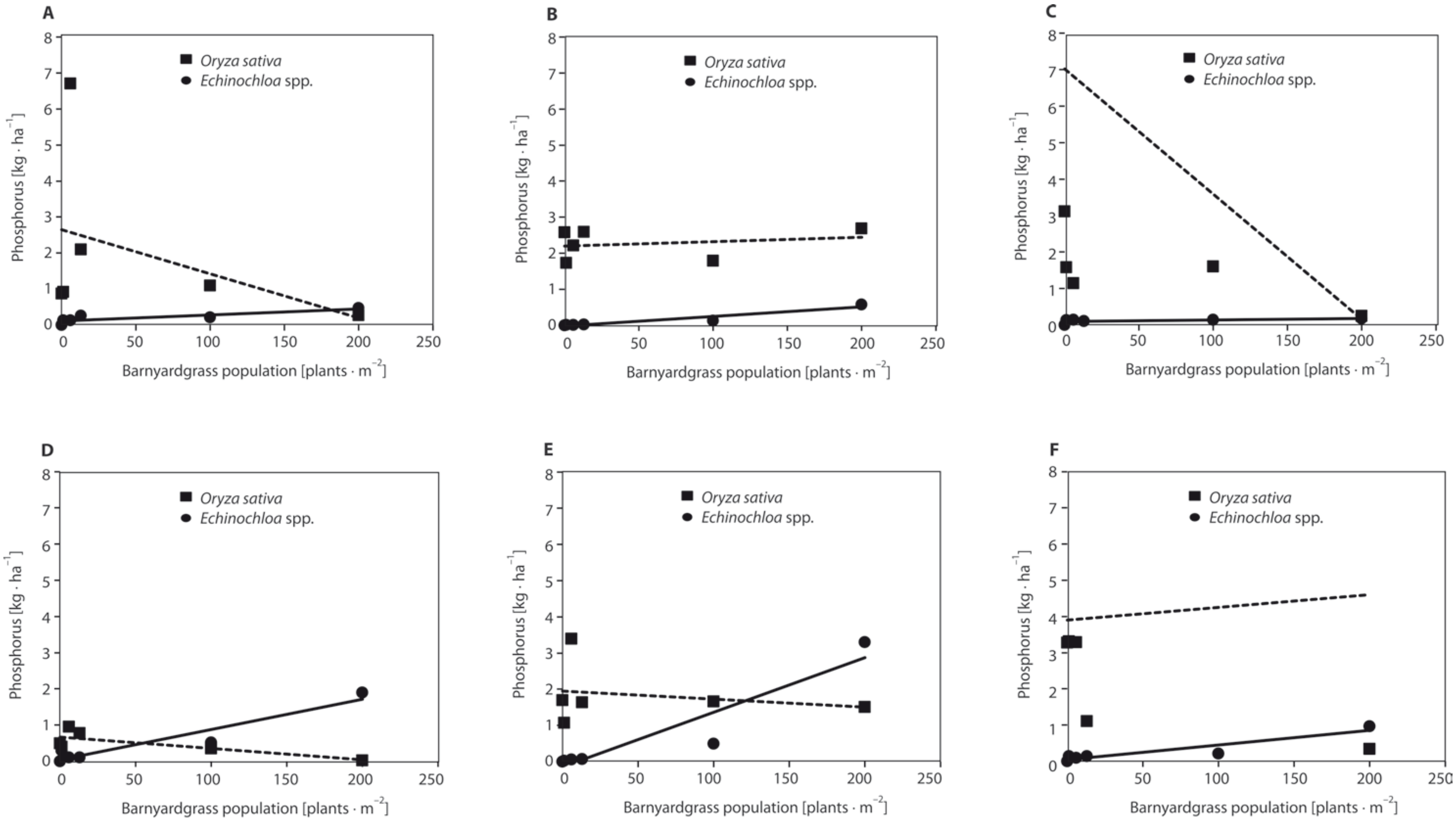

Fig. 5. Phosphorus extracted by the leaves (A, B, C) and tillers (D, E, F) of rice cultivar IRGA 424 CL and barnyardgrass at 43 (A, D), 63 (B, E), 93 (C, F) days after emergence relation with the barnyardgrass population. The dotted and the solid lines represents the linear regression of *Oryza sativa* and *Echinochloa* spp., respectively

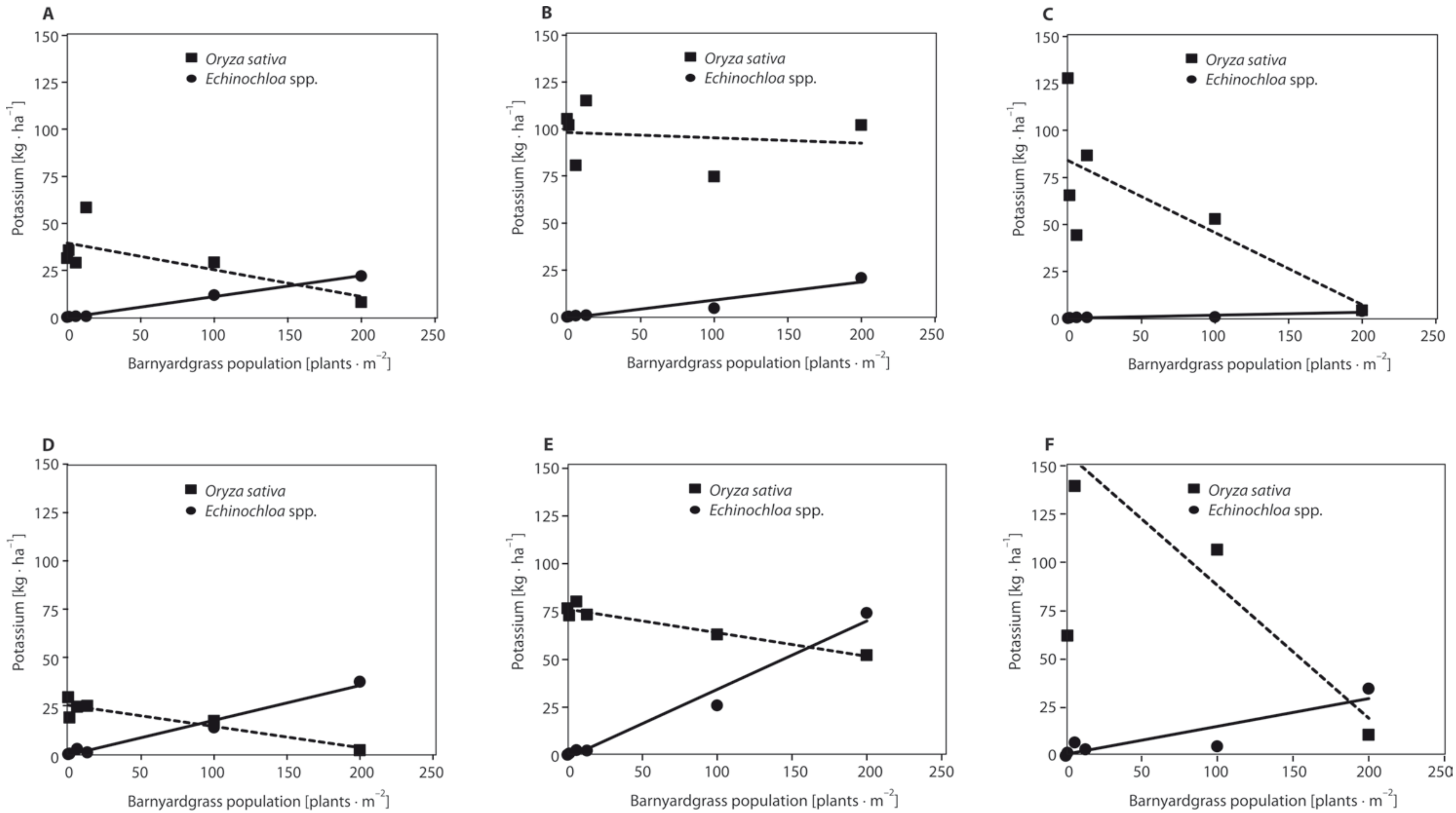

Fig. 6. Potassium extracted by the leaves (A, B, C) and tillers (D, E, F) of rice cultivar IRGA 424 CL and barnyardgrass at 43 (A, D), 63 (B, E), 93 (C, F) days after emergence relation with the barnyardgrass population. The dotted and the solid lines represents the linear regression of *Oryza sativa* and *Echinochloa* spp., respectively

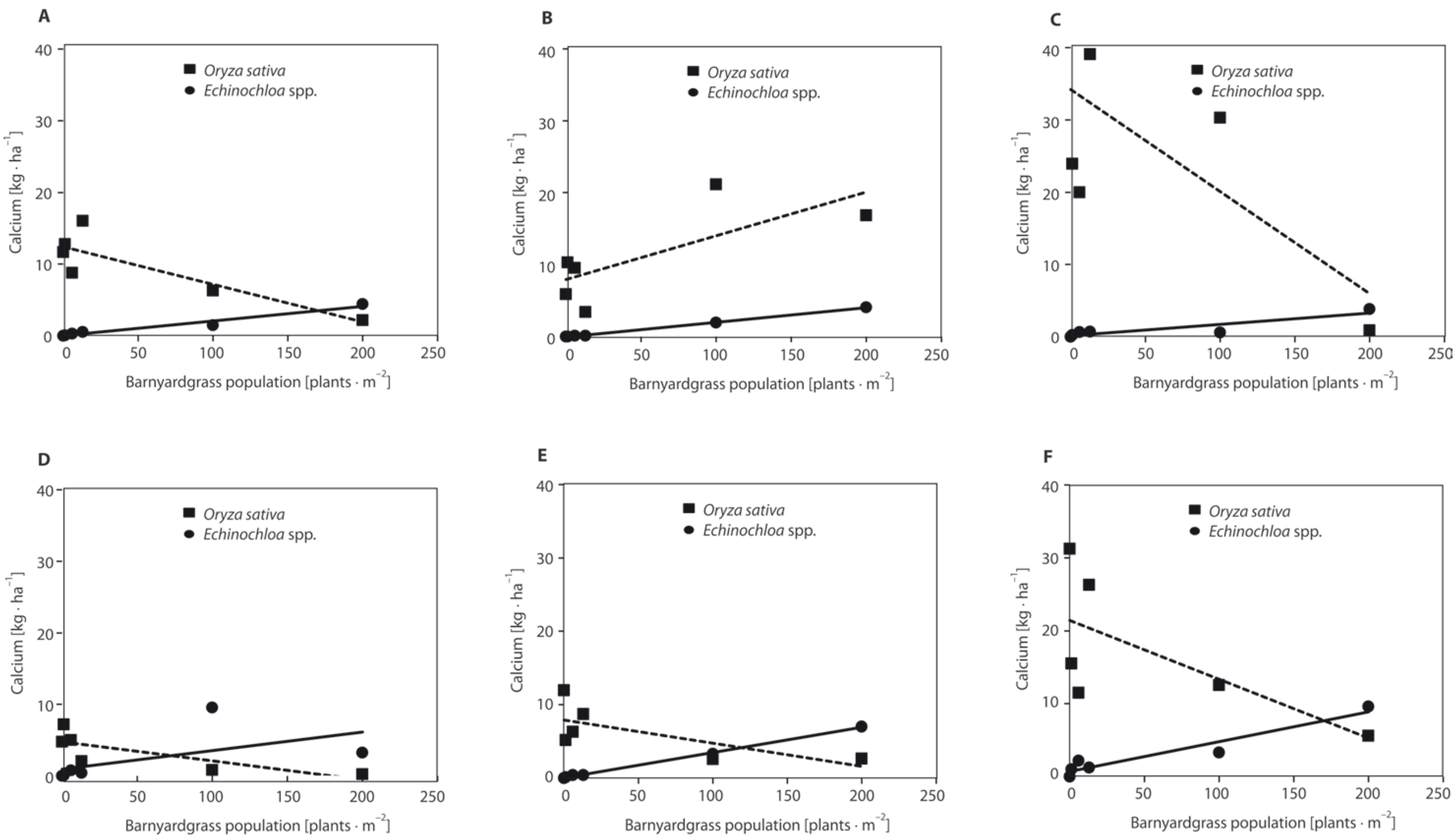

Fig. 7. Calcium extracted by the leaves (A, B, C) and tillers (D, E, F) of rice cultivar IRGA 424 CL and barnyardgrass at 43 (A, D), 63 (B, E), 93 (C, F) days after emergence relation with the barnyardgrass population. The dotted and the solid lines represents the linear regression of *Oryza sativa* and *Echinochloa* spp., respectively

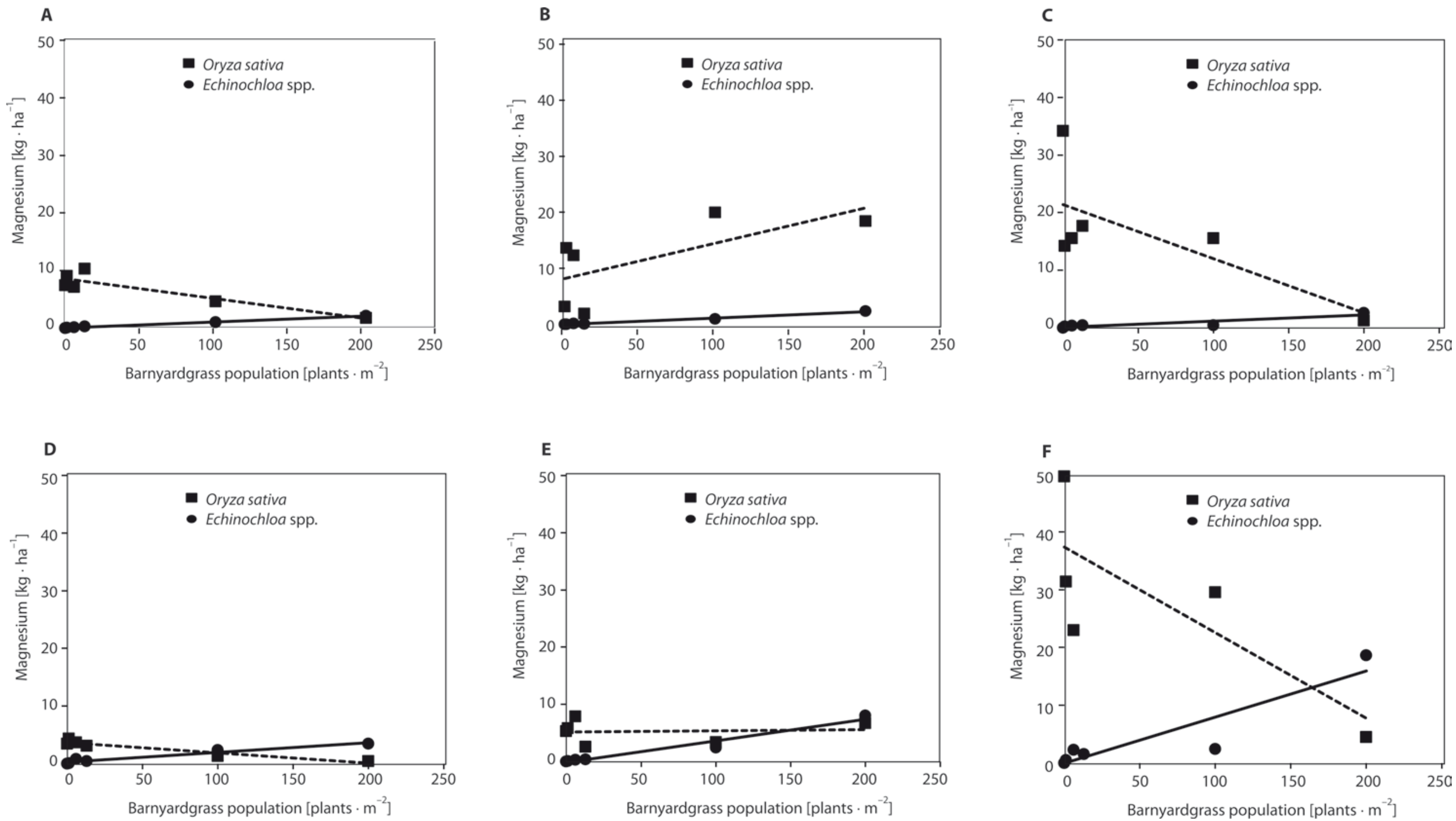

Fig. 8. Magnesium extracted by the leaves (A, B, C) and tillers (D, E, F) of rice cultivar IRGA 424 CL and barnyardgrass at 43 (A, D), 63 (B, E), 93 (C, F) days after emergence relation with the barnyardgrass population. The dotted and the solid lines represents the linear regression of *Oryza sativa* and *Echinochloa* spp., respectively

netto *et al*. 2010), which may be due to the higher yield potential of the cultivar used in the present work. This corroborates the value of *i* being higher than that found for rice in competition with *Cyperus esculentus* using the same cultivar tested (Westendorff *et al*. 2014).

This inference is supported by calculating the inverse of β (s), whose value was 88.49 plants · m^{-2}, which represents the population to reduce 50% of crop productivity, which can be considered low. That is, a relatively low population of weed m^{-2} has the potential to reduce flooded rice yield. Thus, it was observed that the increase of the barnyardgrass population caused great damage to the rice crop development, as evidenced by the decrease in DMAP of leaves and stems, and an increase of crop yield loss.

Mineral nutrition of rice and barnyardgrass

Inadequate N conditions can directly affect plant amino acid synthesis, leaf area, chlorophyll and plant photosynthetic rate, biomass production and consequently reduction in grain yield potential (Cathcart and Swanton 2004). Thus, possibly, competition for N was the main factor that promoted the reduction of DMAP and flooded rice yield observed in the present study.

The amount of P extracted by rice plants was not greatly impacted by the population levels of barnyardgrass plants. This may be due to redox reactions of flooded soils that solubilize Fe oxides and contribute to the release of strongly adsorbed P, contributing to the increase of P in solution at concentrations that do not limit the nutrition of rice plants (Reis *et al*. 2018). Thus, even under a high population of barnyardgrass plants, it is not considered that the accumulation of P by the species was a preponderant factor that justifies the competition, nor the observed reduction in productivity. In addition, the P absorption requirement for rice crops is generally lower than N and K requirements (Rotilli *et al*. 2010).

Even with an increasing barnyardgrass population, the angular coefficients of K extraction by barnyardgrass plants were low, indicating that the presence of weeds may indirectly affect the physiology of the crop and, consequently, K absorption by rice plants and reduce yield. The initially observed N competition may have affected the photosynthetic capacity of rice and thus the lower synthesis of major enzymes and proteins that are present in the K absorption metabolism (Xiong *et al*. 2018). Thus, the suboptimal conditions of K in plant tissue may affect the osmotic balance of the plant cell and the opening and closing of stomata which play an essential role in the plant transpiration mechanism.

The dynamics of Ca and Mg may occur due to this type of soil. Furthermore, rice has a lower demand for Ca and Mg than N and K. The majority of subtropical soils in southern Brazil have a high proportion of Ca and Mg in soil cation exchange capacity, contributing to the greater supply of these elements to crop plants (Streck *et al*. 2008; Che *et al*. 2016) and reducing the magnitude of weed and crop competition. Thus, the high competitive capacity of rice grass for essential macronutrients such as N, K, Ca and Mg resulted in impacts on crop development, the functioning of physiological processes and consequently on grain yield. Due to this, it is inferred that the competition of rice grass for macronutrients is one of the main factors that limit the productivity of flooded rice.

Conclusions

An increase of the barnyardgrass population reduced the dry mass of leaves and stems in flooded rice, evaluated at the vegetative and reproductive stages of the crop, thereby justifying the loss of productivity caused by barnyardgrass unit m^{-2} of 1.13%. The competition for N between rice and barnyardgrass plants was higher in the vegetative period, while for K, Ca and Mg the highest competition occurred in the reproductive period.

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