Interference and threshold level of *Sida rhombifolia* in transgenic soybean cultivars

Interferencia y nivel de daño económico de *Sida rhombifolia* en cultivares de soja transgénica

Leandro Galon [1*], Alessandro Konzen [1], Maico André Michelon Bagnara [1], Leonardo Brunetto [1], Ignacio Aspiazú [2], Antônio Marcos Loureiro da Silva [1], Daiane Brandler [3], Hugo Von Linsingen Piazzetta [1], André Luiz Radünz [4], Gismael Francisco Perin [1]

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Abstract

This study aimed to assess the interference and threshold level (TL) of *Sida rhombifolia,* the arrowleaf sida, competing with different soybean cultivars. The treatments comprised different soybean cultivars (NS 6909, NA 5909, DM 5958, Brasmax ELITE, Brasmax LANÇA, and SYN 13561) and densities of arrowleaf sida plants per square meter (m^{-2}) (0, 2, 3, 4, 9, 15, 16, 23, 22, and 58; 0, 2, 3, 3, 6, 6, 10, 11, 18, and 47; 0, 3, 4, 7, 8, 10, 11, 13, 15, and 24; 0, 1, 4, 6, 12, 18, 19, 31, 44, and 50; 0, 4, 5, 6, 9, 13, 17, 20, 20, and 47; 0, 2, 3, 5, 9, 11, 15, 18, 29, and 30, respectively) for each cultivar. Cultivars NS 6909, NA 5909, and Brasmax Lança were more competitive than DM 5958, Brasmax Elite, and SYN 13561. The TL values varied from 0.55 to 0.95 plants m^{-2} for cultivars NS 6909, NA 5909, and Brasmax Lança, which exhibited greater competitiveness with arrowleaf sida. The lowest values of TL varied from 0.26 to 0.61 plants m^{-2} for cultivars DM 5958, Brasmax Elite, and SYN 13561, which had less competitiveness with weed.

Keywords
Glycine max • arrowleaf sida • integrated weed management

1 Federal University of Fronteira Sul. Campus Erechim. Laboratory of Sustainable Management of Agricultural Systems. 99700-970. Erechim. Rio Grande do Sul. Brazil. * leandro.galon@uffs.edu.br
2 State University of Montes Claros. Department of Agricultural Sciences. 39440-000. Janaúba. Minas Gerais. Brazil.
3 Federal University of Technology Paraná. Campus Pato Branco. Laboratory of Weed Science Research Centre. 85503- 390. Pato Branco. Paraná. Brazil.
4 Federal University of Fronteira Sul. Campus Chapecó. Department of Agronomy. 89815-899. Chapecó. Santa Catarina. Brazil.

Resumen

El objetivo de este estudio fue evaluar la interferencia y determinar el nivel de daño económico (NDE) de escoba dura infestando diferentes cultivares de soja. Los tratamientos fueron cultivares de soja (NS 6909, NA 5909, DM 5958, Brasmax ELITE, Brasmax LANÇA y SYN 13561) y las densidades de escoba dura (0, 2, 3, 4, 9, 15, 16, 23, 22 y 58; 0, 2, 3, 3, 6, 6, 10, 11, 18 y 47; 0, 3, 4, 7, 8, 10, 11, 13, 15 y 24; 0, 1, 4, 6, 12, 18, 19, 31, 44 y 50; 0, 4, 5, 6, 9, 13, 17, 20, 20 y 47; e 0, 2, 3, 5, 9, 11, 15, 18, 29 y 30 plantas m^{-2}), respectivamente, para cada cultivar. Los cultivares NS 6909, NA 5909 y Brasmax Lança son más competitivos que DM 5958, Brasmax Elite y SYN 13561. Los valores de NDE varían de 0,55 a 0,95 plantas m^{-2} para los cultivares NS 6909, NA 5909 y Brasmax Lança, que mostraron mejor competitividad. Los valores más bajos de NDE varían de 0,26 a 0,61 plantas m^{-2} para los cultivares DM 5958, Brasmax Elite y SYN 13561, los cuales mostraron menor competitividad con la maleza.

Palabras clave

Glycine max • escoba dura • manejo integrado de malezas

Introduction

Knowledge and management of factors that lead to reduced crop yield is essential for farmers to obtain better productive results considering the importance of soybeans in Brazil. Weeds can cause significant losses if not properly managed. Competition losses can vary from 2-94% depending on factors such as soybean cultivars, weed densities and species, emergence times, and edaphoclimatic conditions (14, 19, 29, 32).

In general, weeds compete with crops for environmental resources such as water, light, and nutrients and can cause high losses in soybean yield when left uncontrolled (13, 14, 17 22, 23, 32). Among the weeds that cause losses in soybean crops, *Sida rhombifolia*, the arrowleaf sida, stands out mainly because of its adaptability to low fertility, acidic soils, and high competitive ability (12). In addition, it has amphistomatic leaves with anomocytic stomata that can readily adapt to the environment where they grow and develop (11). Therefore, the correct management of arrowleaf sida is essential in soybean crops because its occurrence causes direct (such as reduced grain yield) and indirect losses (such as virus transmission to many crops by being the hosts of silverleaf whitefly) (23).

According to Agostinetto *et al*. (2010) and Zandoná *et al*. (2018), in addition to understanding the damage caused by competition, it is necessary to understand the influence of weed density and distribution when they coexist with crops in a given field. Owing to the efficiency, practicality, and low cost of herbicides, these are used as general management strategies for weeds compared with other control methods (31). Despite the advantages of chemical control, the search for more sustainable production models is a priority in the current discussions on grain production based on threshold level (TL) strategies for weed management. Thus, TL is an essential tool for farmers, allowing crop monitoring and decision making about the most appropriate time and way to manage weeds.

The TL concept recommends that applying herbicides or other control methods is justified only when the damage caused by weeds is more than the cost of control measures (1, 21). High densities of weeds competing with crops render decision-making by producers easier as adopting control measures with low population densities of weeds becomes difficult owing to the quantification of economic advantages associated with the control costs (21).

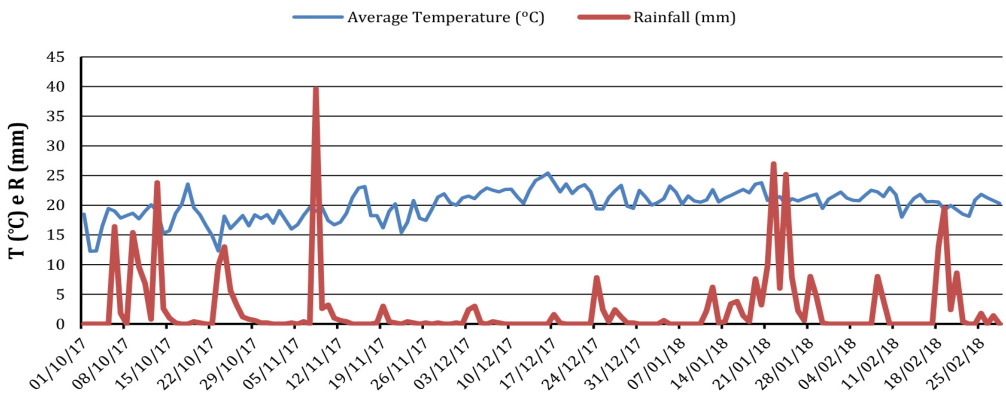
Mathematical models have been used to estimate the loss of grain yield owing to the presence of weeds (18). The hyperbolic relationship between grain yield and weed population was first described by Cousens (1985), wherein an empirical rectangular hyperbola model was adjusted to predict yield loss as a function of weed population demonstrating its superiority over the other models. The rectangular hyperbola model is based on the non-linear relationship between the percentage of yield loss due to interference in competition-free control and weed population (10). It incorporates parameter *i,* which represents the loss of production caused by adding the first weed, and parameter *a*, which symbolizes the loss of crop production as weed density approaches infinity. The biological significance of the model demonstrates that the competition effect of each weed added to the crop decreases as weed density increases owing to intraspecific competition. Initially, yield loss is proportional, but the loss decreases above a particular weed density.

We hypothesized that there would be differences in the competitive abilities of the crop and TL because of soybean cultivars coexisting with increasing densities of arrowleaf sida. Therefore, the objective of this study was to evaluate the interference and TL of arrowleaf sida competing with different soybean cultivars.

Material and methods

Site

The experiment was conducted under field conditions in an experimental area of the Federal University of Fronteira Sul, Campus Erechim/RS/BR, with geographic coordinates of 27°43'47" S and 52°17'37" W, from October 2017 to February 2018. The soil is classified as humic aluminoferric red latosol at an altitude of 670 m above sea level (15). The local climate is Cfa, i.e., a humid temperate climate having hot summers, wherein rains are distributed well throughout the year, based on the classification established by Köppen (figure 1) (8, 20).



Source: Inmet (2018).

Fuente: Inmet (2018).

Figure 1. Rainfall and average daily temperature during the soybean crop cycle from October 2017 to February 2018, UFFS, Erechim/RS.

Figura 1. Precipitación y temperatura media diaria durante el ciclo del cultivo de la soja de octubre de 2017 a febrero de 2018, UFFS, Erechim / RS.

The pH correction and fertilization in the soil were performed based on physicochemical analysis following the technical recommendations for soybean crops (26). The physicochemical characteristics of the soil were: pH = 5.1; Organic matter = 3.0%; P = 5.2 mg dm^{-3}; K = 118 mg dm^{-3}; Al^{3+} = 0.3 $cmol_c$ dm^{-3}; Ca^{2+} = 5.5 $cmol_c$ dm^{-3}; Mg^{2+} = 3.0 $cmol_c$ dm^{-3}; cation exchange capacity (CEC) = 7.4 $cmol_c$ dm^{-3}; CEC at pH_7= 16.6 $cmol_c$ dm^{-3}; H + Al = 7.7 $cmol_c$ dm^{-3}; sum of bases = 53%, and clay content = 60%. The no-tillage system was employed, and vegetation was dried using glyphosate herbicide at a concentration of 1440 g ae ha^{-1}, 20 d before sowing soybean cultivars with a sowing-fertilizing machine on October 4th 2017, distributing 480 kg ha^{-1} based on the formula NPK 02-20-20 in sowing furrow.

Experimental design

The experimental design was completely randomized, with four replicates, and the treatments were composed of six soybean cultivars, i.e., NS 6909 IPRO, NA 5909 RG IPRO, DM 5958 RSF, Brasmax Elite IPRO, Brasmax Lança IPRO, and SYN 13561 IPRO, and ten densities of arrowleaf sida for each cultivar (0, 2, 3, 4, 9, 15, 16, 23, 22, and 58 plants m^{-2}; 0, 2, 3, 3, 6, 6, 10, 11, 18, and 47 plants m^{-2}; 0, 3, 4, 7, 8, 10, 11, 13, 15, and 24 plants m^{-2}; 0, 1, 4, 6, 12, 18, 19, 31, 44, and 50 plants m^{-2}; 0, 4, 5, 6, 9, 13, 17, 20, 20, and 47 plants m^{-2}; and

0, 2, 3, 5, 9, 11, 15, 18, 29, and 30 plants m^{-2}). As the arrowleaf sida weed originated from the soil seed bank, the establishment of densities varied with factors such as competition for resources, vigor, and humidity, which prevented the exact number of plants per area of experimental unit from being established. The different densities of arrowleaf sida acted as replicates, providing the necessary variation for the statistical analysis performed using the nonlinear model proposed by Cousens (1985) and Agostinetto *et al*. (2010).

Plot management

Each experimental unit consisted of a 15 m^2 area (5 m × 3 m) having six soybean lines spaced 0.50 m apart with four central lines considered appropriate evaluation areas and discounting 1 m of front and end borders of each plot. The sowing density of different soybean cultivars was 14 viable seeds per meter, corresponding to a density of 280,000 seeds ha^{-1}, i.e., 28 plants m^{-2}. Soybean cultivars were selected based on their characteristics of undetermined growth and genetic differences. These are also the most cultivated soybean varieties in Rio Grande do Sul. All six cultivars bear resistance to insects and tolerance to herbicides but differ in crop cycles and maturation groups. NA 5909 RG IPRO and Brasmax Elite IPRO have early crop cycles, SYN 13561 IPRO has an early to medium cycle, and NS 6909 IPRO, DM 5958 RSF IPRO, and Brasmax Lança IPRO possess medium cycles. In addition, the cultivars NA 5909 RG IPRO, Brasmax Elite IPRO, SYN 13561 IPRO, NS 6909 IPRO, DM 5958 RSF IPRO, and Brasmax Lança IPRO belong to maturation groups 6.2, 5.5, 6.1, 6.3, 5.8, and 5.8, respectively.

We applied glyphosate herbicide at a concentration of 1440 g ha^{-1} to the soil to reduce the density of competing weed species as the crop reached V3 to V4 phenological stages 40 d after emergence (DAE), and the weed was at the two-four leaves stage. We selected the season because of its suitability for applying herbicides post the emergence of genetically modified soybeans. The arrowleaf plants were protected using plastic cups and buckets to prevent herbicide damage. The application was performed using a precision CO_2-pressurized backpack sprayer equipped with four DG 110.02 spray tips, maintaining a constant pressure of 210 kPa and a travel speed of 3.6 km ha^{-1}, which provided a herbicide spray flow of 150 L ha^{-1}.

Evaluated variables and sampling

The quantification of the plant density (PD), leaf area (LA), soil cover (SC), and dry mass (DM) of the shoots of arrowleaf sida was performed 54 d after crop emergence.The number of plants present within two plots with an area of 0.25 m^2 (0.5 m × 0.5 m) per plot was counted to determine PD. SC was evaluated visually by two individual evaluators, using a percentage scale on which a score of zero corresponded to the absence of cover, and a score of 100 represented the total SC. A portable LA meter model, CI-203 BioScence, was used to determine the LA (cm^2 m^{-2}) by collecting the plants in the center of each experimental unit in an area of 0.25 m^2 (0.5 m × 0.5 m). To determine DM after measuring LA, arrowleaf sida plants were placed in kraft paper bags and dried in a forced-air circulation oven at 72°C until no further weight change occurred.

At the end of the soybean cycle, the grain yields of cultivars were determined by harvesting plants in an area of 6 m^2 (3 m × 2 m) for each experimental unit as the moisture content of grains reached approximately 15%. We determined the moisture content of grains by weighing them and correcting the obtained grain mass for a moisture content of 13%, which were then extrapolated for kg ha^{-1}. The soybean cultivars were harvested 130 d after sowing.

The percentage losses in the grain yield of soybean cultivars concerning experimental units free of competing plants were calculated using Equation 1:

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

where

Ra and Rb = the crop yields with and without the presence of the competing arrowleaf sida plants, respectively.

The values of DM (g m^{-2}), SC (%), and LA (cm^2) were multiplied by 100 before data analysis to eliminate the use of correction factors in the model (1, 29).

Statistical analysis

We determined the association between the percentages of grain yield loss and explanatory variables separately for each soybean cultivar using a nonlinear regression model derived from rectangular hyperbola proposed by Cousens (1985) according to Equation 2:

$$YL = \frac{(i * X)}{(1 + (\frac{i}{a}) * X)} \tag{2}$$

where

YL = yield loss (%)

X = PD, LA, SC and DM of arrowleaf sida.

i and a = the yield losses (%) per unit of the arrowleaf plant as the values of the variables approach zero and infinity, respectively.

Data adjustment for PD, SC, LA, and DM variables was performed using the Proc Nlin procedure of SAS to estimate the competitive ability and TL of the species using the mathematical modeling procedure (27). We used the Gauss-Newton method for estimating the values of parameters wherein the sum of the squares of deviations in observations for the adjusted values is minimized by successive iterations (1). The *F*-statistic value ($p \leq 0.05$) was used as the criterion for fitting the model to the data. The acceptance criterion for matching the model to the data was based on the highest coefficients of determination (R^2) and *F* values, and the lowest mean of squared residuals (MSR).

Parameter estimates obtained from the equation proposed by Cousens (1985) and adapted from Lindquist and Kropff (1996) were used to calculate the level of economic damage, i.e., TL (Equation 3).

$$TL = \frac{(Cc)}{(R * P * (\frac{i}{100}) * (\frac{H}{100}))} \tag{3}$$

where

TL = the threshold level (plants m^{-2})

Cc = the control cost of herbicide and tractor application (dollars ha^{-1})

R = the grain yield of soybean cultivars (kg ha^{-1})

P = soybean price (dollars kg^{-1} of grains)

i = yield loss (%) of soybean per unit of the competing plant as population level approaches zero

H = herbicide efficiency (%).

We estimated three values for variables Cc, R, P, and H (Equation 3). For Cc, we considered the average cost of tractor application, and the maximum and minimum costs were changed by 25% of this average cost. R was estimated based on the lowest, highest, and average yields obtained in Rio Grande do Sul over the last ten years (9). The soybean price P was estimated based on the lowest, highest, and average cost of soybeans paid per 60 kg bag in the last ten years (7). The values of H were established as 80, 90, and 100% of control, with 80% being the minimum weed control considered effective (27). For TL simulations, intermediate values were used for the uncalculated variables.

Results and discussion

Competitive ability of soybean cultivars with arrowleaf sida

The explanatory variables PD, LA, SC, and shoot DM of arrowleaf sida for all soybean cultivars exhibited significant *F* values (table 1).

The rectangular hyperbola model showed adjustments for all evaluated cultivars, with R^2 higher than 0.57 and low MSR values. Variations in data adjustment were observed in relation to the cultivar and studied variables, corroborated by results observed in literature for the rice competing with barnyardgrass (1), beans competing with alexandergrass (21), and soybeans competing with alexandergrass (19). Cargnelutti Filho and Storck (2007) considered the values of R^2 between 0.57 to 0.66 as moderate to good when working with the genetic variation, effect of cultivars, and heritability of corn hybrids, which partly agree with the results observed in this study.

Table 1. Rectangular hyperbola model adjustments obtained for loss of grain yield, as a function of plant density, soil cover, leaf area, and dry mass arrowleaf sida (*Sida rhombifolia*) and soybeans cultivars.

Tabla 1. Ajustes del modelo de hipérbola rectangular obtenidos por pérdida de rendimiento de granos, en función de la densidad de plantación, la cobertura del suelo, el área foliar y la masa seca de los cultivares de afata (*Sida rhombifolia*) y cultivares de soja.

Relative explanatory variables	Parameters[1]		R^2	MSR	F
	i	a			
Density of arrowleaf sida plants					
NS 6909 IPRO	2.74	54.62	0.60	40.13	54.84*
NA 5909 RG IPRO	2.74	47.43	0.69	144.80	9.55*
DM 5958 RSF	4.36	49.40	0.85	19.37	120.34*
Brasmax Elite IPRO	2.41	32.76	0.62	20.86	69.25*
Brasmax Lança IPRO	3.77	64.44	0.89	14.91	249.72*
SYN 13561 IPRO	5.35	48.57	0.84	31.73	99.74*
Soil cover from arrowleaf sida plants					
NS 6909 IPRO	1.14	81.70	0.60	40.13	54.84*
NA 5909 RG IPRO	0.01	41.43	0.84	24.50	22.29*
DM 5958 RSF	0.04	43.39	0.78	24.85	115.98*
Brasmax Elite IPRO	2.14	43.87	0.69	9.83	148.14*
Brasmax Lança IPRO	0.08	37.93	0.71	79.27	42.37*
SYN 13561 IPRO	0.04	49.27	0.70	39.30	79.76*
Leaf area of arrowleaf sida plants					
NS 6909 IPRO	0.12	54.10	0.83	26.37	77.24*
NA 5909 RG IPRO	0.22	42.49	0.90	75.93	23.20*
DM 5958 RSF	0.005	32.41	0.73	34.59	65.65*
Brasmax Elite IPRO	0.003	28.41	0.57	25.85	55.36*
Brasmax Lança IPRO	0.009	34.59	0.60	82.73	41.72*
SYN 13561 IPRO	0.005	46.34	0.70	46.34	80.94*
Dry mass of the aerial part of arrowleaf sida plants					
NS 6909 IPRO	0.21	25.98	0.94	95.96	19.72*
NA 5909 RG IPRO	0.04	40.37	0.78	76.03	21.80*
DM 5958 RSF	0.32	28.87	0.74	31.21	73.17*
Brasmax Elite IPRO	0.23	23.31	0.68	25.66	60.69*
Brasmax Lança IPRO	0.10	44.00	0.77	40.41	89.61*
SYN 13561 IPRO	0.32	33.60	0.61	49.04	63.13*

[1] *i* and *a*: losses in productivity (%) per arrowleaf sida unity when the value of the variable approaches zero and infinity, respectively, obtained by the rectangular hyperbolic model $Y= (i.X)/(1+(i/a).X$ (Cousens, 1985). *: Significant at $p \leq 0.05$. R^2: Determination coeficient. MSR: average square of residue.
[1] i y a: pérdidas de productividad (%) por unidad de afata cuando el valor de la variable se aproxima a cero o tiende a infinito, obtenido por el modelo de hipérbola rectangular $Y= (i.X)/(1+(i/a).X$ (Cousens, 1985); respectivamente * Significativo a $p \leq 0,05$ R^2: Coeficiente de determinación MSR: Cuadrado medio del residuo.

The results revealed that the estimated values for parameter *i* tended to be higher for soybean cultivars DM 5958 RSF, Brasmax Elite IPRO, and SYN 13561 IPRO compared with the average values of all evaluated variables, i.e., PD, SC, LA, and DM (table 1, page 99). Additionally, the cultivars NS 6909 IPRO, NA 5909 RG IPRO, and Brasmax Lança IPRO were verified to be highly competitive, presenting lower grain yield losses compared to other cultivars, with lower average values of *i*. These competitive differences may be related to genetic differences present in the cultivars determining characteristics such as crop cycle, maturation group, height, LA index, root system, and ramifications through which plants defend themselves during a shortage of resources, i.e., light, water, and nutrients in the environment. These results are consistent with those reported by Butts *et al*. (2018), who evaluated the competition of *Amaranthus tuberculatus* with soybeans, and observed a 35% reduction in shoot biomass when the crop was put into competition with different densities of three biotypes of the weed species. The study also reported the number of arrowleaf sida required to cause more than 20% losses in soybean grain yield. We discovered that the loss was already evident in seven plants m^{-2} for cultivar SYN 13561 IPRO (21.15%) and in eight plants m^{-2} for DM 5958 RSF IPRO (20.44%) and Brasmax Lança IPRO (20.54%).

The other cultivars tested in the presence of these numbers per square meter exhibited below 18.7% loss in yield (table 1, page 99). Similarly, Galon *et al*. (2019) assessed soybean yield loss demonstrating the differential tolerance of the crop as the cultivars SYN 1059 IPRO, BMX Elite IPRO, and NS 5445 IPRO lost a lower percentage of grains than the cultivars NS 5959 RG IPRO and SYN 13561 IPRO when competing with different alexandergrass densities. Thus, the specific capacity of cultivars to coexist and tolerate the presence of various weed species, i.e., arrowleaf sida or alexandergrass, is evident based on the intrinsic characteristics of each cultivar.

The results revealed that as arrowleaf sida doubled the size of its LA, increasing from 250 cm^2 m^{-2} to 500 cm^2 m^{-2}, the cultivars NS 6909 IPRO, NA 5909 RG IPRO, DM 5958 RSF, Brasmax Elite IPRO, Brasmax Lança IPRO, and SYN 13561 IPRO lost 32.3%, 21.8%, 48.3%, 50.0%, 46.9%, and 48.7% of grain yield, respectively (table 1, page 99). because the loss in grain yield resulted from the failure of soybean to fully shade the soil until 54 DAE, allowing more light penetration through the community canopy, rendering the crop less competitive than arrowleaf sida plants.

When a crop is shaded, competition for solar radiation increases, making the resource search less efficient. Consequently, it is less able to develop and grow, thus decreasing grain yield (25). Similar results were observed by Galon *et al*. (2019), who tested different soybean cultivars in competition with alexandergrass densities and found that increases in the LA of the weed increased yield loss. The yield loss results of the soybean cultivars in relation to the SC percentage were similar to those observed for PD and LA, that is, an increase in the SC percentage of the arrowleaf plants increased crop damage (table 1, page 99). All soybean cultivars exhibited a high percentage reduction in grain yield with increased weed SC. This is consistent with the explanation for PD and LA because the plant that exhibits higher values obtains the advantage of competition over its neighbor, primarily due to light resources. Consequently, it shows more intense growth and development, as previously discussed.

Studies on *Digitaria ciliaris*, *Echinochloa crus-galli* var. crus-galli, *Bidens pilosa*, *Euphorbia heterophylla*, *Urochloa plantaginea*, and *Sida rhombifolia* demonstrate the high competitiveness of these species with soybeans (2, 4, 19, 21, 25). The incidence of sunlight owing to low SC can stimulate the emergence of weeds. However, there was no increase in germination in the presence of light for arrowleaf sida because it is insensitive to this condition (16), which allows the species to establish under a wide range of environmental conditions, and thus compete with the crops.

Accumulating 100 g m^{-2} of DM, arrowleaf sida decreased the grain yield of cultivars NS 6909 IPRO, DM 5958 RSF, Brasmax Elite IPRO, and SYN 13561 IPRO by more than 11%, and that of NA 5909 RG IPRO and Brasmax Lança IPRO by less than 4%. (table 1, page 99). Additionally, the same authors mentioned that cultivars with high stature, rapid emergence, and greater accumulation of biomass in shoots are more competitive. Bean cultivars competing with alexandergrass (21) exhibited different competitive behaviors, which are probably related to their different intrinsic characteristics, such as growth habit, development cycle, number of branches, and volume of the root system, which affect the competitive ability of the crop and cause differentiation between the cultivars competing with weeds.

The parameter *i* is an index used to compare the relative competitiveness of species (1). Different *i* values were observed for the soybean cultivars for the tested explanatory variables (table 1, page 99). Other studies have also compared the competitiveness of corn cultivars (3), soybeans (18), rice (18), beans (21), and wheat (30). The comparison between the soybean cultivars in terms of explanatory variables (PD, LA, SC, and DM) showed that the order of competitiveness was NA 5909 RG IPRO > NS 6909 IPRO > Brasmax Lança IPRO > DM 5958 RSF > Brasmax Elite IPRO > SYN 13561 IPRO (table 1, page 99). The differences between the results are primarily due to different genetic characteristics or the occurrence of a high standard error in the estimation of *i*, which can be attributed to variability associated with field experimentation (1). Other studies reported similar results when verifying that rice cultivars competing with rice grass (1), beans (21), or soy (19) responded differently in terms of the evaluated parameters when infested with weeds.

For all explanatory variables, cultivars from the same growth cycle or maturation group had different i-values (table 1, page 99). This demonstrates that soybean cultivars respond differently to competition with arrowleaf sida, primarily because of the morphophysiological characteristics of the cultivars, which define their ability to compete with weeds for environmental resources (3). Another explanation is related to the different statures of the cultivars, important in the competition for light, affecting yield, depending on the stage at which shading occurs in relation to the definition of the yield components (25). According to these authors, shaded leaves receive less intense and reflected light, which causes a gradual decrease in photosynthetic rate as they approach the ground.

The estimates of *a*, regardless of the explanatory variable, were all less than 100% (table 1, page 99), demonstrating that it was possible to adequately simulate the maximum losses in soybean grain yield with different densities of arrowleaf sida. If crops have high productive potential and adequate conditions for soil fertility, water availability, and luminosity, a lower daily percentage loss will be caused by certain species of weeds (21).

The comparison between the evaluated explanatory variables for all soybean cultivars demonstrated a better fit of the model in the order PD > LA > SC > DM, considering the highest mean values of R^2 and F and the lowest mean values of MSR (table 1, page 99), indicating that PD can be used to replace the other variables to estimate soybean grain yield losses.

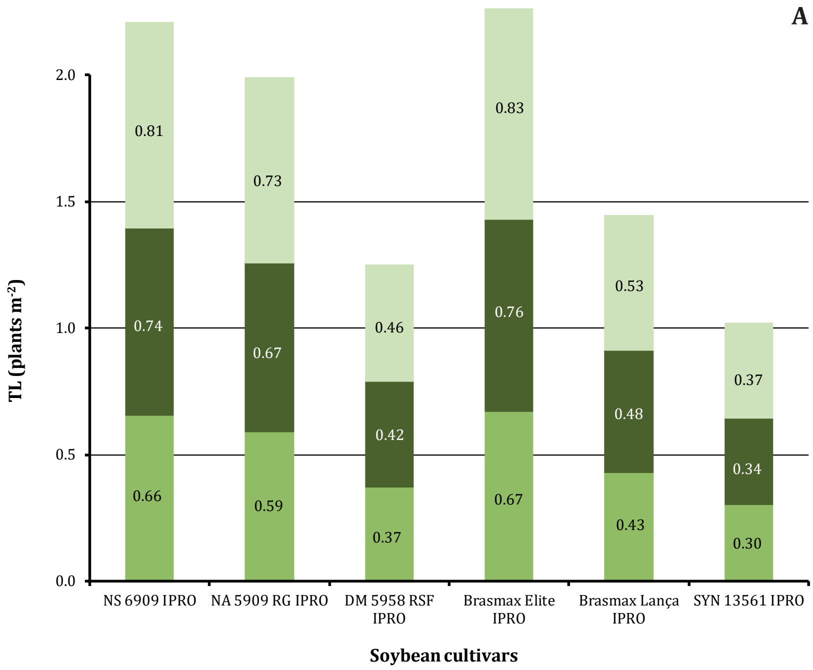
To simulate the TL values, the PD of the arrowleaf sida was used, as it exhibited the best fit for the rectangular hyperbola model. It is the most commonly used variable in experiments with this objective owing to its ease, speed, and low cost (1, 19, 21).

Economic damage level of arrowleaf sida in soybean

The successful implementation of management systems for arrowleaf sida in soybean fields can be achieved by determining the density that exceeds TL. We observed that the cultivars NS 6909, NA 5909 RG IPRO, and Brasmax Elite IPRO had the highest TL values in all performed simulations, ranging 0.50-0.95 plants m^{-2} (figure 2, page 102 and figure 3, page 103).

The lowest TL values were obtained for cultivars DM 5958 RSF, Brasmax Elite IPRO, and SYN 13561 IPRO, ranging 0.26-0.61 plants m^{-2}. This is probably due to the lower initial growth speed or because they are very productive cultivars, and thus, are more sensitive to competition with weeds, even at low densities. According to Balbinot Jr. and Fleck (2005), cultivars that present a high growth rate at the beginning of the cycle and appropriate plant characteristics, especially stature, suffer less competition with weeds. Galon *et al.* (2019) also observed that soybean cultivars that presented the highest grain yields suffered the most competition with alexandergrass, that is, the lowest number of plants m^{-2} was necessary to reach the TL.

In the average of all soybean cultivars, there was a difference in TL of approximately 24% when comparing the lowest with the highest grain yields (figure 2A, page 102). Therefore, the higher the productive potential of the cultivars, the lower the density of arrowleaf plants required to overcome TL, making the adoption of control measures worthwhile. When evaluating the TL for alexandergrass infesting bean (21) and soybean (19) cultivars, it was observed that it varied depending on the evaluated cultivars, and those with the greatest productive potential demonstrated a smaller TL.



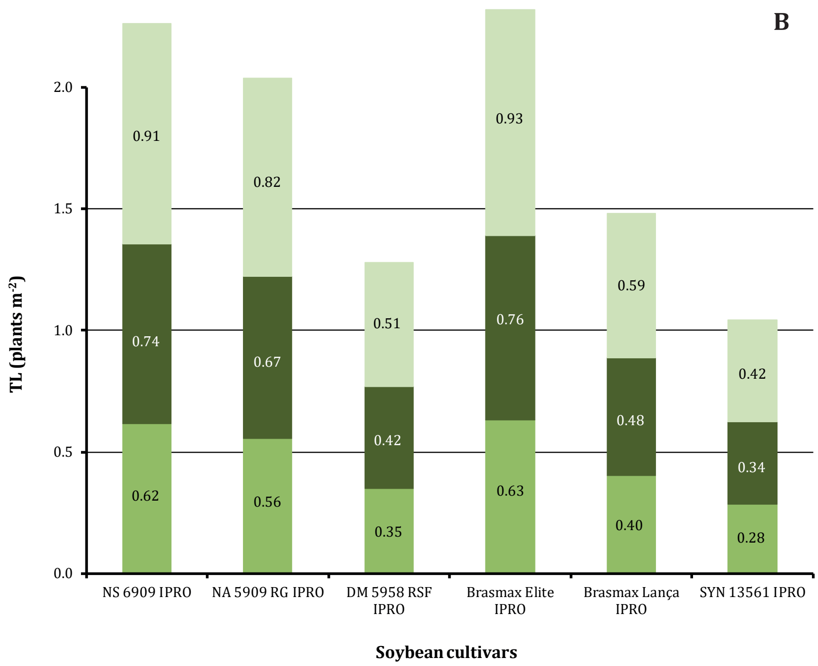


Figure 2. Threshold level (TL) of arrowleaf sida (*Sida rhombifolia*) as a function of soybean grain yield (A) and price of cultivars (B). UFFS, Erechim-RS, 2018.

Figura 2. Nivel de daño económico (TL) de escoba dura (*Sida rhombifolia*) en función del rendimiento de granos (A) y del precio (B) de soja cultivares. UFFS, Erechim-RS, 2018.

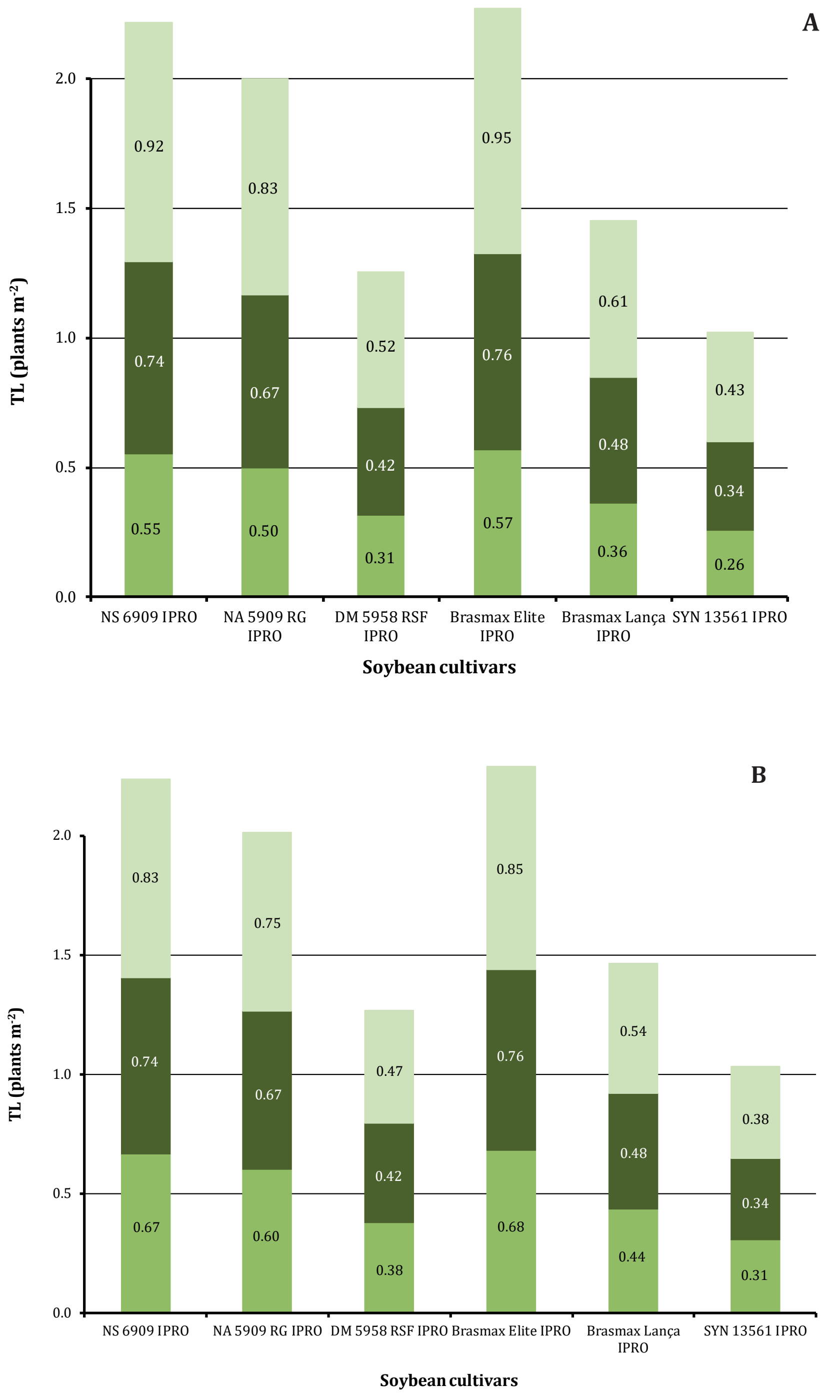


Figure 3. Threshold level (TL) of arrowleaf sida, *Sida rhombifolia*, as a function of control cost (A) and herbicide efficiency (B) and soybean cultivars. UFFS, Erechim-RS, 2017/18.

Figura 3. Nivel de daño económico (TL) de escoba dura (*Sida rhombifolia*) en función del costo de control (A) y de la eficiencia de los herbicidas (B) y de cultivares. de cultivares. UFFS, Erechim-RS, 2017/18.

The average results for all soybean cultivars with the highest versus the lowest price paid per bag exhibited 1.47 times higher variation in TL (figure 2B, page 102). Therefore, the lower the price paid per bag of soybeans, the higher the population of arrowleaf sida needed to overcome TL, thus compensating for the control method. Tavares *et al*. (2019) and Galon *et al.* (2019) reported similar results concerning the price paid per bag of wheat and soybean, respectively, corroborating the findings of this study.

The minimum cost for the average arrowleaf sida cost to control in all cultivars was 40.14% lower when compared with the maximum cost. Thus, the higher the cost of the control method, the higher the TL and the more arrowleaf sida plants per square meter needed to justify the control measures (figure 3A, page 103). The use of TL as a tool for weed management is only justified in farms that use good agricultural practices for soybean management, such as crop rotation, proper plant arrangement, use of more competitive cultivars, adequate sowing times, and correct soil fertilization.

For the efficiency of chemical control with herbicides, there were changes in the TL of 12.28 and 11.76% when comparing the average efficiency (90%) with the lowest (80%) and the highest (100%), respectively (figure 3B, page 103). Therefore, the control level influences TL, and the more efficient the herbicide, the lower the TL (the smaller the number of arrowleaf sida per square meter necessary to adopt the control measures). This was also verified by Agostinetto *et al*. (2010) and Galon *et al*. (2019), who applied herbicides to control barnyard grass and alexander grass in irrigated rice and soybean crops, respectively. Song *et al*. (2017) obtained TL of five common weed species assuming a 90% efficiency of the herbicide for the studied region of 0.70 plants m^{-2} as a threshold to control them in a soybean field, which corroborates with the results of this study.

Although the soybean cultivars differed from each other, the TL values indicated that the control was justified in low weed populations, even in situations where the soybean bag value was the lowest, exhibiting the high competitive capacity of this weed and the need to manage it to avoid losses. Konzen *et al*. (2021) reported that arrowleaf sida, when competing with soybean cultivars, reduced the dry mass and leaf area of crop plants, with interspecific competition being more harmful than intraspecific competition.

Considering the average soybean yield of 2,760 kg ha^{-1} for the last 10 years in the state of Rio Grande do Sul (9), an average price of $18.87 per 60 kg bag, and arrowleaf sida Cc of $17.07 ha^{-1}, we estimated that these costs were equivalent to 1.96% of production costs. The presence of 1 plant m^{-2} arrowleaf sida caused yield losses of 2.36%, 2.59%, 4.00%, 2.24%, 3.56%, and 4.85% in soybean cultivars NS 6909 IPRO, NA 5909 RG IPRO, DM 5958 RSF, Brasmax Elite IPRO, Brasmax Lança IPRO, and SYN 13561 IPRO, respectively, (table 1, page 99), and all cultivars exhibited losses higher than the control cost. These results indicate that arrowleaf sida are very competitive, even in low populations, and control measures that eliminate up to 99% of the infestation may not be sufficient to avoid losses in soybean grain yield.

When prices of agricultural products are high compared to the usual prices, the adoption of weed control measures with 100% effectiveness becomes important. Thus, even if only a few weeds remain in a given area, they will cause remarkable economic losses considering the product value, and small grain yield losses will result in a significant decrease in profits. Any stress can potentially be economically harmful.

Conclusions

The nonlinear regression model of the rectangular hyperbola adequately estimated the grain yield losses of NS 6909 IPRO, NA 5909 RG IPRO, DM 5958 RSF, Brasmax Elite IPRO, Brasmax Lança IPRO, and SYN 13561 IPRO soybeans in the presence of increasing arrowleaf sida densities and exhibited the best fit for the variable density of the arrowleaf sida plants. The soybean cultivars NS 6909 IPRO, NA 5909 RG IPRO, and Brasmax Lança IPRO were more competitive than DM 5958 RSF, Brasmax Elite IPRO, and SYN 13561 IPRO considering the explanatory variables (PD, LA, SC, and DM). The TL values varied from 0.55 to 0.95 plants m^{-2} for cultivars NS 6909 IPRO, NA 5909 RG IPRO, and Brasmax Lança IPRO, which proved to be more competitive with arrowleaf sida. The lowest TL values ranged 0.26-0.61 plants m^{-2} for the cultivars DM 5958 RSF, Brasmax Elite IPRO, and SYN 13561 IPRO, which had less competitive potential with weeds. The TL values decreased with an increase in grain yield and price of soybeans, a reduction in the cost of controlling arrowleaf sida, and herbicide efficiency, which justifies the adoption of control measures at lower weed densities.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

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