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PLANT PROTECTION - Article

Weed interference period and economic threshold level of ryegrass in wheat

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ABSTRACT: The study of weed interference periods and the economic threshold level (ETL) of weeds on crops allows the adoption of management methods and the rationalized use of herbicides. The objective of this study was to determine the periods of interference and to test mathematical models to determine the economic threshold level of ryegrass in the wheat crop. Two experiments were carried out in a randomized block design with four replications. The first experiment was conducted in the 2014/2015 agricultural season. The periods of interference and control of ryegrass were studied in wheat. The periods of interference and/or control were: 0, 10, 20, 30, 40, 50 and 120 days after emergence (DAE). The second experiment was conducted in the 2016/2017 agricultural season. The ETLs were studied, being the treatments composed of wheat cultivars and 12 populations of ryegrass, in competition with the respective cultivars. The results allowed concluding that the management methods of weed ryegrass must be adopted in the period between 11 and 21 days after crop emergence, which is described as a critical period of control of this weed. The wheat grain yield loss competing with ryegrass reached 59% when grown with ryegrass. For ETL, the linear regression model of the rectangular hyperbola adequately estimates grain yield losses in the presence of ryegrass. The cultivar presenting the lowest values of ETL, that is, less capacity to live with the weed, was TBIO Alvorada. The other cultivars presented similar ETL values.

Key words: *Triticum aestivum, Lolium multiflorum,* competition.

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INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the most grown cereals in the world, occupying the third place in total production. It is used mainly for human and animal feeding (FAO 2018). In Brazil, wheat crop is grown in the South region, being Rio Grande do Sul (RS) the second largest producer state, responsible for approximately 1.3 million tons in the 2017 agricultural season. (CONAB 2018). However, some factors may limit wheat yield potential, with weed plants being the main crop injury (Meulen and Chauhan 2017). It is estimated that weed plants reduce approximately 18.6% of wheat grain yield (Gharde et al. 2018).

In the Southern Brazil, ryegrass (*Lolium multiflorum* Lam.) stands out among the most problematic weeds injuring wheat crop. It causes loses to the productivity and quality of the harvested grains, besides increasing the costs of harvesting operations, transport, and drying process of grains (Lamego et al. 2013).

To control weeds in wheat, it is usually used some crop selective herbicide. However, the excessive and repetitive use of these products leads to the selection of resistant weeds, such as ryegrass resistant to EPSPs (5-enolpyruvylshikimate-3-phosphate synthase) inhibitors (glyphosate) and ALS (acetolactate synthase) inhibitors (iodosulfuron) (Heap 2018). The resistant weeds result in higher production costs, mainly due to the use of alternative herbicides, often with higher prices than the traditional ones (Rigoli et al. 2008).

The knowledge of the wheat competitive characteristics related to crop morphology is an important tool to define more sustainable management strategies (Beres et al. 2010; Bertholdsson 2011). The leaf area and height of wheat plants are important because they provide a better absorption of solar radiation and ground cover, reducing the potential growth of weeds and increasing the competitiveness of the crop (Radosevich et al. 2007).

Among many tools available to study plants competition in a community, it is possible to highlight the studies that take into account the weed interference periods, compared to a crop of interest (Swanton et al. 2015), and also the economic threshold level (ETL) (Galon et al. 2007; Agostinetto et al. 2010). In this way, this is another study with applicability, since it relates grain yield losses using the density, dry matter, soil cover and leaf area of weeds compared to control costs, allowing to evaluate the gain obtained according to the treatment (Kalsing and Vidal 2013). Studies on the interference and competitiveness of weed and crops allow developing more effective weed management strategies with less impact on the environment (Zhang et al. 2016).

The crops injury level due to the weed competition is related to the stage and duration (Tironi et al. 2014). Therefore, it is important to determine the period in which the interference with the weeds caused damages to the crop grain yield, determining the moment in which the control must be realized. In this way, it is possible, through field trials, to estimate the critical period of interference prevention (CPIP), in which weed control is necessary (Tursun et al. 2016). This experiment design has as advantage an easy establishment of the experiments under field conditions (Swanton et al. 2015).

In order to estimate ETL, regression equations or injury functions are applied, related to crop yield losses with weed infestation. When all the information related to the production practice is available, they play an important role in changing the management, which depends mainly on herbicides, towards an ecophysiological knowledge system or a more sustainable model (Galon et al. 2007). Thus, it is important to know the interactions occurring between plants in communities, making possible the development of more efficient and sustainable strategies for the management of weeds (Beres et al. 2010; Galon et al. 2017).

Wheat is a growing crop in Brazil and knowledge of the interference caused by weeds is essential. Given this, it is justified the need to know the period and conditions necessary to control ryegrass in the wheat crop.

The hypothesis tested in this study was that there are different morphological and grain yield responses of wheat in competition with ryegrass, both related to the periods of interference and to ETL. The objective of this work was to establish the periods of interference and to test mathematical models to determine the ETL of ryegrass in the wheat crop.

MATERIAL AND METHODS

Study area characterization

Two experiments were installed at the Universidade Federal da Fronteira Sul experimental area (27°43'38" S and 52°17'18" W) in the 2014/2015 (periods of interference) and 2015/2016 (economic threshold level) agricultural seasons in a no-tillage system. The climate of the region is classified as Cfa (temperate humid with hot summer) according to the Köppen-Geiger classification (Peel et al. 2007). The climatic conditions during the period of the study are shown in Fig. 1.

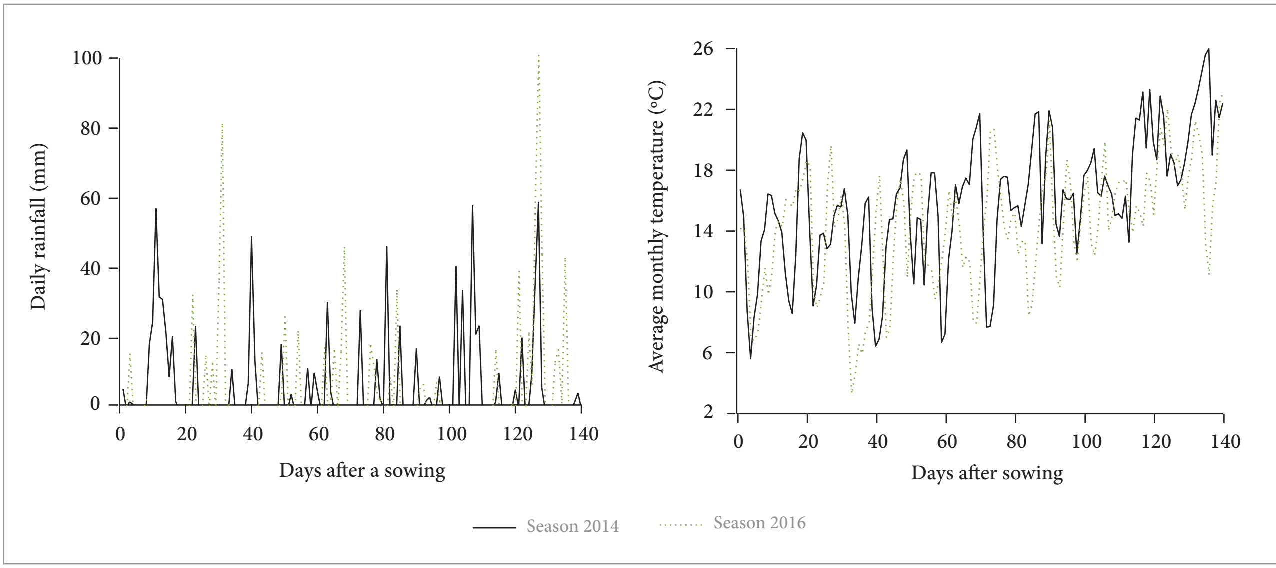

Figure 1. Rainfall and average monthly air temperature during the study.

The soil management classified as Rhodic Hapludox (Soil Survey Staff 2014) was carried out based on soil chemical analysis, with the following characteristics: pH = 5.1; organic matter = 3.0%; grit = 13%; silte = 17%; clay = 60%; Silte: P = 5.2 mg·dm^{-3}, K = 118 mg·dm^{-3}, Ca + 2 = 5.5 cmol$_c$·dm^{-3}; Mg^{+2} = 3.0 cmol$_c$·dm^{-3}; Al^{+3} = 0.3 cmol$_c$·dm^{-3}; H + Al = 7.7 cmol$_c$·dm^{-3}; Effective CEC = 16.6 cmol$_c$·dm^{-3}.

The study area was under a no-till system with cover crop composed by black oat + turnip, burndown with glyphosate herbicide (1080 g·ha^{-1} e.a) before wheat sown. Insects and diseases were treated preventively, applying insecticides and fungicide during the crop development.

Periods of Interference

Experimental design

The experimental design was a randomized block design, with four replications. The TBIO Pioneiro wheat cultivar was used. Presenting a medium cycle, in row spacing of 0.17 m, average density of 290 plants·m^{-2}. Each experimental unit represented a total area of 11.05 m^2 (2.21 × 5 m) and a useful area of 2.55 m^2 (3.0 × 0.85 m).

The experiment was composed of two factors: periods of interference and periods of weed ryegrass control. During the period of interference, the crop was maintained in the presence of the weed, increasing initial competition periods: 0, 10, 20, 30, 40, 50 and 120 days after crop emergence (DAE), performing the control. In the control period, the crop was kept free of ryegrass in the same periods described previously, and the plants emerged after these intervals were no longer controlled. The ryegrass control was performed with hoeing in each proposed period. A density count was realized to determine the ryegrass seed bank, reaching a population of 137 ryegrass plants·m^{-2}. Other weed species in the experimental area not subject to study were eliminated by hoeing.

Studied variables

At the end of each coexistence or control period, the leaf area (FA) was measured with a portable electronic integrator CI-203, CID Bio-Science brand, in 10 plants per experimental unit.

The wheat grain yield was determined in an area of 2.55 m^{-2} (3.0 × 0.85 m), adjusting the grains moisture at 13% and estimating for kg·ha^{-1}. The grains were then used to determine a thousand grains weight, counting 8 samples of 100 seeds, and the hectoliter weight, determined using a scale.

Statistical analysis

The foliar area, hectolitre weight and a thousand grains weight were submitted to analysis of variance by the F test. If there was a significant difference between treatments, it was applied the Tukey test between the periods of interference and the T test to compare the averages within each period of control and interference.

The yield data were submitted to regression analysis by the sigmoidal model, using Eq. 1:

$$Y = Y_0 + a/(1 + e^{(-(x-x_0)/b)}) \quad (1)$$

where Y = wheat grain yield; Y_0 = minimum yield at control treatment; a = maximum value minus minimum value observed at hoeing control estimated by the model; x = number of days after crop emergence; x_0 = number of days where 50% reduction occurred; and b = slope of curve. The critical interference period of ryegrass on wheat was estimated by subtracting 5% of the average yield in plots maintained without weed cohabitation throughout the cycle. This value was considered as the cost of adopting the chemical control.

Economic threshold level (ETL) study

Experimental design

The experimental design was a randomized complete block design, and the treatments were composed of five wheat cultivars (TBIO Alvorada, BRS 327, BRS 328, BRS Marcante e TBIO Pioneiro), and 12 ryegrass populations (0, 26, 78, 92, 110, 146, 182, 218, 238, 430, 550 and 658; 0, 94, 96, 158, 184, 194, 268, 334, 352, 376, 726 and 1204; 0, 298, 310, 368, 394, 398, 400, 512, 584, 594, 626 and 1242; 0, 204, 216, 226, 302, 356, 370, 382, 430, 538, 540 and 940; and 0, 110, 102, 120, 186, 190, 194, 230, 240, 262, 442 and 1256 plants·m^{-2}), in competition with the respective cultivars. The cultivars of wheat used presented medium height characteristics (TBIO Alvorada, BRS 328 and BRS Marcante) and medium/high height (BRS 327 and TBIO Pioneiro), and early cycle (BRS 327, BRS 328 and BRS Marcante) and medium cycle (TBIO Alvorada and TBIO Pioneiro) (Franco and Evangelista 2018).

The experimental units were composed of an area of 11.05 m^2 (2.21 × 5 m), sown with a seed drill and fertilizer with 13 rows, spaced 0.17 m between rows, making up the width of 2.21 m and 5 m in length at each experimental unit. The seeding density of the wheat cultivars was 51 viable seeds per linear meter, providing the establishment of a population of approximately 300 plants·m^{-2}.

The weed competitor was composed by *Lolium multiflorum* (ryegrass), being established from the soil seed bank by applying the herbicide pyroxsulam at 18 g a.e·ha^{-1}.

Variables analyzed

At 30 days after crop emergence (DAE), the following variables were evaluated: plant population (PP), leaf area (FA), soil cover (SC) and shoot dry matter (DM) of the ryegrass plants. The determination of the explanatory variable plant population was performed by counting the plants present in two areas of 0.25 m^2 (0.5 m × 0.5 m) per plot. The quantification of the leaf area of the competing plant was carried out with a portable electronic integrator model CI-203, brand CID Bio-Science. The soil cover by ryegrass plants was evaluated visually, individually in each experimental unit, using a percentage scale, in which the zero mark corresponds to the absence of soil cover and the 100 mark represents total soil cover. The shoot dry matter of the ryegrass plants was determined by sampling the plants in an area of 0.25 m^2 (0.5 × 0.5 m) per plot, and drying in an air forced circulation oven at a temperature of 60 ± 5 °C until reaching a constant weight.

At the end of crop cycle, the harvest was performed by cutting and threshing the plots. The yield was estimated by harvesting an area of 4.5 m^2, analyzing the weed interference and the economic threshold level of ryegrass weeds on wheat.

Statistical analysis

Using the crop yield data, it was calculated the percentage losses between treatments with weed interference and treatments without weed interference (control), according to Eq. 2:

$$\text{Losses (\%)} = \left(\frac{\text{Ra} - \text{Rb}}{\text{Ra}}\right) x\,100 \quad (2)$$

where *Ra* and *Rb* = crop yield without and with ryegrass interference, respectively.

The DM (g·m^{-2}), SC (%) and FA (cm^2) values were multiplied by 100 previously to the data analysis, avoiding the use of the correction factor in the model (Galon et al. 2007; Agostinetto et al. 2010).

The relationship between percentage loss of wheat grain yield as a function of the explanatory variables was calculated separately for each cultivar, using the nonlinear regression model derived from the rectangular hyperbola proposed by Cousens (1985), according to Eq. 3:

$$Pp = \frac{(i * X)}{(1 + (\frac{i}{a}) * X)} \quad (3)$$

where Pp = Yield loss (%); X = ryegrass population, shoot dry matter, leaf area or soil cover; i and a = yield loses (%) per ryegrass plants unit when the variable value is near zero and when the value tends to infinite, respectively. For calculations, it was applied the Gauss-Newton method where, by successive iterations, the parameters are estimated, in which the sum of the squares of the deviations of the observations, relative to the adjusted values, is minimal (Ratkowsky 1983). The F value ($p \leq 0.05$) was used as criterion of data analysis to the model. The criterion of acceptance of the data to the model adjustment was based on the higher value of the coefficient of determination (R^2) and the lower value of the mean square error (MSE).

For Economic Threshold Level (ETL) calculations, the *i* parameter estimations were obtained accordingly with Cousens (1985) and Lindquist and Kropff (1996) equations (Eq. 4):

$$ETL = \frac{(Cc)}{(R * P * (\frac{i}{100}) * (\frac{H}{100}))} \quad (4)$$

where ETL = Economic Threshold Level (plants·m^{-2}); Cc = Control cost (herbicide and aplication, dolars·ha^{-1}); R = wheat grain yield (kg·ha^{-1}); P = wheat grain price (dolars kg·grãos^{-1}); i = Wheat grain yield losses (%) by weed plant unit; H = herbicide efficiency (%).

For Cc, R, P and H variables, three values were estimated. Thus, for the control cost (Cc), the average price was considered, with the maximum and minimum cost being changed by 25% in relation to the average cost. The grain yield of wheat (R) was based on the lower, medium and higher yields obtained in the RS state in the last 10 years. The price of the product (P) was estimated from the lowest, middle and highest price of wheat paid per bag of 60 kg in the last 10 years. The values for the herbicide (H) efficiency were established in the order of 80%, 90% and 100% control, with 80% being the minimum control considered effective of the weed (SBCPD 1995). For the ETL simulations the intermediate values were used for the variables that were not object of calculation.

RESULTS AND DISCUSSION

Statistical analysis

It was observed influence of ryegrass control and interference periods on leaf area, hectolitre weight and grain yield of wheat (Figs. 2, 3 and 4). However, the variable a thousand-grain weight did not show significant effect at 5% probability (Fig. 5).

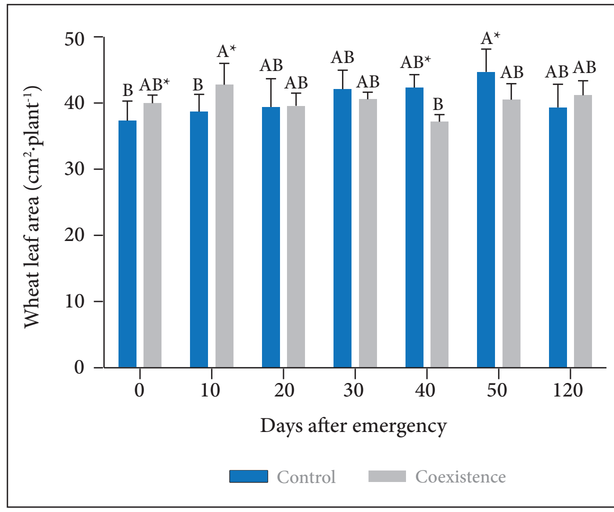

Figure 2. Wheat leaf area (cm^2·plant^{-1}), cultivar TBIO Pioneiro, in each period of control and/or interference with ryegrass. Means preceded by * compare control and interference within each evaluated period and differ by the t test ($p < 0.05$); means followed by distinct capital letters differ by the Tukey test ($p < 0.05$) the periods of control and/or interference.

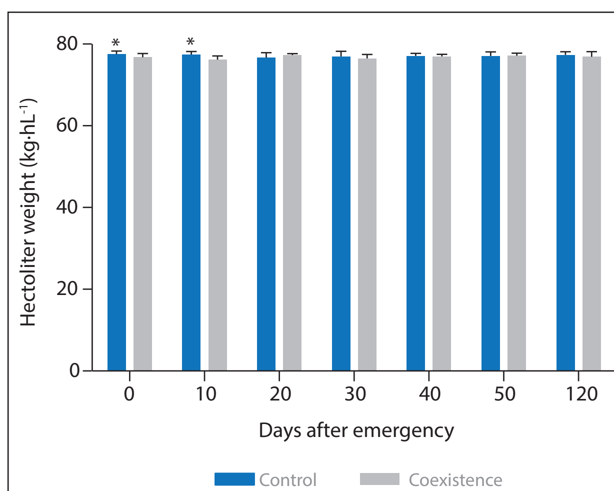

Figure 3. Hectolitre weight of wheat, cultivar TBIO Pioneiro, in each period of control and/or interference with ryegrass. Means preceded by * compare control and interference within each evaluated period and differ by the t test, since averages that compare within each group (control and coexistence) do not differ by the Tukey test ($p < 0.05$).

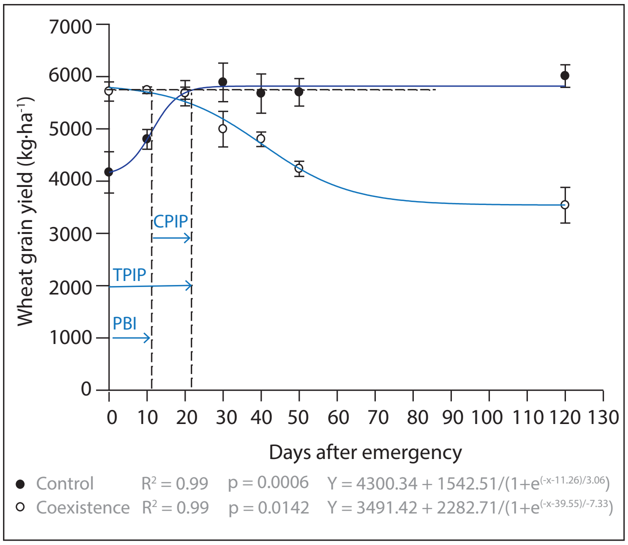

Figure 4. Wheat grain yield (kg·ha^{-1}), cultivar TBIO Pioneiro, according to the periods of control (□) and interference (○) of ryegrass. PBI = Period Before Interference; CPIP = Critical Period of Interference Prevention; TPIP = Total Period of Interference Prevention.

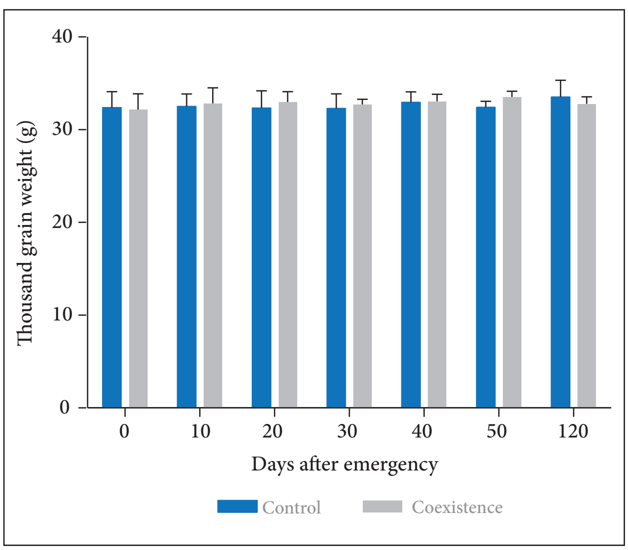

Figure 5. A thousand-grain weight (g) of wheat, cultivar TBIO Pioneiro, in each period of control and/or interference with ryegrass. Means comparing the control and coexistence within each period evaluated and the periods within each group (control and interference) did not differ by the t and Tukey test ($p < 0.05$), respectively.

The variables plant population, soil cover, leaf area and dry matter of ryegrass for all evaluated wheat cultivars presented significant F values (Table 1). The results show that, for wheat cultivars TBIO Alvorada, BRS 327, BRS 328, BRS Marcante and TBIO Pioneiro, the rectangular hyperbola model was adjusted accordingly for all cultivars, with R^2 values above 0.57 and low MSE, which characterizes good data fit to the proposed model. Cargnelutti Filho and Storck (2007), when working with genetic variation, cultivar effect and heritability of maize hybrids, considered the R^2 values between 0.57 and 0.66 to be good, which corroborates, in parts with the results found in the present study. As for ETL, it was possible to observe differences between the cultivars under study, as well as the level of technology to be used in the crop area, as can be observed in Figs. 6, 7, 8 and 9.

Interference periods

In this work, periods of ryegrass interference were determined as a function of days after crop emergence (DAE). As an efficient alternative for the better understanding this relationship when weed and crop are in communities, establishing management strategies with greater sustainability is becoming a trend for future researches in this area of study (Meulen and Chauhan 2017).

The results concerning wheat leaf area, for each period of control and/or interference, show differences between the weed control times, that is, according to crop growth (Fig. 2). It was observed, in the control period, greater leaf area at 50 DAE when compared to the initial control periods (0 and 10 DAE). This fact may be due to ryegrass regrowth after the burndown. The reduction of leaf area index is noticeable in wheat plants with increasing weed density, regardless of sowing time (Hussain et al. 2015). For the period of interference, a larger leaf area was observed at 10 DAE, differing only from 40 DAE, which reduced the growth of this variable by approximately 15%.

In the periods of 0 and 10 DAE, which were compared the control with the interference, it is observed the increase of the leaf area for the interference, evidenced with the significant difference by the t test. However, this result may be more related to weed control (hoeing) than competition itself. The results showed leaf area of 42.33 and 44.70 cm^2·plant^{-1} at 40 and 50 DAE in the control period, in which the crop was maintained without ryegrass competition (Fig. 2). It was verified that leaf area was impaired by the competition with the ryegrass and that if the wheat is grown along the weed in those periods, the crop grain yield can decrease.

For the hectolitre weight, when comparing the control and/or interference of ryegrass on wheat, within each period, significant results were verified only for the control at 0 and 10 DAE, but this difference is within the limits of the standard deviations, as can be observed in Fig. 3. It was

Table 1. Adjustments obtained for grain yield loss, based on plant population, soil cover, leaf area and dry matetr of ryegrass (*Lolium multiflorum*) and wheat cultivars, TBIO Alvorada, BRS 327, BRS 328, BRS Marcante and TBIO Pioneiro.

Relative explanatory variables	Parameters[1]		R^2	MSE	F
	i	*a*			
Plant population					
TBIO Alvorada	0.58	111.80	0.96	89.38	208.57*
BRS 327	0.22	141.50	0.75	45.50	290.77*
BRS 328	0.25	127.80	0.79	72.11	285.95*
BRS Marcante	0.24	189.20	0.85	51.66	392.57*
TBIO Pioneiro	0.19	155.40	0.69	21.06	423.57*
Soil cover					
TBIO Alvorada	0.17	89.98	0.88	114.40	161.90*
BRS 327	0.06	120.60	0.85	53.09	248.48*
BRS 328	0.14	82.85	0.61	116.70	185.24*
BRS Marcante	0.03	190.60	0.91	104.30	195.46*
TBIO Pioneiro	0.05	114.70	0.82	20.61	507.56*
Foliar area					
TBIO Alvorada	0.0010	98.03	0.87	165.50	96.84*
BRS 327	0.0007	95.93	0.57	174.70	65.68*
BRS 328	0.0004	109.80	0.74	68.42	332.65*
BRS Marcante	0.0007	91.49	0.77	258.60	76.40*
TBIO Pioneiro	0.0002	152.60	0.60	51.10	167.47*
Dry matter					
TBIO Alvorada	0.16	92.04	0.61	96.60	192.60*
BRS 327	0.05	97.84	0.81	118.50	103.91*
BRS 328	0.04	98.04	0.70	47.50	447.12*
BRS Marcante	0.04	105.30	0.80	293.30	65.98*
TBIO Pioneiro	0.02	123.00	0.77	66.23	158.35*

[1] *i* and *a* = yield losses (%) by ryegrass plant unit when the variable value is near zero or tends to infinity, respectively, obtained by the rectangular hyperbola model $Y = (i.X)/(1+(i/a).X)$ (Cousens 1985). * Significant to $p \leq 0.05$. R^2 = Coefficient of determination; MSE = Mean Square Error.

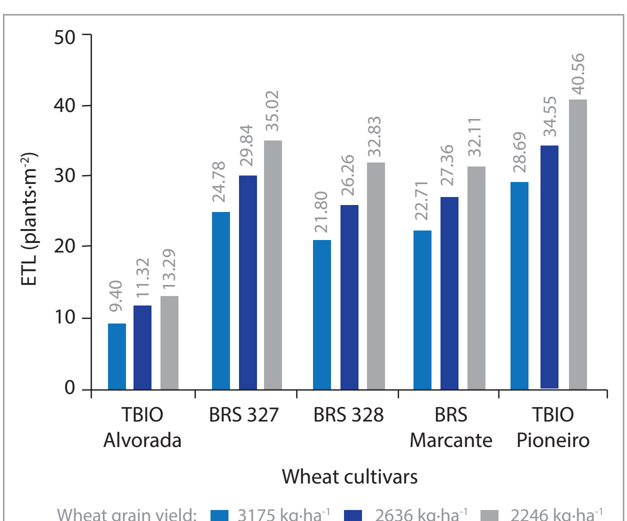

Figure 6. Economic threshold level (ETL) in wheat as a function of grain yield, ryegrass population and wheat cultivars.

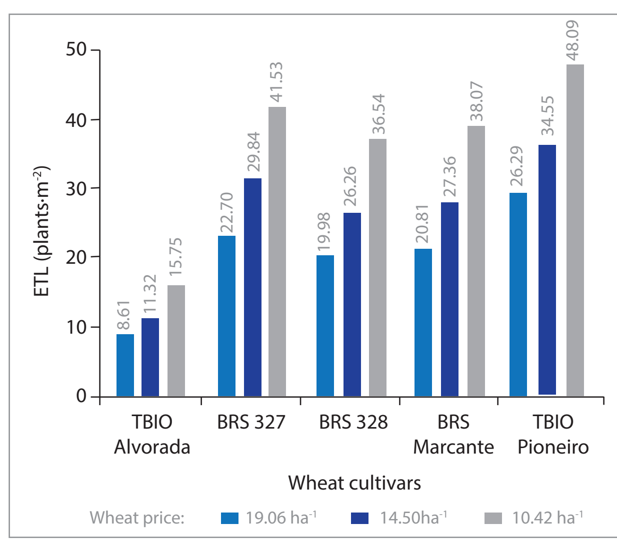

Figure 7. Economic threshold level (ETL) in wheat as a function of wheat price, ryegrass population and wheat cultivars.

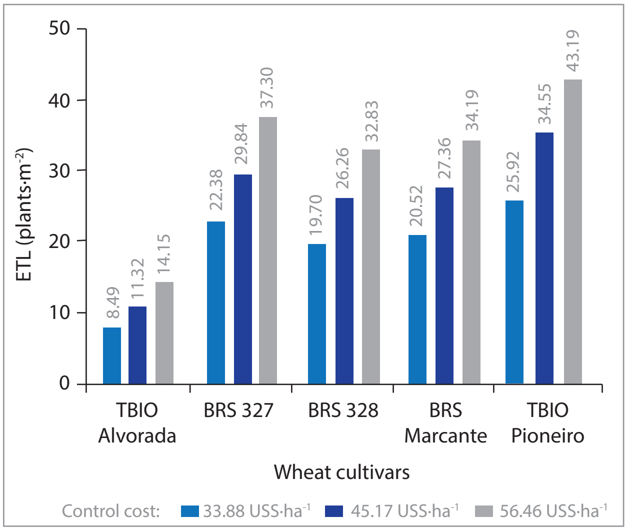

Figure 8. Economic threshold level (ETL) in wheat as a function of control cost, ryegrass population and wheat cultivars.

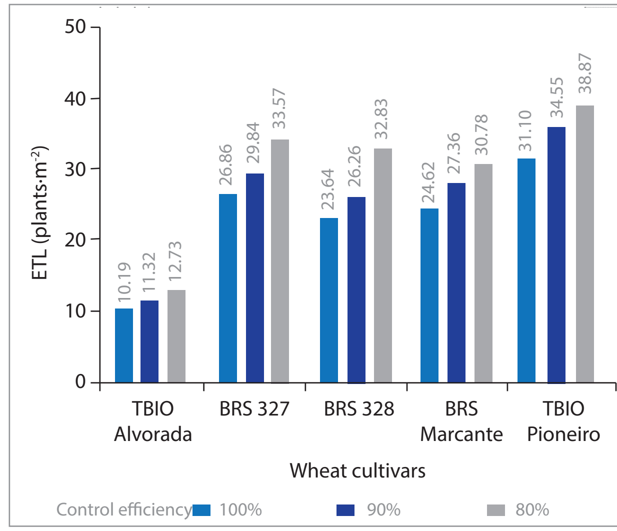

Figure 9. Economic threshold lvel (ETL) in wheat as a function of herbicide efficiency, ryegrass population and wheat cultivars.

observed for the control and for the interference that there was no significant difference between the treatments in all the evaluated periods. In general, the competition imposed by ryegrass was not able to reduce hectolitre weight. This result was also found in the study of Agostinetto et al. (2008). The authors emphasize the maintenance of the quality of wheat grains by reducing the emission of tillers, reducing drains to the main plant and thus increasing the assimilated partition to the reproductive structures.

It should be noted that in all the periods tested, the hectolitre weight was lower than 78 kg·hL^{-1}, minimum standard established for commercialization in Brazil (Brasil 2010), even though the management recommendations for wheat were followed. These results can be explained by the occurrence of high rainfall amounts recorded in the last days prior to harvest (Fig. 1), so that rainfall and high relative humidity contribute significantly to the reduction of hectolitre weight, a thousand-grain weight and grain yield (Guarienti et al. 2005).

The results showed that there was no significant difference in the comparison between control and/or interference in any of the periods, and not even within the periods of control and/or interference for a thousand-grain weight (Fig. 5). In the control and interference periods up to 30 DAE, it was not possible to verify differences in a thousand-grain weight of wheat in competition with *Lolium multiflorum* and *Raphanus raphanistrum* (Lamego et al. 2013). This may be related to the time that the crop supports competition with the weeds, that is, the CPIP, in which competition did not result in reduction of this variable. However, in previous studies, it was verified that when it is maintained the crop with weeds until harvest, there was a 15% reduction in a thousand-grain weight when compared to the control (Lamego et al. 2013).

The definition of the critical period of interference prevention (CPIP) in wheat and other crops is an extremely important tool for the adoption of integrated weed management in order to avoid losses and unnecessary use of herbicides. Therefore, the precise determination of this period is complex, because factors such as sowing time, crop population, nitrogen fertilization rates and time, weed species and populations present in the area, and edaphoclimatic characteristics can considerably influence the results in different locations and years (Jha et al. 2017).

The increasing periods in which wheat was kept in the absence of ryegrass allowed calculating the period before interference (PBI). Thus, it was determined for wheat cultivar TBIO Pioneiro that the PBI is 11 DAE (Fig. 4), that is, from the 11 DAE losses are higher than the control cost. The total interference prevention period (TPIP), determined by the model, was up to 21 DAE. Thus, the range from 11 to 21 is the critical period of interference prevention (CPIP), in which wheat plants should be kept free from infestation by ryegrass plants (Fig. 4).

The results found in the present study are similar to those observed by Agostinetto et al. (2008). The authors determined for the cultivar FUNDACEP 52, seeded in Pelotas, RS, Brazil, that the periods of interference were: PBI = 12 DAE, TPIP = 24 DAE, and CPIP from 12 to 24 DAE. It should be noted that due to the differences in soil, climate and management conditions between the regions, it is relevant to investigate the periods of weed interference of wheat weeds in each crop for the different regions.

Treatments that have been kept without competition up to 120 DAE were those presenting the best grain yield 5866 kg·ha^{-1}. On the other hand, the treatments with competition in the same periods show average grain yield of 3487 kg·ha^{-1}, a reduction of 59% in the crop grain yield. In this way, it is emphasized the need to avoid ryegrass competition with wheat, especially in the periods here described. It is worth mentioning that other researchers have also observed a reduction in the grain yield components and grain yield of wheat with the delay in the control period (Agostinetto et al. 2008; Lamego et al. 2013) or a decrease in plant density as a result of weed competition (Bertholdsson 2011; Hussain et al. 2015).

Wheat yield losses may be correlated, especially when both weed and crop species have similar morphological characteristics, making nutrient, water, space and light requirements similar, competing more intensely for the environmental factors (Cralle et al. 2003; Agostinetto et al. 2008). Thus, some control method needs to be implemented from 11 up to 21 DAE (Fig. 4). The chemical method is the most used control, but research is being developed to generate efficient and non-chemical alternatives for weed control in crops of agricultural interest (Meulen and Chauhan 2017). At present, chemical control alone has not demonstrated sustainability due to the emergence of herbicide resistant weeds (Heap 2018). In addition, due to the negative environmental impacts of herbicide use, it is necessary to work on the possibility of interaction between crop and herbicide (Zand et al. 2010), that is, cultural and preventive methods allied to the chemical control.

Competitiveness and Economic Threshold Level (ETL) between wheat cultivars and ryegrass

In general, for the evaluated variables (PP, FA, SC and DM), the estimated values for parameter *i* tended to be lower for cultivars BRS 327 (early cycle), TBIO Pioneiro (medium cycle) and BRS Marcante (early cycle), respectively. The lowest competitiveness was verified for the cultivar TBIO Alvorada (medium cycle), which presented the highest indexes of parameter *i* for all variables analyzed when compared to the other cultivars (Table 1). The cultivars of wheat presented differentiation when in the presence of weeds competition, being attributed to the intrinsic characteristics of each cultivar or even to the weed species infesting the crop (Beres et al. 2010; Bertholdsson 2011; Lamego et al. 2013). Tironi et al. (2014), when studying the association of barley with ryegrass populations also observed differences in competition, a fact that is mainly associated with the emergence period of weeds in relation to the crop.

For the variable plant population, the estimated values for parameter *i* tended to be lower for the cultivars TBIO Pioneiro (medium cycle) and BRS 327 (early cycle), hence being the most competitive cultivars. The cultivar TBIO Alvorada (medium cycle) presented the lowest competitiveness (Table 1). This fact is due to the differentiated genetic characteristics that each cultivar presents, as observed by Galon et al. (2007) when evaluating different cultivars of rice in coexistence with weedy rice. The competitive relationships between wheat and ryegrass plants and yield loss of weed infested crops are associated to the cultivars used in the association, plant arrangement, cycle, adopted management, size and proportion of plants that make up the association (Galon et al. 2007; Rigoli et al. 2008; Agostinetto et al. 2010).

Regarding the yield losses of wheat cultivars to the percentage of soil cover, it can be seen that BRS Marcante, although being the most competitive, showed the greatest yield loss for this variable (Table 1). It was observed that the energy expenditure in the competition severely affected the yield components of BRS Marcante. This fact may also be related to the average height of this cultivar, and light may be a limiting resource in wheat competition with ryegrass (Agostinetto et al. 2008). When the crop presents smaller size the weed will shade the same, winning the dispute over the resource.

The lowest yield losses of wheat cultivars in relation to the variable leaf area were observed for BRS Marcante and BRS 327, which presented the same value for parameter *i*, that is, the same competitiveness indexes (Table 1). The responses of the genotypes and the role of interference between weed species and crop are closely linked, in addition to environmental conditions and the importance of the competition period (Worthington and Reberg-Horton 2013).

The ryegrass shoot dry matter caused reductions in wheat grain yield cultivars in ascending order, TBIO Alvorada, BRS 327, BRS 328, BRS Marcante and TBIO Pioneiro (Table 1). When in association with ryegrass biotypes resistant and susceptible to glyphosate, wheat showed losses in leaf area →

and shoot dry matter (Ferreira et al. 2008), similar to that observed in the present study.

As parameter *i* is an index used to compare the relative competitiveness between species (Swinton et al. 1994), differentiated values for wheat cultivars were found in the explanatory variables tested in competition with ryegrass (Table 1). The comparison between wheat cultivars considering parameter i, for the four average explanatory variables (PP, SC, FA or DM), showed that the order of placement in relation to the competitiveness of the cultivars was: TBIO Pioneiro > BRS Marcante > BRS 327 > BRS 328 > TBIO Alvorada (Table 1). The observed differences between the results of the cultivars may be due to the morphophysiological characteristics of these or to the occurrence of a high standard error in the estimation of the parameter *i*. It can be attributed to the variability associated with the field study area and/or the crop phenotypic plasticity (Dieleman et al. 1995). Thus, this variability may difficult the correct estimation of yield losses at low densities of ryegrass plants. This behavior was verified in a study carried out by Galon et al. (2007) when studying the competitiveness of irrigated rice cultivars in the presence of weedy rice.

In all the explanatory variables, it was observed that cultivars of the same growth cycle presented differentiated values of parameter *i* (Table 1). This demonstrates that the wheat genotypes respond differently to competition with ryegrass. This difference in the competitive ability of the genotypes has already been observed in different crops of agronomic interest, and is shown as an alternative for the integrated weed management (Beres et al. 2010; Bertholdsson 2011; Lamego et al. 2013)

The parameter *a* estimation was overestimated by the model, with grain yield losses of more than 100% in all cultivars for the plant population variable (Table 1). These results may be due to the fact that the largest populations of ryegrass were insufficient to adequately estimate the maximum yield loss. According to Cousens (1991), to obtain a reliable estimation for the parameter *a*, it is necessary to include in the experiment very high populations of weed, above those commonly found in agriculture. For the variables soil cover, leaf area and shoot dry matter some cultivars presented losses above, and others below 100%. Bertholdsson (2011) studied the differentiated competitive capacity of wheat cultivars and their allelopathic effect. The author verified evidences that wheat cultivars show particularized behavior regarding morphological and yield variables. This difference was also observed in the allelopathic effect of weeds. One option to avoid overestimating yield losses would be to limit the maximum loss to 100%. However, this limitation would influence the estimation of parameter *i* and may result in less predictability in the rectangular hyperbola model (Streibig et al. 1989). In addition, yield losses greater than 100% are biologically unrealistic and occur when the weed population amplitude is excessively narrow and/or when the highest population values are not sufficient to produce asymptotic yield loss responses (Cousens 1985; Yenish et al. 1997; Galon et al. 2007).

The results showed that the cultivar TBIO Pioneiro presented maximum losses of more than 100% in all the explanatory variables, differently from the cultivar TBIO Alvorada, which presented the same development cycle and showed only a loss of more than 100% for the variable plant population (Table 1). This may be due to the initial growth difference, plant height, tiller production capacity and leaf size, which are directly associated with the yield potential of the species (Mason et al. 2007; Jha et al. 2017).

Comparison between the explanatory variables for all cultivars, in general, showed a better fit to the model for the PP > SC > DM > FA variables, considering the higher mean values of R^2 and the lower mean values of the MSE (Table 1). On the other hand, the comparison between the explanatory variables FA, SC and DM, as independent variables in the model prediction of yield losses, generally showed that SC presented a better fit and could be used instead of PP variable. The quantification of the interference caused by the weeds have higher adjustment to the variables soil cover, fresh and dry weight, compared with the plants density (Fleck et al. 2002a).

The economic threshold level (ETL) simulation was performed using the explanatory variable plant population of ryegrass. The variable showed the best fit to the rectangular hyperbole model, besides being the most used in experiments with the same objective (Galon et al. 2007; Agostinetto et al. 2010).

The successful implementation of weed ryegrass weed management on wheat crop systems may result from determination in the population that exceeds ETL. Thus, it was observed that the cultivar TBIO Pioneiro demonstrated the highest ETL values in all simulations, with variations from 25.92 to 48.09 plants·m^{-2} (Figs. 6, 7, 8 and 9). The lowest ETL values were presented by the cultivar TBIO Alvorada, with variations from 8.49 to 14.15 plant·m^{-2}. The other wheat cultivars (BRS 327, BRS 328 and BRS Marcante) were in intermediate levels of ETL (Figs. 6, 7, 8 and 9).

In the average of all the cultivars and comparing the lowest with the highest grain yield, a decrease of 30% in the ETL was observed, that is, the higher the technological level to increase →

yield, the lower the ryegrass ETL in wheat (Fig. 6). Therefore, the greater the yield potential of the cultivars, the lesser the ryegrass population needed to overcome the ETL, making it advantageous to adopt weed control measures with low populations. Hussain et al. (2015), allying the ETL of *Phalaris minor* Retz. weed on wheat at different sowing times, found 6 to 7 plants·m^{-2} for the first sowing date (November 20) and from 2.2 to 3.3 plants·m^{-2} for the second sowing date (December 10), with weed infestation occurring 15 days after sowing. The same authors observed losses of 28% to 34% in wheat grain yield when it was infested by *P. minor*, with a density of 40 plants·m^{-2}, respectively for the first and second sowing dates.

Regarding the price paid per bag of wheat, taking into account the average values of all cultivars and the highest against the lowest price, there was a three-fold increase in the ETL value (Fig. 7). Thus, the lower the price paid for the bag of wheat, the greater the population of ryegrass needed to overcome the ETL and compensate for the control method. For the ETL calculation, there are three factors considered as main factors: herbicide cost, application cost and crop value per marketed unit. Any change caused in these items causes variation in ETLs, due to the increase in control costs linear relationship with ETL increase (Fleck et al. 2002b).

For the average control cost of ryegrass in all cultivars, it was observed that the minimum cost was 40% lower when compared to the maximum cost. Thus, the greater the cost of the control method, the greater the ETL, that is, the greater number of ryegrass plants per m^2 required to justify the control (Fig. 8). Galon et al. (2007), when assessing the ETL of rice grass in irrigated rice, observed similar results.

Comparing the average herbicide efficiency (90%) to lower (80%) or higher (100%), were found changes in ETL of approximately 12.5% and 9.8%, respectively (Fig. 9). Thus, the control efficiency influences the ETL, and the higher the herbicide efficiency, the lower the ETL (the smaller the number of ryegrass·m^{-2} required to adopt control measures). When assessing the interference and the ETL of rice grass in three arrangements of rice seeding, Agostinetto et al. (2010) observed a reduction in ETL when the control efficiency of the herbicide increased.

At the present moment of agriculture, with the adoption of technology by farmers aiming greater yields, consequently will occur the decrease of ETL to be adopted, including for the crop and weed studied here. This reasoning will also occur for the price paid to the product and for the cost to weed control. Some studies have reported similar results to those found in the present study, the cases of *Sida glaziovii* ETL in soybean (Fleck et al. 2002b), *Echinochloa* spp in irrigated rice (Galon et al. 2007) and *Ipomoea* spp. in dry beans (Vidal et al. 2010; Galon et al. 2016).

Graphical representation of results

Figure 10 shows the critical period for the weed ryegrass management, which is not recommended to exceed 21 DAE

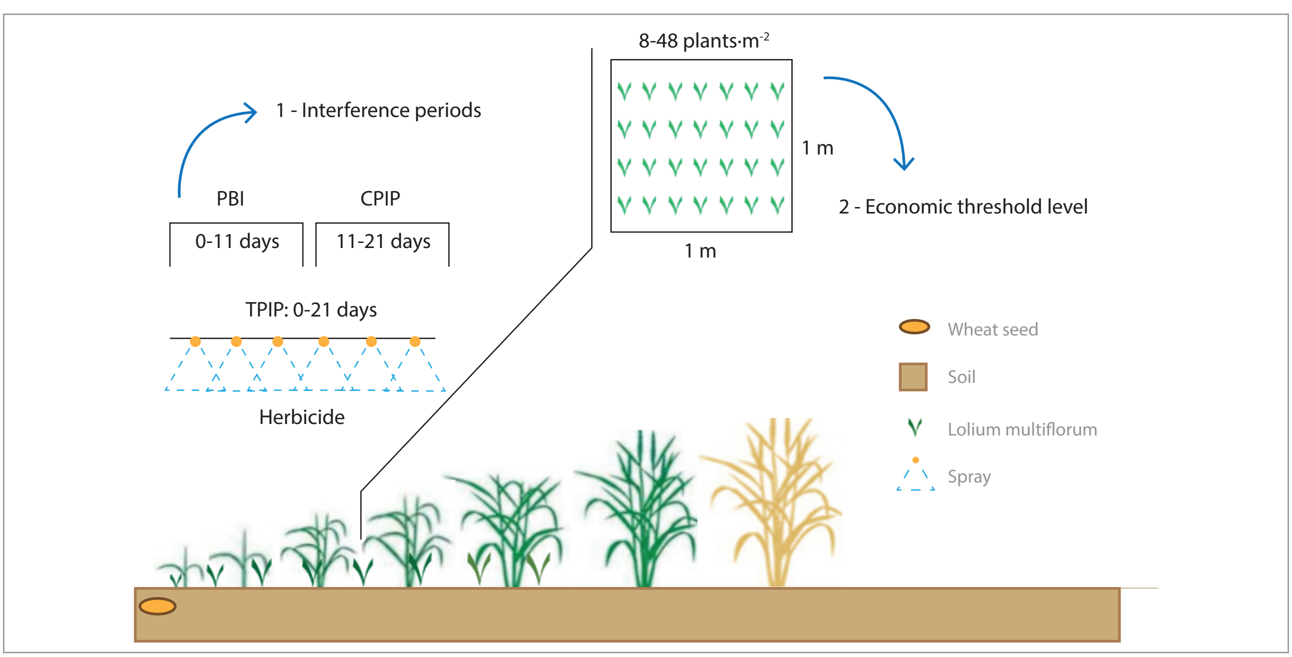

Figure 10. Graphical representation of *Lolium multiflorum* interference on wheat crop. PBI = Period Before Interference; CPIP = Critical Period of Interference Prevention; TPIP = Total Period of Interference Prevention.

of the crop. Together with the ideal control period, the number of plants enough to indicate the ETL is presented, which in turn is dependent on several factors previously presented in the study.

In summary, it can be observed that the understanding of weed population dynamics, wheat cultivars and species interference is an important form of interaction between different methods of control, especially cultural and chemical control by the use of herbicides (Zand et al. 2010). Promising researches by specialists in the field of weed sciences are being developed to generate effective and non-chemical alternatives for weed control in crops.

CONCLUSION

The results allowed concluding that the ryegrass affects wheat grain yield. The ideal ryegrass control period is until 21 days after the crop emergence.

The Economic Threshold Limit varied according to cultivars, control efficiency, herbicide cost, wheat price and grain yield, ranging from 8.49 to 48.09 plants·m^{-2}.

AUTHOR'S CONTRIBUTION

Conceptualization, Perin G. F.; Methodology, Santin C. O.; Investigation, Chechi L. and Castoldi C. T.; Writing – Original Draft, Basso F. J. M. and Pilla T. P.; Writing – Review and Editing, Forte C. T.; Funding acquisition, Galon L.; Resources, Franceschetti M. B.; Supervision, Galon L. and Bagnara M. A. M.

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