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Morphological and physiological changes in barley cultivars under black oat competition

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Abstract: Background: Weeds compete with crops, demanding efficient control to avoid yield losses. Highly competitive cultivars are a cultural method that can increase weed suppression and reduce the effects of crop-weed competition. **Objective:** The present study aimed to assess the competitive abilities of barley cultivars (crop) against black oat (weed) and their interference in crop physiology. **Methods:** A preliminary additive experiment was carried out with increasing densities of barley and black oat to determine the minimal density from where there was no drier mass increasing per area. In the second experiment, a replacement series experiment, five plant proportions (100:0; 75:25; 50:50; 25:75, and 0:100) of the crop were used and the competitor was installed. Fifty days after the emergence, morphophysiological and physiological variables, as well as their respective relative competitiveness indexes, relative clustering coefficient, and species aggressiveness, were all assessed. **Results:** The variables associated with the photosynthesis were dependent on the cultivar. BRS Cauê was the cultivar that performed better against black oat, with an increase in the overall photosynthetic rate, due to a smaller leaf area loss, as the competition increased. BRS Brau reduced the photosynthesis into smaller proportions for the competitor. The water use was not impacted to the same extent as photosynthesis. **Conclusions:** BRS Cauê was the most competitive cultivar, suffering the lowest impact of competition with black oat.

Keywords: *Avena strigosa*; *Hordeum vulgare*; Weed interference; Winter cereals; Physiological parameters

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1. Introduction

Barley is the fourth most cultivated cereal worldwide and it is widely used for livestock feed, human food, and malt production (Cuesta-Seijo et al., 2016). In Brazil, the Rio Grande do Sul (RS) State is the main producer, with approximately 30% of the domestic barley production and an average grain yield of 2.595 kg ha^{-1} (Conab, 2021). Inadequate rains, such as the dry harvest and frosts are unfavorable for the yield and quality of barley (Tavares et al., 2015), including weeds that reduce the productive potential of the crop (Nunes et al., 2007). The average productivity in RS is below those observed in other States in the southern region of the country, which renders approximately 3.621 kg ha^{-1} (Conab, 2021).

Among the factors limiting crop productivity is the competition with weeds, which significantly alter the grain's quality (Galon et al., 2011; Wanic et al., 2013). Several dicots and monocot weed species are frequently found in barley fields, including important species, such as *Lolium multiflorum* Lam., *Raphanus raphanistrum* L., *Raphanus sativus* L., *Chenopodium album* L., *Sonchus oleraceus* L., and *Avena strigosa* Schreb. (Vargas, Roman, 2005).

In recent years, black oats have been infesting the southern Brazilian barley fields strongly, due to their higher occurrence and abundance, especially in those areas that are managed with black oat for livestock forage, and for soil cover crops with a no-tillage system (Tafernaberri Jr et al., 2012; Fontana et al., 2015; Forte et al., 2018). In addition, black oat has a high rusticity, with a low soil fertility requirement, rapid growth, and an initial development that is increasing the competitive potential of the species (Tafernaberri Jr et al., 2012).

Barley has a rapid initial growth and a high efficiency in capturing the available soil resources (Molla, Sharaiha, 2010). Several studies have reported the competitive ability of crops, such as weeds, with reductions of up to 79% in the barley biomass and grain yield, due to the competition (Pilipavicius et al., 2011; Wanic et al., 2013). It is also essential to verify the influence of plant density on the competitive abilities of barley against black oat (Fontana et al., 2015; Andrew, Storkey, 2017).

Despite the importance of knowing the competitive abilities of barley as a tool for integrated weed management and reducing herbicide dependence, few studies have been analyzing the intra- and inter-specific competition at the morphological and physiological levels. In this context, research to determine the competitive abilities of barley with weeds becomes relevant, to adopt more sustainable management methods and alternatives to chemical, or even the adoption of integrated weed management. Studies to ascertain the competitive ability of community species stand out because the population of cultivated plants is generally constant but the population of the weeds varies, according to the soil seed bank and the environmental conditions that alter the level of infestation (Agostinetto et al., 2010; Galon et al., 2011). It is important to check the influence of variation in the proportion of the plants among the species. The weed density is the factor that most affects the growth and development of crops of agronomic interest.

Research studies involving physiological characteristics in a competition study between barley and black are scarce, as well as other studies of competition between the species that are influenced by the physiological and morphological parameters (Concenço et al., 2009; Fontana et al., 2015; Baldessarini et al., 2020). The present study hypothesizes that there is a differentiation in the competitive abilities of barley with black oats among the cultivars. This difference affects the variables that are related to crop morpho-physiology. Given the above, the present research aimed to evaluate the competitive abilities of barley cultivars against black oats, and their possible interference in crop physiology.

2. Materials and methods

The experiments were conducted in the greenhouse of the Federal University of the Southern Frontier (UFFS), Erechim *Campus*, State of Rio Grande do Sul, Brazil in the winter growing season of 2015/16. The experimental units were composed of plastic pots, with a capacity of 8 dm^{-3}, filled with soil from an agricultural area that was classified as Humic Aluminoferric Red Latosol (Embrapa, 2013). According to the soil analysis, the pH correction and the soil fertilization were performed following the technical recommendations for barley. The chemical and physical soil characteristics were: pH_{water} = 4.8; organic matter = 3.5%; P = 4.0 mg dm^{-3}; K = 117.0 mg dm^{-3}; Al^{3+} = 0.6 $cmol_c$ dm^{-3}; Ca^{2+} = 4.7 $cmol_c$ dm^{-3}; Mg^{2+} = 1.8 $cmol_c$ dm^{-3}; CTC_{total} = 7.4 $cmol_c$ dm^{-3}; $CTC_{pH=7}$ = 16.5 $cmol_c$ dm^{-3}; H+Al = 9.7 $cmol_c$ dm^{-3}; sum of base = 6.8 $cmol_c$ dm^{-3}; base saturation = 41%; and clay = 60%.

The experimental design was completely randomized, with four repetitions. The tested competitors included three barley cultivars (BRS Cauê, BRS Brau, and BRS Korbel), and a black oat biotype, cultivar Embrapa 139 (Neblina). As competitors, the black oat cultivar (Embrapa 139 - Neblina) and the barley cultivars (BRS Cauê, BRS Brau, and BRS Korbel) were used, as they are the most sown in the State of Rio Grande do Sul by the producers. The preliminary experiments were carried out for both barley and black oat when using pure stands, to determine the minimum plant population in which the final product became constant with the population increase (Radosevich et al., 2007). The additive design included eleven pure stand populations with 1, 2, 4, 8, 16, 24, 32, 40, 48, 56, and 64 plants pot^{-1} (equivalent to 25, 49, 98, 196, 392, 587, 784, 980, 1,176, 1,372, and 1,568 plants m^{-2}) of black oat, and every barley cultivar was tested. The barley and black oat plant shoots were harvested 50 days after emergence (the beginning of the reproductive period) to determine the dry shoot weight (DSW). The samples were weighed after drying in a forced circulation oven at a temperature of 65±5ºC until reaching a constant mass. The constant dry mass (DM) production was obtained from the populations of 20 per vase, for all of the barley cultivars and the black oat biotype, being equivalent to 520 plants m^{-2} (data not shown).

Based on the final populations that were obtained from the additive model, three experiments were carried out in a completely randomized experimental design. This was to evaluate the competitiveness of the barley cultivars, BRS Cauê (maturation cycle from 125 to 132 days, and dwarf size less than 0.80 m), BRS Brau (maturation cycle of 132 days, and dwarf length of 76 cm in height), and BRS Korbel (maturation cycle from 125 to 135 days, and a small average size of 0.80 m) against the black oats biotype.

The experiments were arranged in a series of substitutions by using five proportions, with the mixture and the pure stands. The ratios included 100:0, 75:25, 50:50, 25:75, and 0:100, which were equivalent to 20:0; 15:5; 10:10; 5:15, and 0:20 plants pot^{-1}, respectively. The seeds were previously sown in trays, and the seedlings with major uniformity were transplanted into the pots, three days after emergence. The treatment with 20 plants pot^{-1} was the control, as previously defined in the pre-experiment with ratios of 100, both for the barley (crop) and the black oats (weed). The defined point where there was no intraspecific competition did not cause any significant damage.

The physiological variables were measured at 50 days after the emergence: photosynthetic rate (A – µmol m^{-2} s^{-1}), mesophyll concentration of CO_2 (Ci - µmol mol^{-1}), transpiration rate (E – mol H_2O m^{-2} s^{-1}), carboxylation efficiency (CE – mol CO_2 m^{-2} s^{-1}), water conductance (Gs – mol m^{-1} s^{-1}), and the physiological water use efficiency (WUE – mol CO_2 mol H_2O^{-1}), obtained by the ratio between the fixed CO_2 system and the water lost at the same time interval. The gas exchange parameters were measured with an infrared gas analyzer (IRGA), LCA PRO model (Analytical Development Co. Ltd, Hoddesdon, UK). One block was evaluated per day between 8:00 am and 10:00 am under radiance (~1,100 PAR), at a temperature of (15-20°C), with relative humidity (60-70%) at the environments, and a CO_2 concentration at the environment. Additionally, the leaf area (LA) and the dry mass (DM) of the shoots of the plants were evaluated. A CI-203 BioScience Portable Leaf Area Meter was used to measure the AF. All of the plants from each experimental plot were harvested and conditioned in paper bags. They were then placed into a forced air oven at 60 ± 5ºC until the constant mass was achieved, to estimate the DM.

The data set was analyzed by the graphical analysis of variation, or by the relative productivity (Cousens, 1991; Bianchi et al., 2006). The procedure, also known as the conventional method for substitution experiments, consisted of diagrams based on the relative (PR) and total

(PRT) yields. A straight line for the PR value represented that both species had equivalent abilities. If the PR value was in a concave line, this indicated growth damage for one or both of the species, whereas a convex line represented beneficial growth. If the PRT yield was equal to "1" (straight line), this reported competition for the same resources. If the PRT yield was greater than "1" (convex line), then the competition was avoided, whereas if the PRT yield was lower than "1" (concave line), this indicated a mutual injury to growth (Cousens, 1991).

The relative competitiveness (RC), the relative clustering coefficient (K), and the aggressiveness (Ag) of the species were calculated. RC represented the comparative growth of the barley cultivars when concerning the black oat competitor (Y); K indicated the relative dominance of one species over the other, and Ag meant the most aggressive species. The CR, K, and Ag indexes showed the most competitive species, and their joint interpretation determined the level of the species' competitiveness (Cousens, 1991). The barley cultivars that were evaluated (X) were more competitive than black oats (Y) when RC > 1, Kx > Ky, and Ag > 0. Opposite to that, black oat (Y) was more competitive than the barley cultivars (X) when RC < 1, Kx < Ky, and A < 0 (Hoffman, Buhler, 2002). For the estimation of the competitiveness indexes, all of the plant proportions that involved both species were considered by the following equations: RC = PRx/PRy; Kx = PRx/(1-PRx); Ky = PRy/(1-PRy); and A = PRx-PRy, according to Cousens and O'Neill (1993).

It was considered as a null hypothesis when the means of "Ag" were equal to zero (Ho = 0); for RC, when the means were equal to one (Ho = 1); and for K, when the means of differences between Kx and Ky were equal to zero [Ho = (Kx-Ky) = 0]. The criterion to consider if the PR and PRT curves that were observed were different from those expected was when the expected values (represented by the dotted lines) were outside the 95% confidence interval of the observed curves (solid, colored lines, with confidence intervals of the same color).

The data results were submitted to the Analysis of Variance by the F-test ($p < 0.05$), and when reported that there were significant effects, the average of the treatments was compared with the respective control (pure stands) by Dunnett's test ($p < 0.05$). The diagrams and coefficients were obtained by the statistical environment of "R" (R Foundation for Statistical Computing, 2014).

3. Results and discussion

For the results and the discussion, the DM and the LA of the plants were primarily considered. The physiological parameters were discussed with due caution since they represented point assessments made with the IRGA equipment, which reflected the physiological status of the plant at the moment of the evaluation. That is to say, at an interval of approximately 2 minutes. When considering the importance of competitiveness, the physiological variables that were evaluated punctually have provided the only evidence of the reaction of the plants when imposed by competition stress.

3.1 Relative Yield

For the group of parameters that were associated with morphologic (Figure 1), the relative yields showed high reliability for DM and LA, with variations for PR and PRT among the barley cultivars. The LA demonstrated high stability, with a narrow confidence interval of the observed

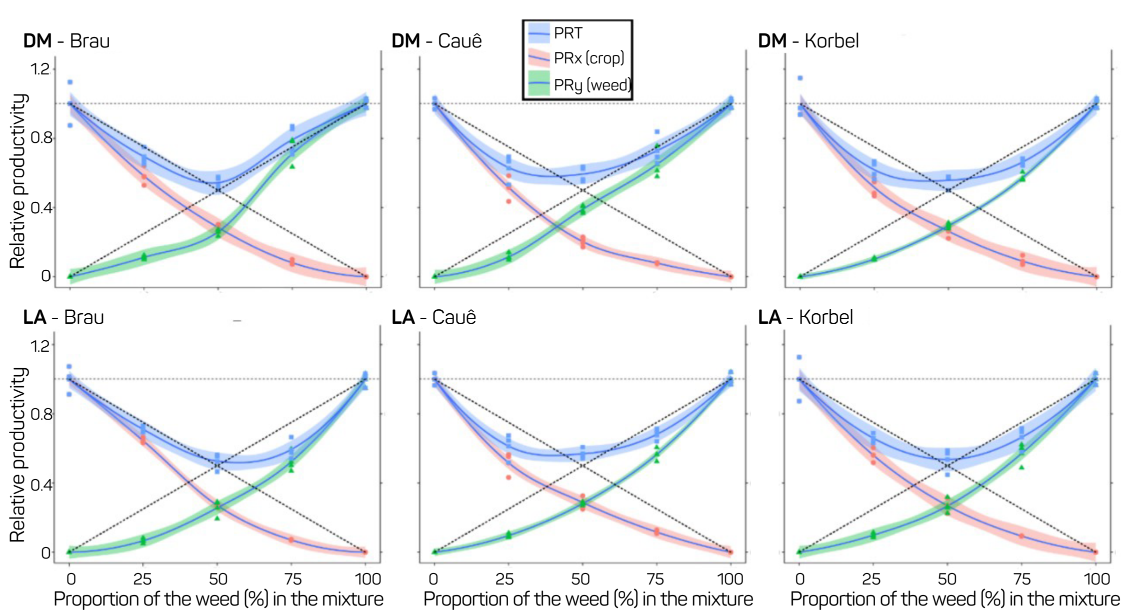

Figure 1 - Variables associated with the morphology of barley cv. BRS Brau, BRS Cauê, and BRS Korbel, under competition with the weed black oat, function as plant proportion. DM = shoot dry mass and LA = leaf area. Colored bands represent the 95% confidence interval

data. At the same time, the rest of the variables were only considered punctually when there was visible stability of one of the competitors (Figure 1). Other studies have illustrated that LA and DM are the main variables affected in this model of an experiment, as reported for barley versus ryegrass (Galon et al., 2011), wheat versus ryegrass (Galon et al., 2019), and soybean versus hairy beggarticks, or with wild poinsettia (Forte et al., 2017).

The LA for both the barley and the competitor presented similar behavior when observed for DM, with consistent losses for both species, and for all of the barley cultivars when in competition, with a mean reduction in the PRTs of about 40-50% concerning their respective controls (Figure 2). Similar results were observed by Fontana et al. (2015) when working with barley and competing with black oats. They showed concave lines for the DM and LA of barley, indicating their lower competitiveness when compared with the weed. The authors suggested that this fact could be explained by the great phenotypic similarity between black oats and barley, belonging to the same botanical family, Poaceae.

The DM was reduced by the competition for both black oat and the barley cultivars, with a great reduction observed even for the PRTs (Figure 1). In general terms, regardless of the barley cultivar, the crop tended to be more affected than the weed in the competition, with more significant differences between the observed (solid lines with the confidence interval) and expected (dotted lines) PR values. The reduction of weed DM was expected and this often depended on the intrinsic characteristics of the cultivar (Lamego et al., 2013). This all became evident with the high competitiveness that was imposed by the weed species on the barley.

As DM was a directly measured variable, being less affected by the environment at the moment of the evaluation than the physiological parameters that were measured with the IRGA, it described greater reliability of the competition, which caused a reduction of up to 50% in PRTs for DM (Figure 1). When in competition with ryegrass, even in low populations, decreases in the barley DM are reported, especially when there is a low water supply, and with greater intensity at the end of the cycle (Galon

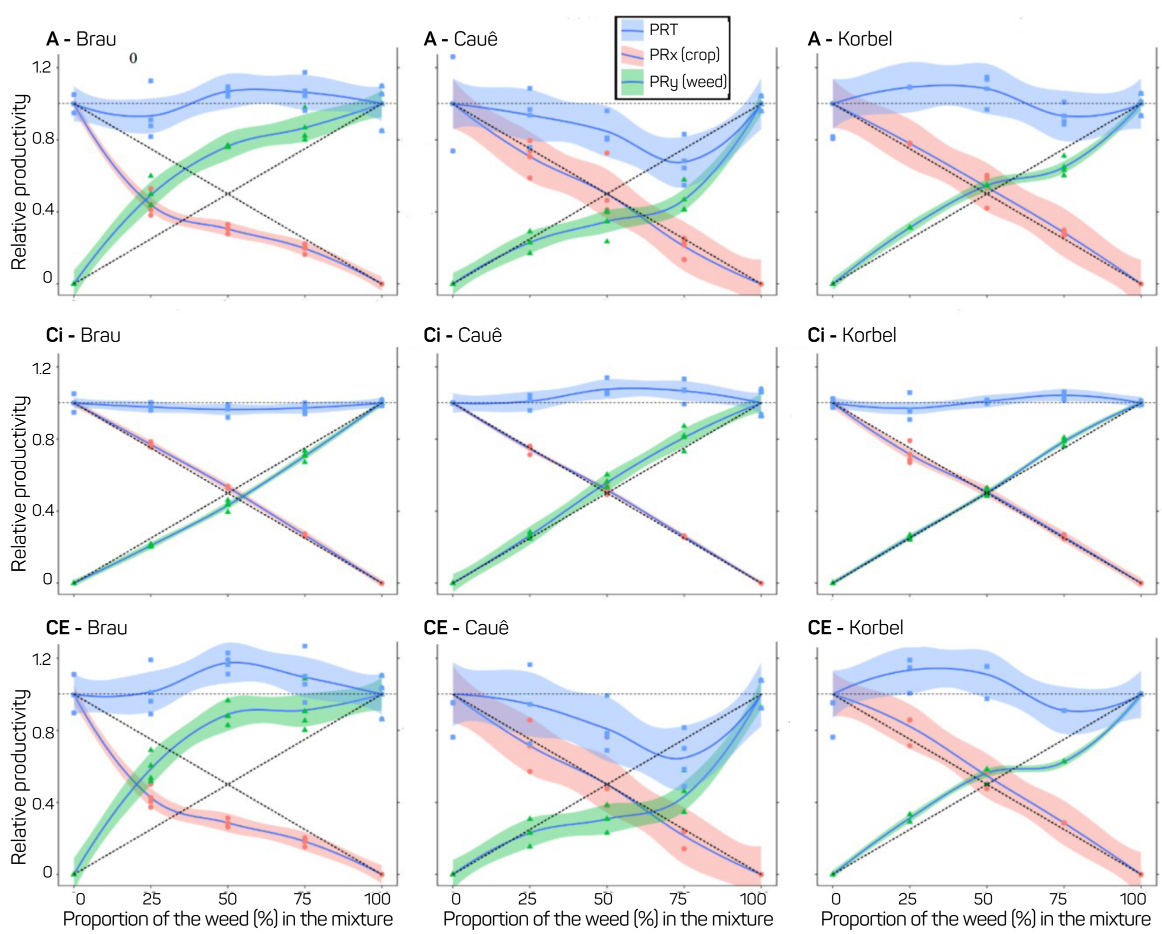

Figure 2 - Variables associated with the photosynthesis of barley cv. BRS Brau, BRS Cauê, and BRS Korbel, under competition with the weed black oat, function as plant proportion. A = photosynthesis rate; Ci = CO_2 concentration in the mesophyll; CE = carboxylation efficiency. Colored bands represent the 95% confidence interval

et al., 2011, Wanic et al., 2013). It is worth mentioning that having to consider only the characteristics, such as DM and LA, in the plants under the competitive conditions; it might be incomplete to understand each species' specific behavior when in competition with other species.

The DM of the barley cultivars, as well as the competitor (Table 1), differed from the respective competition-free controls according to Dunnett's test at 5%, for all levels of interaction between the species, except in the 25:75 mixture (barley:black oat), where the DM of black oat was equivalent to that as observed for the separately grown species. The relative competitiveness (RC) indicated systematically that the species in a greater proportion took advantage of the competition since values higher than "1" were observed when the crop predominated (density 75:25), and less than "1", with the predominance of the competitor (density 25:75), always with values differing from "1", according to the "t" test at 5% (Table 1). These results corroborate those reported by Pilipavicius et al. (2011). The decrease in weed competition was correlated to the increase in barley density.

Table 1 - Competitivity indexes based on parameters associated with morphological (LA - leaf area), between barley cvs. BRS Brau, BRS Cauê and BRS Korbel, and the weed black oat, in terms of relative competitiveness (CR), the clustering coefficient of the crop (Kc) and weed (Kd), and aggressiveness (Ag)

	LA[2]	Dif.	CR[3]		Kc[4]		Ag[5]	
			Leaf area (LA) – cultivar BRS Brau					
100:0(T)	2140.53	0.00						
75:25	1838.52	-302.01*	3359	(± 0.353)*	605	(± 0.02)*	298	(± 0.015)*
50:50	1158.61	-981.92*	1085	(± 0.107)ns	371	(± 0.002)ns	15	(± 0.022)ns
25:75	604.70	-1535.83*	409	(± 0.025)*	228	(± 0.005)*	-207	(± 0.019)*
0:100	0.00	-2140.53*						
0:100(T)	2307.08	0.00				Kd		
25:75	1608.62	-698.46*			212	± 0.022		
50:50	1181.13	-1125.95*			347	± 0.038		
75:25	608.65	-1698.43*			373	± 0.042		
100:0	0.00	-2307.08*						
			Leaf area (LA) – cultivar BRS Cauê					
100:0(T)	1622.08	0.00						
75:25	1117.48	-504.60*	1789	(± 0.072)*	364	(± 0.04)ns	152	(± 0.014)*
50:50	932.48	-689.60*	1024	(± 0.065)ns	405	(± 0.031)ns	6	± 0.019
25:75	754.62	-867.46*	0.62	(± 0.034)*	395	(± 0.018)ns	-144	(± 0.017)ns
0:100	0.00	-1622.08*						
0:100(T)	2712.70	0.00				Kd		
25:75	2043.61	-669.09*			0.32	± 0.019		
50:50	1526.49	-1186.21*			392	± 0.009		
75:25	1045.63	-1667.07*			436	± 0.029		
100:0	0.00	-2712.70*						
			Leaf area (LA) – cultivar BRS Korbel					
100:0(T)	1965.45	0.00						
75:25	1469.30	-496.15*	1926	(± 0.17)*	429	(± 0.031)*	177	(± 0.023)*
50:50	1056.90	-908.55*	1016	(± 0.077)ns	0.37	(± 0.035)ns	2	(± 0.022)ns
25:75	733.82	-1231.63*	494	(± 0.024)*	309	(± 0.003)ns	-194	(± 0.018)*
0:100	0.00	-1965.45*						
0:100(T)	2422.20	0.00				Kd		
25:75	1843.28	-578.92*			328	± 0.021		
50:50	1293.42	-1128.78*			367	± 0.037		
75:25	954.70	-1467.50*			454	± 0.05		
100:0	0.00	-2422.20*						

[1]Proportion of crop and weed plants, in which (T) is pure stands (control) with the intraspecific competition. [2]Quantification of the assessed variable at the indicated competition level and differences compared to the test/control treatment by Dunnett's ($p<0.05$). [3]Significant when it differed from "1", by the t-test ($p<0.05$). [4]Difference between Kc and Kd, at the same competition levels, compared by the t-test ($p<0.05$). [5]Significant when it differed from "0" by the t-test ($p<0.05$). * = significant difference ($p<0.05$); ns = non-significant.Crop: Weed[1]

At equal densities, the barley cultivar BRS Brau was superior, BRS Cauê was inferior, and BRS Korbel did not differ from the competitor, which showed that in an equal occurrence, the crop and the weed were equivalent in the competition for the environmental resources, denominated by the interspecific competition. Several studies have also demonstrated differences in the competitive ability between the related species, such as rice and barnyard grass (Agostinetto et al., 2010), barley and ryegrass (Galon et al., 2011), wheat and *Alopecurus myosuroides* (Andrew, Storkey, 2017), and between soybean and hairy beggarticks, or wild poinsettia (Forte et al., 2017).

The K index estimated the relative dominance of one genotype over the other, and this was obtained by a value for the crop (Kc) and another for the weed (Kd). The superiority of one of the competitors was measured by the difference between Kc and Kd when compared by the t-test at 5%. For the DM, the advantage was with the black oats (Kd higher than Kc) when it was planted in higher density than barley, and also when it was equivalent to the density of BRS Cauê. In the other situations, there was no difference between the crop and the weed (Table 1). Changes in the competitive ability of wheat related to the density and the planting season and the choice of cultivar have been reported. The competitiveness decreased when it was associated with high densities and early sowing (Andrew, Storkey, 2017).

The aggressiveness (Ag) that was based on DM, in general terms, was attributed to the predominating species in the mixture. Similar results were also found by Fontana et al. (2015), who identified that barley presented greater interspecific competition and that the weed, with higher proportions (25:75), further reduced the accumulation of DM and LA. For Galon et al. (2011), when assessing the barley competition with ryegrass, A was also dependent on the cultivar, so this is justified in organic farming systems that the choice for the most competitive cultivars becomes preponderant (Andrew, Storkey, 2017).

The LA differed from the respective controls that were grown in the absence of competition for all of the plant proportions, according to Dunnett's test at 5% (Table 1). The RC that was based on LA was highly consistent, indicating superiority of the crop when it represented the majority in the proportion, independent of the cultivar, and without difference between the crop and the weed when the densities were equivalent (Table 1). The same behavior was observed for A, based on LA.

The values of Kc that were based on LA indicated that BRS Brau and BRS Korbel were superior to the weed when the crop was in a greater proportion, and black oat was only superior to BRS Brau when it was in a higher proportion. In other situations, the barley and black oat were equivalents (Table 1). Based on the PR's and the PRT's, it can be inferred that there was equivalence in the mechanisms of competition and the demand for environmental resources between the barley and black oat. This competition equivalence was partly due to their close botanical degree, as both are Poaceae species, which are adapted to the cold climate, with carbon metabolism by the cycle C3. The differences in the behavior of the parameters RC, Kc/Kd, and A, as observed for DM (Table 2) and LA (Table 1), mainly allowed one to infer that there might be differences in the competitive abilities among the barley cultivars BRS Cauê, BRS Brau, and BRS Korbel, which may indicate the selection of BRS Cauê in an environment that is different from that of the origin of the black oat biotype.

Table 2 - Competitivity indexes based on parameters associated with morphological (DM- dry mass) between barley cvs. BRS Brau, BRS Cauê and BRS Korbel, and the weed black oat, in terms of relative competitiveness (CR), the clustering coefficient of the crop (Kc) and weed (Kd), and aggressiveness (Ag)

Crop: Weed[1]	DM[2]	Dif.	CR[3]		Kc[4]		Ag[5]	
			Dry mass (MS) – cultivar BRS Brau					
100:0(T)	19.84	0.00						
75:25	15.39	-4.45*	1745	(± 0.125)*	471	(± 0.046) ns	164	(± 0.023)*
50:50	11.28	-8.56*	1097	(± 0.024)*	398	(± 0.017) ns	25	(± 0.006)*
25:75	6.45	-13.39*	349	(± 0.043)*	266	(± 0.024)*	-311	(± 0.036)*
0:100	0.00	-19.84*						
0:100(T)	22.91	0.00				Kd		
25:75	21.7	-1.21 ns			379	± 0.019		
50:50	11.88	-11.03*			351	± 0.016		
75:25	10.27	-12.64*			902	± 0.186		
100:0	0.00	-22.91*						

Dry mass (MS) – cultivar BRS Cauê									
100:0(T)	20.70	0.00							
75:25	14.23	-6.47*	1513	(± 0.109)*	363	(± 0.043)^{ns}	114	(± 0.021)*
50:50	8.38	-12.32*	517	(± 0.024)*	255	(± 0.019)*	-189	(± 0.009)*
25:75	6.53	-14.17*	367	(± 0.015)*	257	(± 0.005)*	-276	(± 0.023)*
0:100	0.00	-20.70*						
0:100(T)	22.91	0.00				Kd		
25:75	19.86	-3.05*			391	(± 0.036)		
50:50	17.92	-4.99*			644	(± 0.029)		
75:25	10.54	-12.38*			661	(± 0.129)		
100:0	0.00	-22.91*						
Dry mass (MS) – cultivar BRS Korbel									
100:0(T)	21.46	0.00						
75:25	14.78	-6.68*	1.7	(± 0.104)*	362	(± 0.036)^{ns}	141	(± 0.019)*
50:50	11.29	-10.17*	893	(± 0.044)^{ns}	359	(± 0.026)^{ns}	-31	(± 0.013)^{ns}
25:75	7.73	-13.73*	474	(± 0.07)*	299	(± 0.045)*	-202	(± 0.03)*
0:100	0.00	-21.46*						
0:100(T)	22.91	0.00				Kd		
25:75	17.50	-5.41*			0.34	(± 0.012)		
50:50	13.49	-9.42*			418	(± 0.015)		
75:25	9.32	-13.59*			449	(± 0.021)		
100:0	0.00	-22.91*						

[1]Proportion of crop and weed plants, in which (T) is pure stands (control) with the intraspecific competition. [2]Quantification of the assessed variable at the indicated competition level and differences compared to the test/control treatment by Dunnett's ($p < 0.05$). [3] Significant when it differed from "1", by the t-test ($p < 0.05$). [4]Difference between Kc and Kd, at the same competition levels, compared by the t-test ($p < 0.05$). [5]Significant when it differed from "0" by the t-test ($p < 0.05$). * = significant difference ($p < 0.05$); ^{ns} = non-significant.

3.2 Variables Associated with Photosynthesis

Not only is the accumulation of a dry mass of each species in competition to be understood but their physiological aptitude can also contribute to explaining each plant's behavior when subjected to these conditions of competition against other species, especially when the species have with same photosynthetic metabolism.

For the PRs that were based on the physiological parameter A, they showed stability for the barley as a function of the increase of its proportion in the mixture with black oat, for the cultivars BRS Cauê and BRS Korbel. This was while the photosynthesis was reduced in the presence of smaller proportions of the competitor for BRS Brau (Figure 2). The competitor's photosynthesis rate was injured by low proportions of BRS Cauê and BRS Korbel, showing higher photosynthesis than expected when the competition occurred with BRS Brau (Figure 2).

The decreased A, and even the genetic characteristics of the cultivar BRS Brau, or even by the reduction of the LA, provided by the competition (proportions 25:75, Figure 1). Since these variables were directly linked to the light absorption by the photosynthetic pigments (Taiz et al., 2017), and in part, the responses were due to the environmental and genetic effects. After all, both barley and black oats are plants with C3 metabolism (Tesar, 1984). It can be ruled out that the interference was due to photosynthetic metabolism characteristics or another factor.

When plants compete, light is one of the factors that they compete for, although shading can influence photosynthetic efficiency. It was noted that for the PRTs, which represented the behavior of the mixed population of the weeds and the crop in their different proportions, it was evident that only in the presence of BRS Cauê that there were losses in the mixed population (PRT's), mainly due to the reductions in A, which were attributed to the weed (Figure 2), without damage to the crop. This showed that BRS Cauê somehow managed to overcome the impact that was caused by the black oats by its photosynthetic metabolism, most likely by increasing the interception of light, due to the reduced loss of LA (Figure 1).

Regarding the photosynthesis rate (A), BRS Cauê stood out for not having differed from its control without competition in all of the proportions tested (except evidently when it was not present), having presented RC and A as identical to that of the competitor, and for having kept the Kc values at least equal those of Kd (Table 3). It is evidenced that although it does not benefit from the competition, it is not affected until the level of the occurrence of black oats is equivalent to the plants of this barley cultivar (50:50). BRS Brau and BRS Korbel presented lower values of A when compared to the competitor (Table 3).

Table 3 - Competitivity indexes based on parameters associated with photosynthesis (A- photosynthetic rate), between barley cvs. BRS Brau, BRS Cauê and BRS Korbel, and the weed black oat, in terms of relative competitiveness (CR), the clustering coefficient of the crop (Kc) and weed (Kd), and aggressiveness (Ag)

Crop: Weed[1]	A[2]	Dif.	CR[3]		Kc[4]		Ag[5]	
Photosynthetic rate - (A) – cultivar BRS Brau								
100:0(T)	17.00	0.00						
75:25	9.98	-7.02*	299	(± (0.013)*	268	(± 0.037)*	-692	(± 0.059)*
50:50	10.38	-6.62*	0.4	(± 0.014)*	0.44	(± 0.022)*	-459	(± 0.011)*
25:75	13.36	-3.64*	683	(± 0.048)*	736	(± 0.056)^{ns}	-185	(± 0.032)*
0:100	0.00	-17.00*						
0:100(T)	8.97	0.00				Kd		
25:75	10.37	1.39^{ns}			3.03	(± 0.508)		
50:50	13.71	4.74*			3238	(± 0.041)		
75:25	17.69	8.71*			4963	(± 3.287)		
100:0	0.00	-8.97*						
Photosynthetic rate - (A) – cultivar BRS Cauê								
100:0(T)	13.90	0.00						
75:25	13.10	-0.80^{ns}	1039	(± 0.051)^{ns}	877	(± 0.169)^{ns}	11	(± 0.022)^{ns}
50:50	13.88	-0.02^{ns}	1609	(± 0.501)^{ns}	1218	(± 0.48)^{ns}	153	(± 0.116)^{ns}
25:75	11.62	-2.28^{ns}	1344	(± 0.147)^{ns}	805	(± 0.119)*	107	(± 0.041)^{ns}
0:100	0.00	-13.90*						
0:100(T)	17.07	0.00				Kd		
25:75	10.64	-6.43*			909	(± 0.126)		
50:50	11.84	-5.23*			547	(± 0.087)		
75:25	15.72	-1.35^{ns}			304	(± 0.052)		
100:0	0.00	-17.07*						
Photosynthetic rate - (A) – cultivar BRS Korbel								
100:0(T)	14.44	0.00						
75:25	15.00	0.56^{ns}	832	(± 0.003)*	1176	(± 0.007)*	-105	(± 0.002)*
50:50	15.50	1.06^{ns}	982	(± 0.075)^{ns}	1206	(± 0.177)^{ns}	-0.01	(± 0.041)^{ns}
25:75	16.42	1.98^{ns}	1318	(± 0.034)*	1193	(± 0.034)*	136	(± 0.011)*
0:100	0.00	-14.44*						
0:100(T)	16.97	0.00				Kd		
25:75	14.67	-2.30*			1362	(± 0.005)		
50:50	18.55	1.58*			1205	± 0.004)		
75:25	21.20	4.23*			628	(± 0.067)		
100:0	0.00	-16.97*						

[1]Proportion of crop and weed plants, in which (T) is pure stands (control) with the intraspecific competition. [2]Quantification of the assessed variable at the indicated competition level and differences compared to the test/control treatment by Dunnett's ($p < 0.05$). [3]Significant when it differed from "1", by the t-test ($p < 0.05$). [4]Difference between Kc and Kd, at the same competition levels, compared by the t-test ($p < 0.05$). [5]Significant when it differed from "0" by the t-test ($p < 0.05$). * = significant difference ($p < 0.05$); ^{ns} = non-significant.

With the reduction in A that was observed for the weed when competing with BRS Cauê, there was a proportional increase in Ci since it was less consumed, as the photosynthetic process rate was lower (Figure 2). The other values of Ci showed that as the photosynthesis was increased for both the weed and the barley cultivars, there was a proportional reduction in Ci (Taiz et al., 2017). Ci is considered a physiological variable that is influenced by abiotic factors, including light. The increase in Ci might indicate a plant's attempt to escape the stress that is generated by the competition for environmental resources (Matos et al., 2013).

The values of Ci, although presented, were not considered in the discussion since both the absolute values of high and low Ci could be considered positive for the species, depending on the situation. If it is high, it might indicate that the CO_2 capture from the external environment to the inside of the leaf might have been positive; but if it is low, it can also indicate high photosynthesis rates. The interpretation of the competition indexes based on these parameters is more prone to errors than the correct ones, without a clear understanding of the physiological context to which the plants were submitted.

The CE was proportional to A; that is, the higher was A, the greater the CE by the photosynthetic cycle (Figure 2). For Machado et al. (2005), CE was closely related to Ci and the assimilation rate of carbon dioxide. Both BRS Cauê and BRS Korbel were able to maintain the CE rates close to the expected values, regardless of their proportion in the mixture with the competitor. Still, only BRS Cauê was able to concomitantly maintain its CE (PRx), and reduce the competitor's CE (PRy), which resulted in losses in the community as a whole (PRT), indicating probable competition for the same resources between black oat and the barley cultivars (Figure 2).

BRS Brau showed low CE when compared with the black oats (weed). Taiz et al. (2017) emphasized that if the CO_2 concentrations of the intercellular cells were very low, the inflow of this component into the mesophilic cells became restricted. The plant uses CO_2 coming from the breath to keep a minimum level of the photosynthetic rate, making it limited, but Ci in the BRS Brau was not affected but A was. These physiological differences might indicate differences between the barley cultivars when imposed by the competition (Table 4).

Table 4 - Competitivity indexes based on parameters associated with photosynthesis (Ci- mesophyll concentration of CO_2), between barley cvs. BRS Brau, BRS Cauê and BRS Korbel, and the weed black oat, in terms of relative competitiveness (CR), the clustering coefficient of the crop (Kc) and weed (Kd), and aggressiveness (Ag)

Crop:Weed[1]	Ci[2]	Dif.	CR[3]		Kc[4]		A[5]	
Mesophyll concentration of CO_2 (Ci) - cultivar BRS Brau								
100:0(T)	242.50	0.00						
75:25	248.67	6.17^{ns}	1228	(± 0.014)*	1113	(± 0.040)*	95	(± 0.004)*
50:50	258.00	15.50*	1235	(± 0.037)*	1137	(± 0.012)*	0.10	(± 0.012)*
25:75	259.33	16.83*	1138	(± 0.024)*	1095	(± 0.017)*	64	(± 0.01)*
0:100	0.00	-242.50*						
0:100(T)	310.67	0.00				Kd		
25:75	292.33	-18.33^{ns}			792	(± 0.017)		
50:50	268.50	-42.17*			764	(± 0.042)		
75:25	259.50	-51.17*			806	(± 0.049)		
100:0	0.00	-310.67*						
Mesophyll concentration of CO_2 (Ci) - cultivar BRS Cauê								
100:0(T)	254.50	0.00						
75:25	252.75	-1.75^{ns}	939	(± 0.016)*	0.98	(± 0.051)^{ns}	-33	(± 0.01)*
50:50	263.67	9.17^{ns}	929	(± 0.027)^{ns}	1077	(± 0.042)^{ns}	-0.04	± (0.016)^{ns}
25:75	264.00	9.50^{ns}	967	(± 0.038)^{ns}	1.05	(± 0.010)^{ns}	-0.02	(± 0.02)^{ns}
0:100	0.00	-254.50*						
0:100(T)	256.50	0.00				Kd		
25:75	276.25	19.75^{ns}			1082	(± 0.043)		
50:50	286.50	30.00^{ns}			1274	(± 0.087)		
75:25	271.75	15.25^{ns}			1522	(± 0.279)		
100:0	0.00	-256.50*						
Mesophyll concentration of CO_2 (Ci) - cultivar BRS Korbel								
100:0(T)	264.50	0.00						
75:25	252.33	-12.17^{ns}	934	(± 0.029)^{ns}	876	(± 0.133)^{ns}	-34	(± 0.015)^{ns}
50:50	268.00	3.50^{ns}	1.01	(± 0.036)^{ns}	1029	(± 0.035)^{ns}	4	(± 0.018)^{ns}
25:75	272.00	7.50^{ns}	982	(± 0.022)^{ns}	1039	(± 0.027)^{ns}	-0.01	(± 0.012)^{ns}
0:100	0.00	-264.50*						
0:100(T)	278.67	0.00				Kd		
25:75	292.00	13.33^{ns}			1.03	(± 0.037)		
50:50	280.25	1.58^{ns}			1014	(± 0.042)		
75:25	284.75	6.08^{ns}			1234	(± 0.072)		
100:0	0.00	-278.67*						

[1]Proportion of crop and weed plants, in which (T) is pure stands (control) with the intraspecific competition. [2]Quantification of the assessed variable at the indicated competition level and differences compared to the test/control treatment by Dunnett's ($p<0.05$). [3]Significant when it differed from "1", by the t-test ($p<0.05$). [4]Difference between Kc and Kd, at the same competition levels, compared by the t-test ($p<0.05$). [5]Significant when it differed from "0" by the t-test ($p<0.05$). * = significant difference ($p<0.05$); ^{ns} = non-significant.

Table 5 - Competitivity indexes based on parameters associated with photosynthesis (E- transpiration rate), between barley cvs. BRS Brau, BRS Cauê and BRS Korbel, and the weed black oat, in terms of relative competitiveness (CR), the clustering coefficient of the crop (Kc) and weed (Kd), and aggressiveness (Ag)

Crop: Weed[1]	CE[2]	Dif.	CR[3]		Kc[4]		A[5]	
Transpiration rate (CE) – cultivar BRS Brau								
100:0(T)	0.07	0.00						
75:25	0.04	-0.03*	243	(± 0.009)*	253	(± 0.029)*	-888	(± 0.063)*
50:50	0.04	-0.03*	324	(± 0.018)*	402	(± 0.02)ns	-601	(± 0.035)*
25:75	0.05	-0.02*	609	(± 0.046)*	675	(± 0.049)ns	-241	(± 0.042)*
0:100	0.00	-0.07*						
0:100(T)	0.03	0.00				Kd		
25:75	0.04	0.01ns			4473	(± 0.789)		
50:50	0.05	0.02*			11843	(± 5.417)		
75:25	0.07	0.04*			568	(± 1.635)		
100:0	0.00	-0.03*						
Transpiration rate (CE) – cultivar BRS Cauê								
100:0(T)	0.05	0.00						
75:25	0.05	0.00ns	1058	(± 0.065)ns	1028	(± 0.337)ns	15	(± 0.024)ns
50:50	0.05	0.00ns	1769	(± 0.523)ns	1335	(± 0.626)ns	192	(± 0.118)ns
25:75	0.04	-0.01ns	1522	(± 0.195)ns	828	(± 0.109)*	0.14	(± 0.042)*
0:100	0.00	-0.05*						
0:100(T)	0.06	0.00				Kd		
25:75	0.04	-0.03*			0.92	(± 0.161)		
50:50	0.04	-0.03*			453	(± 0.067)		
75:25	0.06	-0.01ns			273	(± 0.066)		
100:0	0.00	-0.07*						
Transpiration rate (CE) – cultivar BRS Korbel								
100:0(T)	0.05	0.00						
75:25	0.06	0.01ns	878	(± 0.035)*	1708	(± 0.292)ns	-77	(± 0.022)*
50:50	0.06	0.00ns	973	(± 0.007)*	1227	(± 0.106)ns	-15	(± 0.003)*
25:75	0.06	0.01ns	1371	(± 0)*	1.2	(± 0)ns	155	(± 0)*
0:100	0.00	-0.05*						
0:100(T)	0.06	0.00				Kd		
25:75	0.05	-0.01*			1368	(± 0.076)		
50:50	0.07	0.01*			1.3	(± 0.1)		
75:25	0.08	0.01*			556	(± 0)		
100:0	0.00	-0.06*						

[1]Proportion of crop and weed plants, in which (T) is pure stands (control) with the intraspecific competition. [2]Quantification of the assessed variable at the indicated competition level and differences compared to the test/control treatment by Dunnett's ($p<0.05$). [3]Significant when it differed from "1", by the t-test ($p<0.05$). [4]Difference between Kc and Kd, at the same competition levels, compared by the t-test ($p<0.05$). [5]Significant when it differed from "0" by the t-test ($p<0.05$). * = significant difference ($p<0.05$); ns = non-significant.

The CE (Table 5) showed the same behavior as that observed for A, where BRS Cauê was able to maintain its RC and A at levels similar to those of the competitor when the density of the competitor was equal to, or less than, that of the barley cultivar (Table 3). BRS Brau and BRS Korbel were more easily affected by the presence of the competitor (Tables 3, 4, and 5). With the predominance of BRS Brau when compared to the competitor (75:25), as an example, the Kc was only 0.253, differing at 5% from the Kd, which was 4.473 (Tables 3, 4 and 5), with an evident advantage to the weed.

3.3 Variables Associated with the Water Use

The PRs and the PRTs of E, WUE, and Gs of the barley varieties were not consistent among the cultivars, with levels of alterations that detracted from the simple competitive and varied effects (Figure 3). This fact was probably due, at least in part, to a possible variation in the soil and the air humidity in the different plots at the time of the evaluation with the IRGA. Regarding these variables, it can only be safely stated that as the plant transpiration rate increased, a greater stomatal

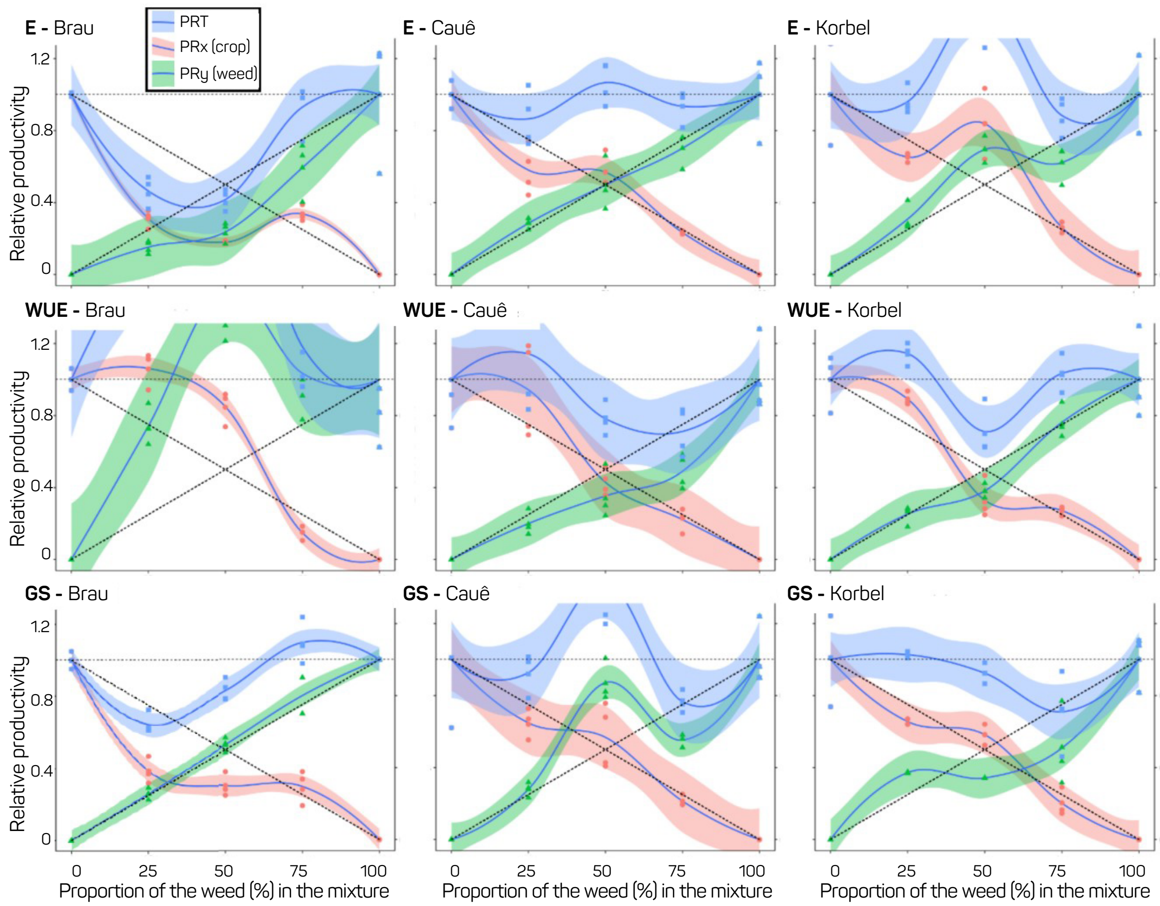

Figure 3 - Variables associated with the water use of barley cv. BRS Brau, BRS Cauê, and BRS Korbel, under competition with the weed black oat, function as plant proportion. E = transpiration rate; WUE = water use efficiency; Gs = water conductance. Colored bands represent the 95% confidence interval

conductance was observed, as a function of the loss of water in the environment, with a proportional reduction in the WUE (Figure 3). The low efficiency in the use of water by this barley plant was not necessarily due to the greater transpiratory intensity since a greater loss of water through transpiration might occur, due to the necessity of this plant to incorporate CO_2. In contrast, low transpiration is associated with a stomatal closure (Brodribb, Hill, 2000; Concenço et al., 2009).

Water is a limiting resource for crops, and when there is low availability of this resource, the barley biomass is reduced by the competition with black oat (Wanic et al., 2013). In these experimental conditions, the parameters associated with water use, such as E, WUE, and Gs might vary. Alternatively, inconsistent variations in the physiological parameters that are linked to the water dynamics at the soil-plant-atmosphere interface, provide evidence that the water competition was not so important under the environmental and edaphic conditions of the present experiment but was affected by factors other than those tested.

3.4 Competitiveness Indexes

The competitiveness indexes numerically described the interaction relationships between the crop and the weed, based on the relative competitiveness (RC), the relative clustering of the crop (Kc) and the weed (Kd), and the aggressiveness (Ag) of the species when confronted (Cousens, 1991; Bianchi et al., 2006).

All of the variables associated with the photosynthesis (Table 1) were included in the competitiveness index analysis, due to the evident stability of their behavior in the relative productivity evaluations (PR's and PRT's). For the parameters associated with water use (Figure 3), only the LA (Table 2) was considered for the competitiveness index calculations; the other parameters were discarded. In general, the results have shown that barley and black oat have similar competitive abilities for environmental resources. The CO_2 concentration in the mesophyll did not negatively affect the crop-weed competition, regardless of the barley cultivar. The photosynthesis rate, the carboxylation efficiency, the transpiration rate, the water conductance, the leaf area, and the dry matter of the shoot on the BRS Brau cultivar, were all affected by the black oat competition, indicating the lower competitive abilities of the BRS Cauê and BRS Korbel cultivars. The BRS Cauê showed lower competition impacts with black oat when based on the physiological and morphological parameters, and the aggressiveness-related indexes, demonstrating the barley cultivar was better to compete with the black oat.

4. Conclusions

The cultivar barley, BRS Brau, reduced the photosynthesis into smaller proportions for the competitor. The water use was not impacted to the same extent as photosynthesis. BRS Cauê was the most competitive cultivar, suffering a lower impact of competition with the black oat.

Authors'contributions

LG, GC, and FS: Conceptualization of the manuscript and development of the methodology. LRA and FN: data collection and curation. LG and GC: data analysis. LG and AA: data interpretation. LG, GC, and AA: funding acquisition and resources. LG, GC, and LRA: project administration. LG: supervision. LRA, FN, and FS: writing the original draft of the manuscript. LG, GC, and FS: writing, review, and editing.

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