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Article

Yield Losses and Economic Threshold of GR® F_2 Volunteer Corn in Bean

Perdas no Rendimento de Grãos e Nível de Dano Econômico de Milho Voluntário RR® F_2 em Feijão

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ABSTRACT - Volunteer corn has high competitive capacity with bean, and the degree of interference varies as a function of corn density and origin (individual plant or clump). This study aimed to quantify bean yield losses under interference with densities of individual plants and clumps (seven plants at the same point) of GR® F_2 volunteer corn and calculate the economic threshold (ET). Two experiments were carried out in a randomized blocks design with three replicates in Passo Fundo, RS, Brazil. The studied volunteer corn densities were 0, 0.5, 1, 2, 4, 8, and 12 individual plants and clumps m^{-2}. The bean yield was assessed and calculated the yield losses (%) in response to volunteer corn interference. The yield loss data were fitted to the rectangular hyperbola model to generate the parameters for ET determining. ET was calculated as a function of cost (US\$ ha^{-1}) and control efficiency (%) of volunteer corn, the price paid for bean (US\$ kg^{-1}), and bean yield (kg ha^{-1}). Interferences caused by densities of volunteer corn of 0.5, 1, and 2 individual plants and clumps m^{-2} in bean resulted in yield losses of 9%, 17%, and 30%, and 33%, 51%, and 70%, respectively. The ET of volunteer corn on bean was, on average, 0.21 individual plants m^{-2} and 0.04 clumps m^{-2}. Increases in yield and price paid for beans, higher efficiency of volunteer corn control, and a decrease in costs of control promote a reduction in ET. Interferences caused by clumps resulted in higher bean yield losses than individual plants.

Keywords: *Phaseolus vulgaris*, *Zea mays*, individual plant, costs, clumps, harvest losses.

RESUMO - O milho voluntário tem elevada capacidade competitiva com o feijão, e o grau de interferência varia com a densidade de plantas e com a origem do milho (planta individual ou touceira). O objetivo deste trabalho foi quantificar as perdas no rendimento de grãos do feijão carioca sob interferência de densidades de plantas individuais e touceiras (sete plantas no mesmo ponto) de milho voluntário RR® F_2 e calcular o nível de dano econômico (NDE). Foram realizados dois experimentos a campo no delineamento de blocos casualizados com três repetições, em Passo Fundo-RS. Brasil. As densidades médias de milho voluntário estudadas foram 0, 0,5, 1, 2, 4, 8 e 12 plantas individuais e touceiras m^{-2}. Foi avaliado o rendimento de grãos do feijão e calculadas as perdas percentuais que foram ajustadas ao modelo da hipérbole retangular de modo a gerar os parâmetros para determinação do NDE. O NDE foi calculado em função do custo (US\$ ha^{-1}) e eficiência de controle (%), do preço pago pelo feijão (US\$ kg^{-1}) e do rendimento de grãos do feijão (kg ha^{-1}). As interferências causadas por densidades médias de 0,5, 1 e 2 m^{-2} plantas individuais ou touceiras resultaram em perdas de 9%, 17% e 30%, e 33%, 51% e 70%, respectivamente. Em média, o NDE de milho voluntário no feijão foi de 0,21 plantas individuais m^{-2} e 0,04 touceiras m^{-2}. Aumentos no

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rendimento de grãos e preço do feijão, maior eficiência de controle do milho e diminuição do custo de controle promovem redução no NDE. Interferências causadas por touceiras resultam nas maiores perdas no rendimento de grãos do feijão que plantas individuais.

Palavras-chave: *Phaseolus vulgaris*, *Zea mays*, plantas individuais, touceiras, perdas na colheita.

INTRODUCTION

Worldwide 30 million hectares of bean (*Phaseolus vulgaris*) are cultivated. India, Myanmar, and Brazil are accounting for about 40% of the global production of 23.3 million tons (FAO, 2017). In Brazil, beans are cultivated on approximately 3 million hectares (first and second growing seasons), covering practically all regions, especially the second growing season in the south-central region, which produces about 80% of the total production with 46% of the entire cultivated area (Conab, 2017).

The second growing season of bean, mainly in the South, Southeast, and Midwest regions of Brazil, is cultivated in succession to corn, which favors a higher occurrence of volunteer corn (VC) interfering with the crop. VC plants originate from seeds lost at harvest (poor harvest) or not harvested in the field and occur in the form of individual seeds and/or as whole ears or rachis segments containing various seeds, which respectively produce individual plants and clumps of F_2 VC (Marquardt et al. al., 2012; Piasecki et al., 2018). According to Deen et al. (2006), corn clumps predominate on the field production areas and are more competitive with crops than individual plants (López-Ovejero et al., 2016; Piasecki et al., 2018).

The competitive capacity of VC regarding of the bean is high since the interference of density lower than a corn plant m^{-2} reduces bean yield up to 19.3% (Sbatella et al., 2016). VC competes with the crop for environmental resources, being the light probably the main interference factor (Piasecki et al., 2018), in which VC has the advantage. Because corn present C_4 photosynthetic pathway, it has advantages over plants with C_3 photosynthetic pathways, such as bean, especially under extreme conditions such as high temperatures and water stress due to lack of water (Sage, 2004). Also, VC grows faster than C_3 crops, especially in their early development stages, which determines the threshold of the plant (Chahal, 2014; Piasecki et al., 2018).

The degree of interference of weeds in crops is defined by the density and period of coexistence (Ghersa and Holt, 1995) and, in the case of VC, by the origin (individual plant or clump) (Piasecki et al., 2018). According to Sbatella et al. (2016), the increase in the density of individual VC plants from 0 to 2.5 plants m^{-2} reduced up to 50% bean yield. In soybean, yield losses greater to 90% were observed in densities of 12 individual plants or clumps of VC m^{-2} (Piasecki et al., 2018).

Empirical mathematical models, such as the hyperbolic derivative (Cousens, 1985), simulate interference effects to predict losses in yield of crops as a response to interference with weed densities (Agostinetto et al., 2004). These models have been used by many researchers to estimate yield losses by weeds in different crops of economic interest (O'Donovan, 1996; Rizzardi et al., 2003; Agostinetto et al., 2004; Westendorff et al., 2014; Agostinetto et al., 2016; Piasecki et al., 2018). The economic threshold (ET) is the best estimate to determine the time to control weeds since it considers as parameters the crop yield, price of the harvested product, cost and control levels (O'Donovan et al., 2005).

Few papers are available in the scientific literature deal with losses in bean yield under interference with VC densities from individual plants and clumps that establish the ET. Thus, this study hypothesized that VC presents a higher competitive capacity than bean and that clumps interference cause higher bean yield losses than individual corn plants in the bean. Thus, this study aimed to quantify bean yield losses under interference with densities of individual plants and clumps of GR® F_2 volunteer corn and calculate the ET.

MATERIAL AND METHODS

In order to establish bean interference with GR® F_2 VC densities from individual plants and clumps, two field experiments were conducted in the 2013/2014 season at the Agricultural

Research and Extension Center (CEPAGRO) of the University of Passo Fundo (UPF), Passo Fundo, RS, Brazil. In both experiments, the experimental design was a randomized blocks design with three replicates. VC was originated from individual seeds in experiment 1 and clumps in experiment 2. Each clump consisted of an ear segment containing seven corn plants. The average corn densities were 0, 0.5, 1, 2, 4, 8, and 12 individual plants (experiment 1) or clumps (experiment 2) m^{-2}.

The experiments were carried in a no-tillage system in an area with crop residues of black oat (*Avena strigosa*), and ryegrass (*Lolium multiflorum*) remains previously controlled with clethodim (76.2 g ha^{-1}) and glyphosate (720 g a.e. ha^{-1}). In both experiments, corn and bean sowing was performed on the same day. VC emergence occurred one day before bean. Fertilizer rate was 5.6 kg N ha^{-1}, 78.4 kg P_2O_5 ha^{-1}, and 50.4 kg K_2O ha^{-1} banded below the seed at sowing. Additional N was broadcast applied in crop bean with V_3-V_4 stage (three to four trifoliate leaves) in the form of 250 kg urea ha^{-1} (112.5 kg N ha^{-1}) (Epagri, 2012). Seed treatment and management of insect pests and pathogens were carried out according to the recommendations for bean cultivation in southern Brazil (Epagri, 2012). Other weeds were controlled through manual weeding.

The corn hybrid AG 8088 PRO_2® was harvested in the 2012/2013 season and originated the F_2 densities used in the experiments. VC densities were randomly distributed and manually buried at approximately 3.5 cm depth in plots of 17.5 m^2 (3.5 x 5 m). Immediately after corn sowing, the bean cultivar BRS Pérola (mid-cycle and semi-erect size) was mechanically sowed at a density that allowed the establishment of 24 bean plants m^{-2} and spaced 0.50 m between rows (Epagri, 2012). After VC emergence, the manual adjustment of densities was performed according to each treatment.

The three central rows (5 m long) of each experimental unit of experiments 1 and 2 were manually harvested, totaling 7.5 m^2 per plot. After harvesting, the material was threshed and weighed, and the bean moisture determined. After adjusted the humidity to 13%, bean yield was calculated per hectare. The one-thousand-grain weight (TGW) was calculated by weighing 250 seeds randomly aleatory collected from the total harvest.

The yield losses (%) was calculated in both experiments regarding the treatments maintained free of VC individual plants or clumps, as Equation (1).

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

where *Yl* is the yield loss, *Ya* is the yield without corn (weed free), and *Yb* is the yield in the presence of VC.

The percentage loss data were adjusted to the nonlinear regression model of the rectangular hyperbola proposed by Cousens (1985), as Equation (2).

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

where *Yl* is the bean yield losses (%), *x* is the density of VC individual plants or clumps, *i* is the percentage of yield loss per unit of VC when its density is close to zero, and *a* is the percentage of yield loss when maize density tends to infinite.

Data were analyzed for normality by the Shapiro-Wilk's test and homoscedasticity by Hartley's test and subsequently submitted to the analysis of variance (ANOVA) ($p \leq 0.05$). To assess the qualitative effect of the origins of VC on the bean yield losses a joint analysis of experiment 1 and 2 was performed according to Banzatto and Kronka (2006). The analyses were performed in the software SAS® version 9.0.0 (SAS, 2002).

For ET calculation, were used the estimates of the parameter *i* obtained from the rectangular hyperbola equation (Cousens, 1985) and the adapted equation of Lindquist and Kropff (1996), as Equation (3).

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

where *ET* is the economic threshold (plants m^{-2}), *Cc* is the control cost (herbicide + application, in US\$ ha^{-1}), *P* is the bean price (US\$ kg^{-1} of grains), *Y* is the bean yield (kg ha^{-1}), *i* is the yield loss per unit of VC when its density is close to zero (%), and *H* is the herbicide control efficiency (%).

Four parameters were considered as reference for ET: the cost of control (US\$ ha^{-1}), control efficiency (%), price pid for bean grain (US\$ kg^{-1}), and bean yield (kg ha^{-1}). Within each parameter, three variations were calculated corresponding to minimum, mean, and maximum values based on data from the last five years historical data in Brazil: control cost (30.00, 40.00, and 50.00 US\$ ha^{-1}), efficiency of control (80, 90, and 100%), price paid for beans (0.41, 0.69, and 1.17 US\$ kg^{-1}), and yield (1,440.7, 1,660.9, and 1,802.4 kg ha^{-1}). The reference values were obtained from bulletins published by official agencies of Brazil (Banco Central do Brasil, 2017; Conab, 2017).

The data adjustment to the model was performed through the procedure Proc Nlin of the software SAS, with a significance of $p \leq 0.05$, by using the Gauss-Newton method, which, through successive interactions, estimates the values of the parameters i and a, in which the sum of squares of deviations of the observations relative to the adjusted values is minimal (Ratkowsky, 1983).

RESULTS AND DISCUSSION

Many studies, when assessing yield losses and ET as a function of the interference of weeds in crops, were performed with a 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 situations where there is little control on weed density and interactions between factors over which the researcher has no control (O'Donovan, 1996; O'Donovan et al., 2005). In the present study, all experiments were conducted with three replicates due to the high control obtained on the establishment of VC densities according to the treatments, and the means of results were fitted to the rectangular hyperbola model proposed by Cousens (1985).

The losses (%) in bean yield were fitted to the regression model derived from the rectangular hyperbola. These values are evidenced by the coefficients of determination (R^2) and residual sum of squares (RSS) (Table 1). R^2 is not the better parameter to measure the non-linear regression but serves as an approximate indicator of the variability explained by curve adjustment (Sartorato et al., 1996). RSS can also be used as an adjustment criterion to the model considering that the values of x (independent) are fixed, and the values of y (dependent) are random variables affected by experimental errors, with higher adjustments the lowest the RSS values are (Passari et al., 2011). Due to the low variation in the emergence of VC plants among treatments, the predictive capacity of the Cousens (1985) model was considered as excellent.

In both experiments, the values of TGW decreased as VC density increased from 0 to 12 plants m^{-2}, with a negative variation of 5.7% for individual plants and 19.8% for clumps (Figure 1). The confidence intervals obtained for TGW confirm the significant difference between treatments. The limitation in supplying environmental resources as a function of the interference probably resulted in a reduction in TGW.

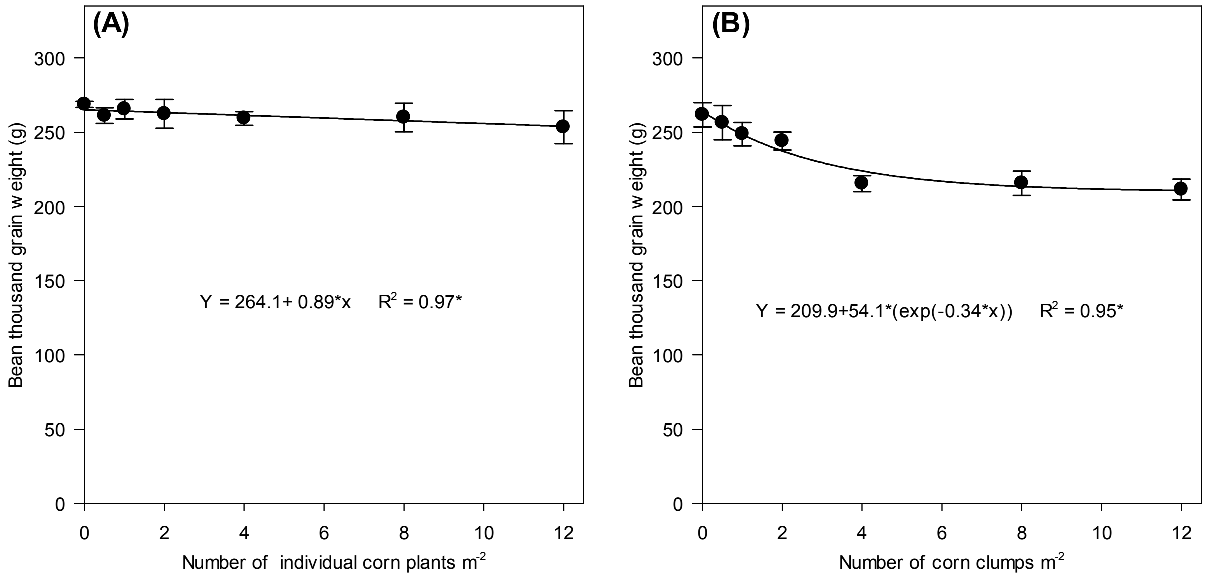
Bean yield decreased as VC densities from both origins increased. With the densities of 0.5, 1, and 2 VC individual plants m^{-2} the bean yield losses was 9%, 17%, and 30.4% and 32.9%, 51%, and 70.3% for clumps (Figure 2). From 4 clumps m^{-2}, a tendency of loss stabilization higher than 90% was observed. Similar results were found for interference between individual corn plants

Table 1 - Parameters estimated by the rectangular hyperbola model for losses of bean yield as a function of interference with densities and origins of the GR® F_2 volunteer corn. Passo Fundo, RS, Brazil

Variable	Parameter i	Parameter a	i/a	R^2	Perda no rendimento de grãos (%)[3]	RSS	F*
Individual corn plants[1]	19.3	142.9	0.13	0.99	y = (19.3*x)/(1+(19.3/142.9)*x)	0.00005362	861.6
Corn clumps[2]	92.6	113.4	0.82	0.98	Y = (92.6*x)/(1+(92.6/113.4)*x)	0.00000485	408.6

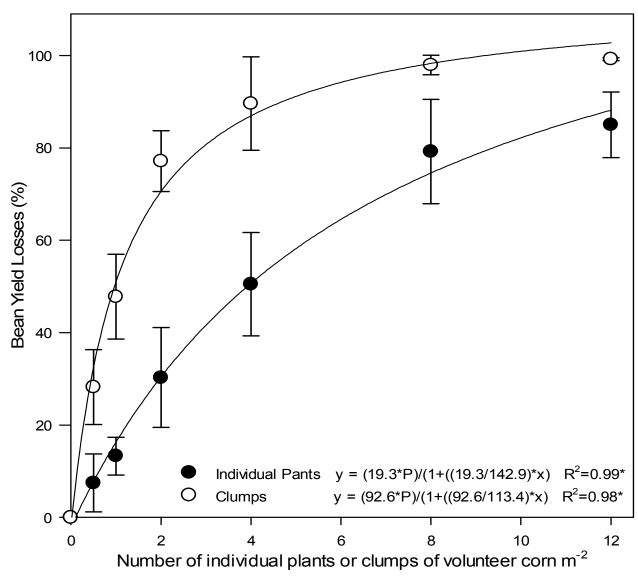
i = percentage of yield loss per unit of corn when the density is close to zero; a = percentage of yield loss when corn density tends to infinite. [1] Experiment 1; [2] Experiment 2. [3] Values obtained through the rectangular hyperbola model (Cousens, 1985). * Significant at $p \leq 0.05$. RSS = Residual sum of squares; R^2 = coefficient of determination.

and bean (Sbatella et al., 2016), as well as for individual plants and clumps of VC interference in soybean (López-Ovejero et al., 2016; Piasecki et al., 2018).



* Significant at p≤0.05. Bars indicate the confidence interval at p≤0.05. Passo Fundo, RS, Brazil.

Figure 1 **-** Effect of the interference of densities of individual plants (A) and clumps (B) of GR® F_2 volunteer corn on one-thousand- weight (TGW) of bean cultivar BRS Pérola.



* Significant at p≤0.05. Bars indicate the confidence interval at p≤0.05. Passo Fundo, RS, Brazil.

Figure 2 **-** Percentage losses of bean yield of the cultivar BRS Pérola as a function of the interference of densities of individual plants and clumps of GR® F_2 volunteer corn.

Regarding the parameters generated by the rectangular hyperbole equation, *i* indicates the initial loss in bean yield per unit of VC when the density is close to zero. The result of the ratio of *i*, calculated for individual plants and clumps, was 4.8. This relationship indicates that corn clumps are 4.8 times more competitive than individual plants in densities close to zero (Table 1).

The degree of intraspecific corn interference can be calculated from the relation between the parameters *i*/*a* (Cousens, 1985). The *i*/*a* ratio resulted in values of 0.13 and 0.82 for individual plants and clumps, respectively (Table 1). The result of this relation (0.82/0.13) was 6.3, indicating that clumps have an intraspecific interference 6.3 times higher than individual plants since there are more corn plants per area. Taking into account that each clump was constituted of seven corn plants, this relation was very close. Also, clumps of VC also compete intensely with the bean for the limited environmental resources, in which VC stands out. In our study, the result of this intense interference led to an expressive reduction in bean yield, even in densities lower than 1 clump m^{-2}.

Regarding the analyses of variance of regression (ANOVA), the F values were significant for all variables. The splitting of qualitative variables (VC origins) through the joint analysis of percentage loss data on yield of both experiments indicated that clumps of VC were more competitive than individual plants (Table 2). In the same density of individual plants, clumps caused higher bean yield losses. These results are attributed to the higher number of corn plants which clumps contain at the same point than single plants, leading to a more intense interference.

Table 2 - Average bean yield (kg ha^{-1}) of the cultivar BRS Pérola as a function of the interference of densities of individual plants or clumps of GR® F_2 volunteer corn. Passo Fundo, RS, Brazil

Volunteer corn densitie m^{-2}	Origin of volunteer corn*	
	Individual plants	Clumps
0	0 A	0 A
0.5	9 B	32.9 A
1	17 B	51 A
2	30.4 B	70.3 A
4	50.1 B	86.8 A
8	74.2 B	98.3 A
12	88.4 B	102.9 A
VC (%)	8.29	
R^2	0.99*	

* Significant at p≤0.05. Means of the splitting of simple effect followed by the same uppercase letter in the row do not differ statistically from each other for the qualitative factor origins in the probability p≤0.05.

VC presents a C_4 metabolism and has advantages in growth and development when compared to the bean, which has a C_3 metabolism (Taiz and Zeiger, 2013). Among the main benefits of corn about the bean is its faster initial growth (higher plant size), which gives it preferential access to the environmental resources (data not shown) and a fast occupation of the ecological site. Similar results were observed among VC plants and soybean, in which corn showed a higher size, limiting the radiation to soybean. When corn intercepts most of the incident radiation, probably contributes to a reduction in crop photosynthesis, suppressing its growth, which results in losses in yield (Piasecki et al., 2018).

From a biological point of view, the obtained results for bean yield losses due to the interference caused by VC densities allow two interpretations: 1) the additive effect in low densities occurs because the areas of influence of plants do not overlap; and 2) in high densities, the interference effect from each corn unit added to bean decreased because of its areas of influence overlapped and as a consequence in the increased intensity of intraspecific interference, yield losses tend to stabilize. Similar behavior was observed in studies of interference among densities of hairy beggarticks and arrowleaf sida with soybean (Rizzardi et al., 2003), VC with soybean (Piasecki et al., 2018), and yellow nutsedge with irrigated rice (Westendorff et al., 2014; Agostinetto et al., 2016).

The results of yield losses in the present study are in accordance with the Law of Decreasing Responses, which indicates that when weed density increases, yield decreases to a point where a subsequent weed addition does not substantially decrease yield. Still, these results are in accordance with the Law of Constant Final Yield, which rules that dry matter production per unit area is independent of plant density in the area (Radosevich et al., 1997).

In cases where high weed densities lead to high crop yield losses, the parameter *a* must be restricted to 100% to avoid overestimating these values (Westendorff et al., 2014) since biological losses higher than 100% do not occur (Fleck et al., 2004; Agostinetto et al., 2004). In the present study, the parameter *a* was not restricted, which resulted in a value above 100% only for the highest clump density (experiment 2) (102.9%). Because in this experiment were observed a tendency to the stabilization from the density of 8 clumps m^{-2} (>95%), this overestimation was not considered with the potential to compromise result interpretation. When the value of *a* is fixed in 100%, there is a tendency for a higher initial inflection of the curve, leading to an overestimation of the parameter *i* (Cousens, 1991). That is the main reason why the value of *a* has not been limited to this study.

In addition to not overestimating *i*, the non-limitation of *a* to 100% allowed to the values of the *i*/*a* ratio be closer to the real conditions since the values of *a* studied for this relation were those calculated as a function of the variability of each situation (Table 1). If the value of *a* were 100, the results of the *i*/*a* ratio would be 0.19 and 0.93 for experiments 1 and 2, respectively. When compared to the calculated values (0.13 and 0.82), they might alter the interpretation of intraspecific interference of the species, especially when the estimated maximum losses are less than 100%. Data interpretation misunderstandings like this can occur when densities are not high enough to estimate the maximum yield loss (Agostinetto et al., 2004). To obtain a reliable estimate of the parameter, the studies should have densities high enough, although they often do not represent what happens in crops (Cousens, 1991).

For ET, a low variation was observed in the calculated values between variables and their levels (Figure 3). In all studied situations the ET was lower than 0.35 individual VC plants m^{-2}, being close to zero when VC corn was originated from clumps (Figures 1 and 2). These results satisfy the hypotheses of our study.

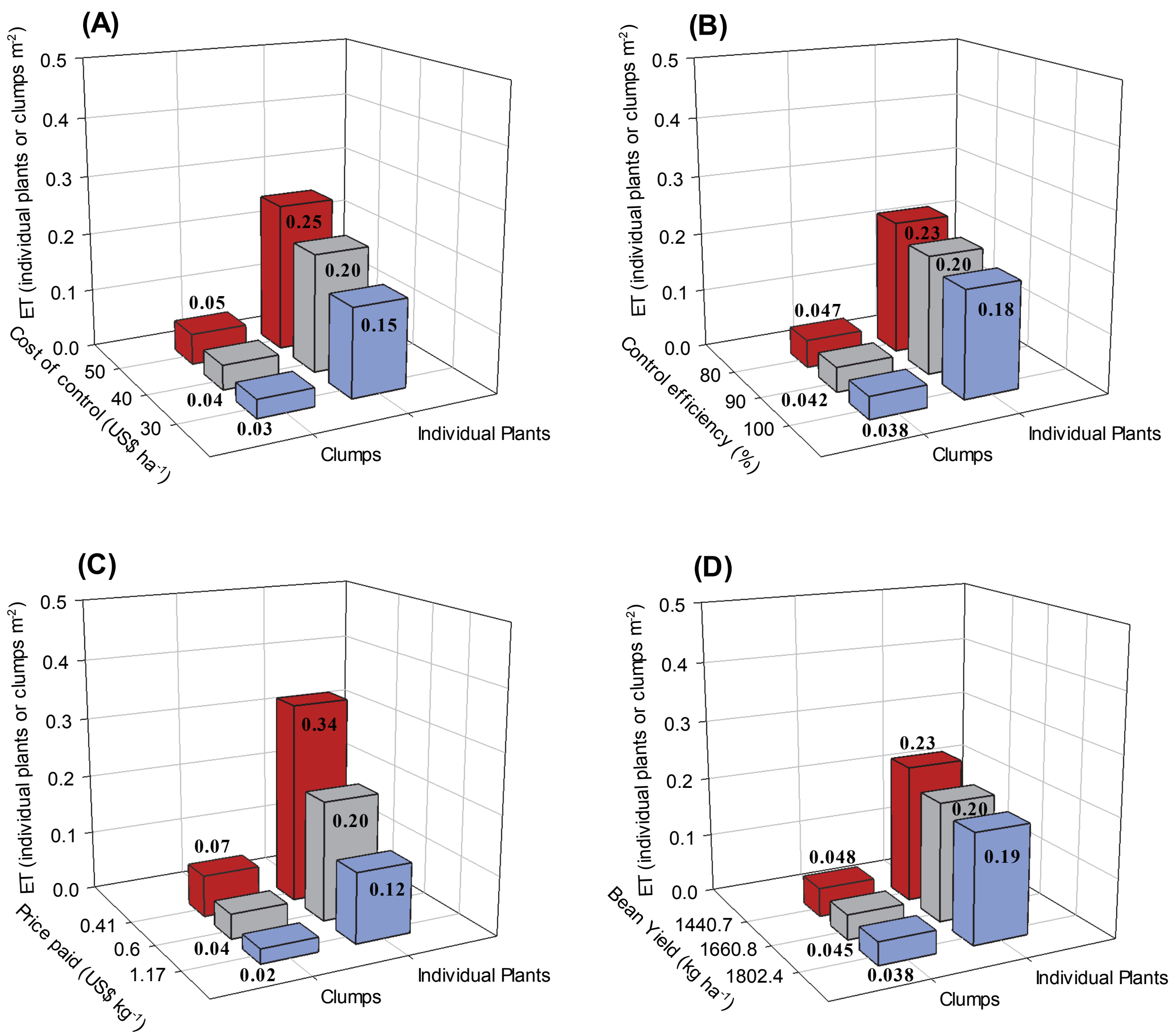


Figure 3 - Economic threshold (ET) of individual plants and clumps of GR® F_2 volunteer corn in bean of the cultivar BRS Pérola according to estimates of (A) control cost (US\$ ha^{-1}), (B) efficiency of corn control (%), (C) price paid for beans (US\$ kg^{-1}), and (D) bean yield (kg ha^{-1}). Passo Fundo, RS, Brazil.

Due to the low variation of results, the average values may be considered in the interpretation. For individual corn plants between studied levels (minimum, average, and maximum) for the calculated variables (control cost, price paid and yield of bean, and control levels), the average value of ET was 0.21 individual plants m^{-2}, while for clumps, the average ET was 0.04 m^{-2} (Figure 3). Thus, to reach an ET that justifies the control the tolerance of the density of VC plants or clumps per area is very low. The ET of individual plants is, on average, 5.25 times higher than that observed for clumps, but when this relation is directed to field conditions, this difference between values is very low. In order to determine the ideal time of VC management originated from individual plants or clumps, accurate samplings must be performed.

For reaching the ET (average of 0.21 plants m^{-2}), a corn plant is required every 4.8 m^2 or 2,100 corn plants ha^{-1}. For clumps, these values are even lower, considering that the average ET was 0.04 clump m^{-2}, i.e., a clump every 25 m^2 or 400 clumps ha^{-1}. Thus, VC control originated from individual plants, or clumps is feasible from 0.21 and 0.04 individual plants or clumps m^{-2}, respectively.

Considering the ET and yield losses caused by the interference of VC with beans, some important measures should be considered to avoid or reduce their occurrence in the crop. The main measures should be taken to avoid losses of corn seeds, such as 1) choosing a cultivar or hybrid of corn with less ear dehiscence; 2) following the official technical recommendations for corn management in order to avoid falling of ears during harvesting; and 3) harvesting with maximum efficiency in order to reduce losses of ears, and pieces of ears (harvest point, maintenance of the harvester machine, speed, cylinder/rotor rotation adjustments, concave opening and sieves, ventilation, etc.).

Therefore, losses in bean yield of the cultivar BRS Pérola under the interference of GR® F_2 VC are influenced by density and origin of volunteer corn. More pronounced bean yield losses occur under higher corn densities and from corn originated from clumps. VC has a high competitive capacity with soybean even under densities lower than a plant or clump m^{-2}. The ET of volunteer corn in the bean is reached under densities lower than or equal to 0.21 individual plants m^{-2} or 0.04 clumps m^{-2}.

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