PLANTA DANINHA

SOCIEDADE BRASILEIRA DA CIÊNCIA DAS PLANTAS DANINHAS

SBCPD

<http://www.sbcpd.org>

ISSN 0100-8358 (print)
1806-9681 (online)

Article

Grain Yield Losses and Economic Threshold Level of GR® F_2 Volunteer Corn in Cultivated F_1 Hybrid Corn

Perdas no Rendimento de Grãos e Nível de Dano Econômico de Milho Voluntário RR® F_2 em Milho Híbrido F_1 Cultivado

PIASECKI, C.[1]*
RIZZARDI, M.A.[1]

ABSTRACT **-** Volunteer corn is competitive with cultivated corn and the degree of interference varies according to their density and origin. This study aimed to determine the grain yield losses of GR® F_1 hybrid corn as a function of the interferences with GR® F_2 volunteer corn densities from individual plants and clumps, and determine the of economic threshold (ET). Two experiments were carried out in the field in a randomized block design with four replications and eight volunteer corn densities between 0 and 12 individual plants or clumps m^{-2}. Each clump consisted of seven corn plants adhered to a piece of the rachis in the same point. The rectangular hyperbola model fitted to the percentage of grain yield losses of corn, generating the parameters for determining ET, which was calculated as a function of cost (US$ ha^{-1}) and efficiency (%) of corn control, the price paid for corn (US$ kg^{-1}), and corn grain yield (kg ha^{-1}). Grain yield losses ranged from 2.7% to 34% for densities of 0.5 and 12 individual plants m^{-2} and 6.1% to 42% for 0.5 and 12 clumps m^{-2}, respectively. The joint analysis of the results of experiments showed that from density of 2 m^{2} clumps are more competitive than individual plants and causes higher yield losses on cultivated corn. The average ET was 0.44 individual plants m^{-2} and 0.19 clumps m^{-2}. However, from these densities, the control should be performed. Increases in corn grain yield and price paid, higher corn control efficiency, and a decrease in control costs promote a reduction in ET of volunteer corn in corn.

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

RESUMO - Milho voluntário é competitivo com o milho cultivado, e o grau de interferência varia com a população e origem das plantas voluntárias. Os objetivos deste trabalho foram quantificar as perdas no rendimento de grãos do milho híbrido simples RR® F_1 em função das interferências com densidades de milho voluntário RR® F_2 originado de plantas individuais e touceiras, e determinar o nível de dano econômico (NDE). Foram realizados dois experimentos em campo, no delineamento de blocos casualizados com quatro repetições; cada um testou oito densidades de milho voluntário entre 0 e 12 plantas individuais ou touceiras m^{-2}. Cada touceira constituiu-se de sete plantas de milho aderidas a pedaço da ráquis no mesmo ponto. O modelo da hipérbole retangular ajustou-se aos resultados de perdas percentuais no rendimento de grãos do milho e foram gerados os parâmetros para a determinação do NDE, que foi calculado em função do custo (US$ ha^{-1}) e eficiência de controle do milho (%), do preço pago pelo milho (US$ kg^{-1}) e do rendimento de grãos (kg ha^{-1}). As perdas no rendimento de grãos do milho variaram de 2,7 a 33,4% para densidades de 0,5 e 12 plantas individuais m^{-2}, e de 6,1 a 42% para 0,5 e 12 touceiras m^{-2}, respectivamente. A análise conjunta dos experimentos

*** Corresponding author:**
<c_piasecki@hotmail.com>

Received: July 1, 2017
Approved: September 25, 20117

Planta Daninha 2019; v37:e019182131

[1] Universidade de Passo Fundo (UPF), Passo Fundo-RS, Brasil.

Doi: 10.1590/S0100-83582019370100006

demonstrou que, a partir da densidade média de 2 m^{-2}, touceiras são mais competitivas que plantas individuais e causam as maiores perdas no rendimento de grãos da cultura do milho. O NDE médio foi de 0,44 planta individual m^{-2} e 0,19 touceira m^{-2}. Dessa forma, a partir dessas densidades , justifica-se a adoção de medidas de controle. Aumentos no rendimento de grãos e preço pago pelo milho, maior eficiência de controle do milho e diminuição do custo de controle promovem redução no NDE de milho voluntário em milho.

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

INTRODUCTION

The official release of commercial cultivation of glyphosate-resistant corn (Roundup Ready®) (GR®) in Brazil occurred in 2008 (CTNBio, 2008). Since there, GR® corn cultivation has been correlated with a higher incidence of GR® F_2 volunteer corn plants interfering with subsequent crops, such as soybean (Davis et al., 2008; Piasecki et al., 2018), bean (Sbatella et al., 2016), and corn (Marquardt et al., 2012), mainly in no-till management system (Beckett and Stoller, 1988; Davis et al., 2008).

Volunteer corn is originated from corn seeds lost at harvest or not harvested from the field and occurs in the form of individual seeds, whole ears or segments of the rachis containing several seeds, which originate individual plants and clumps, respectively (Newcomer, 1971; Beckett and Stoller, 1988). Volunteer corn plants originated from clumps are predominant in the field (Deen et al., 2006) and are difficult to manage due to the lack of uniformity in germination, which generates emergence flows (López-Ovejero et al., 2016). In addition to crop losses, the occurrence of volunteer corn in corn fields is favored by difficulties on the crop establishing, requiring a new sowing (Tye and Smeda, 2014). It could happen in regions where corn is sowed at the end of the winter season (e.g. Parana, Santa Catarina, and the Rio Grande do Sul States – South of Brazil), the late cold occurrence with freezing temperatures occur frequently and damage the crop corn. Also, hydric stress (i.e. excess of water or drought period) occurs in other regions of Brazil where there is a dry season before the crop sowing (e.g. Midwest, Southeast, and Northeast).In these cases, even though corn desiccation with herbicides is carried out, seeds may germinate lately, as well as regrowth may occur when the corn growth meristem is not affected.

The intraspecific competition of hybrid corn cultivated with volunteer corn varies according to the density (Marquardt et al., 2012), generation of corn (F_1 or F_2), and plant origin (individual plants or clumps). Marquardt et al. (2012) assessed grain yield losses of the F_1 generation hybrid corn as a function of the competition with densities of the F_2 generation volunteer corn plants and found linear relationships ranging from 0.5% to 23% in densities of 0.5 and 8 individual plants m^{-2}. On the other hand, losses found by Tye and Smeda (2014) in the same densities were non-linear and ranged from 10.3% to 77.4%. Studies have shown that the competitive potential of F_2 generation hybrid corn is lower than of F_1 generation (Wubben et al., 2002; Tye and Smeda, 2014). However, few studies report the impact of volunteer corn interferences from clumps on grain yield on crops. In addition, the effect of F_2 volunteer corn clumps interference on corn grain yield and the economic threshold has not been reported in the literature.

Empirical mathematical models, such as the hyperbolic derivative (Cousens, 1985), simulate interference effects in order to predict grain yield loss and final yield of crops as a function of the interferences with weed densities (Agostinetto et al. 2004) and have been used by many scientists to estimate yield losses caused by weeds in different crops of economic interest (O'Donovan, 1996; Rizzardi et al., 2003; Westendorff et al., 2014, Agostinetto et al., 2016, Piasecki et al., 2018). After estimating yield losses as a function of weed interferences, it is possible to calculate the of economic threshold (ET). ET is the best estimate to determine the time to control weeds since it considers parameters such as grain yield, crop price, costs, and control levels (O'Donovan et al., 2005).

Thus, the hypotheses of this study were that the interference of densities of GR® F_2 volunteer corn with F_1 hybrid corn reduces crop grain yield and that clumps are more competitive with the crop than individual plants. Thus, this study aimed to quantify grain yield losses of the GR® F_1 hybrid corn as a function of the interference with GR® F_2 volunteer corn densities originated from individual plants and clumps and determine the economic threshold.

MATERIAL AND METHODS

Two field experiments were carried out in a randomized block design with four replicates. The experiments were carried out at the Centro de Pesquisa e Extensão Agropecuária (CEPAGRO) of the Universidade de Passo Fundo (UPF), Passo Fundo, RS, Brazil. The experiments were carried out under the no-tillage system in an area with crop residues of black oat (*Avena strigosa*) and Italian ryegrass (*Lolium multiflorum*) previously controlled with the herbicides clethodim (76.2 g ai ha^{-1}) and glyphosate (720 g ae ha^{-1}). The DeKalb (DKB) 240 VT PRO2™ F_1 generation corn hybrid was used as the crop of the economic interest in both experiments, with 63,000 plants ha^{-1} arranged with rows spaced 50 cm . Volunteer corn and crop corn sowing were carried out on December 12, 2014. Base fertilization consisted of 20.6 kg of N, 80 kg of P_2O_5, and 40 kg of K_2O ha^{-1} banded below the seed at sowing. Crop management was conducted according to the official technical recommendations for corn (Embrapa, 2013). The F_2 generation AG 8088 PRO_2® corn hybrid was harvested in the previous season and stored as ears originated the volunteer corn densities used in the experiments.

Volunteer corn densities were 0, 0.5, 1, 2, 4, 8, 10, and 12 individual plants or clumps m^{-2} for experiments 1 and 2, respectively. Each clump consisted of a segment of the rachis containing seven corn plants at the same point. Volunteer corn densities from individual seeds and clumps were randomly distributed on the ground and then manually buried at 3.5 cm deep in plots of 17.5 m^2 (3.5 × 5 m). Immediately after sowing the volunteer corn, the crop corn was mechanically sown. The emergence of the crop and volunteer plants occurred on the same day. Immediately after the emergence of volunteer corn, a manual adjustment of densities were carried out according to each treatment.

To avoid interference of other weeds, atrazine and glyphosate herbicides were applied according to the recommendations (Embrapa, 2013). When corn reached the V_4-V_5 leaf stage, an additional N fertilization was broadcast applied in the form of 280 kg ha^{-1} of urea (126 kg N ha^{-1}).

The height of the crop and volunteer plants were measured at 20 days after crop emergence (V_5-V_6 leaf stage). Plant size was determined by randomly measuring five cultivated corn plants and five volunteer plants from the soil surface to the tip of the last fully expanded leaf by using a ruler at each experimental unit. In case of the volunteer plants originated from clumps, the average height of plants that composed each clump was considered in the measurement.

Grain yield was obtained by harvesting ears produced from 30 plants in the three central rows of each corn plot. Grains were then threshed, weighed, and after correction the moisture to 13%, the data were estimated in yield kg ha^{-1}.

The percentage of losses were calculated from the data of grain yield in relation to the treatments maintained free from interferences with volunteer corn (zero density), according to Equation 1:

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

where *YL* is the yield loss of corn grain (%), *Ya* is the yield without volunteer corn interference, and *Yb* is the yield in the presence of volunteer corn.

The percentages of yield losses were analyzed for normality by the Shapiro-Wilk's test and homoscedasticity by Hartley's test and after submitted to analysis of variance of regression (ANOVA) ($p<0.05$). To assess the qualitative effect of the origin of volunteer corn on corn yield losses, a joint analysis of both experiments was performed according to Banzatto and Kronka (2006). The analyses were performed in routines generated in the program SAS® 9.0.0 (SAS, 2002).

The nonlinear regression model of the rectangular hyperbola proposed by Cousens (1985) was adjusted to the percentage data of yield losses according to Equation 2:

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

where *YL* is the grain yield loss (%), *x* is the density of corn plants, *i* is the percentage of grain yield loss per unit of volunteer corn when its density is close to zero, and *a* is the percentage of grain yield loss when the volunteer corn density tends to infinity.

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

For calculating the ET, the estimates of the parameter *i* obtained from the equation of the rectangular hyperbola (Cousens, 1985) and the equation adapted from Lindquist and Kropff (1996) were used according to Equation 3:

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

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

In the ET determination, four parameters were considered as reference: cost (US$ ha^{-1}), control efficiency (%), price (US$ kg^{-1}), and corn grain yield (kg ha^{-1}). Within each parameter, three variations were calculated, being considered as minimum, medium, and maximum: control cost (US$ 30.00, US$ 40.00, and US$ 50.00 ha^{-1}), control efficiency (80%, 90%, and 100%), grain yield (6,000 kg, 9,000 kg, and 12,000 kg ha^{-1}), and price paid for corn (US$ 0.15, US$ 0.20, and US$ 0.26 kg^{-1}). The reference values for the price paid for corn were considered according to the international price of the last five years (2013 to 2017) by the Chicago Mercantile Exchange (CME, 2017). To calculate the variations within each parameter, the average value for the other component parameters of the equation was considered.

RESULTS AND DISCUSSION

In both experiments, the regression analysis of variance was significant for the height of cultivated corn and volunteer plants. Similarly, the regression analysis of variance and the joint analysis of the experiments performed for corn yield losses showed significant F values in both experiments, with satisfactory fit of the regression model derived from the rectangular hyperbole to the data, evidenced by the coefficients of determination (R^2) and sum of square residuals (SSR) (Table 1). R^2 is not the most adequate parameter to measure a non-linear regression, but it serves as an approximate indicator of the variability (Sartorato et al., 1996). SSR can also be used as an adjustment criterion for the model, i.e. the better adjustment is the lower SSR value (Passari et al., 2011). Due to the higher experimental control over the density and the emergence of volunteer corn plants among the treatments of both experiments, the predictive capacity of the Cousens model (1985) was considered excellent.

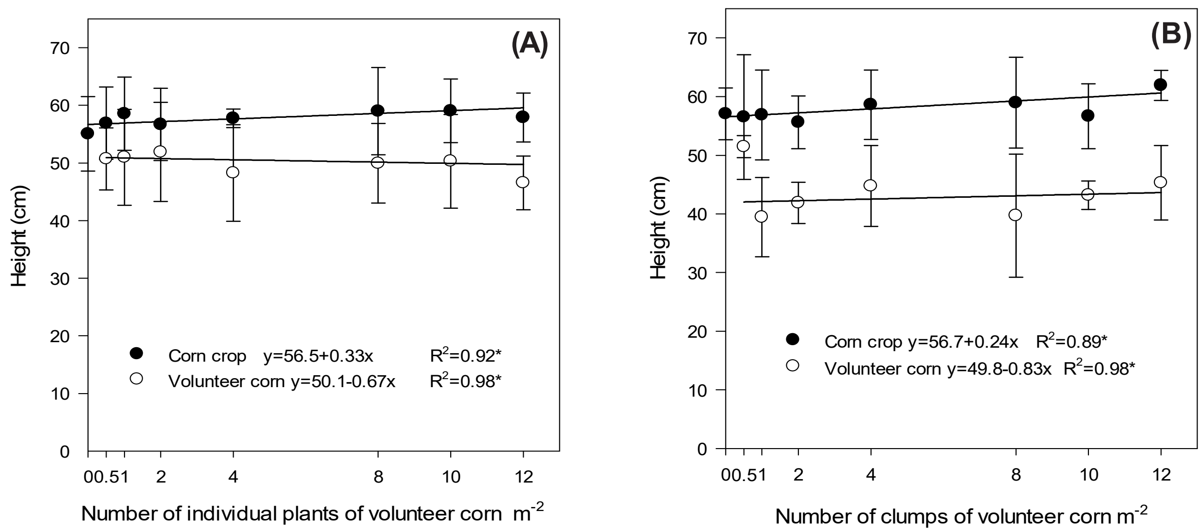
Regardless of the origin of the volunteer plants (individual plant or clump) as a function of an increase in density, a linear increase was observed in the height of cultivated corn, as well as a

Table 1 **-** Parameters estimated by the rectangular hyperbola model for grain yield losses of DKB 240 VT PRO2 hybrid corn as a function of the competition with GR® F_2 volunteer corn densities originated from individual plants and clumps. Passo Fundo, RS

Variable	Parameter		i/a	R^2	Loss of corn grain yield (%)[1]	SSR	F*
	i	a					
Individual plants	5.7	65.3	0.09	0.98*	y = (5.7*x)/(1+(5.7/65.3)*x)	0.00201	284.92*
Clumps	13.6	56.6	0.24	0.95*	y = (13.6*x)/(1+(13.6/56.6)*x)	0.00075	81.09*

[1] i = percentage of yield loss per unit of corn when the population is close to zero; a = percentage of yield loss when corn population tends to infinity. * Significant at p<0.05. SSR = sum of squared residuals; R^2 = coefficient of determination.

reduction in the height of volunteer plants (Figure 1). Considering the smallest density of volunteer corn plants in relation to the largest (0 and 12 m^{-2}), the height of the cultivated corn increased 5% when under interference with individual plants and 7% with clumps, while the height of individual plants reduced by 19.3% and that of clumps by 15.5%, in the same densities (Figure 1).



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

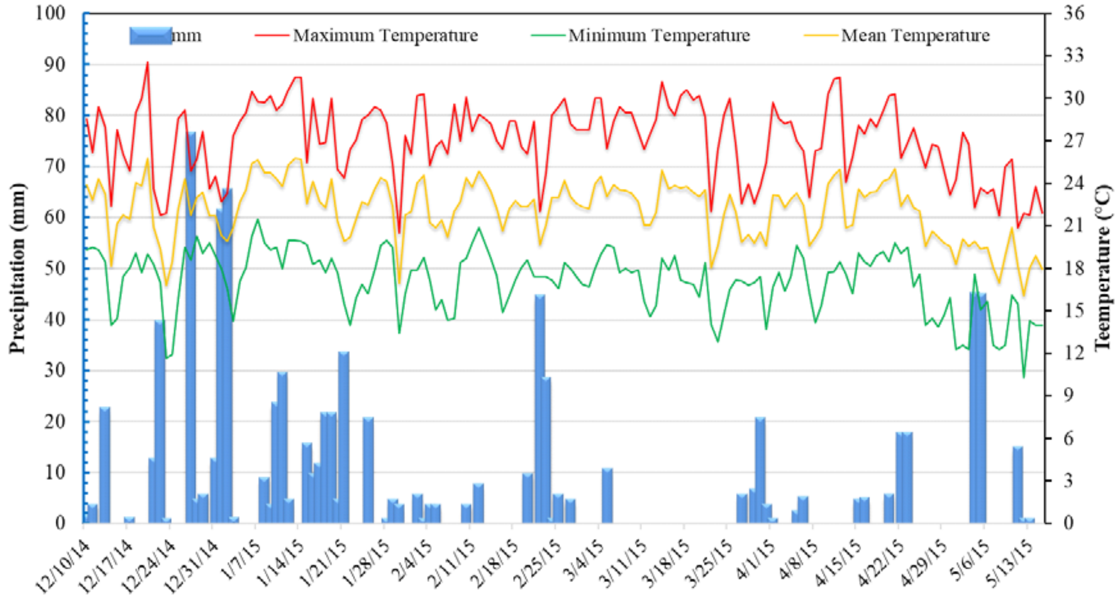
Figure 1 - Average plant height of DKB 240 VT PRO2 hybrid corn and F_2 volunteer corn plants as a function of the interference with individual plant populations (A) and clumps (B) of the GR® F_2 volunteer corn.

The increase in height of cultivated corn in relation to volunteer corn plants may be related to an inherent characteristic of the hybrid (DKB 240 VT PRO_2™ – cultivated corn; AG 8088 PRO_2® – volunteer plants) and the $F_1 \times F_2$ corn generation, in which F_1 stands out (Wubben et al., 2002; Tye and Smeda, 2014). In addition, the increase in plant density results in a higher light irradiation in the far-red length, which is perceived by plant phytochrome and results in a higher reserves expenditure for growth in search of light (Radosevich et al., 2007). In addition, the fertilization in the sowing furrow of the crop favored the access of mineral elements to the crop, which gave it a nutritional advantage over the volunteer corn plants.

The weather conditions during the experiments favored crop development (Figure 2), being observed an average corn grain yield in the treatment without volunteer corn of 12,155 kg ha^{-1} (experiment 1) and 11,622 kg ha^{-1} (experiment 2). The increase in volunteer corn density resulted in higher losses in corn yield regardless of the origin (Figure 3). Although the confidence intervals of the results of losses did not show differences between corn origins, the slicing of qualitative variables (corn origins) through the joint analysis of the data of both experiments indicated that clumps of volunteer corn are more competitive than individual plants in densities higher than 2 m^{-2} (Table 2). These results are attributed to a higher number of corn plants that clumps contain in the same point and, therefore, the interference is higher .

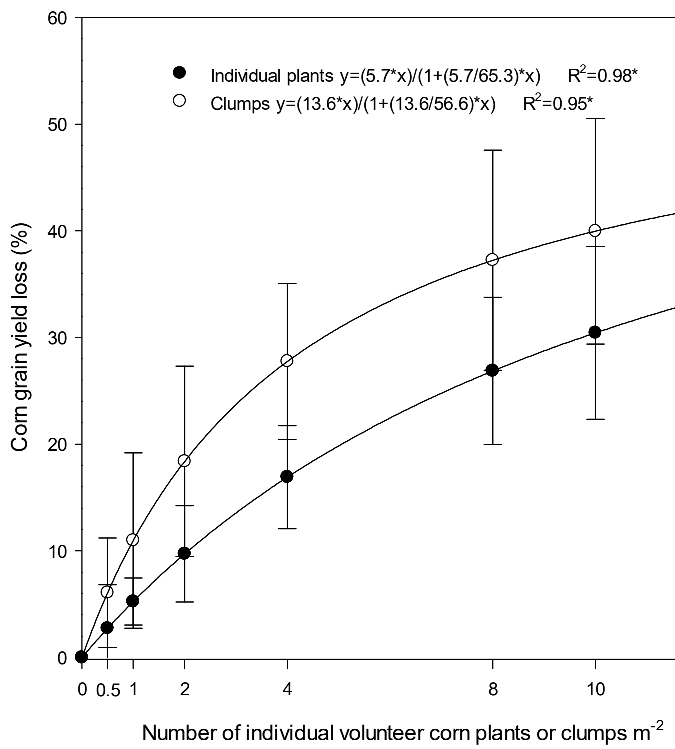
The parameter *i* calculated by the procedure Proc Nlin in the software SAS, used in the equation proposed by Cousens (1985), indicates the initial loss in corn yield per unit of volunteer corn when the density is close zero and indicates the competitive ability of the weed in relation to the crop. With the *i* values, it is possible to make relations of the competitive capacity between the origins of volunteer corn plants and the cultivated corn. For the relation between *i* values obtained for clumps and individual plants of volunteer corn, clumps showed to be 2.4 times more competitive with cultivated corn when compared to individual plants (Table 1).

The parameter *a* indicates the estimated crop yield losses as a function of interference (Cousens, 1985). In cases where high weed density causes high crop yield losses, it is necessary to restrict the parameter *a* to 100% in order to avoid that its values are overestimated (Westendorff et al., 2014) because of losses higher than 100% do not occur biologically. By limiting it to 100%,



Source: Somar Meteorologia.

Figure 2 **-** Climate information for Passo Fundo, RS, from December 10, 2014, to May 15, 2015.



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

Figure 3 **-** Estimated losses (%) in grain yield of DKB 240 VT PRO2 hybrid corn as a function of the competition with individual plant densisites and clumps of GR® F_2 volunteer corn.

there is a tendency for higher initial inflection of the curve, tending to overestimate the *i* values (Cousens, 1985, 1991). In this study, the yield losses of corn were lower than 100% due to interference with densities and origins of volunteer corn, not being necessary the limitation of *a* by 100, and thus, do not overestimate *i* (Figure 3; Table 1). On the other hand, an underestimation of *i* may have occurred because the losses in the largest studied density did not stabilize nor

Table 2 **-** Average corn yield losses (%) as a function of the interference of individual plant densities or clumps of GR® F_2 volunteer corn

Volunteer corn population m^{-2}	Origin of volunteer corn		Pr > F
	Individual plants	Clumps	
0	0 A	0 A	1.0
0.5	2.7 A	6.1 A	0.016
1	5.2 A	11 A	0.011
2	9.7 B	18.4 A	0.008
4	16.9 B	27.7 A	<.0001
8	26.9 B	37.2 A	<.0001
10	30.4 B	40 A	0.0003
12	33.4 B	42 A	0.0003
CV (%)	21.7		
R^2	0.95*		
MSD	7.5		

Means of the slicing of the simple effect followed by the same uppercase letter in the row do not differ statistically from each other for the qualitative factor origins at a probability of p<0.05. * Significant at p<0.05. Passo Fundo, RS.

reached the maximum point (Radosevich et al., 2007). Thus, further studies of the interference of volunteer corn on corn crop should be performed with volunteer corn density higher than those tested in this study.

The i/a ratio reflects the degree of intraspecific competition of the infesting community (Cousens, 1985). This ratio calculated for the experiments demonstrates a higher intraspecific competition for clumps (0.24) when compared to individual plants (0.09), being 2.7 times higher for clumps (Table 1). Clumps contain more corn plants at one point, which intensifies competition (Piasecki et al., 2018). The intraspecific competition between corn plants within each clump favored that the competitive ability relationship was not higher than 2.4 times, considering that each clump was constituted of seven volunteer corn plants in comparison to one single individual plant.

When analyzing from the biological point of view the adjustment provided by the rectangular hyperbole to the data of loss of corn grain yield, two situations are observed. In the first situation, there is an additive effect in low densities, which occurs because the areas of influence of individual plants do not overlap. In the second situation, the effect of interference from each unit of volunteer corn that was added to the cultivated corn decreased under high densities because the areas of influence overlapped, and as a consequence of an increase in the intensity of intraspecific competition, grain yield losses tend to be lower (Radosevich et al., 2007). A similar behavior was observed by Tye and Smeda (2014) in studies of interference between volunteer corn densities with corn.

Thus, by this model, each unit of corn added to the competitive load causes higher losses in grain yield at low densities than in high of weed plants. This behavior follows the response reduction law, which indicates that when the weed density is increased, crop yield decreases to a point where the subsequent addition of weeds does not substantially decrease grain yield. This is also in accordance with the law of constant final yield, which rules that the production of dry matter per unit area is independent of the density of plants present in the area (Radosevich et al., 2007).

A low variation was observed between ET values calculated among the studied variables in both experiments. Under all the study situations, ET was lower than 0.7 m^2 and was close to zero when corn was originated from clumps (Figure 4). This means that the adoption of control measures is justified at low densities of volunteer corn. If volunteer plants are not controlled, significant losses in corn grain yield may occur, which would result in economic losses in the agricultural activity.

Due to the variation in the results of ET for volunteer corn, which was low in relation to other weeds, such as *Cyperus esculentus* in irrigated rice, ranging from 3.3 to 11.6 (Westendorff et al., 2014), the average values were considered in the interpretation of results. Among the levels (minimum, medium, and maximum) for the calculated variables (control cost, price, corn grain yield, and control levels) of individual corn plants, the average ET value was 0.44 individual corn plant m^{-2} and 0.19 m^2 for clump (Figure 4). In these cases, the threshold level would be reached with the presence of an individual corn plant every 2.7 m^2 and a clump every 5.3 m^2. These results demonstrate a higher competitive capacity of volunteer corn clumps with corn crop in relation to individual plants, mainly due to a higher number of plants under this condition when compared to the other. Vidal et al. (2004) found an ET value for *Brachiaria plantaginea* in

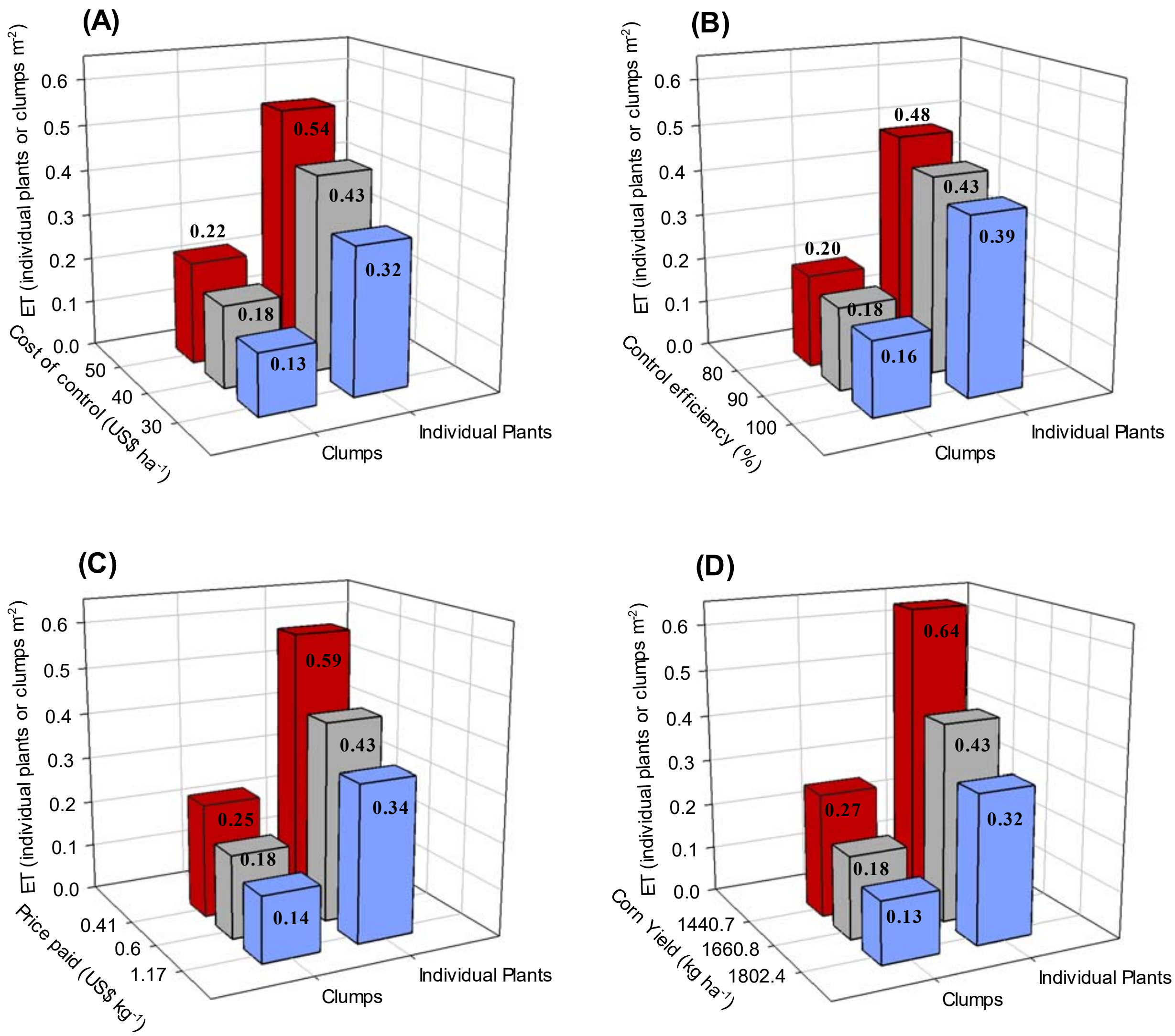


Figure 4 **-** Economic threshold level (ET) of GR® F_2 individual plants and volunteer corn clumps (m^{-2}) in the cultivation of DKB 240 VT PRO2 hybrid corn according to estimates of (A) control cost (US$ ha^{-1}), (B) corn control efficiency (%), (C) price paid for corn (US$ kg^{-1}), and (D) corn grain yield (kg ha^{-1}). Passo Fundo, RS.

corn crop from 5 to 43 (1.5 to 13 plants m^2) times higher than the ET of volunteer corn of the present study (considering an average ET of 0.31 m^2). These results allow us to affirm that volunteer corn is one of the most competitive weeds described for the corn crop, especially when originating from clumps.

In addition to yield losses, volunteer corn in corn crop also cause indirect losses, as it impairs mechanical harvesting, increases impurities and moisture, and reduces the quality of harvested grains (Marquardt et al., 2012). Also, the increase in corn plant density per hectare may result in a higher disease severity throughout the corn cycle and compromise the quantity and quality of harvested grains due to the physical barrier to the penetration of phytosanitary products in the plant canopy (Blandino et al., 2008).

From the ET of volunteer corn in corn, it is possible to determine the limit infestation of volunteer plants in order to carry out the control with a technical and economic efficiency. However, GR® volunteer corn in corn is a weed difficult to control in pre- and post-emergence, which is limited to mechanical management (Marquardt et al., 2012). On the other hand, pre-emergence herbicide applications to control volunteer corn plants may leave herbicide residues in the soil, negatively affecting the crop, with no available herbicide for post-emergence applications yet.

Thus, the best alternatives to avoid or reduce density of GR® volunteer corn plants in corn are preventive actions such as: 1) avoiding successive corn crops; 2) conducting crop management and harvesting operations aiming at minimizing harvest losses; 3) avoiding re-sowing in corn areas; 4) performing crop rotation and biotechnological events that confer tolerance to different herbicides; and 5) in case of successive crops, cultivating glyphosate-sensitive corn in the first season and GR® corn in the second season.

Thus, the interference exerted by GR® F_2 volunteer corn plants and clumps reduces corn grain yield, regardless of their origin. GR® F_2 volunteer corn is more competitive than individual plants. The ET of volunteer corn in the cultivation of corn is reached in a density of around 0.44 individual plants m^{-2} and it is close to zero when the corn is originated from clumps. Increase in grain yield and price paid for corn, higher corn control efficiency, and lower control costs promote a reduction in the ET of volunteer corn.

ACKNOWLEDGMENTS

The authors are grateful to the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the financial support of the fellowship of Cristiano Piasecki.

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