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Competitive Responses of Rye Cultivars When Grown in Coexistence With Weeds

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Abstract

Competitive ability is an essential component of integrated management, as it expresses the capacity of crops to compete efficiently for resources against weed species. Therefore, this study aimed to evaluate the competitive ability of rye cultivars BRS Serrano, BRS Progresso, and BR1 when grown in coexistence with the weeds Italian ryegrass (*Lolium multiflorum*) and wild radish (*Raphanus raphanistrum*), at different plant proportions in the associations. The combinations between the crop and the weeds followed proportions of 100:0, 75:25, 50:50, 25:75, and 0:100%, or 20:0, 15:5, 10:10, 5:15, and 0:20 plants per pot, defined in preliminary (additive) experiments. At 45 days after emergence, gas exchange, leaf area (LA), and shoot dry mass (DM) of the species were evaluated. Competitiveness was estimated using replacement series diagrams and relative competitiveness indices. Rye cultivars showed greater competitive ability than the weeds, causing more pronounced reductions in the LA and DM of Italian ryegrass and wild radish. The physiological performance of rye was less affected when infested with Italian ryegrass and more affected in the presence of wild radish, especially for cultivar BR1. Interspecific competition was more detrimental than intraspecific competition, causing significant reductions in the species. On average, competition reduced rye DM by about 45% and weed DM by 15% compared with non-competitive conditions. Wild radish caused greater losses in LA, DM, and gas exchange of rye compared with Italian ryegrass, confirming its higher competitive aggressiveness.

Keywords: *Lolium multiflorum*, plant interactions, *Raphanus raphanistrum*, *Secale cereale*

1. Introduction

Rye (*Secale cereale*) is an annual bunchgrass plant with vigorous early growth, belonging to the Poaceae/Gramineae family. It is hardy and suitable for use in human and animal nutrition, as well as a cover crop for the adoption of no-till farming (Adhikari et al., 2018; Ghimire et al., 2019; Toebe et al., 2020).

When decomposing, rye biomass releases compounds such as benzoxazinoids and organic acids that suppress the germination and growth of many weeds (Ghimire et al., 2019), making it a useful crop for managing these species when they infest crops in succession or rotation.

Rye cultivation has gained socioeconomic importance in southern Brazil, occupying around 2,600 hectares with an average yield of 1.65 t ha^{-1} (CONAB, 2026). However, many factors cause low rye grain productivity, particularly interference and damage caused by weeds when not properly managed. Among the weed species that infest winter crops, including rye, ryegrass (*Lolium multiflorum*), turnip (*Raphanus raphanistrum*), and radish (*R.*

sativus) stand out due to their highly competitive ability (Costa & Rizzardi, 2015; Agostinetto et al., 2017; Franz et al., 2020; Nichelati et al., 2020; Balem et al., 2021; Mario et al., 2024).

Ryegrass and turnip compete for available resources in the environment, such as water, light, and nutrients, which affect the expression of the productive potential of crops. This competition complicates the expansion of cultivated areas, interferes with growth and development, and reduces grain yield and quality. In many cases, these weeds can also serve as hosts for insects and diseases (Lamego et al., 2013; Tavares et al., 2019; Silva et al., 2019; Franz et al., 2020; Galon et al., 2025). Additionally, these species are resistant to many herbicides: turnip is resistant to acetolactate synthase (ALS) inhibitors, while ryegrass is resistant to ALS inhibitors, acetyl-CoA carboxylase (ACCase) inhibitors, and 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) inhibitors (Heap, 2026).

Ryegrass is an annual winter species, belonging to the Poaceae/Gramineae family, which causes significant productivity losses in crops it infests. This is due to its high competitiveness, extensive tillering, large root system, release of allelopathic substances, high seed production, and ease of dispersion (Lamego et al., 2015; Agostinetto et al., 2017; Chaudhari et al., 2019; Nichelati et al., 2020). This species can also be used as green manure, soil cover, winter forage, hay, and silage production. It exhibits high natural reseeding, premature dehiscence, seed dormancy, and a large seed bank in the soil (Lamego et al., 2013; Fernández-Moreno et al., 2017; Oliveira et al., 2019).

Turnip/radish (*Raphanus raphanistrum* and/or *R. sativus*) is a Brassicaceae/Cruciferae species with an annual life cycle, high seed production, and vigorous growth. It is widely distributed in winter crops in southern Brazil and demonstrates highly competitive ability with crops (Lamego et al., 2013; Costa & Rizzardi, 2015; Silva et al., 2019; Tavares et al., 2019; Ramos et al., 2021). This weed has a large root system, high prolificacy, and seed dormancy, which contributes to reducing the production potential of crops (Lamego et al., 2013; Costa & Rizzardi, 2015; Silva et al., 2019). Its difficult control is also linked to its use as a cover crop in no-till farming systems or as green manure, which increases the soil seed bank in southern Brazilian farms (Costa & Rizzardi, 2015; Tavares et al., 2019). Turnip also demonstrates a high shading capacity in the early stages of crop growth due to its competitive ability, with a sparse and branched canopy that exacerbates the negative effects of competition (Tavares et al., 2019; Silva et al., 2019; Franz et al., 2020; Sun et al., 2021).

In agricultural systems, the population density of cultivated plants tends to remain relatively constant, while weed abundance varies according to the supply of the soil seed bank, the density and distribution of pre-existing infestations, adopted management practices, and environmental conditions, among other factors. These variations affect the ratio between crops and weeds, making it essential to understand the effects of this variation on the competitive performance of the species coexisting in the same environment (Leon et al., 2023; Luo et al., 2024).

Competitive interactions between weeds and cultivated plant genotypes require specific experiments for their characterization, with substitution trials being one of the most commonly used methods. Interpretation is based on the performance of biometric or ecophysiological parameters (Bianchi et al., 2006; Agostinetto et al., 2013; Leon et al., 2023). In general, well-established crops are more competitive than weeds because they have a uniform stand, optimal density, and emerge before the infesting species (Agostinetto et al., 2013; Rubin et al., 2014). However, when competition occurs between species with similar ecological characteristics, where emergence is simultaneous, both species exploit essentially the same ecological niche, and interference between them can negatively affect the growth and development of the community present in the area (Agostinetto et al., 2013; Silva et al., 2019; Nosratti et al., 2024).

Cultivars within the same species may show significant differences in their ability to compete with weeds, due to differences in environmental adaptability, growth rate, and resource use efficiency (Agostinetto et al., 2013; Brunetto et al., 2023; Caldas et al., 2023; Jastrzębska et al., 2023). Cultivars with greater vigor and faster early growth tend to suppress the development of weeds more effectively. Therefore, selecting cultivars with greater competitive ability can be an important strategy in integrated weed management, reducing the need for chemical control and promoting more sustainable agricultural systems, lowering costs, minimizing environmental impacts (Brunetto et al., 2023; Jastrzębska et al., 2023; Nosratti et al., 2023), and even producing healthier food.

Considering the increasing cases of resistance and the need for more sustainable weed management, combining cultural and mechanical control with chemical control, using cultivars with higher competitive ability emerges as a viable alternative in rye-growing farms (Walsh, 2019). Thus, the present research hypothesizes that there are differences in competitive ability among rye cultivars in coexistence with weeds, particularly turnip and ryegrass.

Therefore, this study aimed to quantify the competitive ability of different rye cultivars in association with ryegrass and turnip, in varying plant proportions.

2. Method

2.1 Location, Soil Characteristics, and Experimental Design

Eleven experiments were conducted in the greenhouse at the Federal University of Fronteira Sul (UFFS), Erechim Campus/RS/Brazil. The experimental units consisted of plastic pots with a capacity of 8 dm^3, filled with typical Aluminoferric Red Latosol (Streck et al., 2018). The chemical and physical properties of the soil were as follows: pH in water = 4.8; Organic matter (OM) = 3.5%; P = 4.0 mg dm^{-3}; K = 117.0 mg dm^{-3}; Al^{3+} = 0.6 cmolc dm^{-3}; Ca^{2+} = 4.7 cmolc dm^{-3}; Mg^{2+} = 1.8 cmolc dm^{-3}; CEC (effective) = 7.4 cmolc dm^{-3}; CEC (at pH 7.0) = 16.5 cmolc dm^{-3}; $H^{+}Al$ = 9.7 cmolc dm^{-3}; Base saturation (SB) = 6.8 cmolc dm^{-3}; Base saturation percentage (V) = 41%; Clay = 60%, Sand = 15%, and Silt = 25%. Soil fertilization and pH correction were carried out based on the physicochemical analysis and following technical recommendations for rye cultivation (CQFS-RS/SC, 2016). The experimental design used in all experiments was a randomized block design with four replications.

2.2 Installation of Preliminary Experiments in Additive Series

Initially, additive series trials were set up for three rye cultivars (BRS Serrano, BRS Progresso, and BR1), as well as two competitors: ryegrass (*Lolium multiflorum*) and turnip (*Raphanus raphanistrum*). These trials were conducted in monoculture. For each species, ten densities, ranging from 1 to approximately 800 plants m^{-2}, were tested to obtain the dry mass accumulation curve of the aerial part as a function of density, to establish the point at which an increase in density of the crop/weed does not result in an increase in dry mass accumulation in the aerial part (data not shown). It was estimated that 20 plants per pot (~283 plants m^{-2}) represented the minimum density that ensures stable aerial dry mass or constant final yield.

2.3 Installation of Definitive Experiments in Substitution Series

Next, six substitution series experiments were installed in a randomized block design with four replications, where the competitors tested included the rye cultivars: BRS Serrano, BRS Progresso, and BR1, competing with ryegrass and turnip. The relative proportions (%) of rye: ryegrass or rye: turnip were 100:0, 75:25, 50:50, 25:75, and 0:100% of the maximum competitive ability, which corresponded to 20:0, 15:5, 10:10, 5:15, and 0:20 plants per pot of the crop vs. weeds (Figure 1). To ensure uniformity in the seedlings, seeds were initially sown in trays and later transplanted into the pots. This procedure was carried out to precisely establish the desired densities in each treatment and maintain uniformity among the plants used in the experiments.



Figure 1. Overview of the experiment involving the competition of rye (*Secale cereale*) cultivars with the weeds ryegrass (A: *Lolium multiflorum*) and turnip (B: *Raphanus raphanistrum*)

2.4 Variables Evaluated in Rye and Weed Plants

At 45 days after emergence, the following physiological variables were measured: sub-stomatal CO_2 concentration (*Ci*—µmol mol^{-1}), transpiration rate (*E*—mol H_2O m^{-2} s^{-1}), and stomatal conductance of water vapor (*Gs*—mol m^{-2} s^{-1}). These physiological variables were determined using an infrared gas analyzer (IRGA) from ADC, model LCA PRO (Analytical Development Co. Ltd, Hoddesdon, UK), on the middle third of the first fully developed and healthy leaf of the rye plants, as well as the weeds in competition with the crop. Measurements were taken between 08:00 and 11:00 a.m., maintaining uniform environmental conditions during the analyses.

After the measurement of the physiological parameters, the plants were collected to determine morphological variables such as leaf area (*LA*—cm^2 pot^{-1}) and aerial dry mass (*DM*—g pot^{-1}). LA was quantified using an electronic integrator (Licor 3100C), measuring the leaves of all plants in each treatment. The aerial parts of rye plants and the competing weeds were then collected to determine the aerial dry mass (DM). The samples were placed in *kraft* paper bags and placed in an oven with forced air circulation at 60±5 °C. When the dry masses became uniform, they were weighed on a precision scale.

2.5 Analysis of Substitution Trials

The data were analyzed using the graphical analysis method of variation or relative productivity (Cousens, 1991; Bianchi et al., 2006; Agostinetto et al., 2013), where the variation or relative performance of one variable is compared to another. This procedure, also known as the conventional method for substitution experiments, consists of constructing a diagram based on relative (PR) and total relative productivity (PRT). When the result of PR is a straight line, it means the competitive abilities of the species are equivalent. If PR results in a concave line, growth was impaired in one or both species. Conversely, if PR results in a convex line, there is a growth benefit to one or both species. When PRT equals 1 (straight line), competition occurs for the same resources. If PRT is greater than 1 (convex line), competition is avoided. If PRT is less than 1 (concave line), mutual growth impairment occurs (Cousens, 1991; Bianchi et al., 2006).

Relative competitiveness indices (CR), relative clustering coefficient (K), and aggressiveness (AG) were also determined. CR represents the comparative growth of rye cultivars (BRS Serrano, BRS Progresso, and BR1, X) relative to the competitor ryegrass and/or turnip (Y). K indicates the relative dominance of one species over another, while AG shows which species is more aggressive. Thus, CR, K, and AG indices reveal which species is more competitive, and their joint interpretation provides greater accuracy in assessing the competitiveness of the species (Bianchi et al., 2006; Agostinetto et al., 2013; Rubin et al., 2014). Rye cultivars (X) are more competitive than ryegrass and/or turnip (Y) when $CR > 1$, $Kx > Ky$, and $AG > 0$. Conversely, ryegrass and/or turnip (Y) are more competitive than rye cultivars (X) when $CR < 1$, $Kx < Ky$, and $AG < 0$ (Bianchi et al., 2006; Agostinetto et al., 2013; Rubin et al., 2014). To calculate these indices, 50:50 proportions of the species involved in the experiments (rye and ryegrass; rye and turnip) were used, applying the following equations: $CR = PRx/PRy$; $Kx = PRx/(1-PRx)$; $Ky = PRy/(1-PRy)$; $A = PRx - PRy$ (Bianchi et al, 2006; Agostinetto et al., 2013; Rubin et al., 2014).

The statistical analysis procedure for relative productivity or variation included the calculation of the differences for the PR values (DPR) obtained at the 25%, 50%, and 75% proportions, relative to the values belonging to the hypothetical line at those respective proportions, which were: 0.25; 0.50; and 0.75 for PR (Bianchi et al., 2006). The t-test was used to test the differences related to the indices DPR, PRT, CR, K, and AG (Bianchi et al., 2006). The null hypothesis to test the differences for DPR and AG was that the means were equal to zero ($Ho = 0$); for PRT and CR, that they were equal to 1 ($Ho = 1$); and for K, that the mean differences between Kx and Ky were equal to zero [$Ho = (Kx - Ky) = 0$].

The observed PRT and PR curves were considered different from the expected ones when the expected values (represented by dashed lines) were outside the 95% confidence interval of the observed curves, which were represented by solid and colored lines with confidence intervals of the same color (Franceschetti et al., 2024). Furthermore, the criterion for considering the PR and PRT curves as different from the hypothetical lines was that, in at least two of the tested density proportions of the competing species, they did not intersect with the colored lines, as adapted from Bianchi et al. (2006).

The results obtained for the morphophysiological variables expressed as mean values per treatment were subjected to analysis of variance using the F-test. When significant, the treatment means were compared using the Dunnett test, considering monocultures as the control in these comparisons. In all statistical analyses performed, a probability of 5% was adopted.

3. Results and Discussion

The analysis of variance of the data showed that there was a significant interaction between the plant proportions of rye cultivars (BR1, BRS Progresso, and BRS Serrano) in competition with ryegrass and/or turnip for the variables leaf area (LA), internal CO_2 concentration (Ci), transpiration rate (E), stomatal conductance (Gs), and aerial dry mass (DM).

3.1 Morphological Variables

The graphical results indicate that the three rye cultivars exhibited similar behavior when subjected to competition with weeds, with significant differences in at least two plant proportions for most of the variables evaluated (Figures 2, 3, 4, 5 and 6).

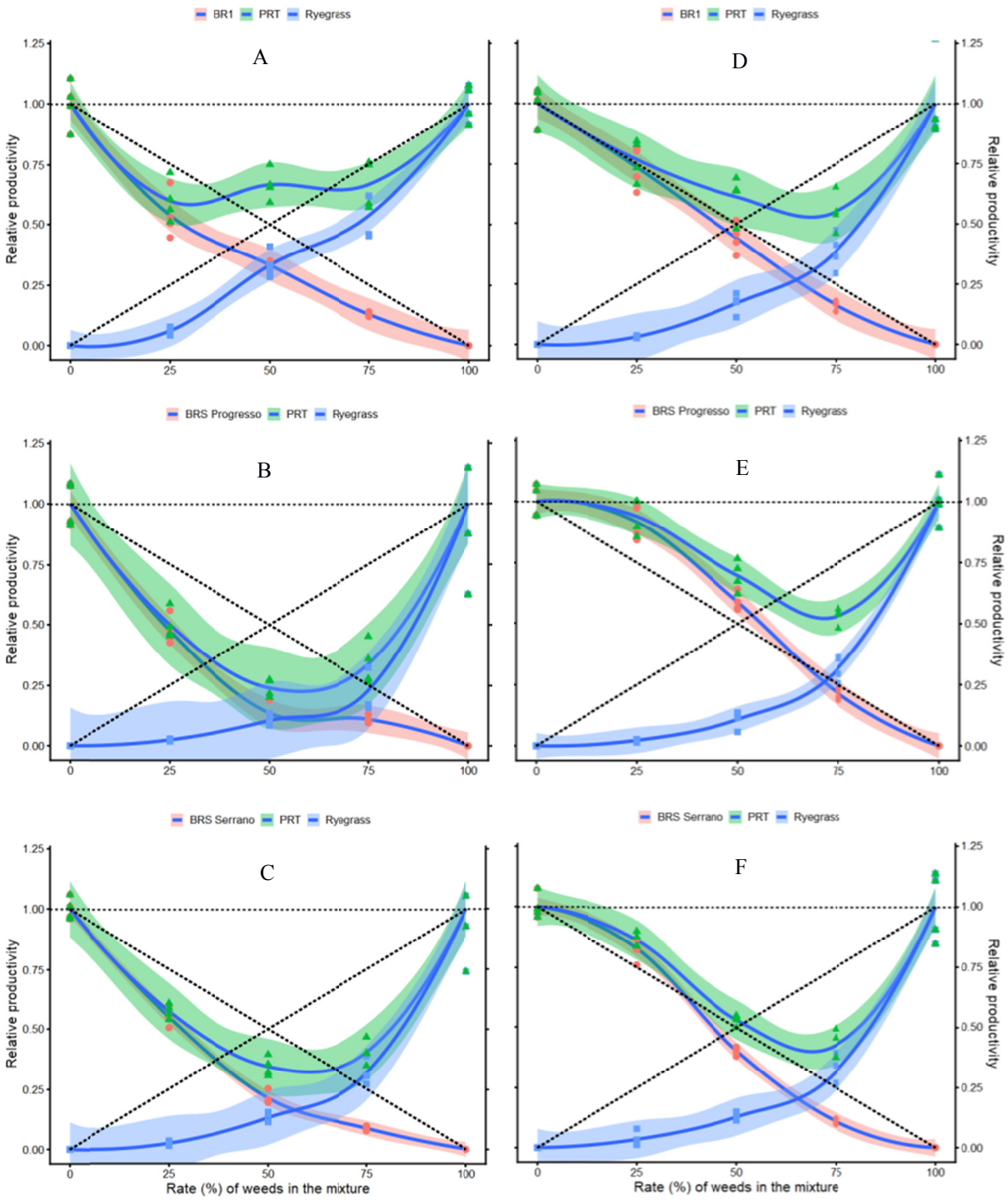


Figure 2. Relative productivity (RP) for leaf area (A, B, and C) and aerial biomass (D, E, and F) of the rye cultivars BR1, BRS Progresso, and BRS Serrano. (●) rye, (■) ryegrass, and total (▲). Dashed lines represent the expected values in the absence of competition, solid lines represent the observed values when the species competed at different plant proportions, and colored bands represent the standard deviation of the observations

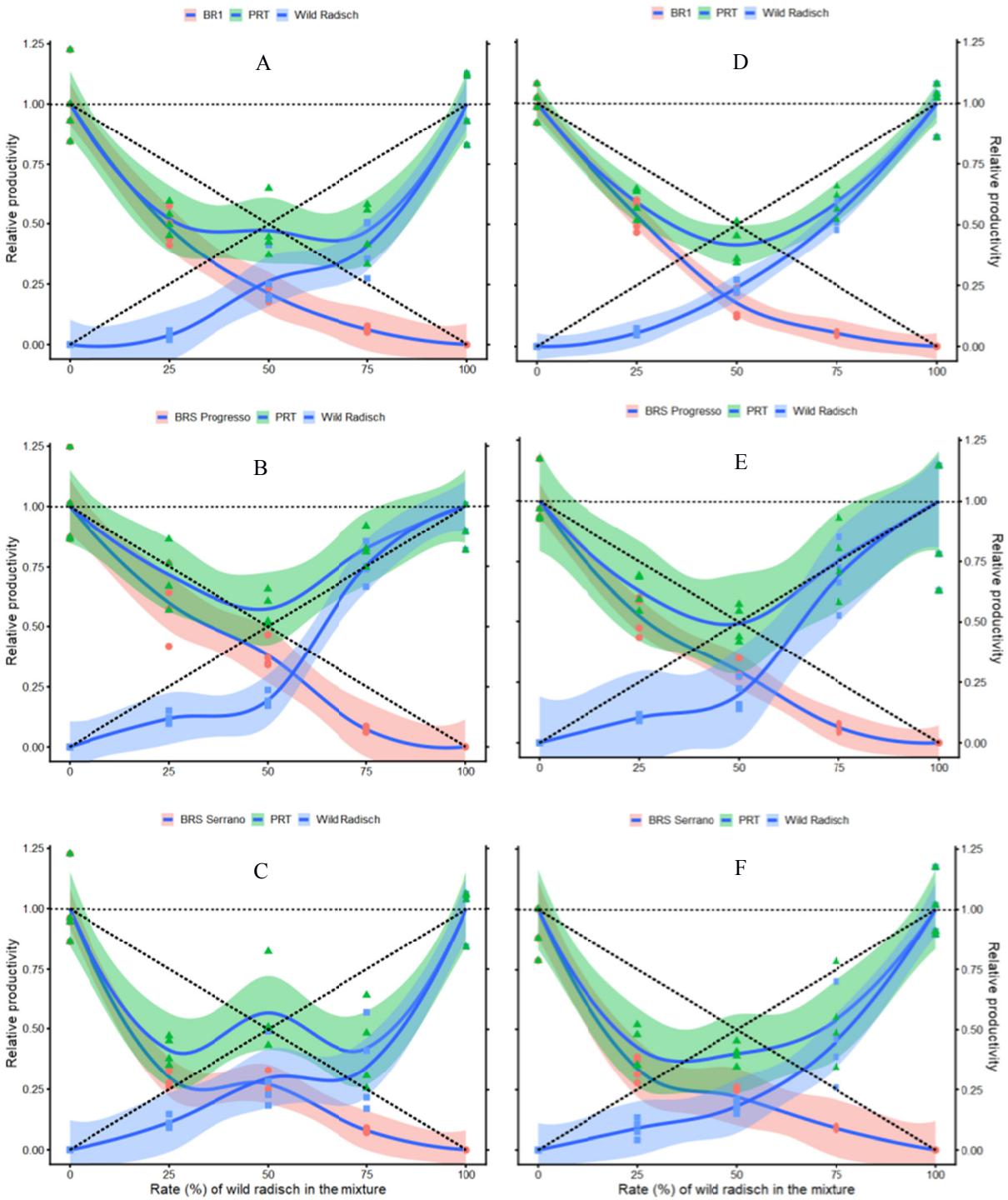


Figure 3. Relative productivity (RP) for leaf area (A, B, and C) and aerial biomass (D, E, and F) of the rye cultivars BR1, BRS Progresso, and BRS Serrano. (●) rye, (■) turnip, and total (▲). Dashed lines represent the expected values in the absence of competition, solid lines represent the observed values when the species competed at different plant proportions, and colored bands represent the standard deviation of the observations

The series substitution experiments between the rye cultivars versus ryegrass and/or turnip indicated competition between the species, in which the productivity values obtained at different species proportions generally deviated from the expected yield line, especially regarding LA and DM. In general, the association between the species was more harmful to ryegrass than to turnip when coexisting with the rye crop (Figures 2, 3, 4, 5 and 6; Tables 1, 2, and 3). The results from the PRT of concave curves and values lower than 1 suggest that competition occurred

between rye, ryegrass, and turnip for the same resources in the environment. According to Rubin et al. (2014), when PRT < 1, there is mutual antagonism between the species competing for environmental resources, without altering final productivity. Similar results to those of the present study were found by Galon et al. (2025) when evaluating the competitive ability of triticale cultivars in competition with different populations of ryegrass and turnip.

Upon evaluating Figures 2 and 3, it was generally observed that in all proportions there was a decrease in the variables, especially LA and DM, as the density of competitors (ryegrass and turnip) increased in coexistence with rye. In other words, the observed PRs were much lower than expected, with concave curves. Galon et al. (2025) also observed similar results for triticale PRs, considering the LA and DM of the crop and weeds (ryegrass and turnip), which resemble the results observed in the present study. Weeds typically appear in densities higher than cultivated plants in agricultural areas, and in most situations, this makes them described as the more competitive species in using the available resources in the environment (Bianchi et al., 2006).

In the series substitution experiments of rye versus ryegrass (Figure 2), both leaf area (Figures 2A, 2B and 2C) and dry matter of the aerial part (Figures 2D, 2E and 2F) showed reductions for rye and the weed in all evaluated combinations. Among the cultivars, BR1 was affected in the LA variable, registering a reduction of about 30% compared to the expected. The cultivar BRS Progresso also suffered an impact in LA, standing out as the most affected. When analyzing the community (crop + ryegrass), the smallest loss in LA occurred for BR1, while BRS Progresso and BRS Serrano showed reductions greater than 50% of the expected value.

For the DM variable, the rye cultivars demonstrated superior performance compared to LA in competition with ryegrass (Figure 2). In this condition, the values were close to or even above the expected, especially when rye was in higher proportion in the mixtures. The exception was the BRS Serrano cultivar (Figure 2F), which showed a reduction of approximately 20% in DM when at a disadvantage in the plant proportion against ryegrass. In all cases, the community was harmed, and the total DM was below the expected (Figures 2D, 2E and 2F).

The ability of a weed to adapt to changes in factors affecting its growth and development is directly related to its ability to compete for those resources with the cultivated species (Kaur et al., 2018; Chauhan, 2020). Thus, it is observed that ryegrass had a significant competitive effect on rye, reducing the accumulation of LA and DM, particularly when present at higher density in association with the crop. Rye and ryegrass belong to the same botanical family (Poaceae/Gramineae), which makes competition for environmental resources more pronounced. Competition for resources (water, light, and nutrients) between species can affect the use of these resources, regulating the morphological characteristics of plants and consequently leading to reduced crop production (Chauhan, 2020; Feng et al., 2020).

Turnip (Figure 3), in general, caused less damage to the LA of rye than ryegrass (Figures 3A, 3B and 3C), concentrating its effect on the crop in reducing the accumulation of DM (Figures 2D, 2E and 2F). Both rye cultivars and turnip were negatively affected in all proportions when associated, with the damage extending also to the community for LA and DM (Figure 3). Asato et al. (2025) report that plant morphology can be influenced by stress effects that occur in the community where they are present. These stress effects can be related to environmental, soil, and management factors adopted with the species, which will interfere positively or negatively with the production of LA and DM and other plant organs (Asato et al., 2025).

In general, interspecific competition reduced both leaf area (LA) and shoot dry mass (DM) of rye and both weed species, confirming mutual detriment due to the use of the same resources. According to Galon et al. (2025), when working with triticale crops infested with ryegrass and turnip, they also observed mutual damage in the plant association when they coexisted in the community, similar to the results observed in the present study. Regarding LA, the BR1 and BRS Progresso cultivars tended to be more affected; since this variable is directly linked to photosynthetic capacity, such reductions imply a limitation in biomass accumulation (Pierik & Ballaré, 2021). The plant may prioritize the growth of stems (stalk) over leaves due to the increased competition for light as it grows taller. Light is one of the most important resources during the initial growth stage of plants, and when its availability is limited under competition, the productive potential of the crop is affected (Pierik & Ballaré, 2021).

In terms of DM, rye performed better than in LA, which could indicate physiological plasticity in this regard when competing with ryegrass, but this characteristic does not hold when competition occurs with turnip. Luo et al. (2024) observed differences in competitive interactions when working with leguminous and grass species in association or monoculture. The weeds were more affected than rye, reinforcing the competitive superiority of the crop, associated with vigorous initial growth and the possible release of allelopathic chemicals (Manfron et al., 2022), which negatively interferes with the growth of its neighbors. However, this difference is not

significant enough to provide reassurance to farmers in managing weeds—the rye, on its own, at the field sowing densities, is not capable of suppressing ryegrass and/or turnip, requiring control of the species that infest the crop, especially if they occur in high densities during the critical competition period.

Tables 1 and 2 show the proportional morphophysiological responses of rye, ryegrass, and turnip when in competition. Competition reduced both LA and DM in rye cultivars as well as in the weeds (ryegrass and turnip) in all proportions, especially in higher competitor densities. However, rye consistently performed better, with smaller reductions compared to the weed species. Thus, it is observed that rye has a good ability to compete with the weeds that infest it. This was also observed by Chehade et al. (2021) when evaluating the allelopathic effect or suppression of rye grown in isolation or in association with clover in suppressing weed species.

Table 1. Morphophysiological responses of rye cultivars subjected to interference from the ryegrass competitor (*Lolium multiflorum*), expressed in leaf area (*LA*—cm^2 per pot), aerial biomass (*SDM*—g per pot), internal CO_2 concentration (*Ci*—µmol mol^{-1}), transpiration rate (*E*—mol H_2O m^{-2} s^{-1}), and stomatal conductance of water vapor (*Gs*—mol m^{-2} s^{-1}). UFFS, Erechim Campus, RS

Genotype	Plant Proportion (Rye:Ryegrass)	LA	SDM	Ci	E	Gs
BR1	100:0 (C)	4547.0	18.0	335.6	1.6	0.07
	75:25	3261.4*	17.6	363.6*	1.8	0.09
	50:50	3019.1*	15.9	352.6*	2.8*	0.17*
	25:75	2328.3*	11.8*	358.2*	2.8*	0.17*
	CV (%)	*10.8*	*12.8*	*1.8*	*14.3*	*19.4*
Ryegrass	100:0 (C)	3627.4	13.3	322.3	2.9	0.23
	75:25	2599.5*	6.8*	319.5	2.7	0.21
	50:50	2409.4*	4.5*	298.6	1.1*	0.05*
	25:75	877.6*	1.7*	321.1	1.3*	0.06*
	CV (%)	*16.5*	*25.2*	*5.1*	*27.2*	*31.1*
BRS Progresso	100:0 (C)	5839.1	20.9	259.2	1.3	0.11
	75:25	4283.7*	23.1*	264.0	2.3*	0.24*
	50:50	2472.0*	16.9*	267.2	2.6*	0.27*
	25:75	2010.9*	9.2*	252.3	2.0*	0.17*
	CV (%)	*8.4*	*6.5*	*2.3*	*17.2*	*27.4*
Ryegrass	100:0 (C)	6007.3	12.1	369.6	3.3	0.36
	75:25	2532.3*	5.1*	375.0	3.4	0.33
	50:50	1565.4*	3.1*	384.6	3.4	0.32
	25:75	581.5*	1.6*	365.6	1.9*	0.44
	CV (%)	*30.6*	*25.9*	*4.6*	*29.1*	*41.4*
BRS Serrano	100:0 (C)	873.9	26.8	330.2	5.0	0.28
	75:25	3546.7*	32.8*	362.9*	5.4	0.30
	50:50	1494.6	31.6*	376.8*	4.4	0.28
	25:75	2441.7*	23.1	373.8*	3.7*	0.25
	CV (%)	*20.6*	*9.0*	*2.5*	*12.9*	*31.1*
Ryegrass	100:0 (C)	2269.1	21.7	309.3	2.8	0.33
	75:25	689.6*	9.2*	316.8	3.2	0.22*
	50:50	472.6*	4.7*	332.4*	2.5	0.15*
	25:75	220.5*	1.9*	328.2*	2.4	0.15*
	CV (%)	*46.8*	*17.5*	*3.2*	*19.5*	*23.9*

Note. * The mean differs from each control (C) by the Dunnett test ($p < 0.05$).

For the BR1 cultivar, LA reduced by about 30% compared to the control in the 75:25 ryegrass ratio, with more significant decreases in the 25:75 ratio (Table 1). Even so, the loss was more pronounced for ryegrass, indicating higher competitive ability than rye. In DM, the BR1 cultivar maintained values close to expected, with reduction

only in the 25:75 ratio. The LA of the BRS Progresso cultivar was affected in the higher weed presence proportions.

In contrast, against turnip, LA remained relatively stable up to the 50:50 ratio (Table 2). The DM of the BRS Progresso cultivar showed an advantage over ryegrass (Table 1), but was significantly affected by turnip (Table 2). The BRS Serrano cultivar, in turn, suppressed ryegrass very well, both in LA and DM, even when it represented only 25% of the plant proportion in the association (25:75).

Table 2. Morphophysiological responses of rye cultivars subjected to interference from the competitor turnip (*Raphanus raphanistrum*), expressed in leaf area (*LA*—cm^2 per pot), shoot dry mass (*SDM*—g per pot), internal CO_2 concentration (*Ci*—µmol mol^{-1}), transpiration rate (*E*—mol H_2O m^{-2} s^{-1}), and stomatal conductance of water vapor (*Gs*—mol m^{-2} s^{-1}). UFFS, Erechim/RS Campus

Genotype	Plant Proportion (Rye:Wild radish)	LA	SDM	Ci	E	Gs
BR1	100:0 (C)	5491.4	21.7	317.8	3.9	0.20
	75:25	3541.0*	15.5*	329.7	5.0	0.29*
	50:50	2320.1*	7.7*	302.0	3.7	0.22
	25:75	1355.1*	4.8*	284.6*	4.4	0.22
	CV (%)	*19.7*	*16.4*	*6.0*	*20.2*	*22.9*
Wild radish	100:0 (C)	6570.5	38.7	320.9	2.9	0.22
	75:25	3591.5*	27.8*	346.8	4.1*	0.33
	50:50	3437.6*	18.6*	367.2*	4.2*	0.41*
	25:75	998.1*	8.5*	351.0	3.8	0.38*
	CV (%)	*30.8*	*12.8*	*6.7*	*16.2*	*23.9*
BRS Progresso	100:0 (C)	3708.7	17.2	306.9	4.0	0.32
	75:25	2960.5	12.0*	295.6	4.6*	0.35
	50:50	2823.6	10.1*	313.3	5.4*	0.36
	25:75	1073.5*	4.4*	327.5	5.6*	0.34
	CV (%)	*22.8*	*16.7*	*5.0*	*7.0*	*17.5*
Wild radish	100:0 (C)	3004.6	11.4	369.6	3.3	0.36
	75:25	3012.2	10.5	375.0	3.4	0.33
	50:50	1157.2*	4.5*	384.6	3.3	0.32
	25:75	1400.2*	4.7*	365.6	1.9*	0.44
	CV (%)	*20.0*	*35.2*	*4.6*	*29.1*	*41.4*
BRS Serrano	100:0 (C)	4445.6	15.9	336.8	1.7	0.26
	75:25	1785.0*	7.2*	317.3*	2.8*	0.32*
	50:50	2419.3*	7.0*	322.2	3.2*	0.33*
	25:75	1422.0*	5.7*	310.8*	3.6*	0.35*
	CV (%)	*18.9*	*25.9*	*3.9*	*13.5*	*12.2*
Wild radish	100:0 (C)	3652.7	17.5	387.2	3.5	0.35
	75:25	1667.3*	10.5*	371.5	3.9	0.38
	50:50	2165.4*	6.3*	359.1	3.5	0.28
	25:75	1653.0*	6.2*	377.2	3.3	0.26
	CV (%)	*35.3*	*31.4*	*5.6*	*42.0*	*28.5*

Note. * Mean differs from each control (C) by Dunnett's test ($p < 0.05$).

It is worth highlighting that cultivars of a given crop exhibit distinct genetic characteristics related to plant height, architecture, leaf area index, biomass production, root volume, resource use efficiency, and establishment speed, among other traits that distinguish them and affect their competitive ability when infested by weeds—this was also observed in the present study, albeit subtly. Other authors have also found differences in wheat (Lamego et al., 2013) and triticale (Galon et al., 2025) cultivars when competing with ryegrass, which are similar to the results observed in this study.

Regarding the competition between rye and turnip, both species were greatly negatively affected by the competition (Table 2). It is noted that there is similarity between rye and turnip when in competition, as both species compete intensely for the same available resources. This fact was also reported by Leon et al. (2023) when working with replacement series experiments using *Amaranthus hybridus* and *Setaria faberi* in competition with corn (*Zea mays*) at the ratios of 1:0, 0.75:0.25, 0.5:0.5, 0.25:0.75, and 0:1.

Regarding competitiveness indices (Table 2), in competition with ryegrass, the BRS Progresso cultivar showed the highest competitiveness for LA (CR = 8.72; and $K_{rye} > K_{ryegrass}$ and positive AG), while BR1 showed balanced performance (CR ≈ 1.0) and BRS Serrano showed an intermediate behavior (CR = 1.65). For DM, the BRS Progresso cultivar was the most efficient (CR = 6.08; $K_{rye} > K_{ryegrass}$ and positive AG), followed by BRS Serrano (CR = 3.19; $K_{rye} > K_{ryegrass}$ and positive AG) and BR1 (CR = 2.68; $K_{rye} > K_{ryegrass}$ and positive AG), all higher than ryegrass. For turnip, the BRS Progresso cultivar also showed a competitive advantage in terms of the indices, with CR = 2.00 for LA; $K_{rye} > K_{turnip}$ and positive AG, and a consistent performance for DM (CR = 1.58; $K_{rye} > K_{turnip}$ and positive AG). On the other hand, the BR1 and BRS Serrano cultivars had lower competitiveness, with values close to or below neutrality, without any significant effect on at least two indices, indicating that turnip had a greater effect on these cultivars. As previously reported, there is differentiation between cultivars of a crop when they are placed in competition with weeds (Lamego et al., 2013).

In general terms, the results observed in Tables 1 and 2 indicate that rye tends to have a higher competitive ability in biometric variables compared to ryegrass and turnip. The BRS Progresso cultivar shows better resistance to competition with turnip, while BRS Serrano and BR1 coexisted better with ryegrass. This differential competitive performance is associated with the distinct morphophysiological and genetic traits of each cultivar, as discussed earlier. Additionally, the differences in LA and DM between cultivars suggest a redirection of resource allocation to structures of higher physiological priority, such as roots or stems, when competition limits the availability of light, water, and nutrients (Pierik & Ballaré, 2021; Savić et al., 2025), which is more pronounced in BR1 and BRS Serrano cultivars.

Among the weeds, ryegrass was more suppressed by rye than turnip, highlighting the importance of the latter species as a key competitor in agricultural systems, especially when it infests crops sown during the winter season. This fact has also been reported in other studies involving wheat, barley, canola, and triticale in the presence of ryegrass and turnip weeds (Lamego et al., 2013; Pies et al., 2019; Tavares et al., 2019; Nichelati et al., 2020; Galon et al., 2025), corroborating the results observed in this study.

3.2 Effect of Competition on the Physiological Variables of the Species

The relative productivity of internal CO_2 concentration (Ci) (Figure 4) showed that, in general, the impact of competition was small. Rye maintained relative productivity (PR) values close to or slightly above the expected values in almost all treatments, except when BRS Serrano competed with turnip at the lowest density (25:75), where a reduction in PR of around 5 to 10% was observed compared to the expected value. Similar results were reported by Thiel et al. (2018), who observed stability in gas exchange parameters in plants under competition, suggesting that stomatal adjustments precede significant biomass losses.

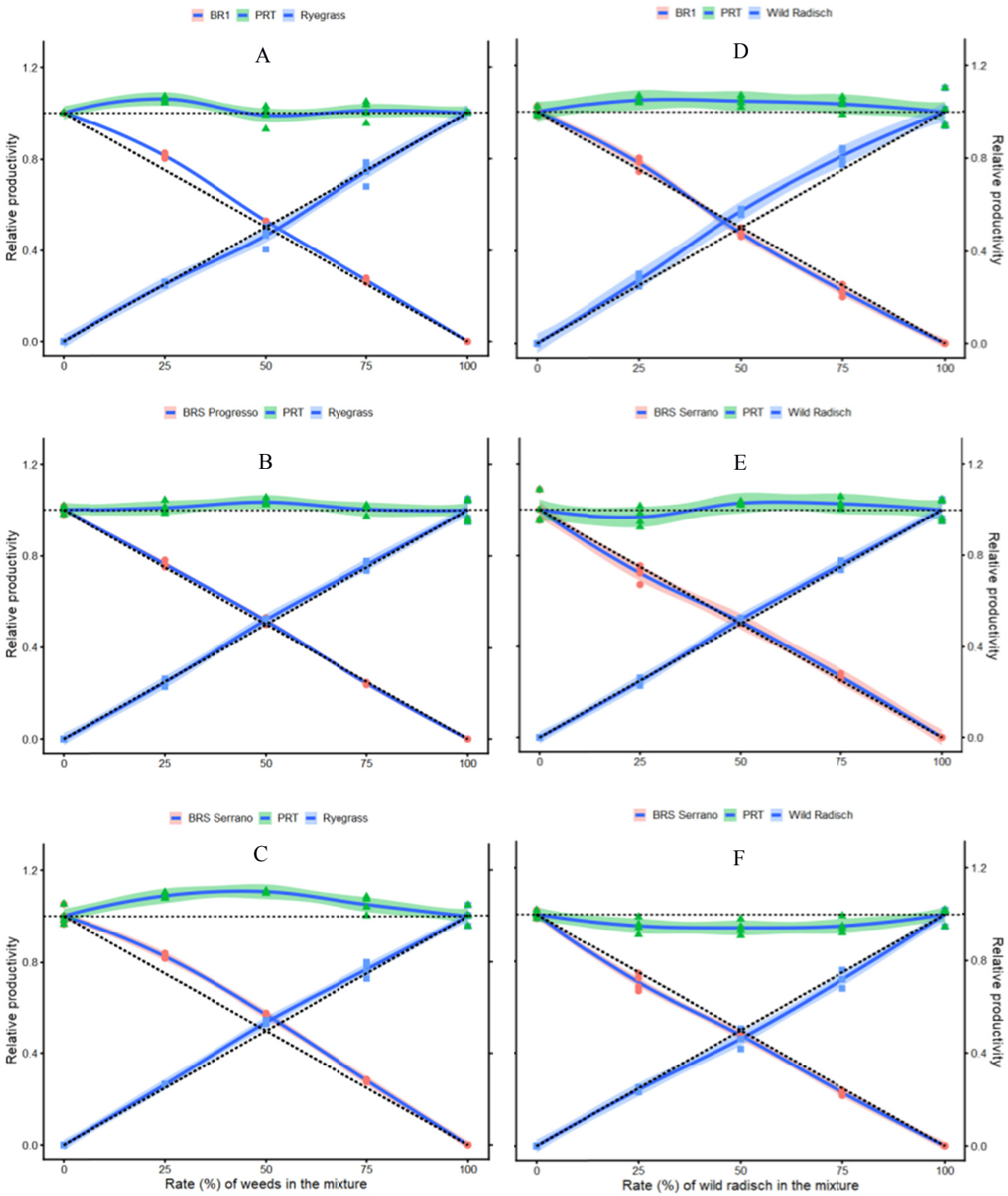


Figure 4. Relative productivity (RP) for sub-stomatal CO_2 concentration (Ci) of the rye cultivars BR1, BRS Progresso, and BRS Serrano against ryegrass (A, B, and C) or turnip (D, E, and F). (●) rye, (■) weed, and total (▲). Dashed lines represent the expected values in the absence of competition, solid lines represent the observed values when the species competed at different plant proportions, and colored bands represent the 95% confidence interval of the observations

For the transpiration rate (E), in the presence of turnip, rye exhibited a PR approximately 20 to 25% higher than expected (Figure 5). When competing with ryegrass, BRS Serrano was the most sensitive, showing reductions of up to 50% across all densities with the presence of the competitor, which also reflected in poorer ryegrass

performance. The BRS Progresso cultivar maintained superior performance by up to ~20% at the lowest competition density (25:75).

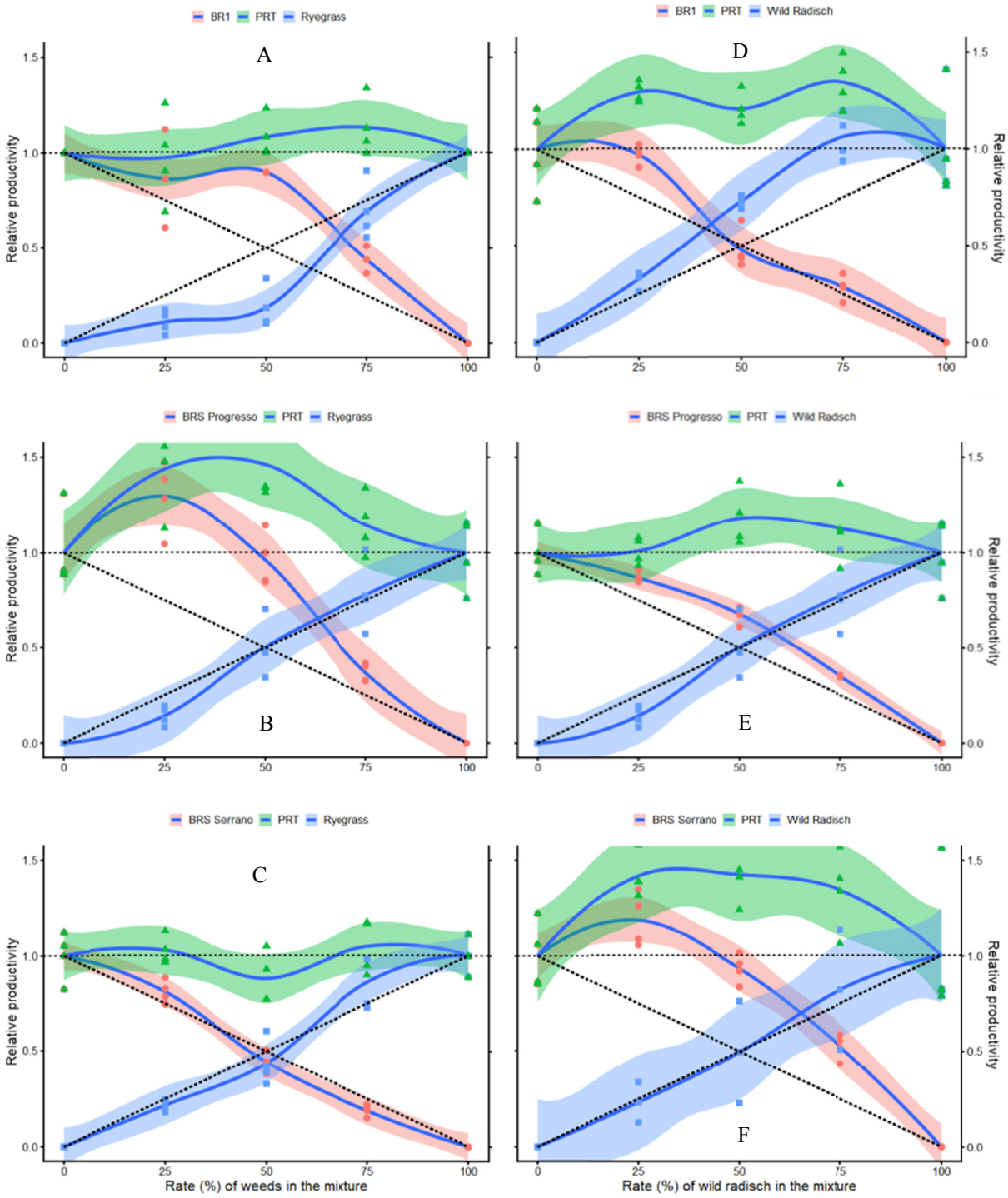


Figure 5. Relative productivity (RP) for transpiration rate (E) of the rye cultivars BR1, BRS Progresso, and BRS Serrano against ryegrass (A, B, and C) or turnip (D, E, and F). (●) rye, (■) weed, and total (▲). Dashed lines represent the expected values in the absence of competition, solid lines represent the observed values when the species competed at different plant proportions, and colored bands represent the 95% confidence interval of the observations

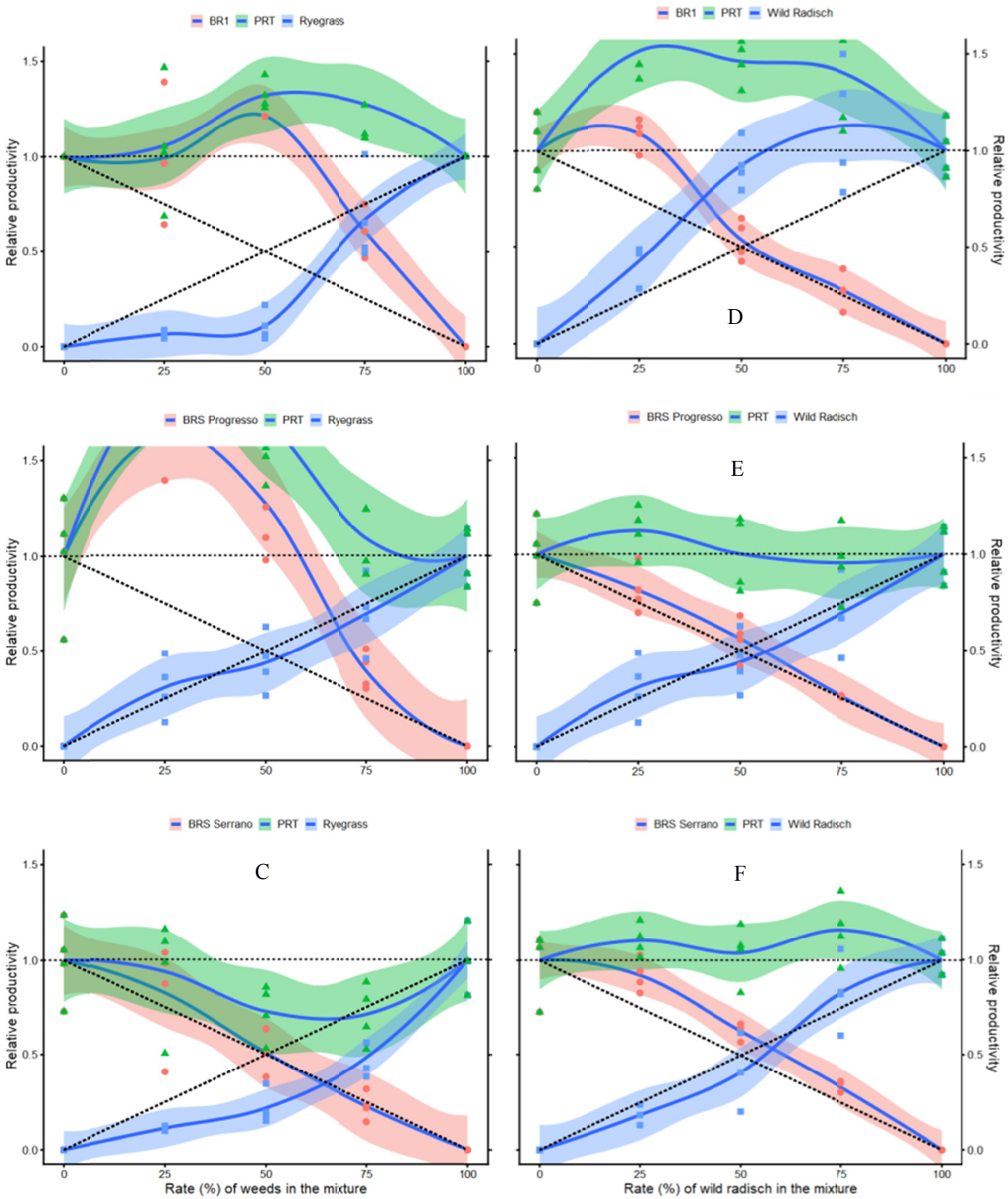


Figure 6. Relative productivity (RP) for stomatal conductance (Gs) of the rye cultivars BR1, BRS Progresso, and BRS Serrano against ryegrass (A, B, and C) or turnip (D, E, and F). (●) rye, (■) weed, and total (▲). Dashed lines represent the expected values in the absence of competition, solid lines represent the observed values when the species competed at different plant proportions, and colored bands represent the 95% confidence interval of the observations

These results suggest that turnip exerts less pressure on the transpiration rate of rye, while ryegrass causes greater competitive stress, especially in less tolerant cultivars. This is probably attributed to the fact that both ryegrass and rye belong to the same botanical family. McKenzie-Gopsill et al. (2020) and Singh et al. (2022) also report in their studies that weeds negatively interfere with the liquid photosynthesis and efficient water use

of cultivated plants when they coexist in a community, which is somewhat similar to the findings observed in this study. Stomatal conductance (Gs) was similar to what was observed with transpiration (Figure 6).

In competition with turnip, the impacts were reduced or nonexistent, and the BR1 cultivar stood out at the lowest density (25:75). The community (crop + competitor) was also benefited, with average increments of approximately 15% in the PR of Gs when turnip was the competitor. With ryegrass, the BRS Serrano cultivar maintained PR values close to expected, while BR1 and BRS Progresso benefited from increased stomatal conductance. Ryegrass, in turn, was affected by the presence of rye, highlighting the ability of the crop to suppress the stomatal opening of its competitor. Physiologically, weed species with a higher ability to maintain Gs under competition tend to outperform the crops in terms of final yield, a fact also confirmed by Thiel et al. (2018).

Overall, the results from Figures 4 to 6 demonstrate that rye has a good physiological adjustment capacity when competing with ryegrass and/or turnip, with differences between cultivars. The BR1 cultivar showed greater plasticity in maintaining stomatal conductance and transpiration; BRS Serrano was more susceptible to competition with ryegrass. Turnip did not cause significant interference in the physiological variables of rye. The effect of weeds on crop physiology is variable, depending on various stress factors, which may involve the species present in competition, the crop and cultivar, edaphoclimatic characteristics, management practices, the growth stage of the crop when the effect occurs, and others (Agostinetto et al., 2017; Thiel et al., 2018).

The physiology of rye plants when competing with ryegrass is shown in Table 1. For the BR1 cultivar, there was an increase in internal CO_2 concentration (Ci) in all proportions evaluated compared to the control (100:0), indicating an attempt by the crop to respond to the interference of the competitor. The transpiration rate (E) and stomatal conductance (Gs) were also significantly higher than the control in the 50:50 and 25:75 proportions, demonstrating greater stomatal opening under higher competitive pressure.

In the BRS Progresso cultivar, Ci did not differ from the control. In contrast, E and Gs were higher than the control in all competition proportions, indicating an intensification of gas exchange in response to interspecific interference. For BRS Serrano, Ci increased in all proportions when compared to the control. The transpiration rate only decreased at the highest ryegrass proportion (25:75), while stomatal conductance did not differ from the control, demonstrating less sensitivity of this parameter to competition with ryegrass.

Table 2 presents the physiological behavior of rye cultivars when competing with turnip. For BR1, competition with turnip reduced Ci only at the 25:75 proportion, compared to the control. The transpiration rate did not differ from the control in any of the proportions evaluated, while stomatal conductance was higher at the 75:25 proportion, indicating a moderate stomatal response to competition.

For BRS Progresso, Ci did not differ from the control in any of the proportions in competition with turnip, while the transpiration rate was higher than the control in all proportions, indicating an increase in water loss by transpiration under turnip interference. Stomatal conductance did not differ between treatments. For BRS Serrano, turnip reduced Ci at the 75:25 and 25:75 proportions compared to the control, indicating greater physiological sensitivity of this genotype to competition. In addition, E and Gs were significantly higher than the control in all proportions evaluated, showing a strong stimulus for gas exchange even under interspecific interference.

In general, the control plants of the rye cultivars presented lower values of E and Gs compared to the competition with ryegrass, indicating an attempt by the crop to respond to competition, with genotype-dependent responses. The same was observed in competition with turnip, especially for BRS Serrano, which seems to react more intensely to competition with this weed.

The competitiveness indices (CR, K, and AG) of rye in competition with ryegrass and turnip varied according to cultivar and the analyzed variable (Table 3). For internal CO_2 concentration (Ci), the BR1 cultivar performed better against ryegrass ($CR > 1$; $K_{rye} > K_{ryegrass}$ and A positive), confirming superior physiological performance. The cultivars BRS Progresso and BRS Serrano also showed advantages under these conditions, albeit to a lesser extent. In contrast, against turnip, the BR1 cultivar exhibited $CR < 1$; $K_{rye} < K_{ryegrass}$ and A negative. The cultivars BRS Progresso and BRS Serrano maintained results close to neutrality against turnip.

For transpiration (E), the BR1 cultivar again stood out against ryegrass ($CR = 6.03$; $K_{rye} > K_{ryegrass}$ and A positive), indicating high physiological efficiency under competition (Table 3). The cultivars BRS Progresso and BRS Serrano showed values close to neutrality or absence of significance in at least two indices. Against turnip, the BR1 cultivar showed reduction ($CR < 1$; $K_{rye} < K_{turnip}$ and A negative), while the cultivars BRS Progresso and BRS Serrano showed $CR > 1$, $K_{rye} > K_turnip$ and A positive, although without a significant effect. These

results suggest that turnip may exert greater physiological pressure, reducing gas exchange efficiency in some cultivars.

Table 3. Competitiveness indices of morphophysiological variables between rye cultivars with ryegrass (*Lolium multiflorum*) and turnip (*Raphanus raphanistrum*), competing in equal plant proportions (50:50), expressed by relative competitiveness (CR), relative clustering coefficients (K), and aggressiveness (AG). UFFS, Erechim Campus/RS

Cultivars × Weeds[1]	Rye × Ryegrass				Rye × Turnip			
	CR[2]	Kx[3] (rye)	Ky (ryegrass)	AG[4]	CR	Kx (rye)	Ky (turnip)	AG
Leaf Area (LA)								
BR 1	1.02±0.07	0.49±0.02	0.51±0.07	0.01±0.03	0.88±0.15	0.27±0.02	0.38±0.11	-0.05±0.05
BRS Progresso	8.72±1.98*	1.09±2.49	0.12±0.02	0.75±0.13*	2.00±0.18*	0.63±0.08*	0.24±0.02	0.19±0.03*
BRS Serrano	1.65±0.12*	0.27±0.02*	0.15±0.01	0.08±0.01*	1.02±0.17	0.38±0.04	0.47±0.17	-0.02±0.05
Dry Matter (DM)								
BR 1	2.68±0.27*	0.81±0.10*	0.21±0.03	0.27±0.03*	0.73±0.10	0.22±0.05	0.32±0.02	-0.06±0.02
BRS Progresso	6.08±1.29*	1.45±0.12*	0.12±0.02	0.48±0.02*	1.58±0.22	0.42±0.04*	0.25±0.05	0.09±0.03
BRS Serrano	3.19±0.21*	0.68±0.02*	0.15±0.01	0.28±0.01*	1.24±0.17	0.28±0.03	0.22±0.02	0.04±0.03
Internal Concentration of CO_2								
BR 1	1.15±0.06	1.11±0.03*	0.87±0.07	0.06±0.02	0.83±0.02*	0.91±0.03*	1.34±0.03	-0.09±0.01*
BRS Progresso	1.09±0.08	1.21±0.03	0.89± 0.07	0.04±0.01*	0.98±0.01	1.04±0.01	1.09±0.02	-0.01±0.01
BRS Serrano	1.06±0.01*	1.33±0.02*	1.16±0.02	0.03±0.01*	1.04±0.05	0.92±0.02	0.87±0.06	0.02±0.02
Transpiration Rate								
BR 1	6.03±1.40*	8.52±0.20*	0.25±0.09	0.71±0.06*	0.66±0.08*	0.99±0.24*	2.73±0.19	-0.25±0.06*
BRS Progresso	1.07±0.12	1.31±0.04*	0.77±0.01	0.01±0.06	1.44±0.24	2.15±0.22	1.19±0.41	0.07±0.08
BRS Serrano	1.06±0.14	0.81±0.08	0.85±0.24	0.01±0.06	2.33±0.73	7.95±2.11	1.36±0.63	0.44±0.15
Stomatal Conductance								
BR 1	5.83±4.84*	5.67±0.49*	0.13±0.05	1.11±0.04*	0.59±0.09*	1.25±0.26	2.91±5.23	-0.39±0.10
BRS Progresso	4.79±1.23*	2.79±1.30*	0.08±0.05	0.34±0.07*	1.41±0.29	1.39±0.29	0.89±0.28	0.12±0.088
BRS Serrano	2.54±0.42*	1.11±0.24*	0.29±0.08	0.29±0.06*	1.81±0.46	1.72±0.14*	0.82±0.29	0.22±0.09

Note. * Significant difference by the t-test ($p < 0.05$). [1] Assessment of the indicated parameter at the defined variable at density 50:50, compared to the respective controls by Dunnett's test ($p \leq 0.05$); [2] Significant when differed from "1" by the t-test; [3] Difference between Kcrop and Kweed, at the same competitive level (50:50), compared by the t-test with Welch's criteria; [4] Significant when it differed from "0" by the t-test. * Significant difference ($p \leq 0.05$).

For stomatal conductance (Gs), the BR1 and BRS Progresso cultivars showed good performance against ryegrass (CR = 5.83 and 4.79; $K_{rye} > K_{ryegrass}$ and A positive), standing out as the most competitive under these conditions. The BRS Serrano cultivar also demonstrated an advantage, but with lower indices than the two previous ones (CR = 2.54; $K_{rye} > K_{ryegrass}$ and A positive). While against turnip, competitiveness was more evenly distributed, with BRS Progresso and BRS Serrano exhibiting CR > 1; $K_{rye} > K_{turnip}$ and A positive, while BR1 showed a marked reduction (CR < 1; $K_{rye} < K_{turnip}$ and A negative).

These results confirm that rye's physiological performance is less affected by ryegrass, especially the BR1 cultivar. However, against turnip, more pronounced reductions were observed in the physiological variables, especially in the BR1 cultivar. This corroborates observations that turnip exerts significant interference on crops grown in winter due to its high competitive ability and resource use efficiency, as also noted by Franz et al. (2020). Previous studies report that ryegrass, in certain crops, is less aggressive than turnip (Tarouco et al., 2016), supporting the results observed in this study. The impacts on the competitiveness indices for Gs and E in competition suggest a possible imbalance in the internal water status of the crop plants, as reported by McKenzie-Gopsill et al. (2020) and Singh et al. (2022).

Competition for environmental resources occurred between rye cultivars and weeds (ryegrass and/or turnip), negatively affecting the growth of all species. Turnip showed greater competitive ability than ryegrass, particularly reducing rye leaf area and aerial biomass, with stronger physiological impacts on the BR1 cultivar.

Overall, rye cultivars outperformed the weeds, with BRS Progresso showing the highest suppressive capacity, BR1 being more susceptible to turnip interference, and BRS Serrano exhibiting intermediate behavior. Interspecific competition was less harmful than intraspecific competition. The use of highly competitive rye cultivars, such as BRS Progresso, is essential to enhance production stability and reduce weed pressure in winter cropping systems.

References

Adhikari, L., Mohseni-Moghadam, M., & Missaoui, A. (2018). Allelopathic effects of cereal rye on weed suppression and forage yield in alfalfa. *American Journal of Plant Sciences, 9*, 685-700. https://doi.org/10.4236/ajps.2018.94054

Agostinetto, D., Fontana, L. C., Vargas, L., Markus, C., & Oliveira, E. (2013). Relative competitive ability of crabgrass in coexistence with flooded rice and soybean. *Pesquisa Agropecuária Brasileira, 48*, 1315-1322. https://doi.org/10.1590/S0100-204X2013001000002

Agostinetto, D., Tarouco, C. P., Nohatto, M. A., Oliveira, C., & Fraga, D. S. (2017). Metabolic activity of wheat and ryegrass plants in competition. *Planta Daninha, 35*, e017155463. https://doi.org/10.1590/S0100-83582017350100044

Asato, A. E. B., Steinicke, C. G., Stein, G., Schreck, B., Kattenborn, T., Ebeling, A., … Hines, J. (2025). Seasonal shifts in plant diversity effects on above-ground–below-ground phenological synchrony. *Journal of Ecology, 113*, 472-484, 2025. https://doi.org/10.1111/1365-2745.14470

Balem, A., Padilha, L. R., Michelon, C. J., & Costa, L. (2021). Control ryegrass and wild radish in wheat with post-emergent herbicides. *Revista de Ciência e Inovação, 6*, 45-56. https://doi.org/10.26669/2448-4091251

Bianchi, M. A., Fleck, N. G., & Lamego, F. P. (2006). Proporção entre plantas de soja e plantas competidoras e as relações de interferência mútua. *Ciência Rural, 36*, 1380-1387. https://doi.org/10.1590/S0103-84782006000500006

Brunetto, L., Galon, L., Cavaletti, D. C., Munareto, J. D., Castamann, A., & Perin, G. F. (2023). Competitive response and level of economic damage of quinoa in the presence of alexandergrass. *Revista Brasileira de Ciências Agrárias, 18*, e2543. https://doi.org/10.5039/agraria.v18i1a2543

Caldas, J. V. S., Silva, A. G., Braz, G. B. P., Procópio, S. O., Teixeira, I. R., Souza, M. F., & Reginaldo, L. T. R. T. (2023). Weed competition on soybean varieties from different relative maturity groups. *Agriculture, 13*, 725. https://doi.org/10.3390/agriculture13030725

Chaudhari, S., Jennings, K. M., Culpepper, S., Batts, R. B., & Bellinder, R. (2019). Turnip tolerance to preplant incorporated trifluralin. *Weed Technology, 33*, 123-127. https://doi.org/10.1017/wet.2018.66

Chauhan, B. S. (2020). Grand challenges in weed management. *Frontiers in Agronomy, 1*, 3. https://doi.org/10.3389/fagro.2019.00003

Chehade, L. A., Puig, C. G., Souto, C., Antichi, D., Mazzoncini, M., & Pedrol, N. (2021). Rye (*Secale cereale* L.) and squarrose clover (*Trifolium squarrosum* L.) cover crops can increase their allelopathic potential for weed control when used mixed as dead mulch. *Italian Journal of Agronomy, 16*, 1869. https://doi.org/10.4081/ija.2021.1869

CONAB (Companhia Nacional de Abastecimento). (2026). *Acompanhamento de safra brasileira—grãos*. Brasília, CONAB. Retrieved January 26, 2026, from https://www.gov.br/conab

Costa, L. O., & Rizzardi, M. A. (2015). Competitive ability of wheat in association with biotypes of *Raphanus raphanistrum* L. resistant and susceptible to ALS inhibitor herbicides. *Ciência e Agrotecnologia, 39*, 121-130. https://doi.org/10.1590/S1413-70542015000200003

Cousens, R. (1991). Aspects of the design and interpretation of competition (interference) experiments. *Weed Technology, 5*, 664-673. https://doi.org/10.1017/S0890037X00027524

CQFS-RS/SC (Comissão de Química e Fertilidade do Solo). (2016). *Manual de adubação e calagem para os estados do Rio Grande do Sul e de Santa Catarina* (11th ed., p. 376) Porto Alegre.

Feng, L., Raza, M. A., Shi, J., Ansar, M., Titriku, G. K., Meraj, T. A., … Yang, W. (2024). Delayed maize leaf senescence increases the land equivalent ratio of maize soybean relay intercropping system. *European Journal of Agronomy, 118*, 126092. https://doi.org/10.1016/j.eja.2020.126092

Fernández-Moreno, P. T., Cruz, R. A., Smeda, R.J., & De Prado R. (2017). Differential resistance mechanisms to glyphosate result in fitness cost for *Lolium perenne* and *L. multiflorum*. *Frontiers in Plant Science, 8*, 1-16. https://doi.org/10.3389/fpls.2017.01796

Franceschetti, M. B., Galon, L., Toso, J. O., Melo, T. S., Menegatti, A. D., Concenco, G., … Perin, G. F. (2024). Morpho-physiological responses of potato cultivars under weed competition. *Comunicata Scientiae, 15*, e4088. https://doi.org/10.14295/cs.v15.4088

Franz, E., Tironi, S. P., Luz, G. L. da, Cezarotto, L. A., Zago, D. V., Munaretto, D., … Dalcanton, F. (2020). Competitive ability of canola cultivars in competition with turnip. *Brazilian Journal of Development, 6*, 82507-82523. https://doi.org/10.34117/bjdv6n10-617

Galon, L., Iager, T., Toso, J. O., Bagnara, M. A. M., Tonin, R. J., Concenço, G., & Perin, G. F. (2025). Morphophysiological responses of triticale cultivars under weed competition. *Revista de Ciências Agroveterinárias, 24*, 429-449. https://doi.org/10.5965/223811712432025429

Ghimire, B. K., Yu, C. Y., Ghimire, B., Seong, E. S., & Chung, I. M. (2019). Allelopathic Potential of phenolic compounds in *Secale cereale* cultivars and its relationship with seeding density. *Applied Sciences, 9*, 3072. https://doi.org/10.3390/app9153072

Heap, I. (2026). *International survey of herbicide-resistant weeds*. Retrieved from June 23, 2025, http://www.weedscience.org

Jastrzębska, M., Kostrzewska, M., & Marks, M. (2023). Is diversified crop rotation an effective non-chemical strategy for protecting triticale yield and weed diversity? *Agronomy, 13*, 1589. https://doi.org/10.3390/agronomy13061589

Kaur, S., Kaur, R., & Chauhan, B. S. (2018). Understanding crop-weed-fertilizer-water interactions and their implications for weed management in agricultural systems. *Crop Protection, 103*, 65-72. https://doi.org/10.1016/j.cropro.2017.09.011

Lamego, F. P., Reinehr, M., Cutti, L., Aguiar, A. C. M., Rigon, C. A. G., & Pagliarini, I. B. (2015). Morphological alterations in wheat, italian ryegrass and radish seedlings when in competition in at the initial stages of growth. *Planta Daninha, 33*, 13-22. https://doi.org/10.1590/S0100-83582015000100002

Lamego, F. P., Ruchel, Q., Kaspary, T. E., Gallon, M., Basso, C. J., & Santi, A. L. (2013). Competitive ability of wheat cultivars against weed. *Planta Daninha, 31*, 521-531. https://doi.org/10.1590/S0100-83582013000300004

Leon, R. G., Oreja, F. H., Mirsky, S. B., & Rebert-Horton, C. (2023). Addressing biases in replacement series: the importance of reference density selection for interpretation of competition outcomes. *Weed Science, 71*, 606-614. https://doi.org/10.1017/wsc.2023.53

Luo, C. L., Duan, H. X., Wang, Y. L., Liu, H. J., & Xu, S. X. (2024). Complementarity and competitive trade-offs enhance forage productivity, nutritive balance, land and water use, and economics in legume-grass intercropping. *Field Crops Research, 319*, e109642. https://doi.org/10.1016/j.fcr.2024.109642

Manfron, A. C. A., Bondan, C., Fontaneli, R. S., & Zeni, M. (2022). Impact of rye as a cover on weed biomass in the subsequent crop: Meta-analysis. *Research, Society and Development, 11*, e9911527910. https://doi.org/10.33448/rsd-v11i5.27910

Mario, R. B., Leães, G. P., Backes, R. L., Leichtweis, E. M., Bortolin, E. S., Tronquini, S. M., … Ulguim, A. R. (2024). 2,4-D and saflufenacil application time on the quality of Italian ryegrass (*Lolium multiflorum*) seeds. *Ciência Rural, 54*, e20230580. https://doi.org/10.1590/0103-8478cr20230580

Mckenzie-Gopsill, A. G., Amirsadeghi, S., Fillmore, S., & Swanton, C. J. (2020). Duration of weed presence influences the recovery of photosynthetic efficiency and yield in common bean (*Phaseolus vulgaris* L.). *Frontiers in Agronomy, 2*, 593570. https://doi.org/10.3389/fagro.2020.593570

Nichelati, F. D., Nottega, E. L., Guerra, N., Fioreze, S. L., Oliveira Nete, A. M., & Oliveira, Z. B. (2020). Weed interference in canola (*Brassica napus* L.) crop. *Ciência Agrícola, 18*, 39-47. https://doi.org/10.28998/rca.v18i1.7807

Nosratti, I., Korres, N. E., & Cordeau, S. (2023). Knowledge of cover crop seed traits and treatments to enhance weed suppression: a narrative review. *Agronomy, 13*, 1683. https://doi.org/10.3390/agronomy13071683

Oliveira, A. P. T., Rosa, P. P., Chesini, R. C, Camacho, J. S., Nunes, L. P., Faria, M. R., … Ferreira, O. G. (2019). Features and use of ryegrass (*Lolium multiflorum* L.) in feeding ruminants—A literature review. *Revista Científica Rural, 21*, 347-365. https://doi.org/10.30945/rcr-v21i3.2792

Pierik, R., & Ballaré, C. L. (2021). Control of plant growth and defense by photoreceptors: from mechanisms to opportunities in agriculture. *Molecular Plant, 14*, 61-76. https://doi.org/10.1016/j.molp.2020.11.021

Pies, W., Werlang, T., Luz, A. C. P., Galon, L., & Tironi, S. P. (2019). Competitive barley ability coexisting with ryegrass densities. *Revista Brasileira de Ciências Agrária*, *14*, 1-6. https://doi.org/10.5039/agraria.v14i2a5630

Ramos, A. R., Zampar, A., & Silva, A. W. L. (2021). Dry matter productivity and bromatological quality of ryegrass genotypes cultivated in Southern Brazil. *Arquivo Brasileiro de Medicina Veterinária e Zootecnia, 73*, 247-255. https://doi.org/10.1590/1678-4162-11885

Rubin, R. S., Langaro, A. C., Mariani, F., Agostinetto, D., & Berto, R. M. (2014). Relative competitive ability of irrigated rice with red rice susceptible or resistant to the herbicide imazapyr + imazapic. *Arquivos do Instituto Biológico, 81*, 173-179. https://doi.org/10.1590/1808-1657001242012

Savić, A., Popović, A., Đurović, S., Pisinov, B., Ugrinović, M., & Todorović, M. J. (2025). A Framework for understanding crop-weed competition in agroecosystems. *Agronomy, 15*, 2366. https://doi.org/10.3390/agronomy15102366

Silva, D. R. O., Aguiar, A. C. M., Gheller, D. P., Novello, B. D., & Basso, C. J. (2019). Interference of brassicaceae and poaceae on canola hybrids. *Planta Daninha, 37*, e019187792. https://doi.org/10.1590/S0100-83582019370100085

Singh, M., Kukal, M. S., Irmak, S., & Jhala, A. J. (2022). Water use characteristics of weeds: A global review, best practices, and future directions. *Frontiers in Plant Science, 12*, 794090. https://doi.org/10.3389/fpls.2021.794090

Streck, E. V., Kämpf, N., Dalmolin, R. S. D., Klamt, E., Nascimento, P. C., Giasson, E., … Schneider, P. (2018). *Solos do Rio Grande do Sul* (3rd ed., p. 252). Porto Alegre: Emater/RS-Ascar.

Sun, C., Ashworth, M. B., Flower, K., Vila-Aiub, M. M., Rocha, R. L., & Beckie, H. J. (2021). The adaptive value of flowering time in wild radish (*Raphanus raphanistrum*). *Weed Science, 69*, 203-209. https://doi.org/10.1017/wsc.2021.5

Tarouco, C. P., Agostinetto, D., Langaro, A. C., Nohatto, M. A., Mariani, F., & Silva, B. M. (2016). Wheat Fundacep Horizonte bcompetitive ability under competition with ryegrass. *Pesquisa Agropecuária Gaúcha, 22*, 1-13. https://doi.org/10.36812/pag.2016221/21-13

Tavares, L. C., Lemes, E. S., Ruchel, Q., Westendorff, N. R., & Agostinetto, D. (2019). Criteria for decision making and economic threshold level for wild radish in wheat crop. *Planta Daninha, 37*, e019178898. https://doi.org/10.1590/S0100-83582019370100004

Thiel, C., David, F., Galon, L., Deuner, S., Forte, C., Perin, G., David, P., Mossi, A., Andres, A., & Concenço, G. (2018). Physiology of weeds in intraspecific competition. *Journal of Agricultural Science, 10*, 334-344. https://doi.org/10.5539/jas.v10n6p334

Toebe, M., Cargnelutti Filho, A., Mello, A. C., Souza, R. R., Soares, F. S., Silva, L. S., & Segatto, A. (2020). Plot size and replications number for triticale experiments. *Ciência Rural, 50*, e20200222. https://doi.org/10.1590/0103-8478cr20200222

Walsh, M. J. (2019). Enhanced wheat competition effects on the growth, seed production, and seed retention of major weeds of Australian cropping systems. *Weed Science, 67*, 657-665. https://doi.org/10.1017/wsc.2019.53

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