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Article

Economic Threshold of Volunteer Corn GR® in Soybean as a Function of Emergence Time and Origin of Corn

Nível de Dano Econômico de Milho Voluntário RR® em Soja em Função da Época de Emergência e Origem do Milho

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ABSTRACT - Volunteer corn is extremely competitive with soybean and the degree of interference varies with the corn density, time of emergence and origin. The objectives of this work were to determine the economic threshold (ET) of volunteer corn GR® F_2 in soybean as a function of the time of emergence (same day and nine days after soybean) and origin (individual plants or clumps). Each clump was manually adjusted to have seven corn plants. Four field experiments were conducted in randomized blocks design with four replicates in Passo Fundo, RS, Brazil. The soybean yield losses (%) were calculated and adjusted to the model of the rectangular hyperbola and generated the parameters for the determination of the ET, that was calculated based on the volunteer corn control costs (US$ ha^{-1}), efficiency of control (%), price paid for soybean (US$ kg^{-1}) and soybean yield (kg ha^{-1}). The ET mean was 0.3 and 0.48 for individual corn plants m^{-2} emerged together and nine days after soybean, and 0.08 and 0.03 m^{-2} for individual plants and clumps, respectively. Increases in grain yield and price paid for soybean, greater control efficiency of corn and lower control cost promote reduction in the ET of volunteer corn in soybean. The control of volunteer corn is justified in a density less than 0.5 individual plant m^{-2} and is close to zero when corn originates from clumps. Volunteer corn is one of the most competitive weed in soybean crops.

Keywords: *Glycine max*, *Zea mays*, individual plants, clumps, rectangular hyperbola.

RESUMO - Milho voluntário é extremamente competitivo com a soja, e o grau de interferência varia com a população, época de emergência e origem. O objetivo deste trabalho foi determinar o nível de dano econômico (NDE) de milho voluntário RR® F_2 em soja em função da época de emergência (mesmo dia e nove dias após a soja) e origem (plantas individuais ou touceiras). Cada touceira foi ajustada manualmente para conter sete plantas de milho. Foram realizados quatro experimentos a campo no delineamento de blocos casualisados com quatro repetições, em Passo Fundo, RS, Brasil. As perdas percentuais no rendimento de grãos da soja foram calculadas e ajustadas ao modelo da hipérbole retangular, sendo gerados os parâmetros para determinar o NDE, que foi calculado em função do custo de controle do milho voluntário (US$ ha^{-1}), eficiência de controle do milho (%), do preço pago pela soja (US$ kg^{-1}) e do rendimento de grãos da soja (kg ha^{-1}). O NDE médio foi de 0,3 e 0,48 plantas individuais de milho m^{-2} emergidas junto e nove dias após a soja, e de 0,08 e 0,03 m^{-2} para plantas individuais e touceiras, respectivamente. Aumentos no rendimento de grãos e preço pago pela soja, maior eficiência de controle do milho e diminuição do custo de controle promovem redução no NDE de milho voluntário em soja. Dessa forma, o controle

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de milho voluntário justifica-se em população inferior a 0,5 planta individual m^{-2} e aproxima-se de zero quando o milho for originado de touceiras. O milho voluntário é uma das mais competitivas plantas daninhas em soja.

Palavras-chave: *Glycine max*, *Zea mays*, plantas individuais, touceiras, hipérbole retangular.

INTRODUCTION

Occurrence of volunteer corn (VC) in soybean crops had been reported before the introduction of herbicide-tolerant transgenic crops (Andersen, 1976). However, the cultivation of glyphosate-resistant (GR®) corn increased the frequency of volunteer plants in soybean crops (Davis et al., 2008), especially when following GR® corn in a no-till rotation system (Beckett and Stoller, 1988; Deen et al., 2006). VC originate from unharvested seeds or those lost during harvest (abandoned crops, poor harvest). These seeds occur individually, producing individual plants, or as whole ears or rachis segments, resulting in clumps derived from several seeds present at a single point (Newcomer, 1971; Beckett and Stoller, 1988).

Corn clumps are common in soybean crops (Deen et al., 2006) and are difficult to manage because seeds germination is nonuniform, resulting in emergence flushes (López Ovejero et al., 2016). Independent of its origin, VC interferes with soybean and causes significant yield losses, especially when corn comes up from clumps (Marquardt et al., 2012; López Ovejero et al., 2016; Piasecki et al., 2018).

The degree of interference of weeds with soybean crop varies according to the weed density and coexistence time (Ghersa and Holt, 1995), and, in the case of VC, to its origin, i.e., from individual plants or clumps. The increased in density of *Bidens* sp. and *Sida* sp. (Rizzardi et al., 2003) and VC originated from individual plants and clumps (Piasecki et al., 2018) increased soybean yield losses, with nonlinear density-to-grain yield ratios of sigmoid or hyperbola type. Non-linearity of response occurs because each plant from the weed community, when in high densities, has a lower impact on grains yield than in relatively low densities (Cousens, 1985). This relation between weed density and grain yield results from the finite availability of environmental resources, being determined by the number of individuals in small densities, but in large densities the final grains yield does not depend on the plants density due to the limited capacity of the environment to provide resources (Radosevich et al., 1997).

Empirical mathematical models, such as the hyperbola model (Cousens, 1985), simulate effects of weed interference to predict yield losses in cereal crops and final grains yield (Agostinetto et al., 2004). However, economic threshold (ET) concept, that is the best estimate to determine the ideal density to control weeds, is less adopted. ET concept considers as decision parameters not only crop losses caused by weed interference, but the final crop yield, the price paid for the crop grain produced, weed control costs and efficiency of weed control (O'Donovan et al., 2005).

The hypothesis of the present work was that the ET of individual VC plants emerged at the same time as soybean is lower than that of plants emerged nine days after, and that the ET of clumps is lower than that of individual plants. Thus, the objectives of this work were to determine the ET of interference of VC GR® F_2 densities as a function of the relative emergence time and origin of the VC (individual plants or clumps) on soybean.

MATERIAL AND METHODS

Four field experiments were performed in a randomized blocks design with four replicates. All experiments were established at the Centro de Pesquisa e Extensão Agropecuária – CEPAGRO (Center of Agricultural Research and Extension) of the University of Passo Fundo, Passo Fundo city, state of Rio Grande do Sul (RS), Brazil.

The experiments were conducted in no-tillage system, in an area with black oat (*Avena strigosa*) and ryegrass (*Lolium multiflorum*) remains, previously controlled with the herbicides clethodim (76.2 g a.i. ha^{-1}), and glyphosate (720 g a.e. ha^{-1}). The BMX Turbo GR® soybean cultivar was sowed in the four experiments, at a density of 30 plants m^{-2} in rows 50 cm apart. The soybean was fertilized with 5.6 kg ha^{-1} of N, 78.4 kg ha^{-1} of P_2O_5 and 50.4 kg ha^{-1} of K_2O, according to the soil analysis recommendations. Soybean seeds were inoculated with *Bradyrhizobium japonicum* and then treated with insecticides and fungicides. Crop management was performed according to the official recommendations for soybean in Brazil (Embrapa, 2012).

GR VC used in the experiments was originate from ears of the corn hybrid AG 8088 PRO_2® that were collected in the F_2 generation during the previous season. Seven days after VC emergence at each experiment, the densities were manually adjusted according to each treatment. To avoid interference from other weeds, glyphosate (720 g a.e. ha^{-1}) was sprayed once at 40 days after soybean emergence.

In experiments 1 and 2, the densities of individual plants of VC coexisting with soybean were 0; 0.5; 1; 2; 3; 4; 5; 6; 7; 8; and 10 m^{-2}. In the first experiment, corn emerged at the same day as soybean, while in the second experiment, it emerged nine days after soybean. To establish the respective corn densities, kernels of VC plants were manually aleatory distributed and buried at a depth of approximately 3.5 cm, in plots of 4.4 m^2 (2.0 x 2.2 m).

In experiments 3 and 4, the densities of individual plants or clumps m^{-2} were 0; 0.5; 1; 2; 4; 8; 10; and 12, respectively. Each clump was manually adjusted to have seven corn plants. VC densities from individual seeds and clumps were randomly distributed and then buried manually at 3.5 cm deep in plots of 17.5 m^2 (3.5 x 5 m). Shortly after corn sowing, soybean was mechanically sowed. In these experiments, VC emerged at the same day as soybean.

The soybean grain yield was obtained through harvesting from a sampling of 2.0 m^2 in each plot in experiments 1 and 2, and 7.5 m^2 in each plot from experiments 3 and 4. After harvest, the plants was threshed and weighed, and the soybean grain moisture content was determined. The soybean grain moisture content was corrected to 13%, and the grain yield per hectare (kg ha^{-1}) was estimated.

Regarding the grain yields in the four experiments, percent losses were calculated relative to the corn-free treatments, according to Equation 1:

$$Yl\ (\%) = [(Ya-Yb)/Ya]*100 \quad \text{(eq. 1)}$$

where: Yl = yield loss of soybean (%); Ya = soybean yield weed free; and Yb = soybean yield in the presence of corn.

Data related to percent losses were adjusted to the rectangular hyperbola of the nonlinear regression model, as proposed by Cousens (1985) (Equation 2):

$$Yl = (i*x)/[(1+((i/a)*x)] \quad \text{(eq. 2)}$$

where: Yl = grain yield losses (%); x = corn density; i = % of crop grain yield loss per unit of corn when its density is close to zero; and a = % of grain yield loss when the corn density tends to infinite.

Data were analyzed for normality according to the Shapiro-Wilk's test and homoscedasticity according to the Hartley's test and subsequently subjected to analysis of variance (ANOVA) ($p \leq 0.05$).

To calculate the ET, we used the estimates parameter *i* obtained from the rectangular hyperbola equation (Cousens, 1985) and the equation adapted from Lindquist and Kropff (1996) (Equation 3):

$$ET = [Cc\ /\ (P * Y * (i/100) * (H/100))] \quad \text{(eq. 3)}$$

where: ET = weed economic threshold (plants m^{-2}); Cc = control costs (herbicide + application, in US\$ ha^{-1}); P = soybean price (US\$ kg^{-1} of grains); Y = soybeans yield (kg ha^{-1}); i = soybeans yield loss (%) per unit of volunteer corn when the density is close to zero: and H = herbicide control efficiency level (%).

For determination of the ET, we considered four parameters as reference: cost of VC control (US\$ ha 1), control efficiency (%), price paid for soybean grains (US\$ kg^{-1}), and soybean yield (kg ha^{-1}). In each parameter, three variations were calculated, which correspond to minimum, medium and maximum values, based on the last five-year historical data in Brazil: cost of control

(US$ 30.00, 40.00 and 50.00 per ha^{-1}); control efficiency (80, 90 and 100%); price paid for soybean grains (US$ 0.22, 0.32 and 0.42 kg^{-1}); and soybean grain yield (2,854, 2,947 and 2,998 kg ha^{-1}). In the calculation of variations in each parameter, we considered the mean value for the other parameters of the equation. The reference values were obtained from bulletins released by official Brazilian institutions (Banco Central do Brasil, 2017; Conab, 2017).

Data adjustment to the model was made by the Proc Nlin procedure of the SAS software program with p≤0.05 significance, using the Gauss-Newton method, which estimates the values of parameters *i* and *a* through successive interactions, where the sum of the squares of deviations of observations from the adjusted values is minimum (Ratkowsky, 1983).

RESULTS AND DISCUSSION

Many studies that assessed yield losses and ET due to weed interferences in crops were conducted with one replication (Sartorato et al.,1996; Rizzardi et al., 2003; Fleck et al., 2004; Agostinetto et al., 2004; Westendorff et al., 2014; Agostinetto et al., 2016). This methodology is indicated for field studies where there is less control of the weed density and interactions of factors upon which the researcher has no control (O'Donovan, 1996; O'Donovan et al., 2005). In the present work, due to the greater control obtained on the establishment of VC densities according to the treatments, and because it is relatively easy to avoid interferences from other weeds (corn and soybean GR®), all experiments were conducted with four replicates, and the results average was adjusted to fit the rectangular hyperbola model proposed by Cousens (1985). Due to short variation of VC emergence among the treatments, the predictive capacity of the Cousens's model (1985) was considered excellent.

For the analyses of variance (ANOVA), the F values were significant for the variables and fitted satisfactorily to the rectangular hyperbola regression model – these values being evidenced by the coefficients of determination (R^2) and by the sum of squares of residue (SSR) (Table 1).

In all experiments, with the increased corn density there was a decrease in soybean yield (Figure 1 and 2). Parameter *i* indicates the initial loss of soybean yield per unit of VC when the plants density is close to zero. The calculated *i* values for the experiments are shown in Table 1, and the percent losses for soybeans yield as estimated by the rectangular hyperbola equation shown in Figure 1 and 2.

For *i* it was observed that the individual corn plants that emerged at the same day as soy were 1.6 times more competitive than that ones emerged nine days after (experiments 1 and 2), whereas clumps were 2.9 times more competitive than individual plants (experiments 3 and 4) (Table 1). The "*i*/*a*" ratio, which reflects the intraspecific competition level of the weed community (Cousens, 1985), was 61% lower for the individual plants that emerged at the same date as soybean, compared to the plants emerged nine days after (Table 1). On the other hand, the greater intraspecific competition of VC that emerged nine days after soybean probably was due to the lower access to limited environmental resources, considering that, in this case, soybean had preferential access. The intraspecific competition of corn clumps was 292% higher compared to individual plants (Table 1). This result is due to the greater number of corn plants at the same

Table 1 - Parameters estimated by the rectangular hyperbola model and analysis of variance for soybean yield losses resulting from interference with densities, origins and times of emergence of volunteer GR® F_2 corn. Passo Fundo, RS

Variable	Parameter		i/a	R^2	Soybean yield losses (%)[5]	SSR	F*
	i	a					
Corn emerged with soybean[1]	16.08	84.8	0.19	0.71	y=(16.08*x)/(1+(16.08/84.8)*x)	17.1	824.6
Corn emerged 9 days after soybean[2]	10.02	32.2	0.31	0.83	y=(10.02*x)/(1+(10.02/32.2)*x)	7.49	356.4
Individual corn plants[3]	56.4	106.4	0.53	0.98	y =(56.4*x)/(1+(56.4/106.4)*x)	137.5	709.8
Corn clumps[4]	164.5	106.2	1.55	0.99	y=(164.5*x)/(1+(164.5/106.2)*x)	29.5	5166.9

i = percent of yield loss per corn unit when density is close to zero; a = percent of yield loss when corn density tends to infinity. [1] experiment 1; [2] experiment 2; [3] experiment 3; [4] experiment 4; [5] values obtained through the rectangular hyperbola model (Cousens, 1985). * Significant at p≤0.05. SSR = sum of squares of residue; R^2 = coefficient of determination.

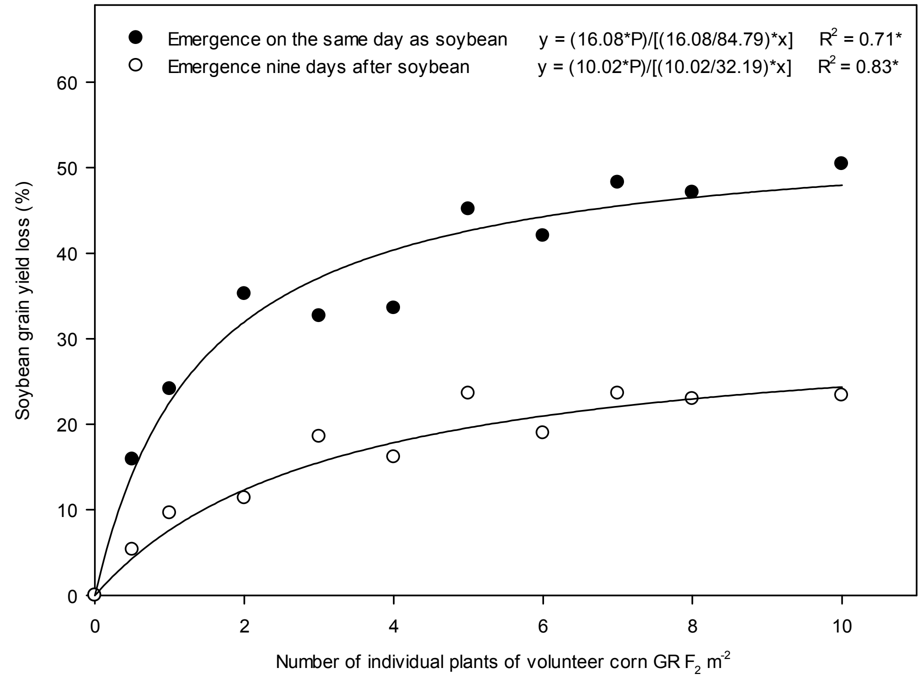

Figure 1 **-** Estimated yield losses of soybean cv. BMX Turbo GR® (%) from interference with densities of individual plants of volunteer GR® F2 corn emerged at the same day and nine days after soybean. Experiments 1 and 2. Passo Fundo, RS.

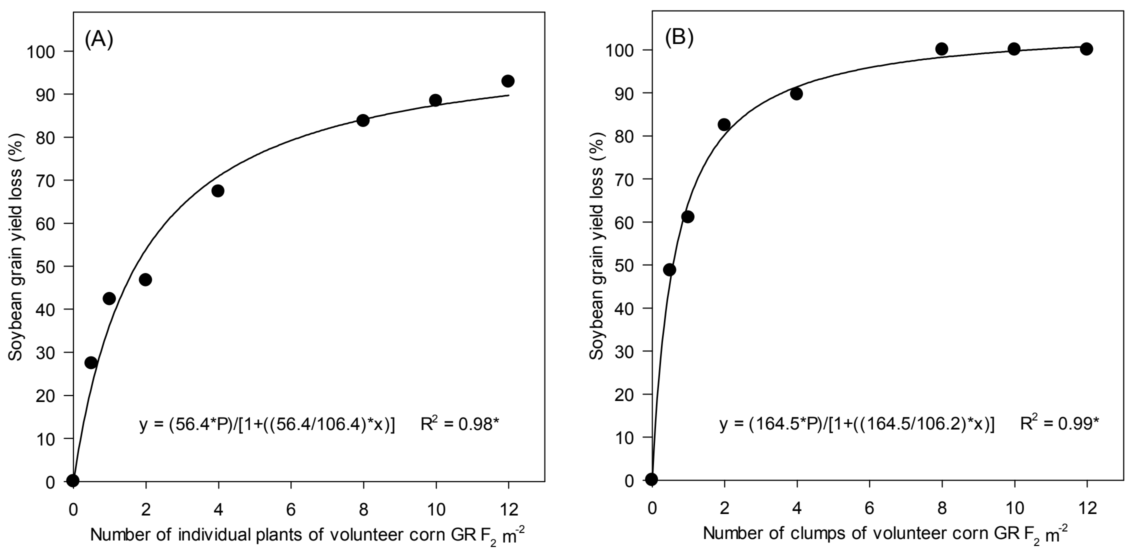

Figure 2 **-** Estimated yield losses of soybean cv. BMX Turbo GR® (%) from interference with densities of individual plants (A) and clumps (B) of volunteer GR® F2 corn. Experiments 3 and 4. Passo Fundo, RS.

point. In addition, interferences posed by clumps resulted in greater soybean yield losses, when compared to individual plants (Figure 2).

Volunteer corn grows faster than soybean and has a preferential access to environmental resources because it is a C_4 plant with advantages over the soybean crop in growth and development (Marquardt et al., 2012; Taiz and Zeiger, 2013). However, studies have shown that higher plant height, especially in the early stages of development, is one of the main characteristics that confer a competitive advantage of corn over soybean (Piasecki et al., 2018). Corn, by intercepting most of incident solar radiation and by shading the soybean plants, contributes to reduce photosynthesis and prevents the soybean crop growth and development (Piasecki et al., 2018). In addition to reduced photosynthesis, photorespiration of soybean plants (C_3 metabolism) under intense shade increases and, consequently, there is more expenditure of energy from the carbohydrates produced by photosynthesis (Taiz and Zeiger, 2013).

By analyzing under the biological point of view the adjustment provided by the rectangular hyperbola, two situations were observed. In the first one, the additive effect in low densities occurs because the areas of influence of individual plants do not overlap. In the second, in large densities, the effect of interference from each corn unit that was added to soybean diminished because the areas of influence overlapped and, as a consequence of the increased intensity of intraspecific competition, soybean yield losses tended to stabilize. Similar behavior was observed in studies of interference of densities of *Bidens* spp. and *Sida rhombifolia* with soybean (Rizzardi et al., 2003).

For each corn unit added to the competitive load in this model, greater soybean yield losses occur in low weed densities than in high ones. This behavior follows the response-decreasing principle which indicates that, when weed densities increase, crop yields decrease, to the extent that further addition of weed plants does not diminish grain yields substantially. It is also in agreement with the law of constant final yield, which states that production of dry matter per unit or land area is independent of the weed densities in the area (Radosevich et al., 1997).

In cases where large weed densities cause high crop yield losses, it is necessary to restrict parameter a to 100% to prevent overestimation of these values (Westendorff et al., 2014), taking into account that, biologically, losses over 100% do not occur (Fleck et al., 2004; Agostinetto et al., 2004). In the present work, parameter a was overestimated to values above 100% in experiments 3 (103.4) and 4 (106.2), resulting in a yield loss estimate of 100.8% for the greater clumps density (experiment 4; Figure 2B). As in experiment 4 there was a tendency of losses to stabilize in densities of four clumps m^{-2} (>90%) and over, it was not considered in this condition that the loss values were overestimated to the point of impairing interpretation of results. The main reason for not limiting value a is that, when this parameter is set to 100%, there is a tendency of inflection of the initial curve and, thus, overestimation of i (Cousens, 1991).

In addition to not overestimating i, non-limitation of a enabled that the "i/a" ratios were closer to real conditions, given that the a values used for this ratio were calculated based on the variability of each situation (Table 1). If a were 100, the results of the "i/a" ratios of experiments 1 to 4 would be 0,16, 0,10, 0.56 and 1.65, respectively and, when compared to the calculated values (0.19, 0.31, 0.53 and 1.55), they could change the interpretation of the species intraspecific competition, especially when the estimated losses were not high. In the case of experiments 1 and 2, if it were assumed 100 for a, interpretation of the intraspecific competition between the times of corn emergence would not be the most appropriate, it because would indicate that a higher intraspecific competition would occur for the corn that emerged together with soybean compared to the emergence occurred nine days later. Misunderstandings such as these may occur when densities are not high enough to enable estimation of maximum yield losses (Agostinetto et al., 2004). In order to obtain a reliable parameter estimation, studies should rely on sufficiently high densities, although not representing the crops reality (Cousens, 1991).

In the four experiments, there was low variation among the ET values calculated for the variables. In all situations of the study, the ET was lower than 0.7 for individual plant m^{-2} and close to zero when corn emerged from clumps (Figure 3 and 4).

Because of the low variation in the ET results for VC, which are low compared to other weeds, e.g. *Cyperus esculentus* in rice paddy, which ranged from 3.3 to 11.6 plants m^{-2} (Westendorff et al., 2014), we considered the mean values for the interpretation of results. Among the levels (minimum, medium and maximum) considered for the calculated variables (control costs, soybean price and yield and control levels), for the individual corn plants emerged at the same date as soybean, the mean ET value was 0.3 m^{-2} of corn plants (experiment 1), whereas for corn that emerged nine days after it was 0.48 m^{-2} (experiment 2) (Figure 3). In these cases, the damage level would be reached with the presence of one individual corn plant at every 3.3 m^2 or 3,003 ha^{-1}, and one individual plant at every 2.2 m^2 or 4,762 ha^{-1}, respectively, for corn plants emerged together with soy or nine days after. These results indicate that the corn plants that emerged after soybean exhibit a lower competitive capacity, but the difference between the values is small, and to determine the ideal time to manage corn in these conditions, precise field samplings must be conducted.

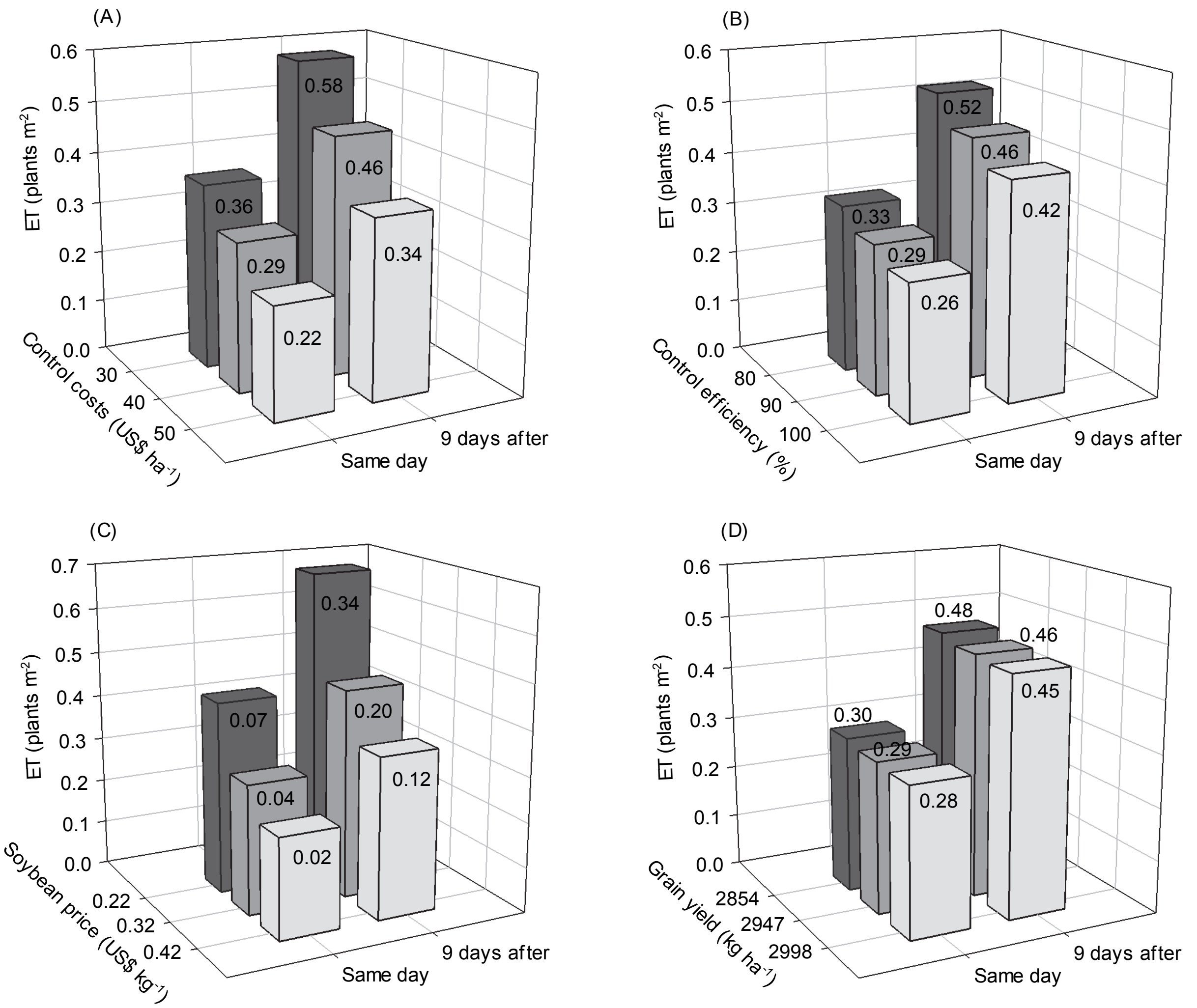

Figure 3 - Economic threshold (ET) of individual volunteer GR® F2 corn plants emerged at the same date and nine days after soybean BMX Turbo GR®, according to estimations of (A) control costs (US\$ ha^{-1}), (B) corn control efficiency (%), (C) price paid for soybean (US\$ kg^{-1}) and (D) soybeans yield (kg ha^{-1}). Passo Fundo, RS.

For individual VC plants that emerged concurrently with soybean (experiment 3) the mean ET value among the variables was 0.08 m^{-2}, while for clumps (experiment 4) it was 0.03 m^{-2} (Figure 4). In these situations, the economic threshold would be reached with the presence of one individual plant every 12.5 m^{-2} or 800 ha^{-1} and one clump every 33.3 m^{-2} or 300.3 ha^{-1}. *Xanthium strumarium* was considered one of the most competitive weed plants in soy crops, with an ET that ranged from 0.05 to 0.12 m^{-2} (Sartorato et al., 1996). The ET values in the present study indicate that VC is among the most competitive weeds documented for soybean crops.

In general, the ET results indicate that tolerant corn density is very low so that control levels can be effective, independent of the its origin and time of emergence. When emerging nine days after soy, VC can interfere with soybean crops and cause significant yield losses, of nearly 0.5 plant m^{-2} (Figure 3). In turn, VC clumps have a greater damage potential compared to individual plants, to the point that a minimum presence of clumps in soybean crops justifies the adoption of control measures (Figure 4).

Thus, it is clear the importance of management of VC plants in soybean crops to prevent considerable crop yield losses. In a few years, new GM corn traits to achieve tolerance to different mechanisms of herbicide action on corn may be developed and released commercially, which will increase the frequency of VC in following crops. In this context, if due attention is not paid during crops planning and growing, volunteer plants will be one of the key weeds in soybean crops, with a potential to cause huge losses.

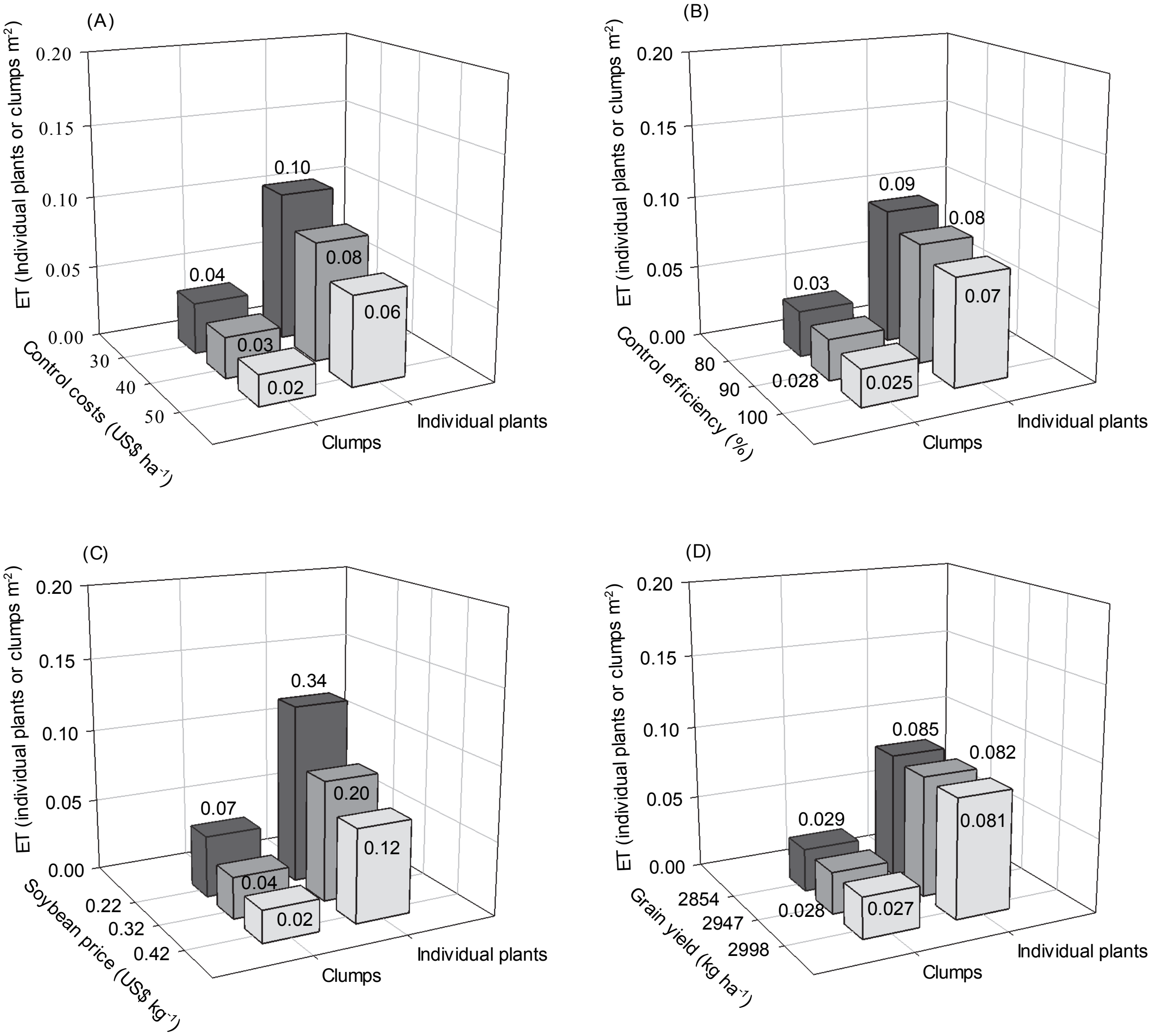

Figure 4 - Economic threshold (ET) of individual plants and clumps of volunteer GR® F2 corn with soybean cv. BMX Turbo GR®, according to estimations of (A) control costs (US$ ha^{-1}), (B) corn control efficiency (%), (C) price paid for soybean (US$ kg^{-1}) and (D) soybeans yield (kg ha^{-1}). Passo Fundo, RS.

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