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Pre-emergence control and interference of voluntary maize plants on a soybean crop in Brazilian *Cerrado*

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ABSTRACT. The succession of soybean/maize has been largely adopted. Storm damage and crop problems can lead to grain loss, generating maize ear fragments or even whole ears that remain in the soil and still display germination viability, resulting in the occurrence of volunteer plants. In this context, the present study aimed to evaluate the interference of voluntary maize plants on soybean and investigate the susceptibility of maize hybrids to pre-emergence herbicides. In the first step, an experiment was performed evaluating the influence of voluntary maize plant density and spatial distribution on soybean. The experiment was performed in a randomized completely block design (RCBD) with four replications, with treatments disposed in factorial arrangement (2 x 4) + 1. The first factor corresponded to the spatial distribution of maize plants: row or in between soybean rows; while the second factor adopted four infestation densities of maize plants m^{-2}: 4, 8, 12, and 16. The additional treatment consisted of a control without maize plants. For the second step, an experiment was conducted in two locations aiming to determine the efficacy of pre-emergence herbicides in the control of voluntary maize. Both experiments were installed in RCBD in a split-plot scheme with four replications. Fomesafen, lactofen, sulfentrazone, chlorimuron-ethyl, diclosulam, flumetsulam, imazethapyr, clomazone, metribuzin, [sulfentrazone + diuron], [imazethapyr + flumioxazin], and a control without herbicide application were evaluated in the main plot. In each subplot, the maize hybrids DKB310 PRO3™ and DKB390 PRO3™ were evaluated. No influence on the position of voluntary maize on the soybean yield was observed. The presence of the maize population led to a progressive decrease in soybean yield, ranging up to 86%, at 16 plants m^{-2}. DKB390 displayed a stand reduction of 82.88% after the use of diclosulam. Diclosulam led to better results regarding maize plant decreases for both hybrids.

Keywords: crop rotation; *Glycine max*; volunteer plants; weed competition; *Zea mays*.

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Introduction

Soybean and maize represent the largest cultivated crop areas in Brazil, at 36.7 and 17.5 million hectares, respectively, for 2019/2020 (Companhia Nacional de Abastecimento [Conab], 2020). The soybean complex accounts for 29.5% of all Brazilian agribusiness exports. On the other hand, Brazilian maize exports reached a record US$ 1.34 billion in 2019 (Federação das Indústrias do Estado de São Paulo [Fiesp], 2020). The production system involving a first soybean crop followed by a maize crop (intercropping, in the off-season) is most representative in the Brazilian Midwest. According to Conab (2020) projections, maize cultivation in the off-season represents over 70% of the total maize production in Brazil.

During the mechanized harvesting of off-season maize, loss of grains, ears, and ear fragmentation is normal (Tabile et al., 2008). These seeds may, in turn, remain viable until soybean sowing begins, resulting in the establishment of voluntary maize plants. The tolerable level of maize grain losses during mechanized harvests is 1.5 bags per hectare, which represents 90 kg of grain deposited in each hectare after the harvest (Mantovani, 2005).

Until a few years ago voluntary maize plants were easily eliminated using glyphosate, either during burndown applications (pre-sowing) or during post-emergence soybean applications, as glyphosate herbicide tolerance technology was available in Brazil only for soybean cultivars. With the development of glyphosate-tolerant maize hybrids, the use of this herbicide in the control of voluntary maize plants has lost its effectiveness, thus leading to the need for other chemical control techniques, resulting in increased production costs (Alms, Moechnig, Vos, & Clay, 2016).

Some studies have demonstrated high maize interference capacity in soybean crops (Marquardt, Krupke, & Johnson, 2012; Caratti et al., 2019), although little information is available for the *Cerrado* biome in Brazil. Moreover, most competition assessments link only the density of voluntary maize plants to interference potential in soybean crops, and do not evaluate possible additional maize damage from maize plant positioning in relation to soybean crop rows. In addition to losses directly related to soybean yields, voluntary maize plants may also impair the yield of mechanized harvesting operations and decrease soybean quality (Braz et al., 2019). As most glyphosate-tolerant maize hybrids also feature *Bt* technology, aiming at tolerance toward defoliating lepidopterans, the presence of volunteer maize plants for much of the year can accelerate tolerance breaks, making the use of this important technology unviable for pest management (Marquardt, Terry, & Johnson, 2013).

The main method applied in the management of glyphosate-tolerant maize has been post-emergence chemical control, using ACCase inhibitor herbicides (Maciel et al., 2013). However, the shaping of other control technologies is necessary, as Enlist™ technology will lead to a significantly reduced number of ACCase inhibitor herbicide options to control voluntary maize. In addition, maize grains germinate alternately, leading to different emergence flows of voluntary plants. Thus, more than one post-emergence ACCase inhibiting herbicide application may be required in the same area, significantly impacting production costs (Ovejero et al., 2016).

In this sense, pre-emergence herbicides can act as an important tool in controlling voluntary maize, as an alternative or complement to the use of post-emergence herbicides. These herbicides can reduce or prevent the emergence and establishment of voluntary maize plants, thus minimizing the negative impact caused by initial soybean interference (Chahal & Jhala, 2015). Despite this potential, the vast majority of herbicide selection studies concerning voluntary maize control only evaluate post-emergence herbicides (Marquardt & Johnson, 2013; Chahal & Jhala, 2015; Alms et al., 2016).

In this context, the present study aimed to evaluate the effect of voluntary maize plant interference at different densities growing on soybean crop rows or in between rows, while also assessing the performance of pre-emergence herbicides in the control of two glyphosate-tolerant voluntary maize hybrids.

Material and methods

Three field experiments were carried out, one aiming at evaluating the influence of voluntary maize plant density and spatial distribution on soybean (grown in soybean rows and in between rows), termed Experiment I, and two experiments aimed at determining the efficacy of pre-emergence herbicides in the control of two voluntary maize hybrids (Experiments II and III).

Experiment I was conducted in the municipality of Rio Verde, Goiás State, Brazil (latitude 17° 46’ 01.10” S, longitude 51° 02’ 18.40” W, and altitude of 828 m), from November 2015 to March 2016. Experiments II and III were conducted, respectively, in Santa Helena de Goiás, state of Goiás, Brazil (latitude 17° 50’ 10.50” S, longitude 50° 36’ 40.50” W, and altitude of 580 m) and Morrinhos, state of Goiás, Brazil (latitude 17° 54’ 07.80” S, longitude 49° 14’ 53.60” W, and altitude of 850 m), from November 2018 to January 2019.

According to the Köppen classification, the climate in the experiment localities is Aw, a tropical climate with a dry season, characterized by more intense rainfall in the summer compared to the winter. Rainfall rates observed during the experiments are presented in Figure 1.

Voluntary maize interference on soybean crop

Prior to the installation of the experiment, soil samples (0-20 cm layer) were collected for physicochemical characterization, as follows: pH at $CaCl_2$ of 5.5; 3.7 $cmol_c$ dm^{-3} of Ca^{+2}; 1.25 $cmol_c$ dm^{-3} of Mg^{+2}; 0.15 $cmol_c$ dm^{-3} of K^+; 0.04 $cmol_c$ dm^{-3} of Al^{+3}; 1.6 $cmol_c$ dm^{-3} of $H^+ + Al^{+3}$; 33 mg dm^{-3} of P; 5.3 mg dm^{-3} of S; 25.5 g kg^{-1} of OM; 531 g kg^{-1} of clay, 54 g kg^{-1} of silt, and 415 g kg^{-1} of sand (loam clayey texture).

The experimental design consisted of a randomized completely block (RCBD) design with four replications, with treatments disposed in a factorial arrangement (2 x 4) + 1. Factor A corresponded to the position where the maize seeds were sown, allocated either in the soybean growth row or in between soybean rows. Factor B adopted four infestation densities of RR™ maize plants (hybrid AS 1633 PRO2™, F1 generation) per m^2 (4, 8, 12, and 16). The additional treatment consisted of a control without the coexistence of maize plants. Each experimental unit comprised 20 m^2 of total area, and the plots consisted of ten rows, 4 m in length, and spaced 0.5 m apart. The usable area consisted of six central lines of 2 m in length (6 m^2).

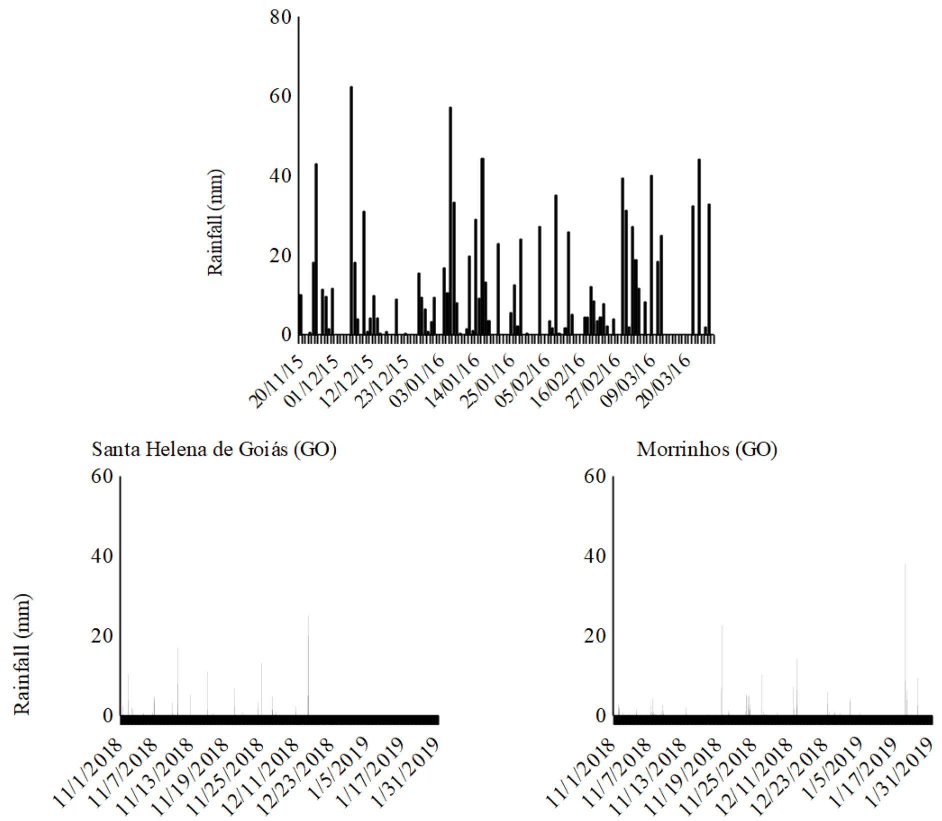

Figure 1. Rainfall data (mm) observed during the experiments. Rio Verde (state of Goiás, Brazil), 2015/2016 and Santa Helena de Goiás and Morrinhos (state of Goiás, Brazil), 2018/2019.

Soybean sowing (Anta 82 RR™) was performed mechanically on November 20, 2015, fertilizing the sowing furrow with 250 kg ha^{-1} of MAP Turbo (10-50-0) + 120 kg ha^{-1} of potassium chloride (60% K_2O). A total of 21 m^{-1} seeds were distributed at a depth of 3 cm. Plant emergence occurred six days after sowing (November 26, 2015). To simulate the coexistence of voluntary maize and soybean crops, manual maize sowing was performed, adopting the predicted population in each treatment, placing the seeds either in the soybean rows or in between rows. Maize sowing was performed immediately after soybean sowing, at a depth of 3 cm.

To evaluate the effect of each treatment on soybean development, the following assessments were performed: 1) plant height at 7 and 28 days after emergence (DAE) and at harvest. Measurement was taken using a graduated ruler from the distance between the soil surface (plant neck) and the apical meristem, sampling five plants per experimental unit; 2) canopy closing percentage at 35 DAE. A visual shade grading (%) between the rows was obtained, and the maximum value (100%) was considered as the condition in which the rows were completely covered by soybean shoots (Heiffig, Câmara, Marques, Pedroso, & Piedade, 2006); and 3) dry mass of soybean shoots at 42 DAE, sampling five plants per experimental unit. The shoots of soybean plants were placed in a forced circulation oven for 72 hours at a constant temperature of 65°C to obtain dry mass values.

The following evaluations were performed at soybean harvest (105 days after sowing): first pod insertion height and number of pods per plant, sampling five soybean plants per plot. In addition, the mass of 100 grains and yield were evaluated, correcting grain moisture to 13% (wet basis).

Efficacy of pre-emergence herbicides in the control of voluntary maize

The soil of the experimental area of Santa Helena de Goiás was sampled from the 0-20 cm layer, presenting the following physicochemical properties: pH in $CaCl_2$ = 6.10; 35.8 g kg^{-1} of OM; 275 g kg^{-1} of clay, 297 g kg^{-1} of silt, and 428 g kg^{-1} of sand (sandy clay loam texture). For the experiment conducted in Morrinhos, the soil analysis results revealed the following properties: pH at $CaCl_2$ = 6.13; 43.0 g kg^{-1} of OM; 556 g kg^{-1} of clay, 167 g kg^{-1} of silt, and 278 g kg^{-1} of sand (clay texture).

The experimental design for both experiments consisted of a RCBD in a split-plot scheme with four replications. Eleven herbicidal treatments were evaluated in the main plot (g ha^{-1}), as follows: fomesafen (200), lactofen (168), sulfentrazone (300), chlorimuron-ethyl (20), diclosulam (29), flumetsulam (132), imazethapyr (106), clomazone (600), metribuzin (480), [sulfentrazone + diuron] ([245 + 490]), and [imazethapyr + flumioxazin] ([120 + 60]), in addition to a control with no herbicide application, used as reference. In each subplot, two simple RR™ maize hybrids were evaluated (F1): DKB310 PRO3™ and DKB390 PRO3™, both belonging to Dekalb's seed portfolio (Dekalb, 2020).

The commercial product used for each active ingredient and the company that manufactured these products are as follows: fomesafen (Flex™, Syngenta), lactofen (Cobra™, Bayer), sulfentrazone (Boral™, FMC), chlorimuron-ethyl (Classic™, Dupont), diclosulam (Spider™, Corteva), flumetsulam (Scorpion™, Corteva), imazethapyr (Pivot™, BASF), clomazone (Gamit™, FMC), metribuzin (Sencor™, Bayer), [sulfentrazone + diuron] (Stone™, FMC), and [imazethapyr + flumioxazin] (ZethaMaxx™, Sumitomo). The main plot comprised six rows sown with maize, 5 m long, spaced 0.5 m apart. The subplot consisted of three maize rows, 5 m long.

In both experiments, maize was sown mechanically at 3 cm depth, at five seeds m^{-1} to obtain a final population of 100,000 plants ha^{-1}. Experiment II was sown on November 13, 2018, and Experiment III on November 14, 2018, with the emergence of maize seedlings five days after sowing, on November 18, 2018, and November 19, 2018, respectively. As these experiments were aimed at the control of maize plants, no base or cover fertilization was applied.

In both experiments, herbicide treatments were applied pre-emergence, immediately after maize sowing, using a CO_2 -based constant pressure sprayer (35 lb pol^{-2}) equipped with six TTI 110.02 spray tips spaced 0.5 m apart, providing an application volume of 150 L ha^{-1}. The environmental conditions during the applications were determined using a thermo-hygro-anemometer, with average relative humidity, temperature, and wind speed of 65.6%, 25.4°C, and 2.4 km hour^{-1} for Experiment II and 70.6%, 20.1°C, and 2.1 km hour^{-1} for Experiment III, respectively. The soil of both experimental areas was moist during herbicide application.

From the twentieth day after maize sowing, during which an emergence flow from the weed community was observed, all plots were weeded until the end of the experiments to avoid weed interference. Thus, only herbicide effects on the development of maize plants were evaluated.

To evaluate the effects of the herbicide treatments on volunteer RR™ maize plants, the following assessments were performed in both experiments: 1) percentage of emerged plants in relation to the control at 7 and 42 DAE, carried out by counting plants throughout the useful area of the experimental units; 2) height of plants at 7, 14, 28, and 42 DAE, determined with the aid of a ruler measuring the distance from the ground surface (plant neck) to the beginning of the sheath of the last expanded leaf of five plants per experimental unit, presenting the results as a height percentage in relation to the control without any herbicide treatment for each hybrid; and 3) phytotoxicity in plants at 7, 14, 28, and 42 DAE was determined using an adapted scale from the European Weed Research Council (EWRC, 1964), applying visual injury observations, where a score of one consists of plants that did not present any injury symptoms and a score of nine indicates fully controlled plants. For phytotoxicity assessments, symptoms were considered only in the youngest leaves of the maize plants.

Statistical analyses

All statistical analyses were carried out using the computer program SAS (Statistical Analysis Software [SAS], 2002). For Experiment I, when significant effects of the quantitative factor (plant density) were found, the data were subjected to regression analysis ($p \leq 0.05$). In Experiments II and III, when a significant effect related to herbicide treatments was observed, the Scott–Knott grouping test ($p \leq 0.05$) was applied, while comparisons between hybrids were detected by the F test ($p \leq 0.05$).

Results and discussion

Voluntary maize interference on soybean crop

The height of soybean plants at 7 DAE displayed a slight decrease with the coexistence of up to eight maize plants per m^2, stabilizing at higher densities (Figure 2). At 28 DAE, the presence of four maize plants per m^2 led to a large reduction in the size of soybean plants, also stabilizing at higher densities.

For these evaluations, the average height of soybean plants was presented in the coexistence treatments in rows and in between rows since no significant spatial distribution effect of maize plants or interactions between the evaluated factors was observed. This behavior demonstrates that, regardless of whether the voluntary maize plant emerges in the soybean row or in between rows, coexistence with this crop will similarly affect the initial height of soybean plants.

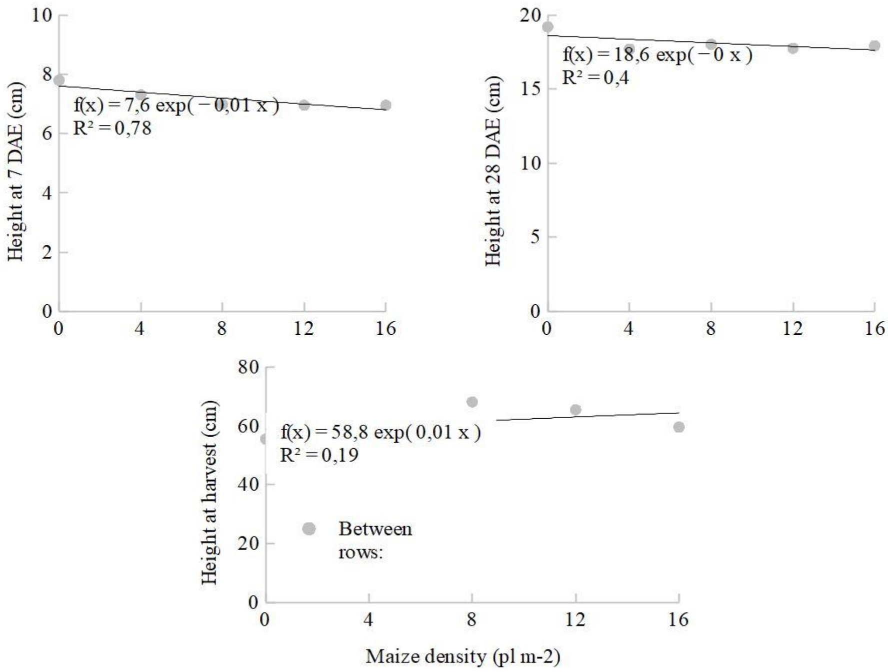

Figure 2. Height of soybean plants at 7 and 28 DAE and at harvest due to increasing densities of voluntary maize infestation. Rio Verde (state of Goiás, Brazil), 2015/2016. *Significant ($p \leq 0.05$); ^{ns}non-significant ($p > 0.05$).

As maize displays a higher growth rate compared to soybean, associated with earlier emergence, this species can attain more forceful access to environmental resources (water, light, and nutrients). Moreover, maize presents a type C4 photosynthetic metabolism, which leads to competitive advantages over soybean under tropical conditions, especially at higher densities (Petter et al., 2015).

Concerning the plant height evaluation performed during the harvest period, in general, recovery of soybean plant size when competing with maize was observed. In treatments where maize plants were placed in between rows, increases in soybean heights of up to eight per m^2 maize plants were noted (Figure 2), which was not observed when maize plants were positioned in line with the soybean crop. This demonstrates that soybean growth was stimulated in search of resources during crop development, with the need to compete for light, which resulted in the observed etiolation (internode elongation) and increased plant heights, corroborating previous assessments (Merotto Jr., Vidal, Fleck, & Almeida, 2002).

Analyzing soybean row closure at 35 DAE (Figure 3), with increasing maize density, soybean plants displayed a higher percentage of row closure, which can be explained by the etiolation of competing plants. Moreover, no effect of maize plant distribution on the sowing area was observed, which reinforces the possibility of plant etiolation due to light competition, since maize presents a high leaf area index, with no differentiation in terms of shading, whether located in rows or in between soybean rows.

Figure 3 also demonstrates that the increase of maize plants alongside soybean resulted in a reduction of the shoot dry mass. In this evaluation, the observed adjustment was exponential, indicating that greater losses in shoot dry mass were observed with the addition of plants in competition with soybean, and after a certain level, this decrease in dry mass becomes proportionally smaller than the initial observed.

Soybean crops, when subjected to low light intensities, present lower dry mass accumulation, growth rate, and net assimilation rates while also presenting high etiolation, predisposing bedding under field conditions (Shibles & Weber, 1965). An experiment performed by Melges, Lopes, and Oliva (1989) reported the importance of irradiance levels for soybean growth and development, since the number of leaves and pods, as well as dry mass accumulation, decreases in shaded conditions.

The evaluation of the first pod insertion height is extremely important, as this character can have a direct influence on yield, although this has not yet been classified as a soybean yield component (Nepomuceno, Alves, Dias, & Pavani, 2007). The average results of the first soybean pod insertion indicate a linear increase in relation to the increased density of voluntary maize plants (Figure 4). This behavior is related to the etiolation observed in soybean plants under intense light competition with maize plants (Merotto et al., 2002). As soybean plants suffer etiolation, the distance between internodes increases, which may negatively affect soybean yield, due to a possible decrease in the number of pods per plant.

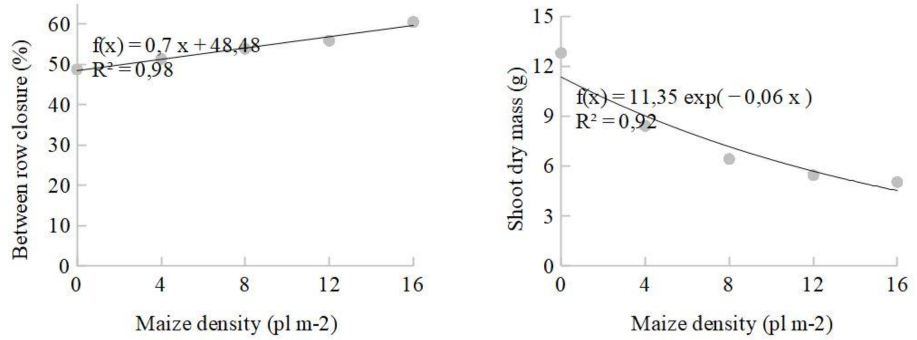

Figure 3. Soybean row closure at 35 DAE and soybean dry mass at 42 DAE, due to increasing densities of voluntary maize infestation in or in between soybean rows. Rio Verde (state of Goiás, Brazil), 2015/2016. *Significant ($p \leq 0.05$).

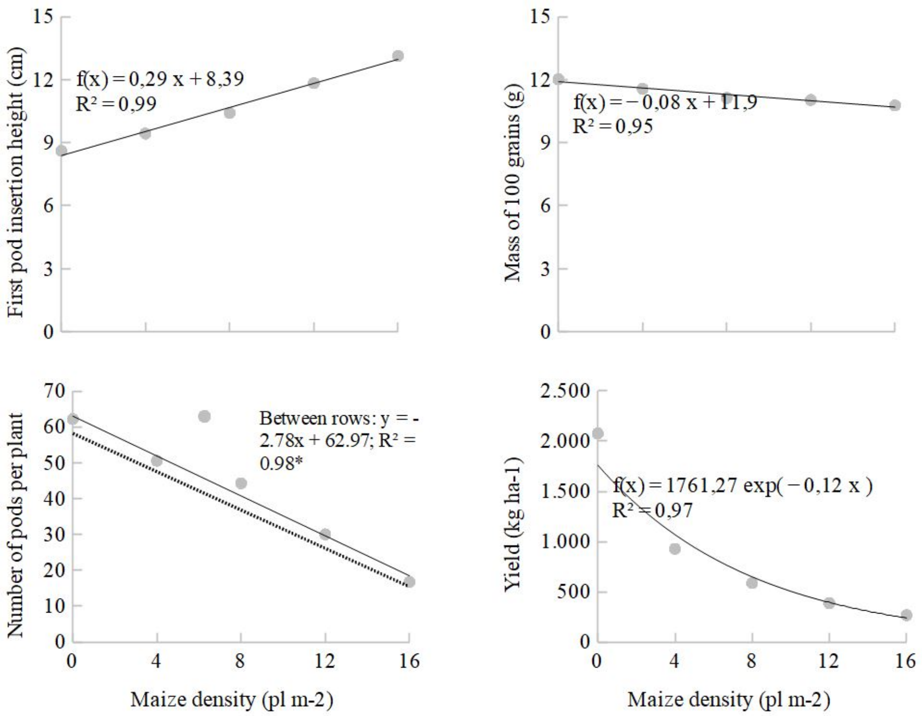

Figure 4. First pod insertion height, 100 grain mass, total number of pods per plant, and grain yield as a function of increasing voluntary maize infestation densities in rows and between rows in soybean crops. Rio Verde (state of Goiás, Brazil), 2015/2016. *Significant ($p \leq 0.05$).

The evaluated soybean cultivar displayed a linear reduction in the mass values of 100 grains when coexisting with maize plants (Figure 4). A reduction of 8.3% in the mass of 100 grains was observed at the highest density (16 maize plants per m^2) when compared to plots that did not grow alongside voluntary maize plants. This may be related to water competition since the soybean grain filling phase is a critical period in terms of water deficit susceptibility (Farias et al., 2001). This behavior can be reinforced when considering the rainfall data of the experimental area (Figure 1), which indicate a lower rainfall volume at the end of January 2016, a fact that reconciled with the cultivar cycle (105 days) and the period in which sowing was carried out (November 20, 2015), agree with the soybean grain filling period.

Similar to the 100 grain mass evaluation, the number of pods per plant was reduced with increasing maize plant density, but at a greater magnitude (Figure 4). These results were different in relation to the distribution of maize plants (row and in between row), although the sharp fall trend in the number of pods per plant was maintained. It is also noteworthy that soybean sowing density influences this variable, since a clear trend of fewer pods per plant was noted in higher population sowing conditions (Braz et al., 2019). The number of pods per plant is one of the grain yield components that most correlates with soybean yield (Santos et al., 2014). Alcântara Neto et al. (2011), when working in the Southern region of Piauí State, Brazil, reported that the variable that most influenced soybean yield was the number of pods per plant.

The results observed for the soybean crop in coexistence with maize plants were derived from a set of negative actions, termed interferences (Ovejero et al., 2016). The light competition was noted among these actions, proven by etiolation during the plant height at harvest assessment, a mechanism in which soybean presents higher metabolic expenses aiming to compensate for its shaded development environment. In addition, nutrient competition probably also occurred. In the presence of maize plants, the extraction per unit area is higher, limiting nutrient availability for the crop displaying lower competitive abilities (Cury et al., 2012).

Due to the reduction in soybean yield components, yield data decreased, reaching a negligible yield of 238.32 kg ha^{-1} at the highest maize plant density (Figure 4), considering the average values from the distribution of volunteer maize plants in crop rows and in between rows. This interference represents a relative loss of 86% with the presence of 16 maize plants per m^2. Coexistence with maize in the eight plants per m^2 population, regardless of the spatial distribution of plants in relation to soybean rows, led to soybean yields below 600 kg ha^{-1}. This value represents only 18% of the national average productivity, which according to Conab (2020) is expected at 3,292 kg ha^{-1} for the 2019/2020 season.

The results of the highly competitive potential of voluntary maize plants interspersed with soybean were similar to those obtained by Rizzardi, Piasecki, Schons, Caverzan, and Langaro (2019), where competition from nine voluntary maize plants per m^2 reduced soybean yields by 75.9%. Alms et al. (2016) observed a 71% reduction in soybean yield due to the presence of six maize plants per m^2 in repeated experiments with two different crops. In another study conducted in the *Cerrado* environment, the presence of 15.2 maize plants per m^2 resulted in a 100% reduction in soybean yield (Braz et al., 2019).

These data demonstrate that the presence of voluntary maize plants in soybean crops represents a major threat to productivity and consequently, to the economic viability of the soybean production system in the Brazilian *Cerrado*. This reinforces the need to develop effective control and sustainable use technologies regarding voluntary maize, especially when the plants are glyphosate tolerant. In addition, the positioning of maize plants in the soybean crop (rows or in between rows) does not influence the noted deleterious effects on yield, and losses are directly related to voluntary plant density per area.

Efficacy of pre-emergence herbicides in the control of voluntary maize

The herbicides diclosulam and imazethapyr, and the association [imazethapyr + flumioxazin] comprised the treatments with the greatest reduction in the maize emergence percentage in the Santa Helena de Goiás experiment, whereas in Morrinhos, the herbicides with the greatest suppression of maize emergence were diclosulam and clomazone (Table 1).

Table 1. Maize emergence percentage as a function of pre-emergence herbicide application. Santa Helena de Goiás and Morrinhos (state of Goiás, Brazil), 2018/2019.

Treatments (g ha^{-1})	% emergence - 42 DAE			
	SHG		MOR	
Fomesafen (200)	82.86	Ab	73.65	Ac
Lactofen (168)	101.19	Aa	93.76	Aa
Sulfentrazone (300)	94.25	Aa	93.56	Aa
Chlorimuron (20)	51.58	Bd	86.36	Ab
Diclosulam (29)	7.04	Bg	26.99	Af
Flumetsulam (132)	96.92	Aa	86.17	Bb
Imazethapyr (106)	39.79	Be	75.87	Ac
Clomazone (600)	71.89	Ac	52.68	Be
Metribuzin (480)	94.58	Aa	81.92	Bc
[SUL+DIU] ([245+490])	97.27	Aa	89.60	Ab
[IMA+FLU] ([120+60])	28.78	Bf	62.98	Ad
Control	100.00	Aa	100.00	Aa
CV (%)		12.99		

[SUL+DIU] = [sulfentrazone + diuron]; [IMA+FLU] = [imazethapyr + flumioxazin]; SHG = Santa Helena de Goiás; MOR = Morrinhos. Average of both maize hybrids. *Means followed by distinct letters, uppercase in rows and lowercase in columns, differ from each other by the F and Scott-Knott tests ($p \leq 0.05$), respectively.

In general, a clear influence of experiment location was not observed as being decisive for greater efficiency in suppression of voluntary plant emergence. This fact demonstrates that the herbicidal molecule has a specific behavior depending on the physicochemical properties of the edaphic environment, and it is essential to take these parameters into account when choosing a herbicide for use in voluntary maize management (Inoue et al., 2003).

Table 2 displays the maize emergence percentage due to herbicide application in both maize hybrids at the experiments conducted in Santa Helena de Goiás and Morrinhos. At 7 DAE, clomazone differed significantly compared to the other herbicides, leading to approximately a 34% reduction in comparison to the control in the DKB310 hybrid. The only herbicide treatments that did not result in decreased maize stands were lactofen and [sulfentrazone + diuron], as well as metribuzin for the DKB310 hybrid. For the DKB390 hybrid, all the herbicides promoted a reduction in maize stands compared to the control treatment, with fomesafen being the herbicide that promoted the highest suppression of maize emergence. The DKB310 hybrid showed higher sensitivity compared to DKB390 for pre-emergence herbicides at Morrinhos, while this behavior was not verified in Santa Helena de Goiás.

At 42 DAE, diclosulam application resulted in the smallest plant population for both maize hybrids when compared to the control without herbicide. DKB310 presented a 68% reduction with diclosulam pre-emergence application in the plant stand when compared to 7 DAE, which is noteworthy when compared to the other herbicides (Table 2). Concerning DKB390, a stand reduction of approximately 91% was observed, proving the best herbicide treatment performance aiming at decreasing plant population among all treatments.

Beyond diclosulam, when the herbicide performances for both hybrids were compared, chlorimuron, imazethapyr, clomazone, fomesafen, and [imazethapyr + flumioxazin] applications resulted in significant plant stand reductions. It should be noted that DKB310 displayed a greater reduction in maize population compared to DKB390 when both hybrids were submitted to clomazone pre-emergence application. On the other hand, DKB390 presented less plants when chlorimuron, diclosulam, imazethapyr, and [imazethapyr + flumioxazin] were applied.

At 7 DAE, part of the herbicide treatments led to a reduction of maize hybrid height in relation to the control, with this behavior being observed in both locations (Table 3). At 7 DAE, chlorimuron, diclosulam, imazethapyr, and the association [imazethapyr + flumioxazin], promoted greater reductions in maize plant height at Santa Helena de Goiás, while, for Morrinhos, the best herbicide options were diclosulam, imazethapyr, and [imazethapyr + flumioxazin]. At 14 DAE, in addition to the treatments mentioned above, in the experiment carried out in Santa Helena, fomesafen performed well in suppressing the height of maize plants. For Morrinhos, an improvement in the performance of chlorimuron was observed in relation to the percentage values of maize plant heights plants seen in the first evaluation.

Table 2. Maize emergence percentage as a function of pre-emergence herbicide application. Santa Helena de Goiás and Morrinhos (state of Goiás, Brazil), 2018/2019.

Treatments (g ha^{-1})	% emergence - 7 DAE				% emergence - 42 DAE			
	DKB310		DKB390		DKB310		DKB390	
Fomesafen (200)	75.85	Ac	75.01	Ad	78.28	Ab	78.23	Ab
Lactofen (168)	96.05	Aa	94.03	Ab	98.53	Aa	96.42	Aa
Sulfentrazone (300)	88.72	Ab	85.75	Ac	95.92	Aa	91.89	Aa
Chlorimuron (20)	83.16	Ac	88.85	Ab	79.98	Ab	57.97	Bc
Diclosulam (29)	79.79	Ac	81.21	Ac	25.25	Ae	8.78	Be
Flumetsulam (132)	84.92	Ac	90.12	Ab	88.64	Aa	94.45	Aa
Imazethapyr (106)	77.74	Ac	83.76	Ac	67.19	Ac	48.47	Bd
Clomazone (600)	65.88	Bd	81.03	Ac	47.14	Bd	77.43	Ab
Metribuzin (480)	94.00	Aa	89.69	Ab	91.00	Aa	85.49	Ab
[SUL+DIU] ([245+490])	96.05	Aa	93.20	Ab	92.54	Aa	94.34	Aa
[IMA+FLU] ([120+60])	81.69	Ac	86.31	Ac	50.79	Ad	40.95	Bd
Control	100.00	Aa	100.00	Aa	100.00	Aa	100.00	Aa
Santa Helena de Goiás	87.24	Aa	85.76	Ab	77.67	Aa	66.69	Bb
Morrinhos	83.41	Bb	89.07	Aa	74.89	Ba	79.07	Aa
CV (%)	8.19				12.99			

[SUL+DIU] = [sulfentrazone + diuron]; [IMA+FLU] = [imazethapyr + flumioxazin]. *Means followed by distinct letters, uppercase in rows and lowercase in columns, differ from each other by the F and Scott-Knott tests ($p \leq 0.05$), respectively. The comparison between location for each maize hybrid was performed by using the F test ($p \leq 0.05$).

Table 3. Height percentage of maize plants in relation to control after pre-emergence herbicide application. Santa Helena de Goiás and Morrinhos (state of Goiás, Brazil), 2018/2019.

Treatments (g ha^{-1})	% height - 7 DAE				% height - 14 DAE			
	SHG		MOR		SHG		MOR	
Fomesafen (200)	46.29	Ac	54.04	Ab	34.22	Bc	78.25	Ab
Lactofen (168)	98.82	Aa	98.14	Aa	96.37	Aa	103.00	Aa
Sulfentrazone (300)	77.44	Ab	89.48	Aa	71.90	Bb	104.20	Aa
Chlorimuron (20)	28.28	Bd	67.84	Ab	19.76	Bc	49.66	Ac
Diclosulam (29)	13.46	Bd	30.30	Ac	9.76	Ac	17.83	Ad
Flumetsulam (132)	89.90	Aa	69.70	Bb	71.84	Ab	74.47	Ab
Imazethapyr (106)	15.32	Bd	44.95	Ac	14.76	Bc	42.70	Ac
Clomazone (600)	67.51	Ab	56.06	Ab	68.27	Ab	73.98	Ab
Metribuzin (480)	93.60	Aa	93.60	Aa	73.21	Bb	118.19	Aa
[SUL+DIU] ([245+490])	85.35	Aa	82.07	Aa	65.22	Bb	95.01	Aa
[IMA+FLU] ([120+60])	15.31	Bd	39.98	Ac	14.76	Bc	42.87	Ac
Control	100.00	Aa	100.00	Aa	100.00	Aa	100.00	Aa
CV (%)	23.68	28.39						
	% height - 28 DAE				% height - 42 DAE			
	SHG		MOR		SHG		MOR	
Fomesafen (200)	64.18	Bc	84.58	Ab	74.82 b	Bb	95.77	Aa
Lactofen (168)	104.92	Aa	97.14	Aa	105.18	Aa	99.46	Aa
Sulfentrazone (300)	99.94	Aa	90.44	Aa	104.28	Aa	96.39	Aa
Chlorimuron (20)	49.47	Ac	54.08	Ac	54.64	Bc	64.54	Ab
Diclosulam (29)	21.44	Ad	12.08	Ad	27.61	Ae	11.53	Bc
Flumetsulam (132)	93.53	Ab	77.77	Bb	100.65	Aa	88.69	Ba
Imazethapyr (106)	57.87	Ac	47.50	Ac	59.29	Bc	68.94	Ab
Clomazone (600)	83.11	Ab	78.97	Ab	97.78	Aa	100.68	Aa
Metribuzin (480)	86.50	Ab	98.77	Aa	94.25	Aa	100.19	Aa
[SUL+DIU] ([245+490])	89.48	Ab	98.60	Aa	100.86	Aa	96.31	Aa
[IMA+FLU] ([120+60])	55.45	Ac	41.95	Ac	43.35	Bd	60.81	Ab
Control	100.00	Aa	100.00	Aa	100.00	Aa	100.00	Aa
CV (%)		20.29				11.70		

[SUL+DIU] = [sulfentrazone + diuron]; [IMA+FLU] = [imazethapyr + flumioxazin]; SHG = Santa Helena de Goiás; MOR = Morrinhos. Average of both maize hybrids. *Means followed by distinct letters, uppercase in rows and lowercase in columns, differ from each other by the F and Scott-Knott tests ($p \leq 0.05$), respectively.

At 28 DAE, diclosulam was the most effective in suppressing the growth of the two maize hybrids. Concerning the height reduction provided by this herbicide, the size of pre-emergence diclosulam-treated plants decreased by approximately 78 and 88% compared to the control without any herbicide application, for the experiments conducted at Santa Helena de Goiás and Morrinhos, respectively. Lactofen and metribuzin displayed no significant effects on maize plant growth suppression in either location.

Again, at 42 DAE, diclosulam provided the greatest maize growth restrictions, regardless of the experiment location. Diclosulam promoted a reduction in maize plant height of 72.39 and 88.47%, when compared to the control after diclosulam application at Santa Helena de Goiás and Morrinhos, respectively. In general, comparing the sensitivity of voluntary maize to herbicides, depending on the experiment location, it appears that throughout the four height assessments, the plants present at Santa Helena de Goiás showed greater sensitivity to the pre-emergence herbicides compared to Morrinhos (Table 4). Possibly, this behavior stems from the fact that the experimental area in Morrinhos has a higher clay content when compared to Santa Helena, which favors herbicide adsorption in the soil (Faria, Fialho, Souza, Freitas, & Silva, 2019).

The most effective herbicides which initially decreased (7 DAE) the height of maize DKB310 hybrid plants were diclosulam, imazethapyr, and [imazethapyr + flumioxazin] (Table 4). For the DKB390 hybrid, three herbicide treatments repeated their already verified efficacy (diclosulam, imazethapyr, and [imazethapyr + flumioxazin]), although fomesafen and chlorimuron also showed statistically similar performance compared to the aforementioned herbicides. Considering the results for both hybrids, diclosulam presents a prominent suppression of voluntary maize, since these results were consolidated at 42 DAE, where the action of this herbicide continued to promote maize growth reductions at the same intensity.

As already mentioned, for height of plants at 14 DAE, greater reductions in the height of maize plants due to pre-emergence herbicides, were observed in the experiment in Santa Helena de Goiás compared to Morrinhos (Table 4). Additionally, at this evaluation period, there was greater sensitivity of the DKB310 hybrid to the herbicides compared to DKB390 in the Morrinhos experiment.

Table 4. Height percentage of maize plants in relation to control after pre-emergence herbicide application. Santa Helena de Goiás and Morrinhos (state of Goiás, Brazil), 2018/2019.

Treatments (g ha^{-1})	% height - 7 DAE				% height - 42 DAE			
	DKB310		DKB390		DKB310		DKB390	
Fomesafen (200)	61.44	Ac	38.88	Bc	89.41	Ab	81.18	Ab
Lactofen (168)	101.85	Aa	95.11	Aa	100.57	Aa	104.07	Aa
Sulfentrazone (300)	85.77	Ab	81.14	Ab	101.67	Aa	99.01	Aa
Chlorimuron (20)	58.58	Ac	37.54	Bc	66.23	Ac	52.95	Bd
Diclosulam (29)	21.04	Ad	22.72	Ac	21.56	Ae	17.57	Ae
Flumetsulam (132)	80.80	Ab	78.78	Ab	90.54	Ab	98.80	Aa
Imazethapyr (106)	31.98	Ad	28.28	Ac	68.81	Ac	59.41	Bc
Clomazone (600)	52.35	Bc	71.21	Ab	96.71	Aa	101.70	Aa
Metribuzin (480)	93.60	Aa	93.60	Aa	94.60	Ab	99.84	Aa
[SUL+DIU] ([245+490])	87.62	Ab	79.79	Ab	100.02	Aa	97.14	Aa
[IMA+FLU] ([120+60])	25.16	Ad	30.13	Ac	57.35	Ad	46.81	Bd
Control	100.00	Aa	100.00	Aa	100.00	Aa	100.00	Aa
CV (%)	23.68				11.70			
Location	**% height - 14 DAE**							
	DKB310				DKB390			
Santa Helena de Goiás	54.37	Ab			52.97	Ab		
Morrinhos	68.91	Ba			81.12	Aa		
CV (%)	28.39							

[SUL+DIU] = [sulfentrazone + diuron]; [IMA+FLU] = [imazethapyr + flumioxazin]. *Means followed by distinct letters, uppercase in rows and lowercase in columns, differ from each other by the F and Scott-Knott tests ($p \leq 0.05$), respectively. The comparison between location for each maize hybrid was performed by using the F test ($p \leq 0.05$).

The last maize plant height evaluation revealed that the herbicide diclosulam remained the most efficient in suppressing maize plant growth for the two assessed hybrids. Beyond diclosulam, the preformulated herbicide mixture [imazethapyr + flumioxazin] comprised the second treatment with the best performance aimed at reducing plant height, with this behavior being observed in both maize hybrids. Comparing the sensitivity of the maize hybrids to the pre-emergence herbicides, the results indicated that volunteer DKB390 plants were susceptible to a slightly higher number of herbicides than the DKB310 hybrid. In general, lactofen, sulfentrazone, flumetsulam, clomazone, metribuzin, and [sulfentrazone + diuron] displayed low (or zero) ability to reduce the height of maize plants in pre-emergence applications.

The applied herbicides resulted in differentiated responses regarding toxicity of voluntary maize plants emerging in the experiment conducted in Santa Helena de Goiás, mainly during the two initial evaluations (Table 5). In the first evaluation (7 DAE), diclosulam and the combination [imazethapyr + flumioxazin] caused injuries with marked damage to the two RR™ maize hybrids. These two treatments were also noteworthy at 14 DAE, although chlorimuron and imazethapyr also provided high hybrid DKB390 intoxication in this assessment. Similar results were reported by Piasecki and Rizzardi (2016), where diclosulam led to over 90% control of voluntary maize plants.

The observed symptoms caused by chlorimuron included intense central leaf vein and plant base chlorosis and purpling, as well as necrosis of leaf blade extremities. The emerged plants in plots receiving diclosulam displayed chlorotic leaves with necrotic and deformed ends, with the base of the sheaths displaying a purple color. Artuzi and Contiero (2006) reported that diclosulam results in purplish symptoms at the base of the central rib of maize leaves, as well as decreased plant stands.

The combination [imazethapyr + flumioxazin] resulted in similar phytotoxicity scores for both hybrids in all the evaluations performed in Santa Helena de Goiás. Symptoms included growth reduction, leaf deformation with chlorotic points, necrosis at the extremities, and a purplish tone at the base of the leaf sheaths. Significant recovery of maize plants from initial injuries was verified at 28 DAE. Diclosulam remained the herbicide resulting in the highest level of maize plant poisoning for both hybrids, but at much lower levels than the previous assessment. In this evaluation, imazethapyr also displayed a similar toxic action to diclosulam for DKB390 hybrid plants (Table 5).

In relation to the data for Santa Helena de Goiás, lactofen was the most selective herbicide concerning maize when applied pre-emergence, albeit with no significant difference from the controls of each hybrid in all intoxication evaluations, demonstrating its unfeasibility in controlling voluntary plants (Table 5). In general, hybrid DKB390 plants showed greater sensitivity to herbicides compared to DKB310. An exception to this observation was the effect of clomazone, which promoted higher levels of injuries in DKB310 compared to DKB390 in the first three evaluations. Clomazone is absorbed predominantly by the apical seedling meristem and by plant roots and neck, then translocated via the xylem to leaves, leading to inhibition of photosynthetic pigment precursor compounds, resulting in decreased carotene and phytol levels and consequently, chlorophyll levels (Karam et al., 2003).

Table 5. Voluntary maize phytotoxicity (EWRC, 1964) due to pre-emergence herbicide application. Santa Helena de Goiás and Morrinhos (state of Goiás, Brazil), 2018/2019.

Treatments (g ha^{-1})	Santa Helena de Goiás					
	7 DAE		14 DAE		28 DAE	
	DKB310	DKB390	DKB310	DKB390	DKB310	DKB390
Fomesafen (200)	5	6	4	6	1	1
Lactofen (168)	1	1	1	1	1	1
Sulfentrazone (300)	2	3	3	3	1	1
Chlorimuron (20)	5	7	6	8	2	3
Diclosulam (29)	8	8	8	8	4	4
Flumetsulam (132)	2	2	2	2	1	1
Imazethapyr (106)	6	7	7	8	3	4
Clomazone (600)	6	4	7	4	2	1
Metribuzin (480)	1	2	2	2	1	1
[SUL+DIU] ([245+490])	2	4	2	3	1	1
[IMA+FLU] ([120+60])	8	8	8	8	3	3
Control	1	1	1	1	1	1
	Morrinhos					
Fomesafen (200)	5	5	3	4	1	1
Lactofen (168)	2	2	2	2	1	1
Sulfentrazone (300)	3	3	2	2	1	1
Chlorimuron (20)	4	4	5	5	1	1
Diclosulam (29)	7	7	8	8	3	3
Flumetsulam (132)	3	3	4	4	1	1
Imazethapyr (106)	4	4	6	6	1	1
Clomazone (600)	8	4	8	3	1	1
Metribuzin (480)	2	2	2	2	1	1
[SUL+DIU] ([245+490])	2	2	1	1	1	1
[IMA+FLU] ([120+60])	5	5	6	6	1	1
Control	1	1	1	1	1	1

[SUL+DIU] = [sulfentrazone + diuron]; [IMA+FLU] = [imazethapyr + flumioxazin].

At 42 DAE, no plant poisoning symptoms in either maize hybrid were observed, regardless of herbicide treatment used (data not shown). This attenuation in the visual symptoms of injuries over time is directly linked to the growth of new leaves. Nevertheless, this behavior does not mean that the plant is completely detoxified from herbicides, and serious effects on species development may still occur.

For the Morrinhos experiment, clomazone caused the most damage to emerged DKB310 hybrids at 7 DAE, followed by diclosulam (Table 5). However, this intense clomazone phytotoxic action was not observed in DKB390, which initially showed great sensitivity to diclosulam (7 and 14 DAE). At 7 and 14 DAE, imazethapyr, [imazethapyr + flumioxazin], and chlorimuron applications led to injuries to maize hybrids, ranging from grades 5 to 6, but still lower than the action demonstrated by diclosulam in both hybrids and by clomazone in DKB310 hybrids, which is quite sensitive to this herbicide.

As verified in the experiment carried out in Santa Helena de Goiás, a significant recovery of maize plants was verified in the evaluation carried out at 28 DAE, since injuries to the two maize hybrids were observed only in the plots that received diclosulam applications. At 42 DAE, no phytotoxicity symptoms were observed in the youngest leaves of the maize plants over the entire experiment, as also noted at Santa Helena de Goiás (data not shown). It is worth noting that, even though there were no apparent symptoms in the new leaves, the maize plants submitted to certain herbicides, such as diclosulam, had a very low plant height, and therefore low potential for competition or causing interference in soybean crops (Mahajan, Hickey, & Chauhan, 2020).

Based on the results for the different variable-responses evaluated in the experiments, the first noteworthy observation is the superior performance of diclosulam, comprising the best herbicide for voluntary maize control in pre-emergence soybean crop applications. In addition, fomesafen, chlorimuron, imazethapyr, and the association [imazethapyr + flumioxazin], showed a performance slightly better than the other herbicides evaluated in the present work, but the results indicate that for these treatments, a complementation with a post-emergence application will be fundamental to achieve success in voluntary maize control (Piasecki & Rizzardi, 2016; Ovejero et al., 2016).

It is also worth noting that, even though the aforementioned herbicides have not shown the same effectiveness verified by diclosulam over voluntary maize, when considering the complex of weeds that infest soybean crops, the use of these products has the advantage of expanding the control spectrum (Coradin, Braz, Machado, Silva, & Sousa, 2019). Furthermore, it is suggested that the performance of these herbicides, aiming at the control of voluntary maize, be evaluated in soils with different physicochemical properties from those observed in the present work, since the behavior of the herbicides in the edaphic environment is influenced by these parameters (Inoue et al., 2003).

Conclusion

No influence on the position of voluntary maize plants on soybean yield was observed. Soybean yields decreased progressively with increasing maize infestations, with a maximum relative loss of 87%, with 16 plants per m^2 of voluntary maize. The herbicide diclosulam presented the best effect in controlling maize plants and led to the largest stand reduction and plant height for the DKB390 and DKB310 hybrids.

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