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Interference and economic damage level of volunteer corn plants in soybeans

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ABSTRACT: Volunteer corn plants have infested crops sown in succession, causing yield losses. The objective of this study was to evaluate the competitive ability and economic damage level (EDL) of soybean cultivars infested by volunteer corn plants. The experiment was conducted in a randomized block design with one replication. The treatments consisted of six soya cultivars and 12 densities of volunteer corn, hybrid Syngenta 488 Vip 3, established for each cultivar, with a minimum of 0 and a maximum of 130 plants m^{-2}. At 30 days after emergence, the plant density, ground cover, leaf area and dry mass of the aerial part of the volunteer corn plants were quantified. In soybeans, grain yield, control cost, bag price and control efficiency were determined. Dry mass was the variable that best fitted the rectangular hyperbola model. The soybean cultivars Nidera 5909 RG, Syngenta 13561 IPRO and Brasmax Lança IPRO showed greater competitive ability and EDL values of 0.07 to 0.20 plants m^{-2} in the presence of volunteer corn. The lowest EDL values ranged from 0.02 to 0.12 plants m^{-2} for the cultivars Dom Mario 5958 RSF IPRO, Nidera 6909 IPRO and Brasmax Lança IPRO, which were the least competitive.

Key words: *Glycine max*; *Zea mays*; weed

Interferência e nível de dano econômico de plantas voluntárias de milho em soja

RESUMO: Plantas voluntárias de milho tem infestado culturas semeadas em sucessão, ocasionando perdas de produtividades. Diante disso, objetivou-se com o trabalho avaliar a habilidade competitiva e o nível de dano econômico (NDE) de cultivares de soja infestada por plantas de milho voluntário. O experimento foi conduzido a campo, em delineamento de blocos casualizados, com uma repetição. Os tratamentos foram constituídos por seis cultivares de soja e 12 densidades de milho voluntário, híbrido Syngenta 488 Vip 3, estabelecidas para cada cultivar, com o mínimo de 0 e máximo de 130 plantas m^{-2}. Aos 30 dias após a emergência, efetuou-se a quantificação da densidade de plantas, cobertura de solo, área foliar e massa seca da parte aérea das plantas voluntárias de milho. Na soja, determinou-se a produtividade de grãos, custo de controle, preço da saca e eficiência de controle. A massa seca foi a variável que apresentou melhor ajuste ao modelo da hipérbole retangular. As cultivares de soja Nidera 5909 RG, Syngenta 13561 IPRO e Brasmax Lança IPRO apresentaram maior habilidade competitiva e valores de NDE de 0,07 a 0,20 plantas m^{-2} na presença do milho voluntário. Os menores valores de NDE variaram de 0,02 a 0,12 plantas m^{-2}, para as cultivares Dom Mario 5958 RSF IPRO, Nidera 6909 IPRO e Brasmax Lança IPRO, sendo que essas apresentaram a menor competitividade.

Palavras-chave: *Glycine max*; *Zea mays*; planta daninha

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Introduction

The sowing of crops after corn has increased in recent years in Brazil, especially in the southern region of Brazil and in the state of Rio Grande do Sul. During the corn harvest, there are many losses of grains and cobs that can give rise to new plants. They compete with the crop of economic interest for water, light and nutrients (Petter et al., 2016; Aguiar et al., 2018). These plants come from grain losses at harvest called volunteer plants or tigueras (Piasecki et al., 2018; Galon et al., 2022). In addition to competing for resources in the environment, volunteer plants can be hosts to pests and diseases that affect crops of economic interest (Aguiar et al., 2018; Piasecki et al., 2018). The high adoption of herbicide-resistant corn cultivars has made it difficult to control and favors the permanence of these plants in the area (Piasecki et al., 2018).

Grain losses in Brazilian corn crops range from 71 to 178 kg ha^{-1} (Paulsen et al., 2014). This fact demonstrates the challenge faced by growers and illustrates the potential damage these plants can cause. Volunteer corn can reduce soybean yields by approximately 16% when it occurs at a density of 0.5 plants m^{-2} (Piasecki et al., 2018).

Estimates of crop yield losses when infested by weeds can be made using mathematical models (Agostinetto et al., 2010; Kalsing & Vidal, 2013; Tavares et al., 2019). Cousens (1985) created the rectangular hyperbola model that relates grain yield loss to weed densities. This author adjusted an empirical model that makes it possible to predict yield loss as a function of weed density, obtaining results that demonstrated the superiority of this model over others that have been tested for similar purposes.

Volunteer plants can appear in crops at lower densities than true weeds. It is therefore important for growers to assess and analyze the cost of control or even quantify the damage that these can cause to crops of economic interest. When they occur in high densities, it simplifies the decision for producers to adopt control measures (Agostinetto et al., 2010). However, when they appear in lower densities, adopting control measures becomes difficult, as farmers need to quantify the economic advantages associated with the cost of control (Tavares et al., 2019; Galon et al., 2022). Faced with this situation, it is necessary to implement management strategies that integrate technical knowledge and economic analysis, together with an understanding of the competitive relationship between crops and weeds (Jha et al., 2017). Determining the economic damage level (EDL) is important to assist the producer in making this decision.

The EDL establishes that the application of herbicides or other control methods is only justified if the damage caused by the weeds is greater than the cost of the measure used (Piasecki et al., 2018; Tavares et al., 2019). Calculating EDL involves many variables that can be influenced by various factors, such as: weed species, density and time of emergence of the weeds in relation to the crop, percentage loss and yield potential of the crop in the presence and absence of weeds, value of the harvested product, costs and efficiency of control, and influence of the remaining weeds on the product (Agostinetto et al., 2010; Brandler et al., 2021). Management practices such as the use of cultivars with greater competitive ability and sowing densities can directly influence the level of losses caused by coexistence with weeds.

Thus, the hypothesis presented in this study is that soybean cultivars may show differences in competitive ability and, consequently, variations in EDL caused by competition with volunteer corn. In view of the above, the objective of this study was to evaluate the competitive ability and EDL of six soybean cultivars infested by 12 plant densities of volunteer corn, hybrid Syngenta 488 Vip 3.

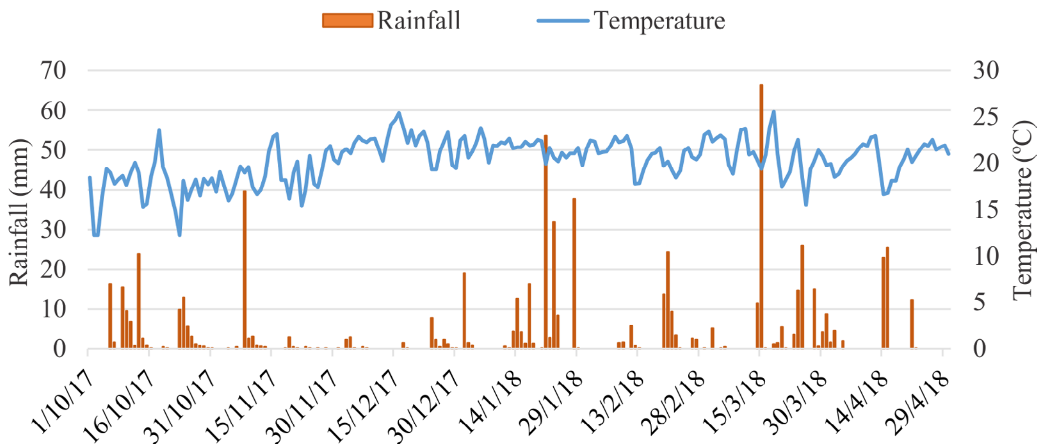
Materials and Methods

The experiment was conducted in the field, in the experimental area of the Universidade Federal da Fronteira Sul (UFFS), Campus Erechim/RS, Brazil, latitude 27.725269° S, longitude 52.294485° W and altitude 650 m, from October 2017 to March 2018. The soil in the experimental area is classified as Latossolo Vermelho Aluminoférrico Húmico (Santos et al., 2018). Soil samples were taken from the 0 to 10 cm layer for chemical analysis, with the following characteristics: pH (water) = 5.1; organic matter = 3.0%; clay = > 60%; P = 5.2 mg dm^{-3}; K = 118.0 mg dm^{-3}; Ca^{+2} = 5.5 $cmol_c$ dm^{-3}; Mg^{+2} = 3.0 $cmol_c$ dm^{-3}; Al^{+3} = 0.3 $cmol_c$ dm^{-3}; H + Al = 7.7 $cmol_c$ dm^{-3}; and, Effective CEC = 16.6 $cmol_c$ dm^{-3}. Fertility correction was carried out in accordance with the technical recommendations for growing soybeans for grain production (SBCS, 2016). The base chemical fertilizer was 433 kg ha^{-1} of the 05-20-20 N-P-K formula. The other managements followed the technical recommendations for the soybean crop.

The environmental conditions at the time of the experiment are shown in Figure 1. The region climate is classified as Cfa (humid temperate with hot summers) according to the Köppen-Geiger classification, in which rainfall is well distributed throughout the year (Peel et al., 2007).

The experiment was conducted in a randomized block design, with the treatments consisting of six soybean cultivars and 12 densities of volunteer corn hybrid Syngenta 488 Vip 3, simulating harvest losses, with one replication. In this research, the different densities of volunteer corn acted as replicates, providing the variance needed to carry out the statistical analysis using the non-linear rectangular hyperbola model proposed by Cousens (1985). This same methodology has been used in several other studies developed with a similar objective to the present study, to assess the competitive ability of cultivars and the economic damage level of weeds infesting crops (Agostinetto et al., 2010; Tavares et al., 2019; Brandler et al., 2021; Galon et al., 2022).

The soybean cultivars used in the experiment were Nidera 5909 RG, Brasmax Elite IPRO, Syngenta 13561 IPRO, Dom



Source: INMET (2023).

Figure 1. Average temperature (°C), rainfall (mm), and relative air humidity (%) during the experiment period from October 2017 to April 2018. UFFS/Erechim/RS, 2023.

Mario 5958 RSF IPRO, Nidera 6909 IPRO and Brasmax Lança IPRO, which coexisted with different densities of volunteer corn, as described in Table 1.

The soybean cultivars were selected for this study because they are the most widely grown in the region for grain production, with the following characteristics: a) Nidera 5909 RG: indeterminate growth habit, early cycle, maturity group 6.2, resistant to insects and tolerant to herbicides; b) Brasmax Elite IPRO: indeterminate growth habit, early cycle, maturity group 5.5, resistant to insects and tolerant to herbicides; c) Syngenta 13561 IPRO: indeterminate growth habit, medium-early cycle, maturity group 6.1, resistant to insects and tolerant to herbicides; d) Dom Mario 5958 RSF IPRO: indeterminate growth habit, medium cycle, maturity group 5.8, resistant to insects and tolerant to herbicides; e) Nidera 6909 IPRO: indeterminate growth habit, medium cycle, maturity group 6.3, resistant to insects and tolerant to herbicides; and f); Brasmax Lança IPRO: indeterminate growth habit, medium cycle, maturity group 5.8, resistant to insects and tolerant to herbicides.

The experiment was set up on October 30, 2017, in a no-till system. The soil was mulched with black oats + vetch, producing 5.00 t ha^{-1} of dry mass. Desiccation was carried out with the herbicide glyphosate (1,440 g a.e. ha^{-1}) 15 days before sowing the soybeans. The experimental units had an area of 15.00 m^2 and consisted of six rows of soybeans, spaced 0.50 m apart and 5.00 m long. The useful area corresponded to 8.00 m^2, i.e. four central rows, excluding one row on each side and 0.50 m at each end (2.00 × 4.00 m). The density of soybean plants sown for each cultivar was 250,000 ha^{-1}.

The densities of volunteer corn were established by manual sowing in each plot using the hybrid Syngenta 488 Vip 3. The densities of volunteer corn were established in order to simulate different harvest losses, from low to high amounts of grain lost in the field, by calculating the amount of seeds needed in each experimental unit according to the proposed treatment, from 0 to 21.5 plants m^{-2}. The densities of volunteer corn varied due to the fact that sowing with a hand-held seed drill has uneven depths from one hole to the next, due to the soil sometimes being more compacted, having more straw, among other things, and so factors such as soil humidity and temperature may have influenced the establishment of an exact number of plants per area (experimental unit).

The densities of volunteer corn were determined by counting in two 0.50 × 0.50 m areas, one measurement being taken in the center and the other on the side of each experimental unit, when the soybean was in the V2 to V3 stage and the weed (volunteer corn) was in the V4 to V5 stage (four to five developed leaves). The remaining weeds not subject to study were controlled with the application of glyphosate (1,440 g a.e. ha^{-1}) to avoid competition.

Quantification of plant density (PD), ground cover (GC), leaf area (LA) and the dry mass of the aerial part (DM) of volunteer corn plants was carried out at 35 days after emergence (DAE) or at the V2 to V3 phenological stage of the soybean. To determine the explanatory variable PD, two

Table 1. Soybean cultivars and volunteer corn densities, hybrid Syngenta 488 Vip 3 (plants m^{-2}) used in the experiment. UFFS, Campus Erechim, agricultural year 2017/18.

Cultivars	Densities of volunteer corn (m^2)
Nidera 5909	0.0, 3.5, 7.0, 7.0, 8.5, 10.0, 10.5, 13.5, 14.0, 17.0, 20.0 and 20.5
Brasmax Elite IPRO	0.0, 3.0, 4.5, 6.0, 6.5, 7.5, 7.5, 9.0, 10.0, 10.0, 10.5 and 12.0
Syngenta 13561 IPRO	0.0, 1.0, 1.5, 8.5, 9.0, 9.5, 10.0, 10.5, 12.0, 12.0, 16.5 and 17.5
Dom Mario 5958 RSF IPRO	0.0, 2.5, 4.0, 5.0, 5.0, 6.0, 8.5, 9.0, 10.0, 11.5, 12.5 and 16.5
Nidera 6909 IPRO	0.0, 3.0, 3.0, 5.0, 8.5, 10.5, 11.0, 12.0, 13.5, 15.5, 16.5 and 21.5
Brasmax Lança IPRO	0.0, 5.0, 5.5, 6.0, 7.0, 7.5, 8.5, 10.0, 10.5, 13.0, 13.5 and 13.5

random samples were taken per plot using a 0.50 m square. The GC by volunteer corn plants was assessed visually, individually, by two assessors, using a percentage scale, in which a score of zero corresponds to no coverage and 100 represents total soil coverage. The competing plants LA was quantified using a portable electronic LA integrator, model CI-203, brand CID Bio-Science, measuring all the plants in 0.25 m^{-2} per plot. The DM of volunteer corn (g m^{-2}) was determined by collecting the plants contained in an area of 0.25 m^2 (0.5 × 0.5 m) per plot and drying them in a forced air circulation oven at a temperature of 60 ± 5 °C until they reached a constant mass.

The grain yield was quantified by harvesting the plants in the 8.00 m^2 (2.00 × 4.00 m) area of each plot. The grains were harvested when their average moisture content reached approximately 15%. After weighing, their moisture content was determined, with the masses corrected to 13% moisture content and the values expressed in kg ha^{-1}.

The percentage losses in soybean yield in relation to the experimental units free of competing plants were calculated according to Equation 1:

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

where: Ra and Rb - crop yield without or with the presence of the competing plant, volunteer corn, respectively.

Before analyzing the data, the values of DM (g m^{-2}), GC (%) or LA (cm^2) were multiplied by 100, thus dispensing with the use of the correction factor in the model (Agostinetto et al., 2010; Tavares et al., 2019).

The relationships between percentage losses in soybean yield as a function of the explanatory variables were calculated separately for each cultivar, using the non-linear regression model derived from the rectangular hyperbola proposed by Cousens (1985), as shown in Equation 2:

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

where: Yl - yield losses (%); X - PD, GC, LA and DM of volunteer corn; i and a - yield losses (%) per unit of volunteer corn plants when the value of the variable approaches zero and when it tends to infinity, respectively. For the calculation procedure, the Gauss-Newton method was used, which, through successive iterations, estimates parameter values in which the sum of the 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 the criterion for analyzing the models data. The criterion for accepting the fit of the data to the model was based on the significance of the F, the highest value of the coefficient of determination (R^2) and the lowest value of the mean square of the residual (MSR).

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

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

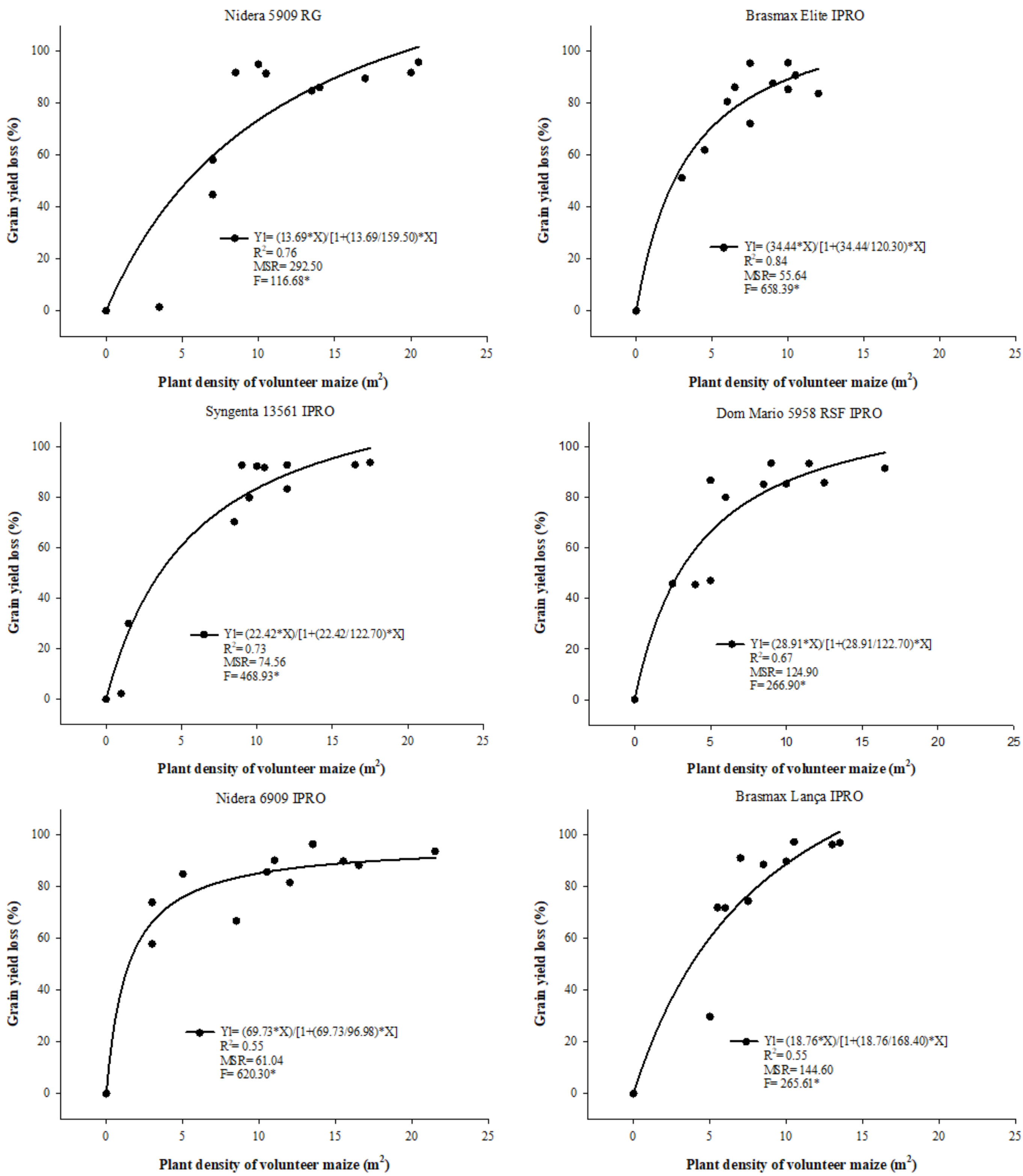
where: EDL - economic damage level (plants m^{-2}); Cc - cost of control (commercial mixture of herbicides, clethodim - 108 g ha^{-1} + mineral oil (0.5% v/v) and tractor ground application, in dollars ha^{-1}); R - soybean grain yield (kg ha^{-1}); P - price of soybeans (dollars kg^{-1} of grains); i - yield loss (%) of soybeans per unit of competing plant, when the population level approaches zero; and, H - level of herbicide efficiency (%).

For the variables Cc, R, P and H (Equation 3), three values occurring in the last 10 years were estimated. Thus, for the control cost (Cc), the average price was considered, with the maximum and minimum cost being altered by 25% in relation to the average cost. Soybean grain yields (R) were based on the lowest, average and highest quantities obtained in Brazil over the last 10 years. The price of the product (P) was estimated based on the lowest, average and highest soybean prices paid at 60 kg over the last 10 years. The values for the efficiency of the herbicide (H) have been established in the order of 80, 90 and 100% of control, with 80% being the minimum control considered effective for the weed (Velini et al., 1995). For the EDL simulations, intermediate values were used for the variables that were not being calculated.

Results and Discussion

The explanatory variables of volunteer corn (PD, LA, GC and DM) evaluated for yield loss in soybean cultivars showed significant F-statistic values (Figures 2, 3, 4 and 5). The rectangular hyperbola model fitted the data adequately, with an average R^2 value of over 0.55 and a low MSR. This indicates a good fit (R^2) of the data to the rectangular hyperbola model and low variability (MSR). The results are similar to those observed by Galon et al. (2022), when evaluating competition and the EDL of guanxuma (*Sida rhombifolia*) infesting six soybean cultivars, found average R^2 values of over 0.57 for the same variables studied in this study and low MSR values.

The soybean cultivars showed different levels of losses in grain yield due to the infestation of varying densities of volunteer corn (Figures 2, 3, 4 and 5). Taking into account the average of the i parameter for the PD, GC, LA and DM variables, the cultivars Nidera 5909 RG, Syngenta 13561 IPRO and Brasmax Lança IPRO were characterized as the most competitive materials in the presence of volunteer corn. Studies indicate that soybean cultivars differ in their ability to compete in the presence of weeds (Forte et al., 2017; Souza et al., 2019; Galon et al., 2022). This is probably due to the

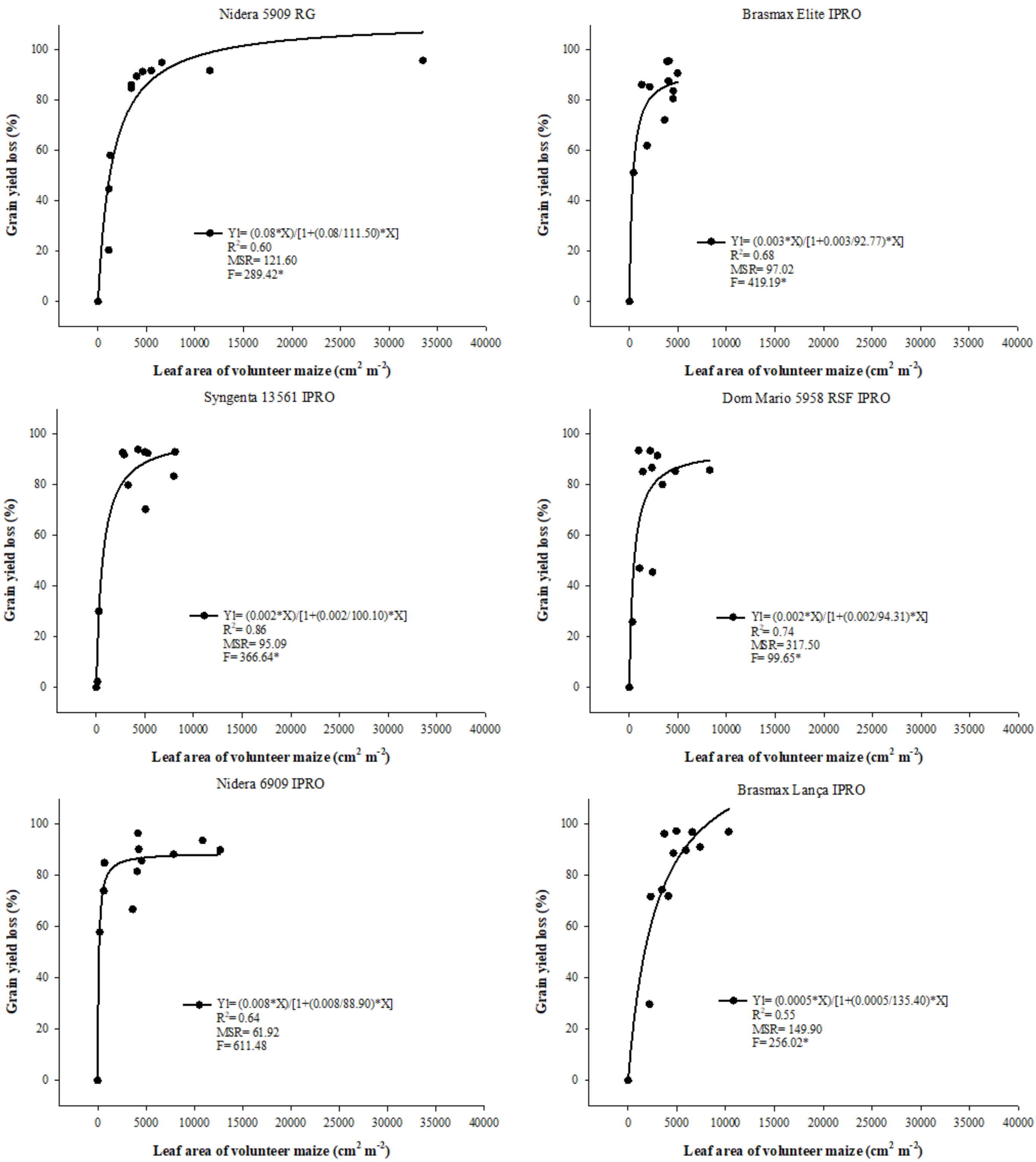


R^2 - Coefficient of determination; MSR - Mean square of the residual; * Significant at $p \leq 0.05$.

Figure 2. Yield loss (Yl) of soybeans as a function of cultivars and the density of volunteer corn plants (m^2) in competition at 35 days after emergence. UFFS, Erechim/RS, 2017/18.

genetic differentiation between the materials evaluated. The difference in competitive ability between the cultivars can be attributed to the higher leaf area index, plant architecture, height, cycle, growth rate and efficient use of environmental resources by the crop (Forte et al., 2017; Souza et al., 2019).

The competition imposed by genetic material is an important tool for integrated weed management. More competitive cultivars can reduce the use of herbicides, resulting in less environmental pollution, safer food production and lower costs (Jha et al., 2017; Tavares et al., 2019).

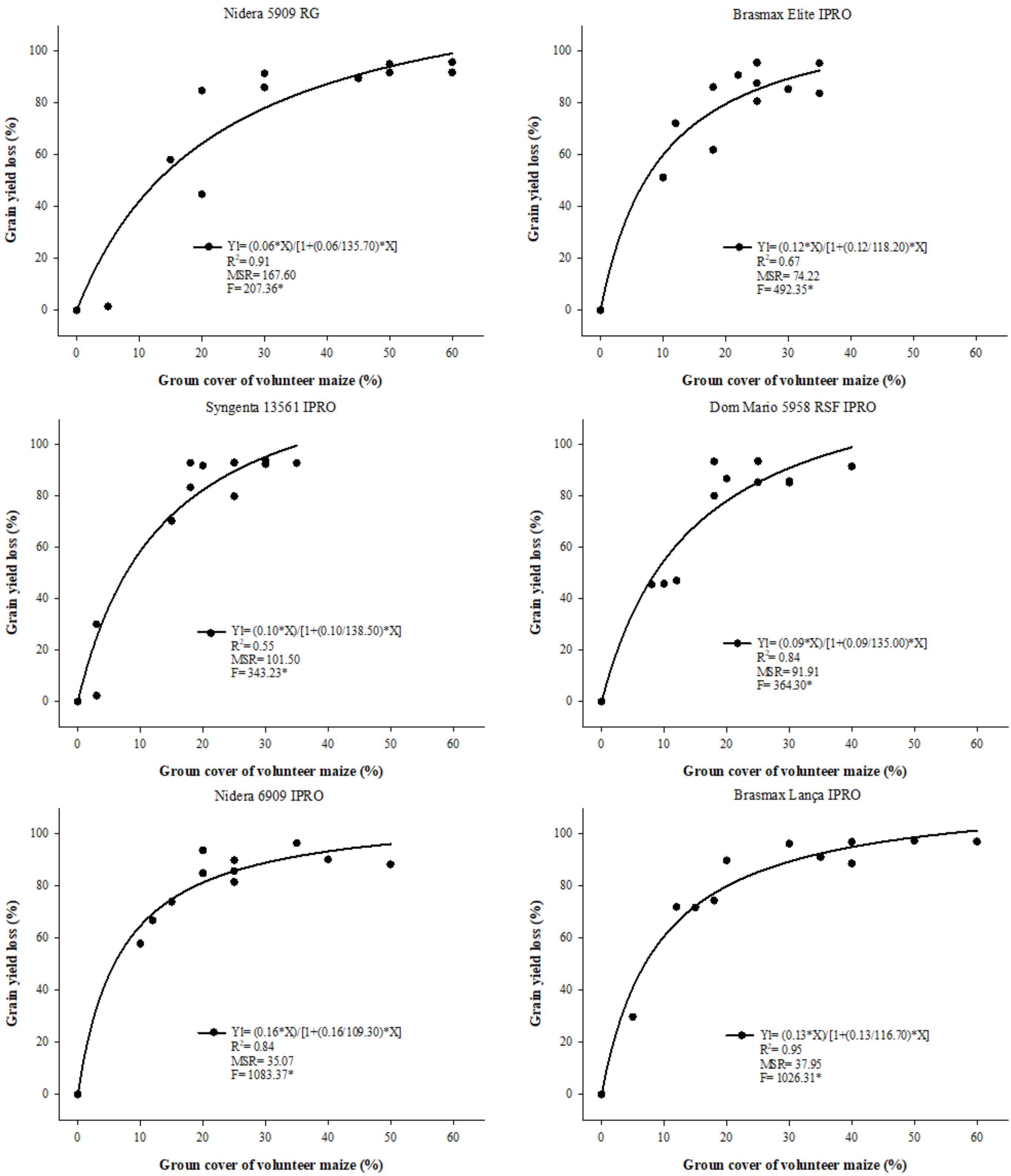


R^2 - Coefficient of determination; MSR - Mean square of the residual; * Significant at $p \leq 0.05$.

Figure 3. Yield loss (Yl) of soybeans as a function of cultivars and leaf area (cm^2 m^{-2}) of volunteer corn plants (m^2) in competition at 35 days after emergence. UFFS, Erechim/RS, 2017/18.

There were minimum and maximum losses, respectively, of 12.61 to 40.56% in the yield of soybean cultivars when they were infested by 1 plant m^{-2} of volunteer corn (Figure 2). This demonstrates the different competitive ability of soybean cultivars and that volunteer corn, even at low densities, can cause major yield losses. At a density of 5 plants m^{-2} of volunteer corn, soybean cultivars suffered yield losses of more than 75%.

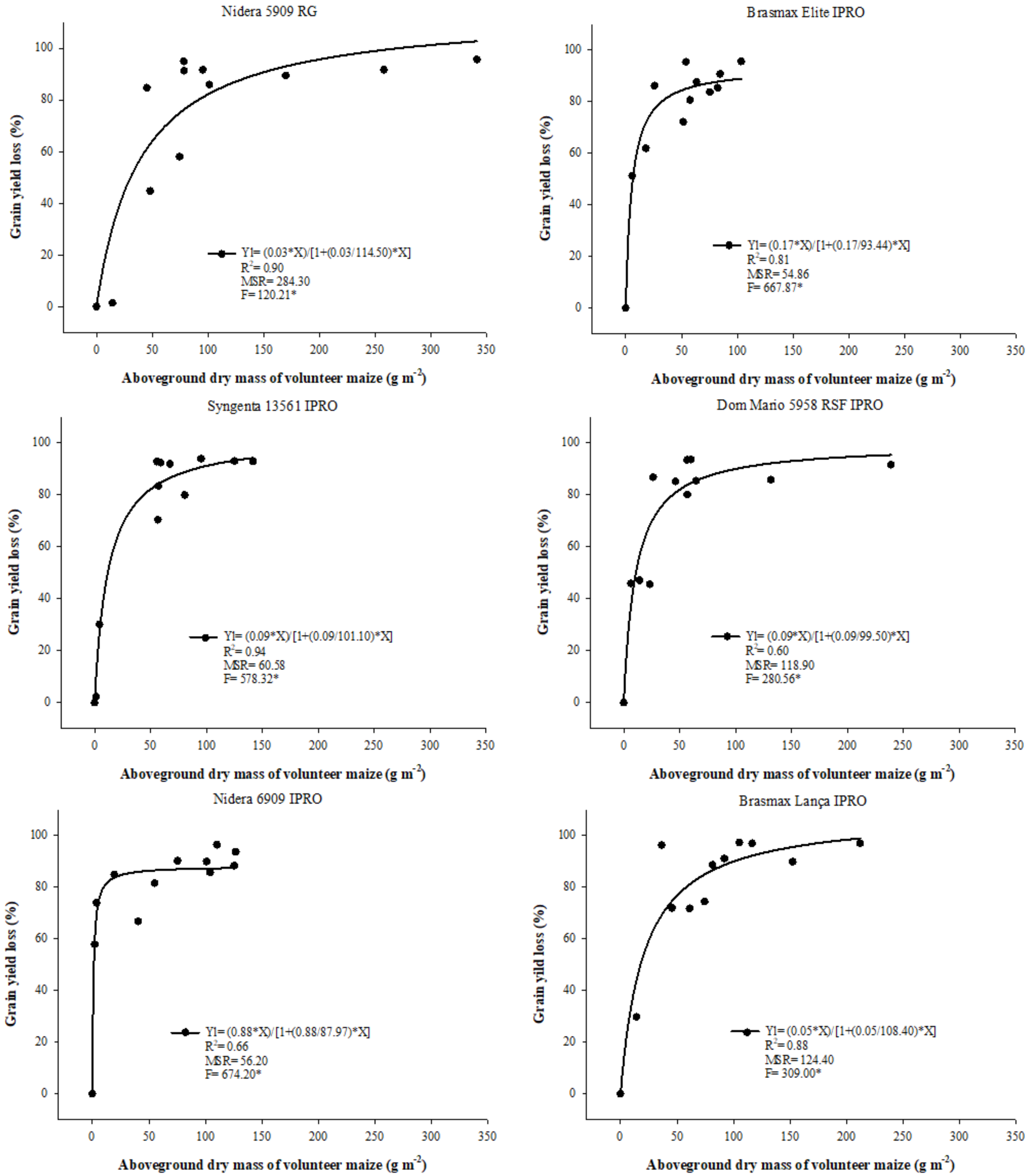
The high level of losses may be associated with the fact that corn has a higher initial relative growth rate and is more efficient at using the environments resources (water, light, nutrients and CO_2). This set of factors justifies the suppression



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

Figure 4. Yield loss (Yl) of soybeans as a function of cultivars and ground cover (%) of volunteer corn plants (m^2) in competition at 35 days after emergence. UFFS, Erechim/RS, 2017/18.

of soybeans (Silva et al., 2012; Pierik & Ballaré, 2021). If we consider the tolerable loss of corn grains by harvesting with a self-propelled harvester to be 90 kg ha^{-1} (Mantovani, 2021) and the average weight of 1,000 corn grains to be approximately 342 g (Bianchetto et al., 2017), we have a quantity of grains corresponding to 90,000 ha^{-1}. Assuming a germination rate of 50%, you have 45,000 corn plants ha^{-1} or 4.50 plants m^{-2}. This demonstrates the potential for yield losses in the soybean crop



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

Figure 5. Yield loss (Yl) of soybeans as a function of cultivars and dry mass of the aerial part (g m^{-2}) of volunteer corn plants (m^2) in competition at 35 days after emergence. UFFS, Erechim/RS, 2017/18.

if volunteer corn control is inadequately carried out. In this way, reducing losses during the harvesting of corn will lead to greater economic returns by increasing the yield of this crop and reducing the potential for losses due to competition with soybeans or other crops sown in succession to corn.

Other studies have also reported a negative effect on the soybean crop when it was infested by 0.5 to 1.00 plants m^{-2} of volunteer corn, with losses in grain yield of more than 10% (Aguiar et al., 2018; Piasecki et al., 2018), or 33% when the UFUS Capim Branco and UFUS Carajás cultivars were infested by various weed species (Souza et al., 2019).

The results show soybean yield losses of 87.19 and 27.59% for the cultivars Nidera 5909 RG and Nidera 6909 IPRO, respectively, when taking into account the accumulation of 5,000 cm^2 m^{-2} of volunteer corn of LA (Figure 3). It is therefore clear that the degree of competition between volunteer corn and soybeans is influenced by the weeds leaf area. These two soybean cultivars have a higher maturity group than the others, characterized by values of 6.2 and 6.3, respectively. Soybean cultivars with later maturity groups have less competitive ability in the presence of weeds than early cultivars (Souza et al., 2019). This behavior may be mainly related to the relative growth rate, which directly influences the speed at which the canopy closes, suppressing weed growth. In this way, cultivars with an earlier cycle exert more effective cultural control than those with a later cycle, also limiting the germination of new plants due to the faster shading of the soil.

The results for yield loss, in relation to the percentage of GC and DM (Figures 4 and 5), are similar to those observed in relation to PD and LA (Figures 2 and 3). The cultivars Nidera 5909 RG, Syngenta 13561 IPRO and Brasmax Lança were the most competitive, showing the lowest yield losses. The increase in LA, GC and DM of volunteer corn is directly related to PD. This fact contributes to explaining the similarity in yield losses when taking into account the i parameter of each of the variables studied. Among the factors linked to this interference imposed by weeds is competition for environmental resources, which can lead to crop yield losses (Jha et al., 2017; Piasecki et al., 2018; Galon et al., 2022).

Considering the i parameter as an indicative index for comparing relative competitiveness between species (Agostinetto et al., 2010), it was observed in this experiment that the most competitive cultivars on average for the variables PD, GC, LA and DM were: Nidera 5909 RG > Brasmax Lança IPRO > Syngenta 13561 IPRO > Dom Mario 5958 RSF IPRO > Brasmax Elite IPRO > Nidera 6909 IPRO (Figures 2, 3, 4 and 5). The differences observed in relation to the competitive ability of soybean cultivars in the presence of volunteer corn can be attributed to the genetic distinction that exists between them, such as development cycle, maturity group, plant architecture, leaf area index, root system volume, better use of space or availability of resources available in the environment, among others, a fact also observed by other researchers involving soybean cultivars in the presence of weeds (Forte et al., 2017; Souza et al., 2019; Galon et al., 2022).

It was observed that the productive potential of the cultivars was inversely proportional to their competitive ability. The cultivars that showed the highest yields (Brasmax Elite IPRO, Dom Mario 5958 RSF IPRO and Nidera 6909 IPRO) possibly allocated more resources to the development of reproductive structures to the detriment of other plant organs that gave them greater competitive ability. Thus, the cultivars Nidera 5909 RG, Syngenta 13561 IPRO and Brasmax Lança IPRO were more competitive, but at the cost of producing less than the others. The allocation of resources, as well as being a fundamental aspect of competition between species, is an important factor that conditions their competitive ability when they coexist in communities (Souza et al., 2019).

The estimates of parameter a for most of the comparisons were overestimated by the model, with yield losses of more than 100% (Figures 2, 3, 4 and 5). These results (losses of more than 100% for parameter a) may be due to the fact that the highest densities of volunteer corn plants are not sufficient to adequately estimate the maximum yield loss of the crop (Cousens, 1991). To obtain a reliable estimate for parameter a, it is necessary to include very high densities of the competitor in the experiment, higher than those commonly found in farming conditions (Cousens, 1991). Similarly, Agostinetto et al. (2010), Brandler et al. (2021) and Brunetto et al. (2023) when studying rice competition with rice grass, canola vs. turnip and quinoa in competition with papuan, respectively, subjected to different management methods, also observed losses of more than 100% for the a parameter.

Limiting the parameter a to 100% would be a possibility to prevent yield losses from being overestimated, but this will influence the estimate of the parameter i, resulting in less predictability of the rectangular hyperbola model (Cousens, 1991). In addition, yield losses of more than 100% are biologically unrealistic and occur when the range of weed densities is excessively narrow and/or when the highest density values are not sufficient to produce an asymptotic yield loss response (Agostinetto et al., 2010).

Among the variables analyzed, the best fits to the model were DM > GC > PD > LA. This took into account the highest average R^2 and F values and the lowest average MSR values (Figures 2, 3, 4 and 5). Therefore, the results show that DM can be used instead of the other variables to estimate the yield losses of soybean cultivars in the presence of volunteer corn densities. Other studies have also found similar results to those observed in this research, when evaluating the competition of soybean cultivars in the presence of weeds (Butts et al., 2018; Souza et al., 2019). However, the simulation of economic damage level (EDL) values was carried out using the variable PD of volunteer corn. This variable was selected because it is easy to determine in the field and because it is the most commonly used in experiments for this purpose (Agostinetto et al., 2010; Tavares et al., 2019).

Successful implementation of volunteer corn weed management systems for soybean crops can be achieved by determining the density that exceeds the EDL. The lowest average value was observed for Nidera 6909 IPRO (0.03 plants m^{-2}) (Figures 6). Taking the same criteria into account, EDL was achieved with 0.16, 0.12, 0.09, 0.07 and 0.06 plants m^{-2} of volunteer corn for the cultivars Nidera 5909 IPRO, Brasmax Elite IPRO, Syngenta 13561 IPRO, Dom Mario 5958 RSF IPRO and Brasmax Lança IPRO, respectively. It was observed that the cultivars Nidera 5909 IPRO, Brasmax Elite

IPRO and Syngenta 13561 IPRO had the highest EDL values in all the simulations carried out, ranging from 0.07 to 0.26 plants m^{-2}. The lowest EDL values were obtained with the cultivars Dom Mario 5958 RSF IPRO, Nidera 6909 IPRO and Brasmax Lança IPRO from 0.02 to 0.09 plants m^{-2}.

Yield, the cost of control, the price paid for a sack of soybean and the efficiency of the herbicide all influence the EDL of volunteer corn on the crop. When soybean cultivars reduced yields by 777 kg ha^{-1}, i.e. from 3,428 to 2,651 kg ha^{-1}, the corn density needed to reach the EDL was increased by 50% for Nidera 5909 IPRO, Brasmax Elite IPRO, Syngenta 13561 IPRO, Dom Mario 5958 RSF IPRO, Nidera 6909 IPRO and Brasmax Lança IPRO (Figure 6). This means that the expected increase in crop yields may be less influenced by weed competition. The reduction in the price of a sack of soybeans by US$ 20.38 (US$ 36.17 to US$ 15.79) was necessary for the increase in the density of volunteer corn to reach the EDL of 56.35% for the six soybean cultivars. By increasing the cost of control by US$ 14.42 (US$ 21.61 to US$ 36.03), the density of volunteer corn needed to achieve the EDL was increased by more than 40% for all the cultivars evaluated. By reducing efficiency from 100 to 80%, i.e. by 20%, the density of volunteer corn needed to achieve the EDL was increased by approximately 25%. Galon et al. (2022) found an increase of more than 10% in the density of guanxuma (*Sida rhombifolia*) to reach the EDL when this weed species infested several soybean cultivars, which is partly similar to the results of the present study.

The oscillations between the highest and lowest grain yields, the price of the bag (60 kg), the cost of control and the efficiency of the herbicide influenced the average of the soybean cultivars Nidera 5909 IPRO, Brasmax Elite IPRO, Syngenta 13561 IPRO, Dom Mario 5958 RSF IPRO, Nidera 6909 IPRO and Brasmax Lança IPRO, causing reductions in EDL of around 23, 56, 40 and 20%, respectively (Figure 6). These results are similar to those found by Tavares et al. (2019), Brander et al. (2021) and Galon et al. (2022) when working with wheat, canola and soybeans infested by weeds.

The cultivars Nidera 5909 IPRO, Brasmax Elite IPRO and Syngenta 13561 IPRO showed the best results when calculating the EDL, taking yield into account. These cultivars can live with a higher number of volunteer corn plants than Dom Mario 5958 RSF IPRO, Nidera 6909 IPRO and Brasmax Lança IPRO (Figure 6). It was observed that the higher the crops productive potential, the lower the plant density needed to exceed the EDL values.

When comparing the yields of the soybean cultivars, taking into account the lowest (2,651 kg ha^{-1}) with the highest (3,428 kg ha^{-1}), there was a difference in EDL of up to 22.66% (Figure 6). Therefore, the higher the productive potential of the soybean cultivars, the lower the density of volunteer corn plants, which is equivalent to the EDL. The results indicate that when opting for more productive cultivars, growers should pay attention to adopting weed control measures, even when they occur at low densities.

On the other hand, the increase in the price of the soybean reduces the impact of the cost of weed control, obtaining a greater economic return from the crop (Figure 6). In this scenario, a lower level of loss is tolerated and EDL occurs with a lower density of volunteer corn plants. The results for the price paid per bag of soy showed a variation of around 2.30 times in the value of the EDL. Thus, it can be said that the lower the price paid for a sack of soybeans, the higher the density of volunteer corn needed to exceed the EDL and thus compensate for the use of the herbicide. Thus, Nidera 5909 IPRO, Brasmax Elite IPRO and Syngenta 13561 IPRO stood out as the most competitive cultivars, with EDL values of more than 0.07 plants m^{-2} of volunteer corn, which

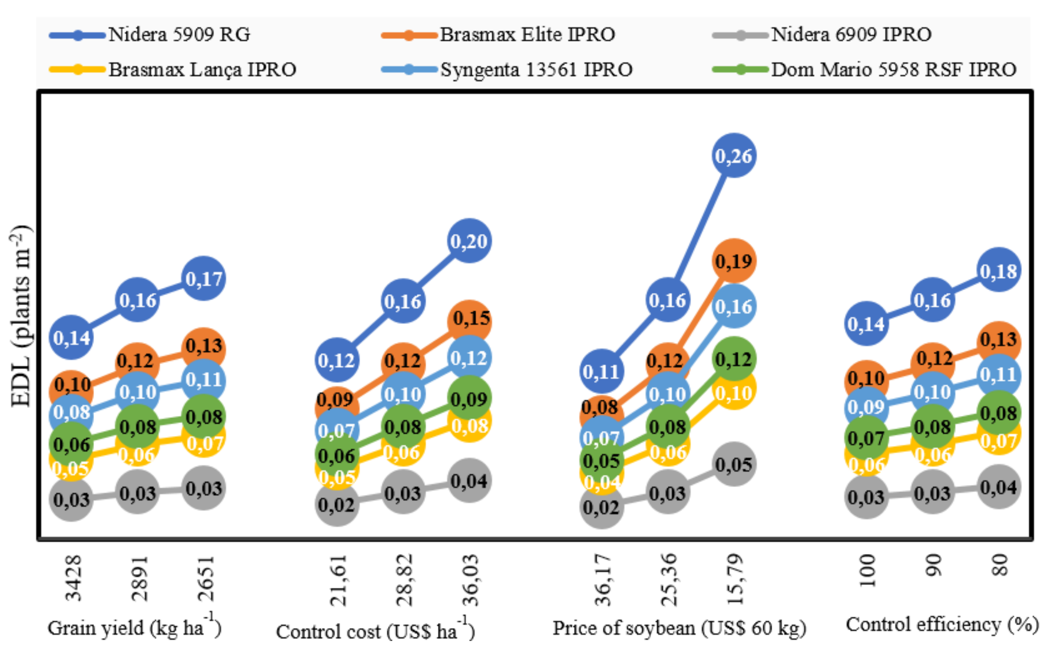


Figure 6. Economic damage level (EDL) as a function of grain yield, control cost, price paid per bag, herbicide efficiency, volunteer corn densities and soybean cultivars.

is mainly attributed to the different genetic characteristics of the materials studied.

With regard to the cost of controlling volunteer corn, there was a variation of approximately 40.02% when comparing the minimum and maximum costs. Thus, the higher the cost of the control method, the higher the EDL and the more volunteer corn plants m^{-2} are needed to justify control measures (Figure 6). For the effectiveness of chemical control, it was observed that the variation of 80 and 100% caused a change in the EDL of approximately 10.00 and 11.11%, respectively, when compared to the average control of volunteer corn. It can therefore be inferred that the level of control directly influences the EDL. In general, the higher the efficacy of the herbicide, the lower the EDL, i.e. the lower the number of volunteer corn plants m^{-2} needed to adopt control measures.

Conclusions

The highest and lowest EDL values ranged, respectively, from 0.07 to 0.20 and 0.02 to 0.12 plants m^{-2} of volunteer corn hybrid Syngenta 488 Vip 3, characterizing the soybean cultivars with the highest (Nidera 5909 RG, Syngenta 13561 IPRO and Brasmax Lança IPRO) and lowest (Dom Mario 5958 RSF IPRO, Nidera 6909 IPRO and Brasmax Lança IPRO) competitive ability.

The EDL of the soybean cultivars decreased with the increase in grain yield, the price of a sack of soybeans, the reduction in the cost of controlling volunteer corn and the efficiency of the herbicide treatment adopted.

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Compliance with Ethical Standards

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