Communications in PLANT SCIENCES

http://cpsjournal.org
e-ISSN 2237-4027
Volume 13 (2023)

RESEARCH ARTICLE

Interference and economic damage level of turnips in rye

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Submitted on June 16, 2023
Accepted on December 15, 2023
Early View on January 04, 2024
Final Publication on January 05, 2024

Authors declare no conflict of interest

KEYWORDS:
Secale cereale
Raphanus sativus
Plant competition

ABSTRACT

Turnip (*Raphanus sativus*) is one of the weeds that have caused the most quantitative and qualitative losses by infesting winter crops, including rye. Therefore, the objective of this work was to test mathematical models and identify explanatory variables to determine the economic damage level (EDL) of the weed turnip in rye genotypes. Treatments consisted of rye genotypes (BRS Serrano, IPR 89, BRS Progresso, and Crioulo) and turnip densities ranging from 0 to 648 plants m^{-2} in competition with the crop. Plant density, leaf area, soil cover, and shoot dry matter of the turnip were evaluated 30 days after species emergence. For rye, grain yield, control cost, bag price, and control efficiency were determined. The rectangular hyperbola model was efficient for estimating rye yield loss due to turnip interference. Plant density best fitted the rectangular hyperbola model. BRS Serrano, BRS Progresso, and Crioulo genotypes showed greater competitiveness and higher EDL values (from 2.03 to 4.36 plants m^{-2}) in the presence of turnip. The lowest EDL values ranged from 1.31 to 2.19 plants m^{-2}, for the genotype IPR 89, which showed the lowest competitive ability. EDL values decreased with increasing grain yield, price of a bag of rye, herbicide efficiency, and with decreasing turnip control costs, justifying the use of control measures at lower weed densities.

Highlighted Conclusions

1. The plant density of ryegrass showed better fit to the rectangular hyperbola.
2. The ryegrass genotypes BRS Serrano, BRS Progresso and Crioulo showed greater competitive ability in the presence of turnips.
3. The rye genotype IPR 89 had the lowest EDL values and the least competitive ability in the presence of turnip.

INTRODUCTION

Rye (*Secale cereale*) is an annual cespitous plant that belongs to the Poaceae family and is a difficult weed to control in the United States, competing with winter wheat (Ostlie et al. 2018). In Europe, rye is the second most important cereal crop, with 5.8 million hectares under cultivation (FAO 2023). Due to its resilience, it has gained socioeconomic importance in recent years in the cold season in southern Brazil. Currently, it is grown on an area of 4.7 thousand hectares in the country, with an average productivity of 2.3 t ha^{-1} and a production of about 11.0 thousand tons (CONAB 2023). Rye is characterized by its vigorous initial growth, rusticity, excellent resistance to biotic and abiotic stresses, and high nutrient use efficiency (Milczarski et al. 2011).

The expansion and confirmation of rye as a productive alternative for the cold season is due to in part to the optimization of production inputs (land, machinery, and people) used for summer crops. It is an important species in crop rotation systems with soybeans, beans, corn, wheat, etc., to cycle nutrients and to break the disease cycle, reducing phytosanitary problems, favoring the adoption of more sustainable management practices, especially the no-tillage straw system (Ferreira et al. 2017; Sherman et al. 2020).

Phytosanitary problems faced by rye include competition with weeds, especially turnip (*Raphanus sativus*), which is one of the most common species in winter crops in southern Brazil (Tironi et al. 2014; Costa and Rizzardi 2015; Galon et al. 2022). Turnip is widespread in Alto Uruguai Gaúcho fields and shows a high ability to compete with winter crops, as well as in high fertility, seed dormancy, and resistance to herbicides that inhibit acetolactate synthase (ALS), which contributes to reducing the potential of crop production (Lamego et al. 2015; Costa and

Rizzardi 2015). Difficulty in control is also related to the use of turnip as a soil cover in no-tillage system with straw or as winter forage for livestock feeding, which increases the seed bank in the soil (Costa and Rizzardi 2015; Tavares et al. 2019).

Turnip competes for resources available in the medium, such as water, light, and nutrients, and for this reason affects the development of the productive potential of the crops, hinders the expansion of the cultivated area, interferes with growth and development, reduces productivity and the quality of harvested grains (Ferreira et al. 2017; Tavares et al. 2019; Brandler et al. 2021; Galon et al. 2022), and in many cases also harbors insects and diseases. Turnip has a high shading capacity in the early stages of crop growth, releases allelopathic substances, and produces a large amount of seeds; therefore, in many cases, it exacerbates damage due to the high competition it presents (Tavares et al. 2019; Sun et al. 2021; Galon et al. 2022).

Therefore, research on the responses to coexistence of rye genotypes in relation to weeds, especially turnip, is important so that more efficient, sustainable, and alternative management than chemical control can be carried out, either by cultural methods or by control based on the EDL concept. This concept states that the use of herbicides or other control methods is justified only when the damage caused by weeds exceeds the cost of the control measure used (Kalsin and Vidal 2013; Tavares et al. 2019).

When weed density is high and competes with crops, the decision to control is facilitated by growers. However, when weeds occur at low densities, it becomes difficult to adopt control measures because of the need to quantify economic benefits relative to control costs (Agostinetto et al. 2010; Tavares et al. 2019; Brandler et al. 2021).

In crops, crop density is generally constant, whereas weed density varies depending on the soil seed bank, environmental and soil conditions, management, and cultural practices used that alter infestation levels (Kalsing and Vidal 2013; Jha et al. 2017). Knowing the disturbance ability of weeds on the crop of interest is extremely important in deciding which control method to use. With this information, the price of the harvested product, the control cost, the grain productivity, and the efficiency of the control method used in a given crop, the EDL of the weed can be calculated, i.e., the density whose interference with the crop exceeds the control cost (Agostinetto et al. 2010; Kalsing and Vidal 2013; Tavares et al. 2019; Galon et al. 2022).

Mathematical models have been used to estimate productivity losses due to weeds (Agostinetto et al. 2010; Kalsing and Vidal 2013; Tavares et al. 2019; Galon et al. 2022). The hyperbolic relationship between grain yield and weed density was originally described by Cousens (1985). This author fitted an empirical model (rectangular hyperbola model) to predict productivity losses as a function of weed density and obtained results demonstrating the superiority of this model over other models.

The rectangular hyperbola model is based on the nonlinear relationship between percent yield loss due to disturbance, relative to the infestation-free control, and weed density (Cousens 1985). It includes the parameters "*i*" representing the production loss due to the addition of the first weed and "*a*" indicating the production loss when weed density approaches infinity. The biological significance of the model shows that the competitive effect of each weed added to the crop decreases as weed density increases, which is due to the onset of intraspecific competition (Agostinetto et al. 2010; Tavares et al. 2019).

Therefore, the grower who decided to grow rye to diversify his farm must use weed control products tools to minimize or even avoid the negative effects of coexistence with the crop. Since there are few herbicides approved for the control of weeds infesting rye (AGROFIT 2023), alternative methods of weed control are important to reduce the environmental impact caused by the excessive use of chemical products.

This work is based on the hypothesis that different rye genotypes differ in their competitive ability against turnip, thus alternating EDL. Therefore, the objective of this work was to test mathematical models and identify explanatory variables to determine the EDL of rye genotypes with turnip infestation.

MATERIAL AND METHODS

The experiment was conducted in 2018 in the experimental area of the Federal University of Fronteira Sul (UFFS), Erechim/RS, where the soil was classified as Humic Aluminoferric Red Latosol (Santos et al. 2018) and the local climate is of type Cfa (humid temperate climate with hot summer) according to the classification established by Köeppen, in which precipitation is well distributed throughout the year (INMET 2023). The weather conditions that occurred during the execution of the experiment are shown in Figure 1.

The pH correction and soil fertilization were carried out according to the physico-chemical analysis and following the technical recommendations for rye crop (Rolas 2016). The chemical and physical characteristics of the soil were: pH_{water} 4.7; OM = 3.04%; P = 8.5 mg dm^{-3}; K= 106 mg dm^{-3}; Al^{3+} = 0.6 cmolc dm^{-3}; Ca^{2+} = 5.1 cmolc dm^{-3}; Mg^{2+} = 3.4 cmolc dm^{-3}; CEC(t) = 9.9 cmolc dm^{-3}; CEC($T_{pH=7,0}$) = 18.6 cmolc dm^{-3}; H+Al = 9.7 cmolc dm^{-3}; V = 48%; and clay = 64%.

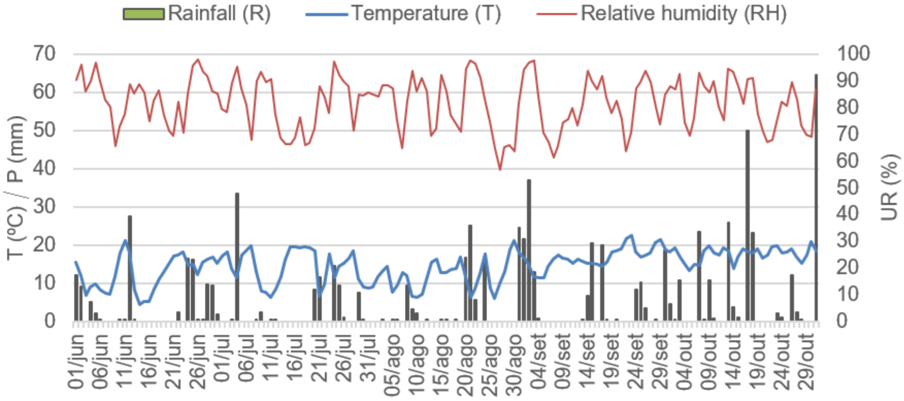

Figure 1. Monthly precipitation (mm), average temperature and relative humidity from June to October 2018, during the experimental period.

Rye was sown in a no-tillage system, with vegetation previously dried with glyphosate (1,440 g ha^{-1}) + saflufenacil (70 g ha^{-1}) + dash (0.5% v/v). The experimental design was completely randomized, without repetition. In the present work, the different turnip densities served as replicates and provided the necessary variance for the statistical analyzes according to the non-linear model of rectangular hyperbola proposed by Cousens (1985). There are other studies in the literature similar to the present study using the same methodology with one replicate (Agostinetto et al. 2010; Tavares et al. 2019; Brandler et al. 2021).

Each experimental unit (plot) consisted of an area of 13.60 m^2 (2.72 x 5.00 m), with sowing in the second half of June 2018 in 16 rows 5 m long and 0.17 m apart, which corresponds to a width of 2.72 m. The sowing density of the rye genotypes was 44 seeds per meter or 2,600,000 seeds ha^{-1}, giving an approximate density of 260 plants m^{-2}. Treatments consisted of rye genotypes and turnip densities as shown in Table 1.

Table 1. Rye genotypes in competition with turnip densities (plants m^{-2}). UFFS, Erechim campus, RS, 2018.

Genotypes	Turnip densities (plants m^{-2})
BRS Serrano	0, 8, 24, 28, 56, 72, 100, 180, 216, 240, 292, and 396
BRS Progresso	0, 8, 28, 36, 40, 44, 104, 104, 128, 152,164, and 648
IPR 89	0, 12, 16, 40, 44, 44, 52, 60, 68, 80, 248, and 332
Crioulo	0, 8, 16, 32, 48, 80, 56, 104, 144, 164, 280, and 380

Since this was an area with natural turnip infestation, the different densities of weed from the soil seed bank were established by applying the herbicide Bentazon (720 g ha^{-1}) – Basagran 600® (1.2 L ha^{-1}) + non-ionic adjuvant - Assist® (1.0 L ha^{-1}) to turnip. The application was carried out using a backpack sprayer, supplied with CO_2 and equipped with four DG 110.02 fan spray nozzles, maintaining a constant pressure of 210 kPa and a displacement speed of 3.6 km h^{-1}, which allowed an herbicide flow of 150 L ha^{-1}. The turnip densities studied were protected with plastic cups or buckets to prevent them from being damaged by the herbicide in each experimental unit. The herbicide bentazon was selected because it controlled the turnip, was selective on the rye, and did not remain in the soil (AGROFIT 2023), so the desired densities were achieved in each experimental unit.

Because the turnip came from the soil seed bank, the establishment of densities (Table 1) varied due to factors such as infestation, vigor, moisture, and others prevented the establishment of exactly the same number of plants per plot (experimental unit).

For basic fertilization, 233 kg ha^{-1} of formula 05-30-15 (N-P_2O_5-K_2O) was used, and for top dressing, 50 kg ha^{-1} of nitrogen in the form of urea (45% of N – 111 kg ha^{-1}) was divided into two applications, one at the beginning of tillering of the rye and the other at the elongation of the internodes, depending on the chemical analysis of the soil and the expected grain yield of the crop. All other management practices used were in accordance with research recommendations for rye cultivation.

Quantification of plant density (PD), leaf area (LA), soil cover (SC), or shoot dry matter (DM) of turnip was conducted 30 days after emergence (DAE) of the crop. To determine the PD variable, plants were counted in two 0.25 m^2 (0.5 m x 0.5 m) area per plot. Quantification of LA of competing plants was done using a portable LA electronic integrator (model CI-203, CID Bio-Science), measuring all plants in an area of 0.25 m^{-2} per plot. SC of turnip plants was visually scored individually by two evaluators using a percentage scale where zero corresponds to the absence of SC and 100 corresponds to complete soil cover. The DM of turnip plants (g m^{-2}) was determined by collecting plants in an area of 0.25 m^2 per plot and drying them in an oven with forced air circulation at a temperature of 60±5ºC until they reached a constant mass.

The productivity of the rye grain was determined by harvesting the plants on a useful area of 4.5 m^2 of each experimental unit, when the moisture content of the grains reached approximately 15%. After weighing the grains, their moisture content was determined, and then the values were normalized to 13% moisture. Using the grain yield data, the percent losses relative to the plots without infestation (controls) were calculated using Equation 1:

$$\text{Loss (\%)} = \left(\frac{\text{Ra} - \text{Rb}}{\text{Ra}} \right) x\, 100 \qquad \text{Equation 1}$$

Where: *Ra* and *Rb*: crop productivity without and with the presence of the competitor plant turnip, respectively.

Prior to data analysis, the values DM (g m^{-2}), SC (%), or LA (cm^2) were multiplied by 100, eliminating the need to use the correction factor in the model (Agostinetto et al. 2010).

Relationships between percent productivity losses in rye as a function of explanatory variables were calculated separately for each genotype, using the nonlinear regression model proposed by Cousens (1985) from the rectangular hyperbola given in Equation 2:

$$\text{Lp} = \frac{(\text{i} * \text{X})}{(1 + (\frac{\text{i}}{\text{a}}) * \text{X})} \qquad \text{Equation 2}$$

Where: Lp = loss of productivity (%); X = turnip density, leaf area, soil cover, or shoot dry matter; *i* and *a* = productivity loss (%) per unit turnip plant when the value of the variables approaches zero and infinity, respectively.

For the calculation procedure, the Gauss-Newton method was used, which estimates, through successive iterations, the values of the parameters for which the sum of the squares of the deviations of the observations relative to the fitted values is minimal (Agostinetto et al. 2010).

The value of the *F*-statistic ($p \leq 0.05$) was used as the criterion for analyzing the data in the model. The acceptance criterion for fitting the data to the model was based on the highest value of the coefficient of determination (R^2) and the lowest value of the mean square of the residual (MSR).

To calculate the economic damage level (EDL), the estimates of parameter *i* were taken from Equation 2 (Cousens 1985) and the Equation 3, adapted from Lindquist and Kropff (1996):

$$\text{EDL} = \frac{(\text{Cc})}{(\text{R} * \text{P} * (\frac{\text{i}}{100}) * (\frac{\text{H}}{100}))} \qquad \text{Equation 3}$$

Where: EDL = economic damage level (plants m^{-2}); Cc = control cost (herbicide and tractor use, in dollars ha^{-1}); R = rye grain yield (kg ha^{-1}); P = rye price (dollars per 60 kg of grains); i = rye productivity loss (%) per unit of competing plants when population approaches zero; and H = herbicide efficiency level (%).

Three values were estimated for variables Cc, R, P, and H (Equation 3) that occurred over the last 10 years. Thus, for control cost (Cc), the average price was used, with maximum and minimum costs changed by 25% from the average cost. Rye productivity (R) was based on the lowest, average and highest yields obtained in Brazil in the last 10 years. Product price (P) was estimated based on the lowest, average, and highest rye price per 60 kg bag in the last 10 years. Herbicide efficiency (H) values were set in the range of 80%, 90%, and 100% of control, with 80% being the minimum control considered effective for the weed (Velini et al. 1995). For the EDL simulations, intermediate values were used for variables that were not calculated. By default, the control cost, productivity, and price of the average product of the last decade were set at RS and the efficiency of the herbicide was set at 90%. R Core Team software (2022) was used for data analysis.

RESULTS AND DISCUSSION

The values of *F*-statistics were significant for the explanatory variables plant density (PD), leaf area (LA), soil cover (SC), and shoot dry matter (DM) for the rye genotypes BRS Serrano, IPR 89, BRS Progresso, and Crioulo (Table 2). The results show that all genotypes adequately fit the rectangular hyperbola model with reasonable R^2 values and low MSR. Cargnelutti Filho and Storck (2007), working with genetic variation, varietal influence and heritability of maize genotypes, classified R^2 values between 0.57 and 0.66 as moderate to good, which corroborates, which is partly consistent with the results of the present study. Galon et al. (2022) also observed R^2 values greater than 0.51 and low MSR values when testing different barley cultivars in competition with turnip, data similar to those of the present study.

Table 2. Adjustments obtained for productivity loss (Pl) as a function of relative variables plant density (plants m^{-2}), leaf area ($cm^2\ m^{-2}$), soil cover (%), and shoot dry matter (g m^{-2}) of turnip (*Raphanus sativus*) in competition with rye genotypes. UFFS, Erechim campus, RS, 2018.

Genotypes	Parameters		R^2	MSR	*F*
	i	*a*			
			Plant density		
BRS Serrano	2.52	60.25	0.52	70.77	167.48*
IPR 89	5.02	83.07	0.90	517.20	45.78*
BRS Progresso	3.25	94.16	0.89	37.96	563.15*
Crioulo	3.25	54.65	0.84	160.10	62.65*
			Leaf area		
BRS Serrano	0.007	57.63	0.56	74.23	159.44*
IPR 89	0.090	70.46	0.90	630.50	36.66*
BRS Progresso	0.006	76.88	0.51	159.90	129.84*
Crioulo	0.002	61.80	0.76	180.80	54.89*
			Soil cover		
BRS Serrano	0.17	60.03	0.61	74.04	159.85*
IPR 89	0.15	93.28	0.68	515.90	45.91*
BRS Progresso	0.15	89.52	0.83	64.46	329.53*
Crioulo	0.11	56.96	0.86	167.00	59.85*
			Shoot dry matter		
BRS Serrano	0.65	53.29	0.63	116.60	99.68*
IPR 89	0.76	81.55	0.93	288.40	86.08*
BRS Progresso	0.30	89.25	0.58	70.37	119.70*
Crioulo	0.09	86.27	0.88	86.86	119.70*

[1]*i* and *a*: productivity losses (%) per turnip unit when the value of the variable approaches zero or tends to infinity, determined according to the rectangular hyperbola model of Cousens (1985), Y= (*i**X)/[1+(*i*/*a*)*X], respectively. *Significant at $p \leq 0.05$. R^2: coefficient of determination. MSR: mean square of the residuals.

The parameter *i* is considered an index for comparing relative competitiveness between species, and the lower the values of this parameter, the more competitive the crop (Agostinetto et al. 2010; Brandler et al. 2021; Galon et al. 2022). When comparing the competitiveness of the studied genotypes, on average of all explanatory variables (PD, SC, LA, and DM), it was found that BRS Serrano and Crioulo had the lowest values of *i* and were the most competitive, followed by BRS Progresso (Table 1). The least competitive rye genotype in turnip infestation was IPR 89. Brandler et al. (2021), working with different canola hybrids (Hyola 433, Hyola 50, Hyola 76, Hyola 571 CL, Hyola 575 CL, and Diamond), and Galon et al. (2022), studying barley cultivars in competition with turnip also found differences in their competitive ability, taking into account the parameter *i*, leading to similar results as in the present work.

The occurrence of differences between rye genotypes in competition with turnips is probably due to the different genetic characteristics they have, i.e., differences in height, tillering rate, maturation cycle, leaf area index, root system, growth and development rate, among others, which makes them different in competition with weeds affecting them. Differences among cultivars in the presence of weeds have also been found in other studies, e.g., in barley, wheat, and canola when infested with ryegrass and turnip (Tironi et al. 2014; Blakely et al. 2017; Tavares et al. 2019; Brandler et al. 2021; Galon et al. 2022).

When comparing the rye genotypes, BRS Serrano, IPR 89, BRS Progresso, and Crioulo for the variable PD, based on unit loss (*i*), yield losses of 2.52%, 5.02%, 3.25%, and 3.25%, respectively, were observed (Table 2). This fact can be explained by the differences in genetic characteristics associated with the developmental cycle of each genotype, as previously described and also observed by other researchers working with the canola crop (Lemerle et al. 2017; Brandler et al., 2021). Competition from genetic material is becoming a potential strategy for integrated management of weeds in current control programs (Jha et al. 2017; Brandler et al. 2021), and thus there is an opportunity to reduce the use of herbicides, thereby reducing the cost of cultivation, environmental and human contamination, and even the production of healthier food.

The results show that when turnip occurred at the lowest infestation density (8 plants m^{-2}), there was an average loss of 20% in grain yield of rye genotypes (Table 2). Since high turnip densities are common in winter crops, it is important to control this species because of its competitive ability to infest rye. Brandler et al. (2021) observed yield losses of nearly 100% in canola hybrids when competing at a density of 400 turnip plants m^{-2}. Due to the fact that rye is a more rustic plant than canola, with greater height and therefore competes better for light resources, the present work observed an average grain loss of 68.84% for all genotypes tested when infested with 400 turnip plants m^{-2}. In addition, rye has allelopathic effects that suppress the development of other plants in its environment (Ferreira et al. 2017). Competition of canola or rye with turnip affects production quantitatively and

DOI: 10.26814/cps2023005 | 10 pages

qualitatively, as weeds alter the crop´s efficiency in using resources available in the environment, such as water, light, CO_2, and nutrients (Kaur et al. 2018; Lemerle et al. 2017).

A loss of 94.45% of grain yield of rye genotype IPR 89 was observed when comparing the average results of parameter *i* of this with the others for LA (Table 2). The genotypes BRS Serrano, BRS Progresso, and Crioula showed the lowest grain yield losses (0.007%, 0.006%, and 0.002%, respectively) compared to IPR 89 for LA. It can be inferred that the degree of competition of the weed against rye is influenced by LA, i.e., the more LA the weed has, the more competitive it is against the crop. As turnip density and LA increased, the weed´s competitive ability became greater than that of wheat (Tavares et al. 2019), canola (Brandler et al. 2021), and barley (Galon et al. 2022). Thus, the high competitiveness of turnips is evident in the infestation of winter-sown crops (wheat, canola, and barley).

The results for productivity losses of rye genotypes in relation to the percentage of SC show similarities with the results observed in relation to PD and LA. The average productivity loss was 78.41% when comparing SC with 10 versus 50% (Table 2). From this, it can be seen that the increase of SC by turnip leads to an increase in productivity loss in rye genotypes. Turnip stands out as a very competitive weed when it infests winter-sown agricultural crops in southern Brazil, as also observed by Tironi et al. (2014), Costa and Rizzardi (2015), Tavares et al. (2019) and Brandler et al. (2021).

Turnip co-evolved with rye and being a weed, i.e., more adapted and rustic, it showed greater growth, and consequently CS it caused a reduction in grain yield in the genotypes of the crop (Table 2). Turnip showed a high ability to compete with wheat (Lamego et al. 2013), in addition to high prolificity, seed dormancy, high biomass production, deep root system and resistance to acetolactate synthase (ALS) herbicides, which contributes to the reduction of crop production potential (Costa and Rizzardi 2015). Difficulty in control is also related to the use of turnip as a soil cover in no-tillage systems with straw or as winter forage for animal feeding, which increases the seed bank in the soil (Costa and Rizzardi 2015; Tavares et al. 2019).

Turnip caused a reduction in LA and DM production of various canola hybrids (Brandler et al. 2021), which consequently can affect crop productivity and quality. With the reduction of LA of soybean due to competition with weeds, there was also a reduction of DM (Caratti et al. 2016), which is probably due to the lower production of photoassimilates by the crop (Rodrigues et al. 2021).

Thus, the degree of competition among rye genotypes was found to be influenced by the LA of the weed, a fact also observed by Tavares et al. (2019) and Brandler et al. (2021) when evaluating the competitiveness of wheat and canola, respectively, in turnip infestations. According to Agostinetto et al. (2008), when turnip is attacked in wheat, the crop quickly closes the inter-rows and consequently becomes more competitive than the weed, with a higher leaf area index and shoot dry matter.

By accumulating 50 g m^{-2} DM, turnip caused a reduction in rye grain yield of 20.19%, 25.92%, 12.84%, and 4.28%, respectively, in BRS Serrano, IPR 89, BRS Progresso, and Crioulo genotypes, respectively (Table 2). Considering that turnip is one of the most important weeds in winter crops in southern Brazil and is difficult to control with herbicides because there are few approved products for rye (AGROFIT 2023) or because this weed has resistance to ALS (acetolactate synthase) inhibitor herbicides (Costa and Rizzardi 2015; Heap 2023), which are the most commonly used for chemical control of this species. Forte et al. (2018), evaluating the dry matter productivity of different winter cover crops in the Alto Uruguai region of Rio Grande do Sul, reported that turnip produced 5.0 t ha^{-1}, indicating the high competitiveness of this weed on the crop.

The results for productivity losses of rye genotypes, in relation to the percentage of SC and DM were similar to those observed in relation to PD (Table 2), with IPR 89 being the least competitive and having the highest productivity losses, which was also observed for PD, LA and SC. The increase of LA, SC, and DM in turnip is directly related to PD, thus explaining the similarity of productivity losses between the variables evaluated. Factors associated with this impairment of crops by weeds include competition for environmental factors such as water, light, and nutrients, or plant density, the timing of the emergence of these plants in a community, or even the management performed with the crops (Jha et al. 2017; Brandler et al. 2021; Galon et al. 2022; Smith and Burns 2022).

Because the parameter *i* is an index used to compare relative competitiveness among species (Agostinetto et al. 2010; Brandler et al. 2021), different values were observed for the rye genotypes BRS Serrano, IPR 89, BRS Progresso, and Crioulo for the explanatory variables tested (Table 2). The comparison between the genotypes considering the parameter *i* with the average of the four explanatory variables (PD, SC, LA, or DM) showed that the order of ranking in terms of competitiveness is the following: BRS Serrano > Crioulo > BRS Progresso > IPR 89. When evaluating wheat cultivars (Tavares et al. 2019), canola hybrids (Brandler et al. 2021), and barley (Galon et al. 2022) in competition with turnip, differences were observed between materials in the presence of weeds, which is similar to the results of the present study. The observed differences between the results related to cultivars or hybrids can be attributed to a series of morphophysiological characteristics associated with the differences between genotypes of the same species (Lemerle et al. 2017; Brandler et al. 2021), to the better use of resources available in the environment (light, water, and nutrients), and to some management practices (Agostinetto et al. 2010; Blakely et al. 2017; Kaur et al. 2018). It should also be noted that competition imposed by the type of genetic material is becoming a potential strategy for integrated management of weeds in current control programs (Blakely et al. 2017; Jha et al. 2017), reducing herbicide use, especially in turnips that already have resistance to ALS inhibitors (Heap 2023).

Tavares et al. (2019), Brandler et al. (2021), and Galon et al. (2022) when studying the effect of turnips on different wheat cultivars, canola hybrids, and barley cultivars considering the accumulation of DM, also found a different behavior and linked it to the intrinsic characteristics of the genotypes. Other authors also confirm that there are differences among cultivars in competition with weeds, attributing this fact to characteristics such as growth habit, development cycle, number of tillers/branches, root volume, and plant height, among others, which affect the crop's competitive ability and cause differentiation among cultivars involved in the competition (Blakely et al. 2017; Lemerle et al. 2017; Galon et al. 2022). According to the same authors, the plants that establish first in a given community are theoretically favored in the competitive process, or because they have different characteristics, such as greater height, leaf area index, higher green or dry matter production, more voluminous root system, etc., where a given cultivar or hybrid has greater competitive ability.

The estimates of parameter *a* were all below 100% regardless of the explanatory variable (Table 2), which shows that it was possible to adequately simulate the maximum losses in rye grain yield with the turnip densities used. It should also be noted that the greater the production potential of the crops and the better the soil fertility, water availability, and light conditions, the lower the daily percentage loss caused by a given weed species. (Agostinetto et al. 2010; Kaur et al. 2018).

The comparison between the explanatory variables for all rye genotypes evaluated showed a better model fit for the variables PD > DM > SC > LA, considering the highest mean values of R^2 and F and the lowest mean values of MSR (Table 2), indicating that PD can be used to estimate grain yield losses of rye. This fact was also observed by Tavares et al. (2019) when they evaluated the competition of turnip-infested wheat cultivars and found that the late cycle (BRS Umbu) increased the loss of grain yields using PD.

The high competition from turnip and the resulting yield losses in rye are partly due to the characteristics of the weed. This is because it has a large leaf area, size, length, and root volume, which contributes to the turnips superiority in competing with environmental resources (water, light, and nutrients). Turnip, even when present in low densities in crops, can cause severe losses to the crops it infests (Tavares et al. 2019; Brandler et al. 2021), a fact also observed by Tironi et al. (2014), when they found that this weed caused greater shading of barley compared to ryegrass, reducing the productivity and quality of the harvested product. Being more rustic, ryegrass grew more and covered more of the soil, causing barley cultivars to suffer lower grain productivity (Galon et al. 2022).

For the simulation of the economic damage level values (EDL), the explanatory variable plant density (SD) of turnip was used because it has a better fit to the rectangular hyperbolic model and because it is the most commonly used in experiments with this objective (Agostinetto et al. 2010; Tavares et al. 2019; Brandler et al. 2021). It should also be noted that this variable has some advantages over the others, such as ease, speed, accuracy, and low cost of determination (Brandler et al. 2021; Galon et al. 2022).

Success in implementing management systems for turnip in rye crops may result from determining the density that exceeds the EDL. The lowest EDL caused by turnip density for the four rye genotypes as a function of grain yield, control cost, rye price, and herbicide efficiency were observed at IPR 89 with an average value of 1.76 plants m^{-2} (Figure 2). Considering the same criteria, the EDL was obtained with 2.71, 2.71, and 3.50 turnip plants m^{-2} for Crioulo, BRS Progresso, and BRS Serrano genotypes, respectively. It was found that BRS Serrano, BRS Progresso and Crioulo genotypes had the highest EDL values in all the simulations performed, ranging from 2.03 to 4.36 plants m^{-2}. The lowest EDL values were obtained with the genotype IPR 89 with variations from 1.31 to 2.19 plants m^{-2}. The observed differences in EDL are due to the different genetic characteristics of the tested cultivars, as previously reported for wheat (Tavares et al. 2019), canola (Brandler et al. 2021), and barley (Galon et al. 2022) in turnip infestations.

Grain yield, control cost, price per bag of rye, and herbicide efficiency influenced turnip EDL on the crop. When rye genotypes reduced grain yield by 776 kg ha^{-1} (from 2264 to 1488 kg ha^{-1}), the turnip density required to achieve EDL increased by 52% for BRS Serrano, IPR 89, BRS Progresso, and Crioulo genotypes (Figure 2). Thus, it can be inferred that the expected increase in crop productivity may be less affected by weed competition, which was

DOI: 10.26814/cps2023005 | 10 pages

also reported by Tavares et al. (2019) when evaluating wheat cultivars in the presence of turnip. Increasing the cost of weed control by US$20.26 (from US$30.39 to US$50.65) increased the turnip density required to achieve EDL by more than 34% for all rye genotypes. Reducing the price of a bag of rye grain by US$ 2.42 (from 15.40 to US$ 12.99) required an increase in turnip density to achieve an EDL of 19.38% for the four rye genotypes. Tavares et al. (2019) also reported that reducing the amount paid per bag of wheat grain increased the turnip density required to achieve weed EDL for the BRS 177, BRS 328, and BRS Umbu cultivars, which is similar to the data in the present study.

When herbicide efficiency was reduced by 20%, i.e., from 100% to 80%, the turnip density required to achieve EDL increased by approximately 20% in rye cultivars BRS Serrano, IPR 89, BRS Progresso, and Crioulo (Figure 2). Similar to the present study, Tavares et al. (2019) also found a 20% increase in turnip density in wheat cultivars to achieve the EDL.

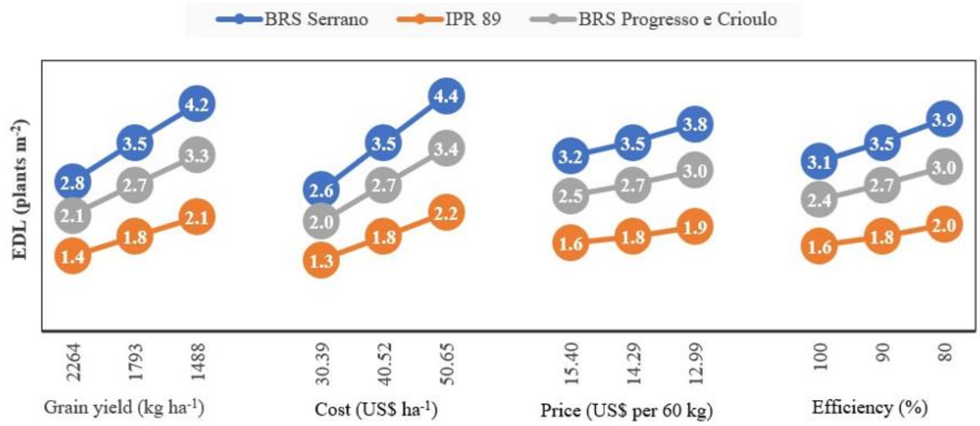

Figure 2. Economic damage level (EDL) as a function of grain yield, control cost, price paid per bag, herbicide efficiency, and rye genotypes.

Variations between the highest and lowest grain yield, control cost, bag price (60 kg), and herbicide efficiency affected the average of the four rye genotypes (BRS Serrano, IPR 89, BRS Progresso, and Crioulo) with variations of about 52, 67, 19, and 25%, respectively (Figure 2). Considering the average data of the variables grain productivity, control cost, price of the rye bag, and efficiency of the herbicide for the genotypes BRS Serrano, IPR 89, BRS Progresso, and Crioulo, the average variation of EDL was about 41%. These results are similar to those obtained by Tavares et al. (2019), Brander et al. (2021), and Galon et al. (2022) when working with turnip infested wheat, canola, and barley, respectively.

The rye genotypes BRS Serrano, BRS Progresso, and Crioulo showed the best results in the calculation of EDL considering grain yield, that is, they can coexist with a higher number of turnip plants than the IPR 89 (Figure 2). Thus, it was found that the greater the production potential of the crop, the lower the plant density required to exceed the EDL values. Similarly, Brandler et al. (2021) reported that the greater the production potential of the canola hybrids Hyola 50, Hyola 76, Hyola 433, Hyola 571 CL, Hyola 575 CL, and Diamond, the lower the EDL values for coexistence with turnip.

On average of all genotypes and comparing the lowest grain yield with the highest grain yield, a difference in EDL of about 34.27% was observed (Figure 2). Therefore, the higher the yield potential of rye genotypes, the lower the turnip plant density required to overcome the EDL, so the use of weed control measures is a compensation. Turnip EDL in canola (Brandler et al. 2021) and barley (Galon et al. 2022) increases when crop prices decrease, increasing control costs and the price of canola and barley, which reduces the impact of the cost of controlling this weed and allows for greater economic profitability of the crop.

Regarding the cost of turnip control for all genotypes, it was found that the minimum cost was about 41% lower compared to the maximum cost (Figure 2). Thus, the higher the cost of the control method, the higher the EDL and the more turnip plants m^{-2} are required to justify control measures. Brandler et al. (2021) also found differences of 40% when comparing the maximum and minimum costs for turnip infesting the canola hybrids Hyola 50, Hyola 76, Hyola 433, Hyola 571 CL, Hyola 575 CL, and Diamond, which are similar to the results of the present study.

The average result of the genotypes BRS Serrano, IPR 89, BRS Progresso, and Crioulo showed a variation of 1.19 times in the EDL value when comparing the highest with the lowest price paid per bag of rye (Figure 2). The lower the price paid per bag of rye, the higher the turnip density had to be to exceed the EDL value to compensate for the control method. When wheat (Tavares et al. 2019) and barley (Galon et al. 2022) cultivars and canola hybrids (Brandler et al. 2021) were evaluated in competition with turnip, similar variations to those reported

DOI: 10.26814/cps2023005 | 10 pages

in the present study were observed when comparing the highest with the lowest amount paid per bag of the crops tested.

Regarding the efficiency of the chemical control method with herbicides, it was found that the average efficiency (90%) compared to the lowest (80%) or highest (100%) had EDL changes of about 11.11 and 9.96%, respectively (Figure 2). The higher the herbicide efficiency, the lower the EDL (fewer turnip plants m^{-2} are required for control action). When comparing herbicide efficiency of 90% with 80% and 100% in canola hybrids (Brandler et al. 2021) and barley cultivars (Galon et al. 2022) under live conditions with turnips, differences of 11 and 10%, respectively, were found, consistent with the results of the present study.

EDLs varied according to rye genotypes with higher values for BRS Serrano > BRS Progresso = Crioulo > IPR 89 (Figure 2). In the study of turnip competition in wheat cultivars (Tavares et al. 2019), canola hybrids (Brandler et al. (2021), and barley cultivars (Galon et al. 2022), a different behavior was observed in EDL associated with intrinsic characteristics among genotypes in the presence of the weed, corroborating with the results of our study. This difference in competitive ability can also be attributed to allelopathic effects, species, density and distribution of plants in competition (Blakely et al. 2017; Tavares et al. 2019; Sun et al. 2021).

The use of EDL as a weed control tool must be accompanied by good agricultural practices in rye cultivation, as its application is only justified in crops that have crop rotation, appropriate plant arrangement, use of more competitive cultivars, appropriate sowing times, and soil fertility correction, among others.

In conclusion, the rectangular hyperbola model adequately estimated rye grain yield losses in the presence of turnips. The plant density variable showed the best fit to the rectangular hyperbola model and adequately estimated rye grain yield losses due to turnip interference. Rye genotypes BRS Serrano, BRS Progresso, and Crioulo were the most competitive, and IPR 89 was the least competitive in the presence of turnip. The highest values of economic damage were observed in the BRS Serrano, BRS Progresso, and Crioulo genotypes, ranging from 2.03 to 4.36 turnip plants m^{-2}. The genotype IPR 89 had the lowest economic damage levels, ranging from 1.31 to 2.19 turnip plants m^{-2}. Economic damage level decreases with the increase in grain yield, the price of a bag of rye, the effectiveness of the herbicide, and the reduction in the cost of turnip control, justifying the use of control measures at lower weed densities.

Acknowledgments

The authors thank the CNPq, FAPERGS, UFFS, and FINEP for the financial support of research and scholarships.

Funding

This research was financially supported by the National Council for Scientific and Technological Development (CNPq), Research Support Foundation of Rio Grande do Sul (FAPERGS) and the Federal University of Fronteira Sul (UFFS).

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