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Competitive response and level of economic damage of quinoa in the presence of alexandergrass

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ABSTRACT: The study of interference and the economic damage level (EDL) of weeds in crops allows more rational management measures to be adopted. Given this, it was the aim of this study to determine the competitive ability and EDL of quinoa genotypes in the presence of alexandergrass. Treatments consisted of three quinoa genotypes (Q 1303, Q 1331, and Q 1324), which competed with 12 alexandergrass densities: 0, 16, 36, 40, 44, 52, 60, 84, 280, 532, and 1,036; 0, 8, 28, 32, 48, 52, 60, 72, 84, 820, and 988; and, 0, 8, 36, 44, 48, 60, 68, 80, 84, 120, 756, and 848 plants m^{-2}, respectively. Alexandergrass plants were evaluated for plant density (PD), ground cover (GC), leaf area (LA), and aerial dry mass (ADM). In quinoa, grain yield, control cost, selling price, and control efficiency were determined. The quinoa genotype Q 1331 shows greater competitive ability when compared to Q 1303 and Q 1324. EDL values varied from 1.81 to 11.74 plants m^{-2} for genotype Q 1331, which was more competitive in the presence of alexandergrass. The lowest EDL values ranged from 1.21 to 8.12 plants m^{-2}, for the genotypes Q 1303 and Q 1324, which have the lowest competitiveness with the competitor.

Key words: *Chenopodium quinoa*; plant interference; *Urochloa plantaginea*

Resposta competitiva e nível de dano econômico de quinoa na presença de papuã

RESUMO: O estudo da interferência e do nível de dano econômico (NDE) de plantas daninhas em culturas permite adotar medidas de manejo mais racional. Diante disso, objetivou-se com este estudo determinar a habilidade competitiva e o NDE de genótipos de quinoa na presença de papuã. Os tratamentos foram compostos por três genótipos de quinoa (Q 1303, Q 1331 e Q 1324), os quais competiram com 12 densidades de papuã: 0, 16, 36, 40, 40, 44, 52, 60, 84, 280, 532 e 1036; 0, 8, 28, 32, 32, 48, 52, 60, 72, 84, 820 e 988; e 0, 8, 36, 44, 48, 60, 68, 80, 84, 120, 756 e 848 plantas m^{-2}, respectivamente. Nas plantas de papuã foram avaliadas a densidade de plantas (DP), cobertura do solo (CS), área foliar (AF) e massa seca da parte aérea (MS). Na quinoa determinou-se a produtividade de grãos, custo de controle, preço de venda e eficiência de controle. O genótipo de quinoa Q 1331 apresenta maior habilidade competitiva ao ser comparado com o Q 1303 e Q 1324. Os valores de NDE variam de 1,81 a 11,74 plantas m^{-2} para o genótipo Q 1331, sendo esse mais competitivo na presença do papuã. Os menores valores de NDE variam de 1,21 a 8,12 plantas m^{-2}, para os genótipos Q 1303 e Q 1324, os quais apresentam as menores competitividades com o competidor.

Palavras-chave: *Chenopodium quinoa*; interferência de plantas; *Urochloa plantaginea*

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Introduction

Quinoa (*Chenopodium quinoa* Willd), native to the family Chenopodiaceae, subfamily Chenopodioideae, originates from the Andes, cultivated for thousands of years in several Latin American countries (Tovar-Hernández et al., 2017; Minh & Nguyen, 2021). It is an annual plant, with a cycle of 80 to 150 days, presenting grains with high nutritional values, due to the high content and quality of proteins, essential amino acids, carbohydrates, lipids, vitamins, and minerals (Gewehr et al., 2012; Maradini Filho et al., 2017; Velásquez-Barreto et al., 2020). Studies report that the protein content present in quinoa is between 10 and 20%, being very similar to that found in wheat (Nowak et al., 2016; Maradini Filho et al., 2017; Qin et al., 2018).

Quinoa grains have quality protein, which meets basic essential amino acid requirements in protein balancing of food and animal feed (Spehar et al., 2011; Maradini Filho et al., 2017). In addition, quinoa meets the growing demand for balanced and functional foods, related to the search for dietary alternatives, such as gluten-free (Spehar et al., 2011). With these properties, quinoa has been in demand worldwide, which has led to the expansion of its cultivation, including as an alternative to commercial crops (Spehar et al., 2011; Maradini Filho et al., 2017).

Quinoa can play an important role in soil protection when employed as a cover crop due to its high biomass production (Spehar et al., 2011; Garcia-Parra et al., 2020). It is used as a succession plant, favoring the sustainable establishment of agriculture, especially for family farming or the smallholding in the diversification of production (Spehar et al., 2011). It is also noteworthy that quinoa shows great adaptability to adverse soil and climate conditions, such as temperature, salt and water stress (Garcia-Parra et al., 2020). Depending on the genotype it can be grown in summer and/or winter, in addition to having natural resistance to insects and diseases (Spehar et al., 2011).

Thus, from the 1990s, after showing significant results in the Brazilian cerrado (Spehar et al., 2011), quinoa aroused interest in producers and technicians in the production sector, and is already being expanded discretely to other regions of Brazil. Because quinoa is not yet a widespread crop in Brazil, studies to assist in the management of this crop with weeds are important, to clarify information related to the installation, conduction, development, and management methods, especially in the Alto Uruguai Gaúcho region, where the crop is little known and there is a need to search for new alternatives or diversification of rural property.

Poorly managed weeds can compromise grain yields or quality of the harvested product by competing for environmental resources, being hosts to diseases and insects, and releasing allelopathic substances that negatively interfere with crops (Kalsing & Vidal, 2013; Jha et al., 2017; Holkem et al., 2022). In the northern crops of Rio Grande do Sul state, the alexandergrass (*Urochloa plantaginea*) has a wide distribution and is at high levels of infestation, because it is a species adapted to the cropping systems that have been adopted in recent years, i.e., mainly due to the monoculture of soybeans and corn (Santi et al., 2014). Thus, the producer who cultivates quinoa as a way to diversify his property needs to adopt ways to manage weeds so that the negative effects of living with the crop are minimized or even avoided.

Besides the high levels of alexandergrass infestation in crops, this species has a great capacity for shading, already in the early stages of cultivation, and for this reason, in many cases, aggravates the damage to neighboring species by negatively influencing plant development. Another factor that contributes to the prominence of the alexandergrass when coexisting with the culture of quinoa in crops is the low capacity of competition that it presents until establishment, around the first 30 days (Spehar et al., 2011), a fact also seen in this study.

Thus, studies that seek to determine responses to the coexistence of quinoa genotypes in relation to weeds, especially alexandergrass, are important so that efficient, sustainable and alternative management to chemical control can be adopted, through the use of cultural methods or control based on the concept of economic damage level (EDL). This concept states that the application of herbicides, or other control methods, is only justified when the damage caused by the weeds becomes greater than the cost of the control measure used (Kalsing & Vidal, 2013; Tavares et al., 2019).

When they appear in high densities in the midst of the crops, it makes it easier for growers to decide whether to control weeds. However, when weeds appear at low densities, adopting measures to control them becomes difficult because of the need to quantify the economic advantages associated with the cost of control (Kalsing & Vidal, 2013; Tavares et al., 2019).

In crops, the density of cultivated plants is usually constant, while weed densities vary according to the soil seed bank, environmental and soil conditions, and the management and cultural treatments adopted that alter the level of infestation (Kalsing & Vidal, 2013; Jha et al., 2017). Knowing the capacity of weeds to interfere with the crop you are interested in is extremely important when deciding which method of control to adopt. With this information, knowing the price of the harvested product, the cost of control, and the estimated productivity of the crop, it will be possible to determine the economic damage level of weeds, that is, the density of these whose interference on the crop will exceed the cost of control (Agostinetto et al., 2010; Kalsing & Vidal, 2013; Brandler et al., 2021).

Mathematical models have been used to estimate crop yield losses due to the presence of weeds (Agostinetto et al., 2010; Kalsing & Vidal, 2013; Brandler et al., 2021). The hyperbolic relationship between grain yield and weed density was first described by Cousens (1985). This author adjusted an empirical model (rectangular hyperbola model) to predict yield loss as a function of weed density, obtaining results that demonstrated the superiority of this model over others.

The rectangular hyperbola model is based on the non-linear relationship between the percentage yield loss from interference, relative to the infestation-free control, and weed density (Cousens, 1985). It incorporates the parameters “i”, which represents the yield loss caused by the addition of the first weed, and the parameter “a”, which shows the yield loss when the weed density tends to infinity. The biological significance of the model shows that the competition effect of each weed added to the crop decreases when weed density increases, as a result of intraspecific competition (Agostinetto et al., 2010; Tavares et al., 2019; Brandler et al., 2021).

The hypothesis of the study is that differentiation in competitive ability and economic damage level occurs according to the sowing of different quinoa genotypes coexisting with different densities of alexandergrass. With this, the objective of this study was to determine the competitive ability and EDL of quinoa genotypes in the presence of alexandergrass.

Materials and Methods

The experiment was conducted in the field, in the experimental area of the Universidade Federal da Fronteira Sul (UFFS), Campus Erechim/RS, Brazil, in the 2018/19 agricultural year. The pH correction and soil fertilization were performed according to the physical-chemical analysis and following the technical recommendations for the culture of quinoa, proposed by Spehar et al. (2011), with modifications to adapt to the soil conditions of the cultivation region of Erechim/RS, Brazil. The chemical and physical characteristics of the soil were: pH in water of 4.8; OM = 3.5%; P = 4.0 mg dm^{-3}; K = 117.0 mg dm^{-3}; Al^{3+} = 0.6 $cmol_c$ dm^{-3}; Ca^{2+} = 4.7 $cmol_c$ dm^{-3}; Mg^{2+} = 1.8 $cmol_c$ dm^{-3}; CEC(t) = 7.4 $cmol_c$ dm^{-3}; CEC(TpH=7.0) = 16.5 $cmol_c$ dm^{-3}; H + Al = 9.7 $cmol_c$ dm^{-3}; SB = 6.8 $cmol_c$ dm^{-3}; V = 41%; and, Clay = 60%.

According to Köppen classification, the region climate is classified as fundamental type C, subtype fa, characterized as humid subtropical, with no defined dry season, with the temperature of the hottest month exceeding 22.0 °C, an average annual temperature of 18.2 °C, and average annual rainfall of 1,869 mm (CEMETRS, 2012). The site is located in the Alto Uruguay physiographic region, Rio Grande do Sul, Brazil, at the geographical coordinates 27° 43’ 47” S latitude, 52° 17’ 37” W longitude, and altitude of 760 m.

The experimental design used was a randomized block design, arranged in a 3 × 12 factorial scheme, with one repetition. Treatments were composed of three quinoa genotypes (Q1303, Q1324, and Q1331) and 12 alexandergrass densities (0, 16, 36, 40, 44, 52, 60, 84, 280, 532, and 1,036; 0, 8, 28, 32, 32, 48, 52, 60, 72, 84, 820, and 988; and, 0, 8, 36, 44, 48, 60, 68, 80, 84, 120, 756, and 848 plants m^{-2}) in competition with the respective quinoa genotypes. Because the alexandergrass comes from the soil seed bank, the establishment of densities was varied, because factors such as infestation, vigor, humidity, among others, prevent the establishment of exactly the same number of plants per area (experimental unit). Each experimental unit was composed of an area of 15.0 m^2 (3.0 × 5.0 m), and sowing was performed in 6 lines, 5 m-long and spaced at 0.50 m, on 12/18/2018. The sowing density of the quinoa genotypes was 50 seeds m^{-2} or approximately 500,000 seeds ha^{-1}. At 30 days after the emergence of quinoa, nitrogen was applied in the form of urea, at a dose of 100.0 kg ha^{-1}, for an expected yield of at least 2.0 t ha^{-1} (Spehar et al., 2011).

Quantification of plant density (PD), leaf area (LA), ground cover (GC) or aerial dry mass (ADM) of alexandergrass were performed at 50 days after emergence (DAE) of the crop. To determine the PD variable, the plants present in two 0.25 m^2 (0.5 × 0.5 m) areas per plot were counted. GC by alexandergrass plants was assessed visually using a percentage scale, in which a score of zero corresponds to no GC and a score of 100 represents total soil coverage. The quantification of the LA of the competing plant was done with a portable electronic LA integrator, model CI-203, measuring all plants in an area of 0.25 m^2 per plot. After measuring the LA, the plants were packed in paper bags and placed in a forced air circulation oven at a temperature of 60.0 ± 5.0 °C to determine the ADM of the alexandergrass (g m^{-2}) until it reached a constant weight (Konzen et al., 2021).

The quantification of quinoa grain yield was obtained by manually harvesting the plants in a 6.0 m^2 useful area of each experimental unit, when the water content of the grains reached approximately 15%. After weighing the grains, the water content was determined, and then the masses were standardized to 13% moisture. With the grain yield data, the percentage losses in relation to the plots kept without infestation (controls) were calculated, according to Equation 1.

$$\text{Loss}(\%) = \left(\frac{\text{Ra} - \text{Rb}}{\text{Ra}}\right) \times 100 \tag{1}$$

where: Ra and Rb - crop yields without or with the presence of the competing alexandergrass plant, respectively.

Previously to the data analysis, the values of GC (%), LA (cm^2), or ADM (g m^{-2}) were multiplied by 100, thus dispensing with the use of the correction factor in the model (Agostinetto et al., 2010).

The relationships between percent yield losses of cultivated quinoa as a function of the explanatory variables were calculated separately for each crop genotype, using the nonlinear regression model derived from the rectangular hyperbola proposed by Cousens (1985), according to Equation 2.

$$\text{Pl} = \frac{(\text{i} \cdot \text{X})}{\left[1 + \left(\frac{\text{i}}{\text{a}}\right) \cdot \text{X}\right]} \tag{2}$$

where: Pl - productivity loss (%); X - plant density (PD), aerial dry mass (ADM), ground cover (GS), or leaf area (LA) of alexandergrass; and, i and a - yield losses (%) per unit of alexandergrass plants when the value of the variable approaches zero or when it tends to infinity, respectively.

For the calculation procedure, the Gauss-Newton method was used, which, by successive iterations, estimates parameter values at which the sum of squares of the deviations of the observations from the fitted values is minimal (Agostinetto et al., 2010). The value of the F-statistic ($p < 0.05$) was used as the criterion for fitting the data to the model. The criterion for accepting the fit of 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 residual (MSR).

To calculate the economic damage level (EDL) we used the parameter i estimates obtained from Equation 2 (Cousens, 1985), and the equation adapted from Lindquist & Kropff (1996), as presented in Equation 3.

$$\text{EDL} = \frac{\text{Cc}}{\left[\text{R} \cdot \text{P} \cdot \left(\frac{\text{i}}{100}\right) \cdot \left(\frac{\text{H}}{100}\right)\right]} \quad (3)$$

where: EDL - economic damage level (plants m^{-2}); Cc - cost of control (weeding with a hoe, in dollars ha^{-1}); R - quinoa grain yield (kg ha^{-1}); P - price of quinoa (US\$60 kg^{-1} of grain); i - loss (%) of quinoa yield per unit of competing plant when the population level approaches zero; and, H - weeding efficiency level (%).

For the variables Cc, R, P, and H (Equation 3) three values occurring in the last 10 years were estimated. Thus, for the cost of control (Cc), the average price of US\$180.29 was considered (number of days it takes a man to weed one ha × the number of hours worked per day × the value in Reais per hour worked), so we have: 5 days × 8 h day^{-1} × R\$18.75 = R\$750.00 ha^{-1}, which equals to US\$180.29. Based on this average cost, the maximum and minimum cost was estimated by adding or subtracting 25%, respectively. Quinoa productivity (R) was referenced to the lowest, average and highest obtained in Peru (USDA, 2022) and Brazil (Spehar et al., 2011). The price of quinoa (P) was estimated from the lowest, average and highest value paid per 60 kg bag (CEPEA, 2022). The values for weeding efficiency (H) were set in the order of 80, 90, and 100% control, with 80% being the minimum control considered effective.

Results and Discussion

The F-statistic values were significant for the explanatory variables: PD, GC, LA, and ADM for all quinoa genotypes (Figures 1 and 2). It was observed that all quinoa genotypes fitted the rectangular hyperbola model adequately, with R^2 values greater than 0.62 and low MSR. According to Cargnelutti Filho & Storck (2007), when working with genetic variation, the effect of cultivars and the heritability of corn hybrids, they considered as moderate to good the R^2 values between 0.57 and 0.66, which corroborates in part with the results found in the present study.

It was found for all variables evaluated, that the estimated values of the i parameter tended to be higher in the quinoa genotypes Q 1303 and Q 1324 (Figures 1 and 2). The highest competitiveness was seen with genotype Q 1331 for PD, GC, LA, and ADM. Several studies have reported differences in the competitive ability of crop cultivars when in the presence of weeds, a fact attributed to the set of morphophysiological characteristics inherent to them (Kalsing & Vidal, 2013; Galon et al., 2019; Tavares et al., 2019; Brandler et al., 2021).

According to Laub et al. (2022) when the crop has low ground cover it allows greater light penetration into the community canopy and, consequently, less competitiveness it will have in the presence of weeds. Spehar et al. (2011) when evaluating some quinoa cultivars (BRS Syetetuba, BRS Piabiru, and Kancolla) found that these showed great genetic variability and differentiation in relation to responses to abiotic or biotic stress effects, which reflected directly in the expression of the grain yield of each genotype.

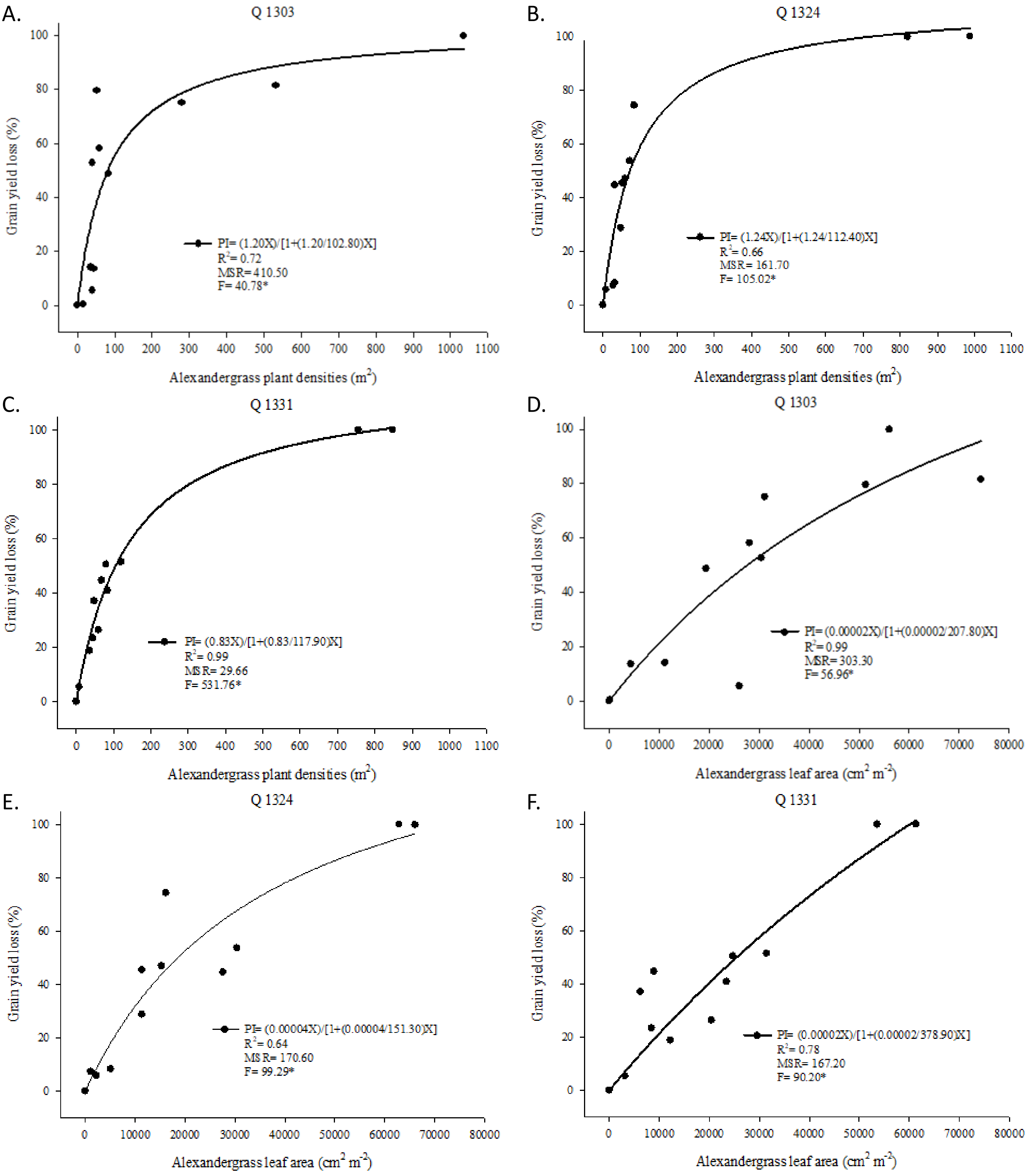
The results showed average quinoa grain yield losses of 55.37, 58.96, and 48.71% for the genotypes Q 1303, Q 1324, and Q 1331, respectively, in the presence of 100 alexandergrass plants m^{-2} (Figure 1A, B, and C). When tripling the density of alexandergrass plants (300 plants m^{-2}) there was an increase in yield losses, reaching 79.97, 86.32, and 80.0% for the respective genotypes, Q 1303, Q 1324, and Q 1331.

Since the determination of quinoa plant density occurred at 50 after crop emergence, the crop-infesting alexandergrass early in growth and development caused high yield losses and tended to dominate the environment with higher tiller production, stature, leaf area index, and, consequently, higher shading.

According to Spehar et al. (2011) quinoa grown in tillage presents low capacity for competition until its establishment, especially in the first 50 days, because the crop presents slow growth and development, thus needing to be free of weed infestation to avoid productivity losses. When a crop is shaded there is high competition for the light resource, which will make it less efficient in seeking solar radiation and consequently develop and grow less than normal (Laub et al., 2022).

Quinoa grain yield loss of more than 20% occurred in all genotypes evaluated for the lowest LA (10,000 cm^2 m^{-2}). Q 1331 had the lowest and Q 1324 the highest loss when compared to Q 1303. When the quinoa was analyzed in relation to the greatest LA (60,000 cm^2 m^{-2}) it was found that the three genotypes showed losses greater than 85% (Figure 1D, E, and F). It can thus be inferred that the degree of competition of the genotypes is influenced by the LA of alexandergrass, as also found by Galon et al. (2022) when evaluating the competition of bean cultivars in the presence of this same weed.

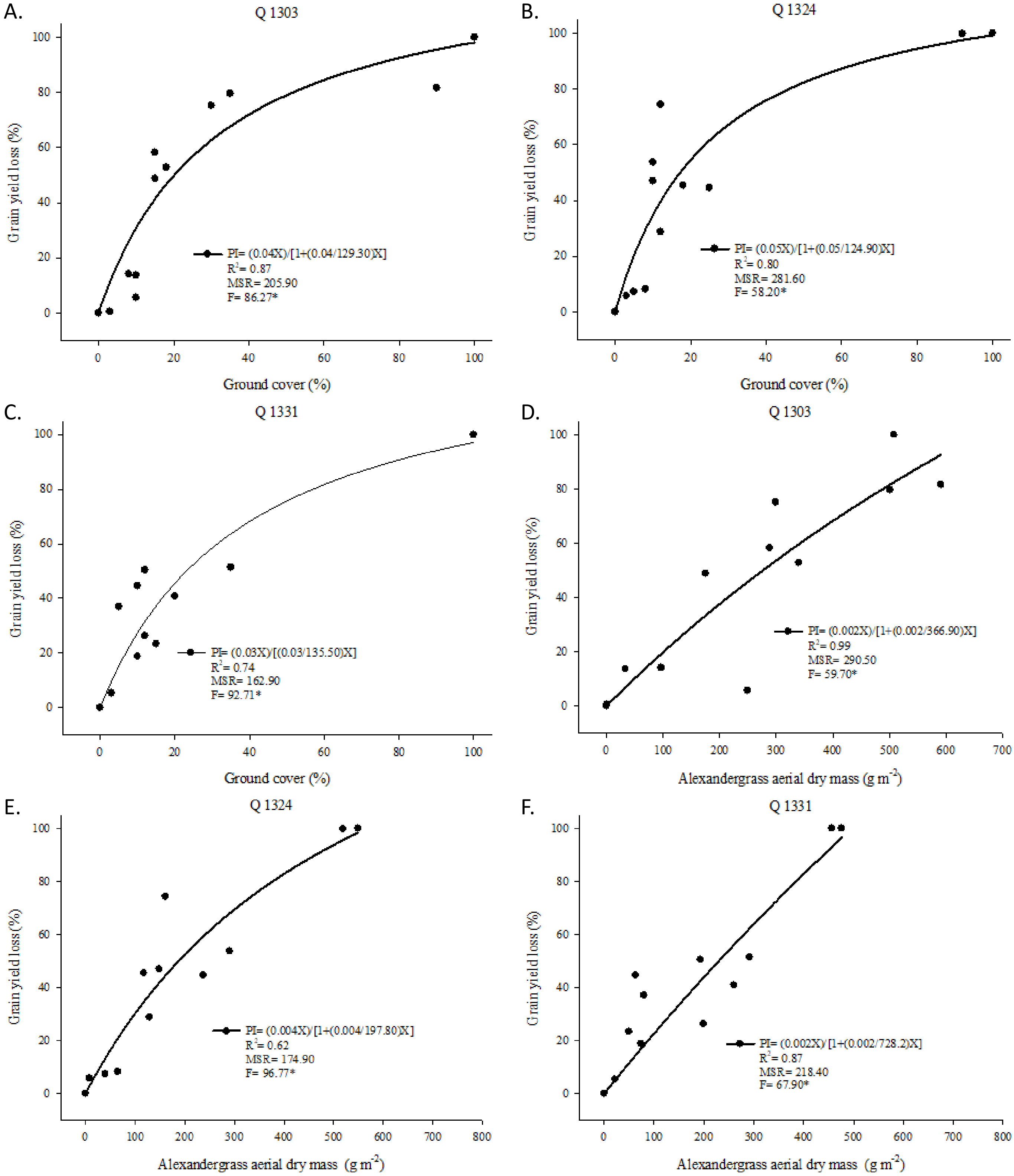
The results regarding the yield loss of the quinoa genotypes, in relation to the percentage of GC (Figure 2A, B, and C), show similarity to that observed in relation to PD (Figure 1A, B, and C), and LA (Figure 1D, E, and F). With increasing percentage of GC by the alexandergrass the greater was the yield loss of quinoa. It can be seen that all quinoa genotypes showed significant yield reductions (more than 40%) when the soil was only 20% alexandergrass cover.



R^2 - Coefficient of determination; MSR - Mean squared residual; * Significant at $p \leq 0.05$.

Figure 1. Yield loss (YL) of quinoa (*Chenopodium quinoa*) as a function of crop genotypes, plant density (A, B, and C), and leaf area (D, E, and F) of alexandergrass (*Urochloa plantaginea*) at 50 days after emergence. UFFS, Erechim/RS, Brazil, 2018/19 crop year.

As the percentage of GC increased, the greater the grain yield losses caused by alexandergrass to quinoa, reaching near maximum losses (more than 90%) when 80% GC by the weed occurred (Figure 2A, B, and C). This fact is in line with what was explained for the PD and LA, where those who present higher rates win in competition, mainly for the light resource, with their neighbors and, consequently, greater growth and development will show, as previously discussed, which interferes negatively in the grain yield of the crop. Among the factors that are tied to this interference imposed by weeds are



R^2 - Coefficient of determination; MSR - Mean squared residual; * Significant at $p \leq 0.05$.

Figure 2. Yield loss (YL) of quinoa (*Chenopodium quinoa*) as a function of crop genotypes, ground cover (A, B, and C), and aerial dry mass (D, E, and F) of alexandergrass (*Urochloa plantaginea*) plants at 50 days after emergence. UFFS, Erechim/RS, Brazil, 2018/19 crop year.

mainly competition for light and nutrients (Jha et al., 2017; Laub et al., 2022).

When accumulating 500 g m^{-2} of aerial dry mass the alexandergrass caused reductions in quinoa yields of 99, 97, and 99%, respectively, for the genotypes Q 1303, Q 1324, and Q 1303 (Figure 2D, E, and F). This result corroborates those found for PD and LA (Figure 1) and GC (Figure 2) where increasing the value of the variables caused high losses to quinoa grain yields. Such results may be related to the high competitive ability of papaya plants, especially for its C4-type carbon metabolism, thus demonstrating high efficiency in exploiting the resources of the environment (Brutnel et al., 2010; Kalsing & Vidal, 2013; Galon et al., 2019), while quinoa presents C3-type metabolism (Geissler et al., 2015), which results in lower competitive ability in coexistence with weeds. When alexandergrass competed with corn (Galon et al., 2019), soybean (Santi et al., 2014), and bean (Kalsing & Vidal, 2013) the weed caused high losses in the growth and development of these crops, which corroborates the results found in the present study.

Since the parameter i is an index used to compare the relative competitiveness between species (Swinton et al., 1994), differentiated values were observed for the quinoa genotypes in the explanatory variables tested (Figures 1 and 2). Research with similar objectives as the current study has also used the i parameter for comparing competitiveness among canola cultivars (Brandler et al., 2021), bean cultivars (Kalsing & Vidal, 2013), corn hybrids (Galon et al., 2019), and wheat cultivars (Tavares et al., 2019).

The comparison between the quinoa genotypes considering the parameter i, on the average of the four explanatory variables (PD, GC, LA, or ADM), showed that the order of placement, in general, in relation to competitiveness was: Q 1331 > Q 1303 > Q 1324 (Figures 1 and 2). The differences observed between the results of the genotypes are largely due to their genetic characteristics, such as issues related to plant stature, rapid emergence, leaf area index, plant architecture, development speed, higher biomass accumulation, root volume among others, or even the occurrence of high standard error in the estimation of the parameter i, which can be attributed to variability associated with field experimentation and/or phenotypic plasticity of the crop (Agostinetto et al., 2010). Corroborates the present result, those observed by other researchers when they verified that bean cultivars (Kalsing & Vidal, 2013) and corn hybrids (Galon et al., 2019) responded differently as to the i parameter when compared by different densities of alexandergrass.

The estimates of the parameter a, independent of the explanatory variable, were overestimated by the model, with yield losses exceeding 100% for all genotypes tested (Figures 1 and 2). These results may stem from the fact that the higher densities of alexandergrass plants were not sufficient to adequately estimate the maximum yield loss of quinoa (Cousens, 1991). According to Cousens (1991), obtaining reliable estimates of this parameter requires the inclusion of very high weed densities, above those commonly found under tillage conditions. Similarly, when studying rice competition with ricegrass (Agostinetto et al., 2010) and canola versus turnip (Brandler et al., 2021), subjected to different management methods, they also found losses greater than 100% for parameter a, which is partly similar to the results observed in the present study.

An alternative to prevent yield losses from being overestimated would be to limit the maximum loss to 100%. However, the limitation will influence the estimation of parameter i, and may result in less predictability in the rectangular hyperbola model. Furthermore, yield losses greater than 100% are biologically unrealistic and occur when the range of weed density is excessively narrow and/or when the highest values of densities are not sufficient to produce asymptotic yield loss response (Agostinetto et al., 2010).

The quinoa genotypes had the same growth cycle, however they showed different responses to the explanatory variables with distinct parameters i (Figures 1 and 2). Studies have found that bean cultivars (Kalsing & Vidal, 2013) and corn hybrids (Galon et al., 2019) of the same cycle showed differentiated competitiveness in the presence of alexandergrass, being expressed by the parameter i. The authors attribute these responses, among other factors, to the differences in productivity that the cultivars presented, which caused less yield loss per weed individual, which corroborates the result found in the present study where the genotype Q 1303 showed the lowest yield loss in the average of 12 densities of alexandergrass in competition. However, Q 1303 showed the lowest grain yield (2.3 t ha^{-1}) when compared to Q 1324 and Q 1331 with yields of 2.4 and 2.7 t ha^{-1}, respectively.

The comparison between the explanatory variables for all quinoa genotypes, in general, showed a better fit to the model for the variables PD > LA > GC > ADM, considering the highest mean values of R^2 and F, and the lowest mean values of MSR (Figures 1 and 2), thus evidencing that the PD is the variable that can be used for simulation of the EDL.

The simulation of EDL values was performed using the explanatory variable PD of alexandergrass by the best fit to the rectangular hyperbola model, due to the fact that it is the most used in experiments with this objective, presents ease of determination and low cost (Kalsing & Vidal, 2013; Galon et al., 2019; Tavares et al., 2019).

Successful implementation of management systems for alexandergrass weeds in the quinoa crop may stem from the determination at density that exceeds the EDL. Thus, it was observed that the genotype Q 1331 presented the highest EDL values in all simulations performed, with variations from 1.81 to 11.74 plants m^{-2} (Figure 3). The lowest EDL values were obtained with cultivars Q 1303 and Q 1324, with ranges from 1.21 to 8.12 plants m^{-2} (Figure 3). Several studies have also found differences in EDL according to the cultivar evaluated, such as those conducted by Kalsing & Vidal (2013) when working with bean cultivars infested by alexandergrass, corn hybrids versus alexandergrass (Galon et al., 2019), and Tavares et al. (2019) when studying wheat cultivars in the presence of turnip.

The results that caused the genotypes Q 1303 and Q 1324 to show lower EDL may have been due to the lower leaf area index, the emergence of few lateral branches, which are short, besides the lower plant stature and slow initial growth, observed in the present study and also in the research of Spehar et al. (2011), which allowed more light to enter the soil and greater growth of alexandergrass. As alexandergrass is characterized by having a C4 metabolism (Brutnel et al.,

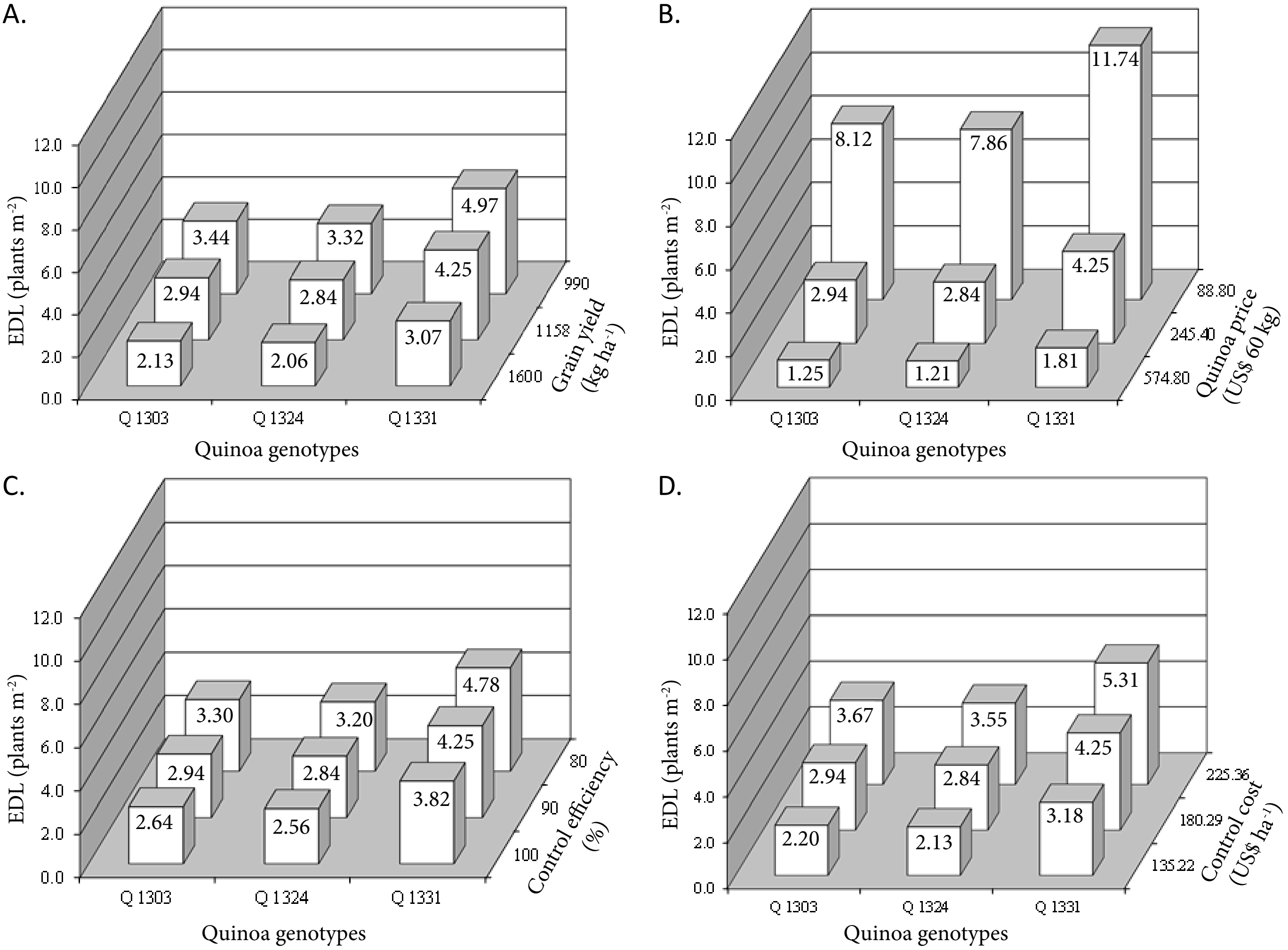


Figure 3. Economic damage level (EDL) as a function of grain yield (A), quinoa price (B), control efficiency (C), and control cost (D) and of alexandergrass densities and quinoa genotypes. UFFS, Erechim/RS, Brazil, 2018/19 crop year.

2010), which under high temperature and light conditions shows rapid initial growth, it can cause the shading of annual crops that have a slower initial growth rate (Laub et al., 2022).

On average across all quinoa genotypes, and comparing the lowest to the highest grain yield, a difference in EDL on the order of 61.89% was observed (Figure 3A). Therefore, the higher the productive potential of the genotypes, the lower the density of alexandergrass plants needed to overcome the EDL, making the adoption of weed control measures compensatory. When evaluating the EDL of alexandergrass it was observed that it varied depending on the bean cultivar (Kalsing & Vidal, 2013) or the corn hybrid (Galon et al., 2019), and that cultivars that showed higher yield potential showed less ability to tolerate competition with lower values for EDLs.

The average results for all genotypes, from the highest versus the lowest price paid per bag of quinoa, showed a 6.5-fold variation in the EDL value (Figure 3B). Therefore, the lower the price paid to a bag of quinoa, the higher the density of alexandergrass required to exceed the EDL and thus compensate for the control method. Tavares et al. (2019) and Galon et al. (2019) also found similar results regarding the price paid a bag of wheat and corn, respectively.

Regarding the efficiency of mechanical control using a hoe, it was observed that the average efficiency (90%) compared to the lowest (80%) or the highest (100%), there are EDL changes of 12.57 and 10.18%, respectively (Figure 3C). Thus, the level of control influenced the EDL, and the higher the weeding efficiency, the lower the EDL (lower number of alexandergrass plants m^{-2} required for control measures), a fact also found by Galon et al. (2019) and Tavares et al. (2019) and when applying herbicides for alexandergrass and turnip control, respectively.

Regarding the average cost of alexandergrass control in all genotypes, it was found that it was 40.05% lower the minimum cost when comparing with the maximum cost. Thus, the higher the cost of the control method, the higher the EDL and the more alexandergrass plants m^{-2} are needed to justify control measures (Figure 3D). The use of EDL as a weed management tool must be associated with good agricultural management practices for quinoa, since its implementation is only justified in crops that use crop rotation, adequate plant arrangement, use of more competitive cultivars, adequate sowing times, soil fertility correction, among others.

Conclusions

Plant density showed a better fit to the rectangular hyperbola model than did ground cover, leaf area, and aerial dry mass.

The quinoa genotype Q 1331 shows greater competitive ability with alexandergrass than Q 1303 and Q 1324.

The EDL values ranged from 1.81 to 11.74 plants m^{-2} for genotype Q 1331, which is more competitive with alexandergrass.

The lowest EDL values ranged from 1.21 to 8.12 plants m^{-2}, for the genotypes Q 1303 and Q 1324, showing the lowest competitiveness with the competitor.

The EDLs decreased with the increase in grain yield, quinoa bag price, weeding efficiency, and the reduction in the cost of alexandergrass control, justifying the adoption of control measures at lower weed populations.

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Compliance with Ethical Standards

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