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INTERFERENCE AND THRESHOLD LEVEL OF *Sida rhombifolia* ON *Chenopodium quinoa* Willd. CROP

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ABSTRACT

Studies on interference and economic threshold level (TL) of weeds on quinoa are scarce. Thus, the goal of this study was to determine the interference and TL of *Sida rhombifolia* (arrowleaf sida) on quinoa varieties. The experiment was organized using a completely randomized design, with four replicates. The treatments were composed of three quinoa varieties (Q 1303, Q 1331 and Q 1324) in competition, respectively, with ten densities of arrowleaf sida (0, 12, 16, 18, 128, 252, 432, 524, 584, and 756; 0, 24, 88, 104, 112, 124, 160, 164, 260 and 320; 0, 16, 72, 104, 116, 144, 156, 160, 228 and 304 plants·m^{-2}). The variables evaluated were plant density, soil coverage, leaf area, dry mass of weed shoots; and the variables related to quinoa were grain yield, control cost, price per bag and control efficiency. Quinoa variety Q 1303 showed greater competitive ability with arrowleaf sida than Q 1331 and Q 1324. The values of TL varied from 1.79 to 11.60 plants·m^{-2} for the Q 1303 variety, while the lowest TL values varied from 0.80 to 6.91 plants·m^{-2} for Q 1234 and Q 1331 varieties, showing less competitiveness in presence of the competitor. The TL values decreased with the increases in grain yield, in the price of the quinoa bag, in the efficiency of weeding and in the reduction of the control cost of arrowleaf sida, justifying the adoption of the weed control measures.
Additional keywords: Arrowleaf sida, competitive ability, interaction between plants, quinoa

RESUMEN

Interferencia y nivel de daño económico de *Sida rhombifolia* en el cultivo de quinua (*Chenopodium quinoa* Willd.)
Estudios sobre la interferencia y el umbral de daño económico (UDE) de malezas en la quinua son escasos. Así, el objetivo de este estudio fue determinar la interferencia y el UDE de *Sida rhombifolia* (afata) sobre variedad de quinua. Los tratamientos fueron compuestos por las variedades de quinua Q 1303, Q 1331 y Q 1324 en competencia, respectivamente, con diez densidades de afata (0, 12, 16, 18, 128, 252, 432, 524, 584 y 756; 0, 24, 88, 104, 112, 124, 160, 164, 260 y 320; 0, 16, 72, 104, 116, 144, 156, 160, 228 y 304 plantas·m^{-2}), en un diseño completamente al azar, con cuatro repeticiones. Las variables evaluadas fueron densidad de siembra, cobertura de suelo, área foliar, y masa seca de brotes de afata; las variables relacionadas con la quinua fueron rendimiento de granos, costo de control, precio por saco de granos y eficiencia de control. La variedad de quinua Q 1303 mostró mayor capacidad competitiva con afata que Q 1331 y Q 1324. Los valores de UDE variaron de 1,79 a 11,60 plantas·m^{-2} para la variedad Q 1303, mientras que los valores más bajos de UDE variaron de 0,80 a 6,91 plantas·m^{-2} para las variedades Q 1234 y Q 1331, los cuales mostraron menor competitividad en presencia del competidor. Los valores de UDE disminuyeron con los incrementos en el rendimiento de grano, en el precio de la bolsa de quinua, en la eficiencia del deshierbe y en la reducción del costo del control de afata, justificando la adopción de medidas de control de la maleza.
Palabras-clave adicionales Afata, capacidad competitiva, interacción entre plantas, quinua.

INTRODUCTION

Chenopodium quinoa (Chenopodiaceae) originates in the Andes region, where it is known as quinua. It has been cultivated for thousands of years in several Latin American countries (Spehar et al., 2011; Minh and Nguyen, 2021). It is an annual plant with a cycle of 80 to 150 days, which produces grains of highest nutritional value, as they contain protein, iron, phosphorus, essential amino acids, carbohydrates, lipids, vitamins, and minerals (Velásquez et al., 2020). Research reports that the protein content in quinoa vary between 10 and 20 %, very similar to that found in wheat grain (Qin et al., 2018). Quinoa has advantages over other cereals for having higher

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levels of vitamins such as riboflavin, niacin, thiamin, B6, and of minerals such as magnesium, zinc, copper, iron, manganese, and potassium (Qin et al., 2018; Velásquez et al., 2020).

In agroecosystems, quinoa can play an important role in soil protection when employed as a cover crop due to its high mass production (Spehar et al., 2011; Garcia et al., 2020). It can also be used as a succession crop, especially for family farming or small properties in the diversification of production, which contributes to the adoption of sustainable practices in agriculture (Spehar et al., 2011). The crop has many varieties, which facilitates its adaptation to different soil and climate conditions, and can be grown both in summer and winter, besides having natural resistance to insects and diseases (Spehar et al., 2011; Garcia et al., 2020).

Thus, after showing significant results in the Brazilian Cerrado in the 1990s, quinoa attracted the interest of farmers and technicians in the farming sector, discretely expanding to some other regions of Brazil. As quinoa is not yet a widespread crop in the country, studies that aim to provide information about weed management are necessary, especially research on development and forms of weed control. When improperly managed, weeds can compromise the grain yield or the quality of the harvested product due to competition for water, light and nutrients.

Among the weed species that infest crops and cause losses in productivity in Brazilian crops, not least in Rio Grande do Sul, *S. rhombifolia* L. (arrowleaf sida), Malvaceae family, stands out because it adapts to poor in fertility, acidic and compacted soils, besides having amphistomatic leaves. These traits allow a better adaptation of this species to the environment in which it grows and develops (Cunha et al., 2012). Therefore, the correct management of this weed is fundamental in quinoa plantations, since in addition to the direct crop yield losses, the weed is a host plant for the silverleaf whitefly, a vector of viruses for various crops (Silva et al., 2011). According to Agostinetto et al. (2010) and Khatounian et al. (2016), in addition to the understanding of the damage caused by competition between plants, comprehending the influence of weed density is also important; when weeds coexist with crops, there will be losses and reduced quality of harvested grains, or even the determination of the population at which TL is reached.

Therefore, studies seeking to determine responses to the coexistence of quinoa varieties and weeds, especially arrowleaf sida, are relevant so that efficient, sustainable and alternative management to chemical control can be adopted, either through cultivation methods or through control based on the concept of threshold level. This concept advocates that the application of herbicides or other control methods is only justified in cases where the losses caused by weeds are greater than the costs of control methods (Kalsin and Vidal, 2013). When there are high densities of weeds competing with crops, the decision to control them is an easy one. However, when weeds occur at low densities, adopting measures to control them becomes difficult because of the need to quantify the economic advantages associated with the control costs (Agostinetto et al., 2010; Tavares et al., 2019; Brandler et al., 2021).

The density of cultivated plants is usually constant in crop fields, while the density of weeds varies according to the soil seed bank, the environmental and soil conditions, and the management and cultural treatments adopted, which alter the level of infestation (Kalsing and Vidal, 2013; Jha et al., 2017). Knowing the weed interference capacity on a crop is crucial when deciding about weed control methods. With this information, by knowing the price of the harvested product, the cost of control, grain productivity and the efficiency of the control method, calculating the TL of weeds is possible, i.e., the density whose interference on crops will exceed the cost of control (Agostinetto et al., 2010; Kalsing and Vidal, 2013; Tavares et al., 2019).

Mathematical models have been used to estimate crop yield losses due to the presence of weeds (Agostinetto et al., 2010; Kalsing and Vidal, 2013; Tavares et al., 2019). The hyperbolic relationship between the grain yield and weed density was initially described by Cousens (1985). This author adjusted an empirical model (rectangular hyperbola method) to predict yield loss due to weed density, obtaining results that demonstrated the superiority of the model over others. The model is based on the non-linear relationship between the percentage of yield loss due to interference, in relation to the infestation-free control, and weed density. It incorporates the parameter "*i*", which represents yield loss caused by the addition of the first weed, and "*a*", which demonstrates yield loss when weed density tends to infinity. The biological meaning of the model shows that the competition effect of each weed added to the crop decreases when the weed density rises, as a result of the intraspecific competition (Agostinetto et al., 2010; Tavares et al., 2019).

Therefore, farmers who decide to cultivate quinoa as a way to diversify their property need to adopt ways to manage weeds so that the negative effects of their interference are minimized or even avoided. Quinoa is a little-known crop in Brazil, requiring research to facilitate its cultivation, which is an alternative mainly for small farmers. Thus, knowing the differentiation in the competitive ability and the TL of quinoa varieties sown in coexistence with densities of arrowleaf sida is relevant for the adoption of a more sustainable management. In this way, the goal of this study was to determine the interference and the TL of infesting arrowleaf sida on quinoa varieties.

MATERIALS AND METHODS

Location of the experiment and plant material. The experiment was conducted in the experimental area of the Federal University of Fronteira Sul (UFFS), Campus Erechim/RS, in the crop year 2018/2019. The site is located in the physiographic region of Alto Uruguay, Rio Grande do Sul, Brazil, in the geographic coordinates of 27º43'47" S and 52º17'37" W, at an altitude of 760 m. According to Köppen's classification, the climate of the region is, characterized as humid subtropical without a defined dry season, with the temperature of the hottest month higher than 22 ºC, average annual temperature of 18.6 ºC, and average annual precipitation of 1869 mm (CEMETRS, 2012).

The chemical and physical characteristics of the soil were pH= 4.8; EC= 0.349 $dS{\cdot}m^{-1}$; OM = 3.5 %; P= 4.0 $mg{\cdot}dm^{-3}$; K= 117.0 $mg{\cdot}dm^{-3}$; Al^{3+}=0.6 $cmol_c{\cdot}dm^{-3}$; Ca^{2+}= 4.7 $cmol_c{\cdot}dm^{-3}$; Mg^{2+}= 1.8 $cmol_c{\cdot}dm^{-3}$ CEC = 16.5 $cmol_c{\cdot}dm^{-3}$; base saturation = 41.2 %, clay= 60 % and sand= 15 %.

The fertilization was performed according to the physical-chemical analysis following the technical recommendations for quinoa cultivation (Spehar et al., 2011).

Each experimental unit (plot) had an area of 15 m² (3 x 5 m), and sowing was performed in six lines, 5 m long and spaced at 0.50 m on December 18, 2018. The sowing density of quinoa varieties Q 1303, Q 1324 and Q 1331 were 50 $seeds{\cdot}m^{-1}$ or approximately 1,000,000 $seeds{\cdot}ha^{-1}$. After 30 days of the emergence of quinoa, nitrogen fertilization was applied in cover, at a dose of 45 kg of N ha^{-1} (Spehar et al., 2011).

Experimental design. The experimental layout used was completely randomized blocks, with four replications, and the treatments consisted of quinoa varieties (Q 1303, Q 1324 and Q 1331) in competition with ten densities of arrowleaf sida, as follows: Q 1303 at densities of 0, 12, 16, 18, 128, 252, 432, 524, 584, and 756; Q 1324 at densities of 0, 24, 88, 104, 112, 124, 160, 164, 260 and 320; and Q 1331 at densities of 0, 16, 72, 104, 116, 144, 156, 160, 228 and 304 $plants{\cdot}m^{-2}$. Since arrowleaf sida came from the soil seed bank, the densities had a different number of plants per area (experimental unit). The density of the competing species was established from the soil seed bank by manual weeding at 35 days after the emergence of the crop (DAE) and when the weed was at the stage of 2 to 6 leaves.

Evaluations of explanatory variables. The quantification of plant density (PD), soil coverage (SC), leaf area (LA) or dry mass of the shoots (DM) of arrowleaf sida were performed at 30 DAE of the crop. To determine the PD variable, the plants were counted in two areas of 0.25 m² (0.5 m x 0.5 m) per plot. The SC of the arrowleaf sida was visually evaluated by two evaluators using a percentage scale in which zero corresponds to the absence of SC and 100 represents total soil coverage. The quantification of LA of the competing plant was performed with a portable electronic integrator, CI-203 model, CID Bio-Science brand, measuring leaf area all plants within an area of 0.25 m^{-2} per plot. After measuring the LA, the plants were placed in kraft paper bags and put into a forced air circulation oven at a temperature of 60 ± 5 ºC for the determination of DM of arrowleaf sida ($g{\cdot}m^{-2}$) when it reached a constant weight.

Statistical analysis. The quantification of the quinoa yield was obtained by manually harvesting the plants in a 6.0 m² usable area of each experimental unit, when the moisture content of the grains reached approximately 15 %. After determining the mass of the grains, their humidity was verified, and later the masses were uniformed to 13 % humidity. With the grain yield data, the loss rates were calculated in relation to the plots without infestation (infestation-free control), according to:

$$\text{Loss (\%)} = \left(\frac{Ra-Rb}{Ra}\right)x100$$

Where: Ra and Rb: crop yield without or with the presence of the competing plant, respectively.

Prior to data analysis, the values of DM ($g \cdot m^{-2}$), SC (%) or LA (cm^2) were multiplied by 100, thus dispensing the use of the correction factor in the model (Agostinetto et al., 2010; Tavares et al., 2019; Brandler et al., 2021).

The relationships between grain yield loss rates of quinoa in function of explanatory variables were calculated separately for each variety using the nonlinear regression model derived from the rectangular hyperbola, as suggested by Cousens (1985), according to:

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

Where Yl = yield loss (%); X = density of arrowleaf sida, dry mass of the shoots, leaf area or soil coverage; *i* and a = yield losses (%) per unit of arrowleaf sida plants when the value of the variable is close to zero and when it tends to infinity, respectively. Fitting the data to the model was performed using the Proc Nlin procedure, from the SAS, version 6, computational program (Cary, NC, USA). For the calculation procedure, the Gauss-Newton method was used, which, by successive interactions, estimates the parameter values in which the sum of squares of the deviations of the observations, in relation to the adjusted values, is minimal (Agostinetto et al., 2010). The value of the F-statistic ($p \leq 0.05$) was used as a criterion for analyzing the data of the model. The criterion for accepting the adjustment of the data to the model was based on the highest value of the coefficient of determination (R^2) and the smallest value of the mean square residual (MSR).

The estimate of the parameter *i* obtained from Equation 1 (Cousens, 1985) and the equation adapted from Lindquist and Kropff (1996) were used to calculate the threshold level (TL), as shown in:

$$TL = \frac{(Cc)}{(R*P*(\frac{i}{100})*(\frac{H}{100}))} \quad (2)$$

Where TL = threshold level (plants m^{-2}); Cc = control cost (weeding with a hoe, in dollars ha^{-1}); R = quinoa grain yield (kg ha^{-1}); *i* = loss (%) of quinoa yield per unit of competing plant when the populational level is close to zero; and H = weeding efficiency level (%). Three values occurring in the last 10 years were estimated for the variables Cc, R, P and H (Equation 2). The calculation of the control cost (Cc) considered the average price of US$ 180.29 (number of days that it takes a man to weed one-hectare x number of hours worked per day x the value in Reais per hour worked). Thus, the calculation was: 5 days x 8 $h \cdot day^{-1}$ x Reais 18.75 = Reais 750 ha^{-1}, which is equivalent to US$ 180.29. The maximum and minimum costs were estimated based on this average cost, adding or subtracting 25 %, respectively. Quinoa yield (R) was based on the lowest, average and highest yield obtained in Peru (USDA, 2022), since no data is available in Brazil. Quinoa price (P) was estimated from the lowest, average and highest price per 60 kg bag. The values for weeding efficiency (H) were established in the order of 80, 90 and 100 % of control, 80 % being the minimum control of the spontaneous plant considered effective.

RESULTS AND DISCUSSION

The F-statistic values were significant for the explanatory variables PD, SC, LA and DM for all quinoa varieties (Figures 1 and 2). All quinoa types fitted adequately to the rectangular hyperbola model, with R^2 values greater than 0.63 and MSR. The results showed variation in the adjustment of the data in relation to the variety and variables studied, results that are similar to those observed in the literature for quinoa x alexandergrass (Brunetto et al., 2023), rice x barnyardgrass (Agostinetto et al., 2010), beans x alexandergrass (Kalsing and Vidal, 2013) and soybean x arrowleaf sida (Galon et al., 2022). According to Cargnelutti and Storck (2007), who studied genetic variation, effects of cultivars and heritability of corn hybrids, considered as moderate to good the R^2 values between 0.57 to

0.66, which partially corroborates the results of this study.

For the variables PD, SC, LA and DM, the average values estimated for the parameter *i* were lower for the quinoa variety Q 1303. The lowest competitiveness was observed in the varieties Q 1324 and Q 1331 for all the relative variables studied (Figures 1 and 2). This is due to the genetic differences of the variety, such as greater height, greater leaf area index, larger root system, among others, which are used by plants as defense resources. Brunetto et al. (2023) studied the competition between quinoa and alexandergrass varieties and found higher competitive ability of Q 1303 and lower competitive ability of Q 1324 and Q 1331.

The same occurred with other studies, which reported different competitive abilities in the presence of weeds, a fact attributed to a set of inherent morphophysiological characteristics (Agostinetto et al., 2010; Kalsing and Vidal, 2013; Tavares et al., 2019).

According to Laub et al. (2022), when the crop has low soil coverage, it allows greater light penetration into the canopy of the community and, consequently, less competitiveness in the presence of weeds. Spehar et al. (2011) worked with native quinoa crops (BRS Syetetuba, BRS Piabiru and Kancolla) and found that these showed greater genetic variability and differentiation in relation to responses to the effects of abiotic and biotic stress, which reflected directly in the grain yield of each variety.

The results showed average quinoa grain yield losses of 47.13, 60.11 and 68,42 % for the varieties Q 1303, Q 1324 and Q 1331, respectively, in the presence of 100 arrowleaf sida plants m^{-2} (Figure 1 A, B, C). When adding three times the PD of weeds (300 arrowleaf sida plants m^{-2}), yield loss increased to 75.31, 83.99 and 90.49 % for the varieties Q 1303, Q 1324 and Q 1331, respectively. As the determination of quinoa PD occurred after 35 days of emergence, arrowleaf sida was already at the early stages of development and caused high yield losses and tended to dominate the environment with an increase of height, leaf area, and dry mass, causing greater shading to quinoa. According to Spehar et al. (2011), quinoa cultivated in plantations has a low competition capacity until its establishment, especially in the first 50 days, since the crop presents slow growth and development, thus needing to be free of weed to avoid yield losses.

This research also demonstrated that quinoa initially showed delayed growth and development, i.e., it develops slowly, as Spehar et al. (2011) also reports. Thus, weeds initially have greater competitiveness, mainly for light. There is a high competition for light when a crop is shaded, which makes it less efficient in the search for solar radiation and, consequently, the crop grows and develops less than usual (Laub et al., 2022).

Quinoa grains had a yield loss above 75 % for all varieties evaluated for the LA variable (8,000 $cm^2 \cdot m^{-2}$), with the Q 1303 variety showing the lowest yield loss, while Q 1331 had the highest loss when compared to Q 1324 (Figures 1 D, E, F). The study revealed that the degree of variety competition with arrowleaf sida is influenced by the weed LA, as other studies have also concluded about the competition between quinoa and alexandergrass genotypes (Brunetto et al., 2023) or soybean crops when infested by arrowleaf sida (Galon et al., 2022).

The results for yield loss of quinoa varieties in relation to the SC rates (Figure 2 A, B, C) were similar to those observed in relation to PD (Figures 1 A, B, C) and LA (Figures 1 D, E, F), i.e., with the increase of arrowleaf sida SC rates in the soil, the greater the injury caused to the crop. Quinoa varieties showed a greater yield reduction when the soil had 20 % coverage with arrowleaf sida, i.e., losses greater than 55 %. This fact is in accordance with the results of PD and LA, where the plant that shows higher rates has an advantage in competition with its neighbors, mainly for light, and, consequently, has a higher growth and development, as previously discussed.

Arrowleaf sida caused yield reductions in quinoa greater than 71.17, 77.42 and 74.15 % when it accumulated 100 $g \cdot m^{-2}$ of DM for the quinoa varieties Q 1303, Q 1324 and Q 1303, respectively (Figures 2 D, E, F). Brunetto et al. (2023) observed that when alexandergrass accumulated 500 $g \cdot m^{-2}$ of dry mass, it reduced quinoa yields in 99, 97 and 99 % for the varieties Q 1303, Q 1324 and Q 1303, respectively, the same varieties tested in this study. Thus, it is clear that both arrowleaf sida and alexandergrass cause high losses in quinoa yield, which is a crop with low competitive ability, especially for its slow early growth. Jha et al. (2017) reported that crops that show fast emergence and growth, larger height and great accumulation of biomass in the shoots have a higher competitive ability, when infested by weeds. Carioca bean crops competing with alexandergrass (Kalsing and Vidal, 2013), as well as the black beans in the presence of beggartick (Galon et al., 2016) showed different behaviors, which is probably due to the different inherent characteristics that plants show, such as growth habit, development cycle and number of branches, etc., which affect the competitive ability of the crop and differentiate cultivars involved in the competition with weeds. Several studies describe the distinction between rice (Agostinetto et al., 2010), corn hybrids (Galon et al., 2019), canola (Brandler et al., 2021) and quinoa varieties (Brunetto et al., 2023) in the competition with weeds.

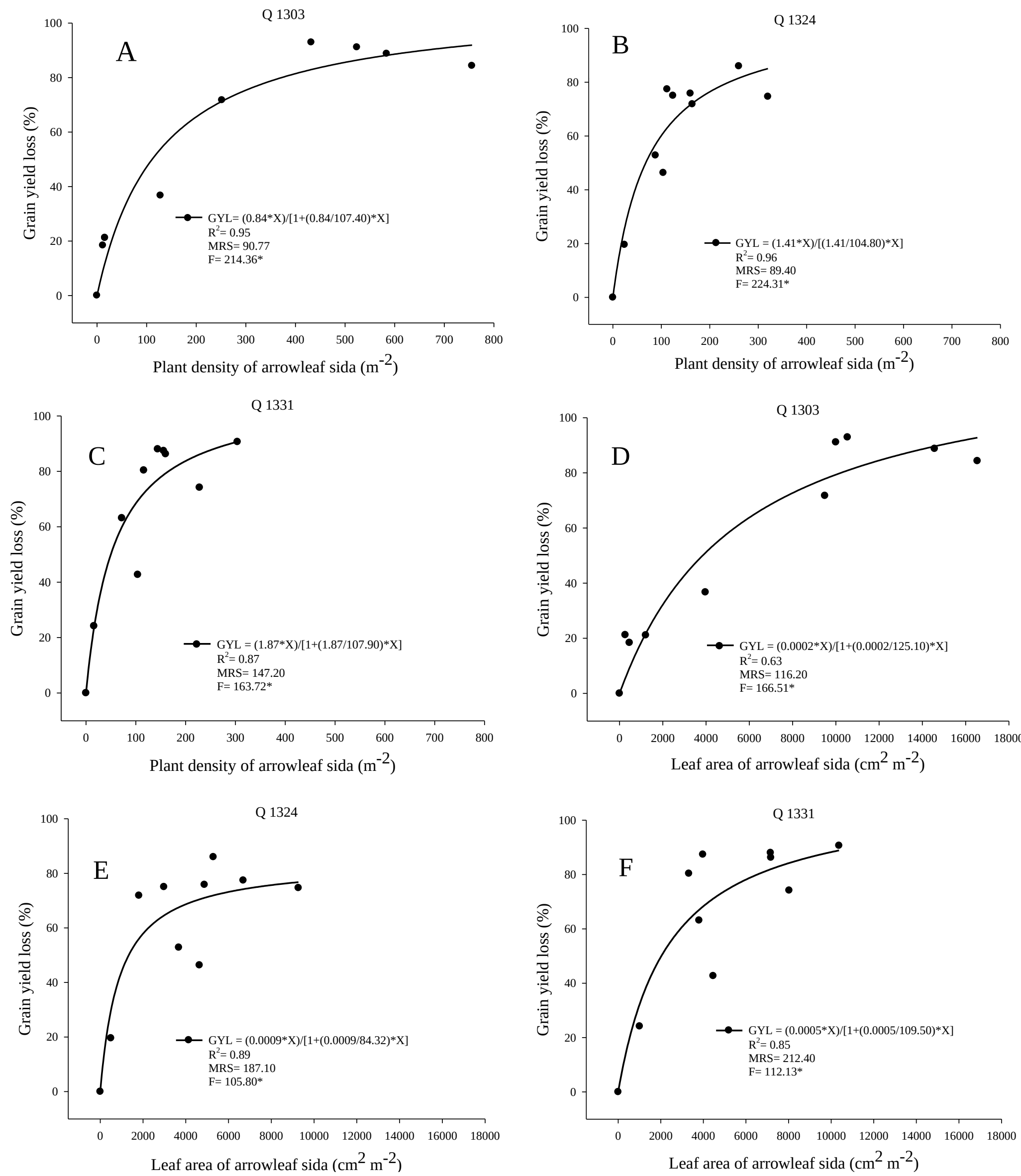

Figure 1. Grain yield loss (GYL) of quinoa (*Chenopodium quinoa*) as a function of crop varieties, plant density (A, B and C) and leaf area (D, E and F) of arrowleaf sida (*S. rhombifolia*) 30 days after emergence. UFFS, Campus Erechim/RS, 2018/19. R^2= Coefficient of determination; MRS: mean residue square; * Significant at $P \leq 0.05$.

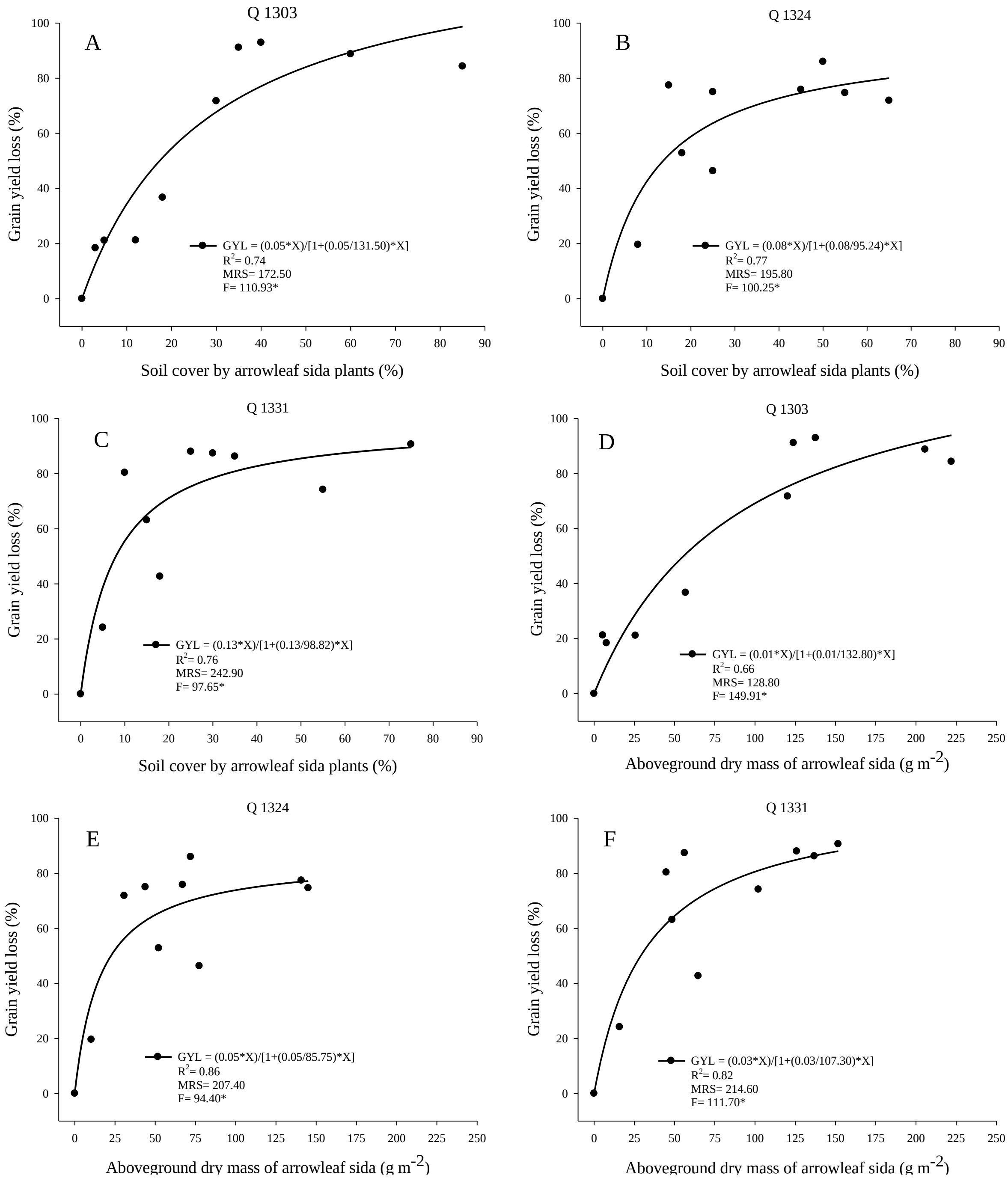

Figure 2. Grain yield loss (GYL) of quinoa (*Chenopodium quinoa*) as a function of crop varieties, soil coverage (A, B and C) and dry mass of the shoots (D, E and F) of arrowleaf sida plants (*S. rhombifolia*) 30 days after emergence. UFFS, Campus Erechim/RS, 2018/19. R^2= Coefficient of determination; MRS: mean residue square; * Significant at $P \leq 0.05$.

Knowing the parameter *i* is an index that can be used to compare the relative competitiveness between species (Agostinetto et al., 2010; Tavares et al., 2019), quinoa varieties presented different values in the explanatory variables tested (Figures 1 and 2). Similar studies have also used the parameter *i* to compare the competitivity of beans (Kalsing and Vidal, 2013; Galon et al., 2016), corn hybrids (Galon et al., 2019), wheat (Tavares et al., 2019) and quinoa varieties (Brunetto et al., 2023).

The comparison between quinoa varieties considering the parameter *i*, on the average of the four explanatory variables (PD, SC, LA or DMAP), demonstrated that the order of placement in relation to competitiveness is Q 1303 > Q 1324 > Q 1331 (Figures 1 and 2). The differences between the results of varieties are largely due to their genetic characteristics or the phenotypic plasticity of the crop (Agostinetto et al., 2010; Brandler et al., 2021), which corroborates the results of this study. Other researchers verified that quinoa varieties and bean crops responded differently to the parameter evaluated when infested by alexandergrass (Kalsing and Vidal, 2013; Brunetto et al., 2023) or beggartick (Galon et al., 2016). Corn hybrids and rice also responded differently when infested by alexandergrass (Galon et al., 2019) and barnyardgrass (Agostinetto et al., 2010), respectively.

Grain yield losses of 0.84, 1.41 and 1.87 % were observed for Q 1303, Q 1324 and Q 1331, respectively (Figures 1A, B and C) when the quinoa varieties were compared in relation to the PD variable. Although all quinoa varieties had the same development cycle, they showed different grain yield losses. This fact can be explained by their genetic differences, such as plant architecture, leaf area, plant height, accumulated biomass, and root system, which make them more or less competitive with arrowleaf sida. Therefore, quinoa varieties respond independently in situations of interspecific competition with arrowleaf sida, which reflects on the different grain yield results. Brandler et al. (2021) also observed differences in the competitive ability of canola crops when placed in the presence of turnips, corroborating the data presented here.

The estimates of parameter *a*, independently of the explanatory variable, were overestimated by the model, with yield losses greater than 100 % for all varieties tested, except for Q 1324 in the variables LA, SC, DM, and for Q 1331 in SC, in which the losses were inferior to 100 % (Figures 1 and 2). These results may stem from the fact that the higher densities of arrowleaf sida plants were not sufficient to adequately estimate the maximum yield loss of quinoa; according to Cousens (1991), to obtain a reliable estimate for this parameter, it is necessary to include in the experiment extremely elevated densities of weeds, above those commonly found in crop conditions. Similarly, Agostinetto et al. (2010), Brandler et al. (2020) and Brunetto et al. (2023), when studying the competition between rice and gulf cockspur, canola with turnip, and quinoa with alexander-grass, respectively, subjected the crops to different management methods and also found losses greater than 100 % for the parameter *a*.

An alternative to prevent yield loss to be overestimated would be to limit the maximum loss to 100 %. However, the limitation might influence the estimation of the parameter *i*, which might result in lower predictability in the rectangular hyperbola model (Cousens, 1991). Moreover, yield losses greater than 100 % are biologically unreal and occur when the range of weed density is excessively narrow and/or the highest values of density are not sufficient to produce asymptotic yield loss response (Agostinetto et al., 2010).

The quinoa variety tested presented the same growth cycle, but had explanatory variables with a different parameter *i* (Figures 1 and 2). Similarly, Brunetto et al. (2023) also found that quinoa varieties Q 1303, Q 1324 and Q 1331 of the same cycle showed different competitiveness abilities expressed by the parameter *i*. The authors reported that this was due to differences in variety yield, which caused less yield loss per individual weed, corroborating the results of this study, where the variety Q 1303 presented the lowest yield loss (46.5 %), followed by Q 1324 (57.63 %) and Q 1331 (66.53 %) when compared to the average of the ten densities of arrowleaf sida competing with quinoa. However, Q 1303 demonstrated the lowest grain yield (2.9 $t \cdot ha^{-1}$) when compared to Q 1324 and Q 1331, with yields of 3.3 and 3.6 $t \cdot ha^{-1}$, respectively, in the treatment free of arrowleaf sida competition (0 $plants \cdot m^{-2}$).

The comparison between the explanatory variables for all quinoa varieties showed a better fit to the model for the PD>LA>DM>SC in general, considering the average values of R^2 and F, and the lowest average values of MSR (Figures 1 and 2), thus demonstrating that PD is the variable that can be used for simulation of the level of economic threshold level (TL).

The simulation of TL was performed using the explanatory variable PD of arrowleaf sida by the best fit to the rectangular hyperbola model, since it was the most used in experiments with this goal, with easier determination and low cost, which other studies with similar objectives have also concluded (Agostinetto et al., 2010; Kalsing and Vidal, 2013; Brunetto et al., 2023).

The success in the implementation of management systems for weed arrowleaf sida in the quinoa culture may result from the determination of the density that exceeds the TL. The lowest TL caused by arrowleaf sida densities for quinoa varieties as a function of grain yield, quinoa price, control efficiency, and control cost (Figure 3) were observed for Q 1331 and Q 1324 with mean values of 2.06 and 2.73 plants·m^{-2}, respectively. Taking into account the same criteria, the highest TL was reached with 4.58 plants·m^{-2} of arrowleaf sida for the Q 1303 variety. It was observed that the Q 1303 variety showed the highest TL values in all the simulations performed, ranging from 4.05 to 5.86 plants·m^{-2}. The lowest TL values were obtained with the Q 1331 and Q 1324 varieties with average variations from 1.82 to 3.49 plants·m^{-2}. The differences verified in relation to the TL are due, as previously reported, to the different genetic characteristics existing between the cultivars in the presence of weeds, such as wheat (Tavares et al., 2019) and canola (Brandler et al., 2021) in the presence of turnip, soybean x arrowleaf sida (Galon et al., 2022) and quinoa x alexandergrass (Brunetto et al., 2023).

Grain yield, control cost, the price paid per bag of quinoa, and control efficiency influenced the TL of arrowleaf sida in the crop. When quinoa varieties decreased grain yield by 610 kg·ha^{-1} (from 1600 to 990 kg·ha^{-1}) the arrowleaf sida density required to reach the TL was increased by 38.21 % for varieties Q 1303, Q 1324, and Q 1331 (Figure 3). Therefore, it is noteworthy that the increase in crop productivity expectations may be less influenced by weed competition, which was also reported by Brunetto et al. (2023) when evaluating quinoa varieties in the presence of alexandergrass. Increasing the control cost by $ 90.14, from US$ 135.22 to US$ 225.36, the arrowleaf sida density required to reach the TL was increased by more than 35 % for all evaluated quinoa varieties. The reduction in the price of a bag of quinoa grain by US$ 486.00 (from US$ 574.80 to US$ 88.80) required an increase in arrowleaf sida density to reach an TL of 63.55 % for quinoa varieties Q 1303, Q 1324, and Q 1331. Brunetto et al. (2023) also reported that the reduction in the amount paid per bag of quinoa grains increased the density of alexandergrass necessary to reach the TL of the weed on the varieties Q 1303, Q 1324, and Q 1331, similar to our data.

With the reduction of control efficiency by 20 %, that is, from 100 to 80 %, the arrowleaf sida density required to reach the TL was increased by approximately 23% considering the quinoa varieties Q 1303, Q 1324, and Q 1331 (Figure 3). Similarly, Brunetto et al. (2023) also found an increase close to 20 % in alexandergrass density to reach the TL in quinoa varieties.

The oscillations between the highest and lowest grain yield, bag price (60 kg), control efficiency, and control cost, influenced the average of the quinoa varieties (Q 1303, Q 1324, and Q 1331) with variations of about 62, 37, 77 and 64 %, respectively. Considering the average data on grain yield, quinoa bag price, control efficiency, and control cost, the quinoa varieties, Q 1303, Q 1324, and Q 1331, there was an average variation in the TL of approximately 60 % (Figure 3). These results are similar to those found by Galon et al. (2022) and Brunetto et al. (2023) in experiments with soybean and quinoa infested by arrowleaf sida and alexandergrass, respectively.

The success in the implementation of management systems of arrowleaf sida in quinoa crops may result from the determination of the density that exceeds the TL. Thus, the variety Q 1303 has shown the highest values of TL in all simulations performed, with variations of 1.79 to 11.60 plants·m^{-2} (Figure 3). The lowest TL levels were obtained with the varieties Q 1324 and Q 1331, with variations of 1.07 to 6.91 plants·m^{-2}.

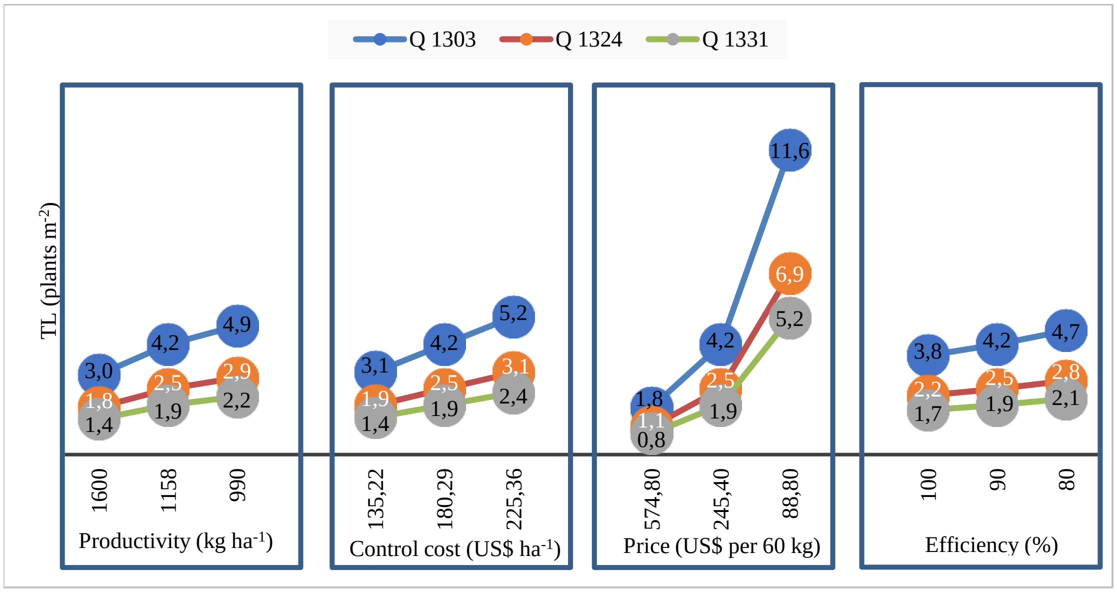

Figure 3. Threshold level (TL) as a function of grain yield, control cost, the price paid for a 60 kg bag, control efficiency (%) and quinoa varieties.

Some studies have also found differences in the TL of weed-infested cultures according to the variety, crop or hybrid tested: Brunetto et al. (2023), when working with the same quinoa varieties in the presence of alexandergrass; Kalsing and Vidal (2013) and Galon et al. (2016), when studying bean crops infested by alexandergrass and beggartick, respectively as well as corn hybrids with alexandergrass (Galon et al., 2019); and Tavares et al. (2019), when researching about wheat crops in the presence of turnip. These studies showed changes in the TL according to the crop evaluated. The results demonstrated that varieties Q 1324 and Q 1331 presented lower TL probably due to the lower leaf area, the emergence of few lateral branches (which were short), besides lower plant height and slow initial growth (Spehar et al., 2011), which allows more light to enter the soil and, consequently, greater growth of arrowleaf sida. It is also noteworthy that arrowleaf sida, for presenting certain characteristics such as adaptability to poorly fertile, acid and compacted soils, or even amphistomatic leaves, with anomocytic stomata of easy adaptation to the environment in which it grows and develops (Cunha et al., 2012), had advantage in the competition with the quinoa varieties Q 1324 and Q 1331. For the varieties Q 1324 and Q 1331, the control of arrowleaf sida must be performed at weed density lower than the density used with variety Q 1303, in order to avoid high losses in the grain yield. Thus, quinoa farmers must use the most competitive quinoa variety if their crop is infested with arrowleaf sida, i.e., Q 1303, which tolerates higher densities of the weed.

On average, the difference of TL was 38.03 % for all quinoa varieties and when comparing the lowest with the highest grain yields (Figure 3). Therefore, the higher the productive potential of varieties, the lower the density of arrowleaf sida necessary to overcome the TL, making the adoption of weed control measures compensatory. When evaluating the TL of soybean infected by arrowleaf sida (Galon et al., 2022) and quinoa varieties infected by alexandergrass (Brunetto et al., 2023), researchers found that TL according to the crops or the varieties, and that the materials that presented higher yield potential can show lower TL.

The average results of all varieties, from the highest versus the lowest price per bag of quinoa, showed a 6.5 variation in the TL value (Figure 3). Therefore, the lower the price paid per bag of quinoa, the higher the necessity of the density of arrowleaf sida to overcome the TL and thus compensate for the control method. Similar results about the price paid per bag of soybean (Galon et al., 2022) and of quinoa (Brunetto et al., 2023), when infected by arrowleaf sida and alexandergrass, respectively, partially confirm the outcomes of this study.

Regarding the efficiency of mechanical control by hoeing (weeding), the average efficiency (90 %), when compared to the lowest (80 %) or the highest (100 %) efficiency, altered the TL to 11.18% and 9.79%, respectively (Figure 3). Thus, the level of control influences the TL and, the higher the efficiency of weeding, the lower the TL (lower number of arrowleaf sida plants·m^{-2} needed to adopt control measures), a fact also observed by Brunetto et al. (2023) in weeding for the control of alexandergrass infesting quinoa, and Galon et al. (2022) when applying herbicides for the control of arrowleaf sida infesting soybean.

The cost of controlling arrowleaf sida in all varieties was 39.96 % lower than the minimum cost in comparison to the maximum cost. Thus, the higher the cost of the control method, the higher the TL, and the more arrowleaf sida plants·m^{-2} will be needed to justify control measures (Figure 3). The use of TL as a tool for weed management should be associated with good agricultural practices for quinoa management, since its implementation is only justified in the crops that use rotation, adequate plant arrangement, more competitive crops, adequate sowing times, soil fertility correction, etc.

The TL varied according to the quinoa varieties with decreasing values for Q 1303 > Q 1324 > Q 1331 (Figure 3). When quinoa cultivars were in competition with papuã densities (Brunetto et al., 2023) and soybean cultivars in the presence of guanxuma (Galon et al., 2022), different behavior was observed for TL, for both crops and weeds. The differentiated characteristics that the varieties demonstrate among themselves in the presence of papuã (Brunetto et al., 2023) and/or guanxuma (Galon et al., 2022) corroborate what was found in the present study. Some studies have reported evidence that quinoa cultivars have shown particular behavior when placed in the presence of biotic or abiotic factors (Spehar et al., 2011; García et al., 2020; Minh and Nguyen, 2021; Brunetto et al., 2023), which influences their higher or lower grain yield, especially when competing with weeds in stress situations. The differentiation that occurs in terms of competitive ability can also be attributed to differences in architecture, leaf area, height, length and volume of roots, produced biomass, allelopathic effects, species, plant density, and plant distribution when in competition (Tavares et al., 2019; Sun et al., 2021).

CONCLUSIONS

The plant density demonstrated a better fit to the rectangular hyperbola model than soil coverage, leaf area, and dry mass of the shoots of arrowleaf sida. Quinoa variety Q 1303 presented greater competitiveness and TL with arrowleaf sida than Q 1331 and Q 1324. The lowest TLs were observed for the varieties Q 1324 and Q 1331, which demonstrate that they are less competitive with the weed. The TL decreased with the increases in grain yield productivity, in the price of the quinoa bag, in the efficiency of weeding and in the reduction in the cost of controlling arrowleaf sida, justifying the adoption of control measures in smaller populations of the weed.

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