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Research Article

Carryover of herbicides used in cotton stalk control on soybean cultivated in succession

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INFORMATION ARTICLE

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The authors declare that there is no conflict of interest regarding the publication of this manuscript.

HIGHLIGHTS

- The single application and the sequential application of the glyphosate + dicamba + saflufenacil treatment has great carryover potential for soybean crops,
- The safety interval for sowing the soybean exceeded 120 days after application with glyphosate + dicamba + saflufenacil.
- The treatment with application of 2,4-D alone showed the lowest carryover potential for soybean.

ABSTRACT

Background: Information on the carryover of herbicides applied to the destruction of cotton stalks, as well as the withdrawal period necessary to prevent the development and productivity of the crop in succession from being affected are limited in the literature.
Objective: The objective was to identify the carryover effect promoted by herbicides used in the management of the destruction of cotton stalks and to estimate the host free period for sowing soybean in succession.
Methods: Two individual experiments were conducted simultaneously, one for single application and the other for sequential application of herbicide treatments. The experiments were installed in a factorial scheme (15x5), in a randomized block design with four replications. The first factor evaluated was herbicide treatments and the second factor was five soybean sowing times after application (0, 30, 60, 90 and 120 days). The herbicides used in the treatments were 2,4-D, glyphosate, saflufenacil, [imazapic + imazapyr], dicamba, fluroxypyr and sulfentrazone.
Results: As this work was conducted, the results provide a carryover indicator. It is concluded that the single application and the sequential application of the glyphosate + dicamba + saflufenacil treatment has great carryover potential for soybean crops, with the host free period for sowing the crop exceeding 120 days after application.
Conclusions: The treatments 2,4-D, 2,4-D + glyphosate, glyphosate + saflufenacil + fluroxypyr had the lowest host free period intervals, even when in sequential application. The treatment with application of 2,4-D alone showed the lowest carryover potential for soybean.

1 INTRODUCTION

The elimination of cotton crop remains after harvest is recommended as a prophylactic measure (Almeida et al., 2008) aiming to interrupt the cycle of the main diseases and insect pests, such as the boll weevil (*Anthonomus grandis*), which causes significant losses of productivity and quality of cotton fiber, being considered one of the main pests of the crop (Soria et al., 2013; Chitarra, 2014; Miranda and Rodrigues, 2015).

After harvesting, the stalks are usually eliminated by cultural, mechanical, chemical methods or by their integration (Sofiatti et al., 2015; Bianchini and Borges, 2013). Mechanical handling of cotton stalks was the most used in the past, being one of the most efficient (Bianchini and Borges, 2013). However, with the implementation of the no-till system, the options for managing the stalks were reduced. This is due to the absence of operations that revolve the soil, and harrowing (mechanical control method) is not carried out in this system, making the use of chemical management essential.

Among the herbicides used to control the stalks, glyphosate and 2,4-D are the most widely used active ingredients. However, with the adoption of transgenic varieties resistant to herbicides, effective herbicide options in the management of cotton groves have become even more limited (Ferreira et al., 2018), which indicates the need to develop new alternatives.

After application, the herbicides can have a residual effect on the soil, increasing the period of control of the stalks and weeds. However, most producers use pre-established herbicide recommendations for management, often without considering the relationship of herbicides with edaphoclimatic factors, with the cultivar used and even with the rotation or succession system implemented in the area. If the herbicides used in the control of cotton stalks persist in the soil, there is the possibility of causing intoxication of the crop sown in succession, this effect being called residual activity or *carryover* (Mancuso et al., 2011; Oliveira Jr, 2011; Gheno et al., 2015; Gheno et al., 2016; Matte et al., 2019).

The herbicide treatments evaluated in the present study were selected based on the results presented by Francischini (2016). However, these results indicated that in several situations there may be a need for up to two sequential herbicide applications, which increases the possibility of carryover for the crop sown in succession.

Information on the carryover of herbicides applied to control the cotton stalks is limited in the literature, as well as the withdrawal period necessary to prevent the development and productivity of the crop in succession from being affected. Therefore, this work aimed to identify the "carryover" effect promoted by herbicides used in the management of the destruction of cotton stalks and to estimate the safety interval for sowing soybean in succession.

2 Materials and Methods

The experiments were conducted in a greenhouse in the municipality of Santo Antonio de Posse - SP (22°36'13.5"S and 46°59'05.7"W, at an altitude of 658 m) during the period from April to December 2014 The average temperatures observed during the conduction period of the experiments are shown in Figure 1.

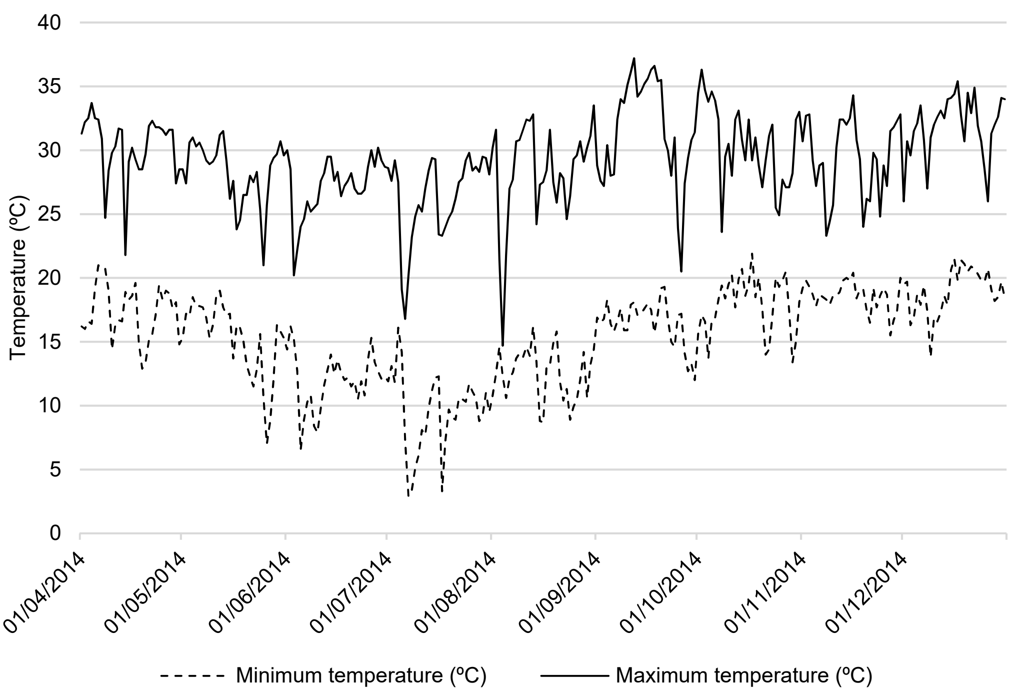

Figure 1 - Minimum and maximum temperature observed during the conduction of the experiments. Santo Antônio de Posse, SP, 2014.

Two experiments were conducted simultaneously, one for single application (Experiment 1) and another for sequential application (Experiment 2) of herbicide treatments. The experiments were installed in a 15x5 factorial scheme, in a randomized block design with four replications. The first factor evaluated was herbicide treatments (Table 1) and the second factor was five sowing times of conventional soybean BRS 232 (0, 30, 60, 90 and 120 days) after application A in experiment 1, and after application B in experiment 2.

Table 1 - List of herbicide treatments used to evaluate the carryover effect in soybean culture after one (application A) and two sequential applications (application A/B) of the treatments

Herbicidal treatment	Aplication A and B Dose a.i. or a.e. g ha^{-1}
2,4-D	1340
2,4-D + glyphosate	1340 + 720
2,4-D + saflufenacil	1340 + 105
2,4-D + [imazapic + imazapyr]	1340 + 105
2,4-D + glyphosate + saflufenacil	1340 + 720 +105
2,4-D + glyphosate + [imazapic+imazapyr]	1340 + 720 +105
2,4-D + glyphosate + saflufenacil + [imazapic+imazapyr]	1340 + 720 +105 + 105
Glyphosate + saflufenacil + [imazapic+imazapyr]	720 +105 + 105
Glyphosate + saflufenacil + fluroxypyr	720 +105 + 400
Glyphosate + fluroxypyr + [imazapic+imazapyr]	720 + 400 + 105
Glyphosate + dicamba + saflufenacil	720 + 960 + 105
Glyphosate + sulfentrazone + 2,4-D	720 + 40 + 1340
Sulfentrazone + 2,4-D	40 + 1340
Fluroxypyr	400
Testemunha sem aplicação	-

All herbicidal treatments were applied in association with Dash HC 0.5%; products in [ ] indicate formulated mixtures; 2,4-D (DMA® 806 BR, 670 g a.e. L^{-1}, SL, Corteva); glyphosate (Roundup Original®, 360 g a.e. L^{-1}, SL, Monsanto); saflufenacil (Heat®, 700 g a.i. kg^{-1}, WG, Basf); [imazapic+imazapyr] (Kifix®, [175 g + 525 g a.i. kg^{-1}], WG, Basf); dicamba (Atectra®, 480 g a.e. L^{-1}, SL, Basf); fluroxypyr (Starane® 200, 200 g a.e. L^{-1}, CE, Corteva); sulfentrazone (Boral® 500, 500 g a.i. L^{-1}, SC, FMC).

The experimental plots were composed of plastic pots with a capacity of 3 dm^3 filled with dry and sieved soil. According to chemical and physical analysis, the soil used had the following characteristics: pH in $CaCl_2$ of 5.4, 18.7 mmol$_c$ dm^{-3} of H^++ Al^{+3}, 40.3 mg dm^{-3} of P, 50.0 mmol$_c$ dm^{-3} of Ca^{+2}, 28.7 mmol$_c$ dm^{-3} Mg^{+2}, 2.4 mmol$_c$ dm^{-3} K^+, CTC at pH 7.0 of 99.8 mmol$_c$ dm^{-3}, 27 g dm^{-3} of O.M., 15% of coarse sand, 33% fine sand, 5% silt, and 47% clay.

In the first experiment the single application of herbicide treatments (A) was carried out on 05/27/2014. On the same date, soybean were sown for the period of 0 days after application (0 DAA). Subsequent sowing was carried out on 05/28/2014 (30 DAA), 06/27/2014 (60 DAA), 07/27/2014 (90 DAA) and 08/27/2014 (120 DAA). Right after each application of the herbicide treatments, all pots received irrigation with a 5 mm water depth. After irrigation, the pots that were not sown remained without irrigation until they received soybean sowing and the seeded pots started to receive irrigation with a 5 mm blade daily until the end of the experiment.

In the second experiment, which presented two sequential applications of the same herbicide treatments (applications A/B), the first application (A) was carried out on 04/27/2014, and the second application (B) was carried out 45 days after the first application (06/11/2014). After application A of the herbicide treatments, the pots received irrigation with a 5 mm water blade and remained without irrigation for 45 days until the second application (B). After the second application (B), a new irrigation was performed with a 5 mm blade. The pots that did not receive the soybean sowing remained without irrigation until receiving the sowing. From the sowing they received a 5 mm daily blade until the end of the experiment.

The 45 day interval between the first and the second application was stipulated simulating the time needed for the cotton stalks to regrow in the field and present enough leaf area for the absorption of herbicidal treatments in the second application (Francischini, 2016). The absence of irrigation in the pots after the applications aimed to simulate a common situation in the cotton producing areas, in which pronounced periods of drought occur after the harvest, during the period destined to the control of the cotton stalks. Thus, for the experiment with two sequential applications (A/B) soybean sowing was carried out on 06/11/2014 (0 DAA), 07/04/2014 (30 DAA), 08/04/2014 (60 DAA), 09/04/2014 (90 DAA) and 10/04/2014 (120 DAA).

In all applications, a backpack sprayer of constant pressure based on CO_2 was used, equipped with a bar equipped with three tips like fan jet XR-110.02, spaced 50 cm apart, under pressure of 2.0 kgf cm^{-2}. These application conditions provided the equivalent of 150 L ha^{-1} of spray solution. The climatic conditions at the time of the application of the treatments were: (A) 67% relative humidity, temperature of 25.9 ºC, wind speed of 0.8 km h^{-1} and humid soil; (B) relative humidity of 79%, temperature of 26.8 ºC, wind speed of 0.6 km h^{-1} and humid soil.

An evaluation of intoxication in soybean plants was performed 14 days after sowing (DAS) using a scale from 0 to 100%, where 0% represents no symptoms, and 100% represents total plant death. At the end of the experiment (30 DAS), plant height and shoot dry weight were evaluated. The dry mass and height data were corrected to percentage values in comparison with the control without application, assuming that the pots that remained without herbicide application presented 100% of the height and produced 100% of dry mass.

The data on phytointoxication, height and dry mass were subjected to analysis of variance by the F test ($p<0.05$) and the averages were compared with the control without application by the Dunnett Test ($p<0.01$).

Based on these data, it was possible to identify the number of days required after application A and A/B for soybean sowing to take place, without the risk of interference from the herbicide treatments used to destroy cotton stalks on soybean development. This period of days was called the safety interval (SI) and was determined from the regression models adjusted for each analyzed variable, presented in Table 2.

To consider soybean sowing safe after using the evaluated herbicide treatments, the following criteria were considered tolerable in this work: phytointoxication - acceptable up to 10%; plant height - maximum 10% reduction in relation to the height of the control; relative dry mass - reduction of a maximum of 10% in relation to the dry weight of the control. In the end, the highest value obtained among the three variables analyzed was chosen as the safety interval.

Table 2 - Adjusted regression models to estimate the Safety Interval for soybean sowing

Modelo de regressão	Equation
Boltzmann's Sigmoidal Model (3 parameters)	$y = \frac{a}{1+e^{-\left(x-\frac{x0}{b}\right)}}$
Boltzmann's Sigmoidal Model (4 parameters)	$y = y0 + \frac{a-y0}{1+e^{-\left(x-\frac{x0}{b}\right)}}$
Streibig's Logistic Model (1988) (3 parameters)	$y = \frac{a}{\left[1+\left(\frac{x}{x0}\right)^{b}\right]}$
Streibig's Logistic Model (1988) (4 parameters)	$y = y0 + \frac{a}{\left[1+\left(\frac{x}{x0}\right)^{b}\right]}$
Exponential Model (2 parameters)	$y = a\, e^{-bx}$
Simetric Model (3 parameters)	$y = a\,\lvert x - x0\rvert^{b}$

on what: *y* = height, dry weight and/or intoxication; *x* = days after sowing; *a, x0* and *b* = estimated parameters of the equation, such that: *y0* = minimum height, dry weight and/or intoxication; *a* = maximum function asymptote (maximum height, dry mass and/or intoxication); *x0* = "days" that provide 50% of the value of the variable "*a*"; *b* = slope of the curve around *x0*.

3 Results and Discussion

There was a significant interaction between herbicide treatments and soybean sowing time for all variables analyzed, when a single herbicide application was performed. The results of phytointoxication in soybean plants are shown in Table 3.

All herbicide treatments when applied on the day of sowing (0 DAA) caused intoxication in soybean plants. The lowest levels of phytointoxication were observed with the application of glyphosate + saflufenacil + fluroxypyr. In the sowing carried out at 30 days after application, the 2,4-D and glyphosate +

Table 3 - Phytointoxication of soybean plants sown at 0, 30, 60, 90 and 120 days after application (application A) of herbicide treatments

Treatment (application A)	Phytointoxication (%) of soybean plants at 14 DAS									
	0 Days		30 Days		60 Days		90 Days		120 Days	
2,4-D	33.7	-	5.5	+	5.2	+	0.5	+	0.0	+
2,4-D + glyphosate	70.7	-	73.5	-	2.2	+	0.2	+	0.0	+
2,4-D + saflufenacil	89.7	-	89.3	-	31.0	-	2.5	+	1.2	+
2,4-D + [imazapic+imazapyr]	89.7	-	90.8	-	52.0	-	4.0	-	0.3	+
2,4-D + glyphosate + saflufenacil	40.2	-	40.3	-	1.7	+	0.0	+	0.0	+
2,4-D + glyphosate + [imazapic + imazapyr]	75.2	-	60.5	-	36.5	-	1.2	+	0.0	+
2,4-D + glyphosate + saflufenacil + [imazapic+imazapyr]	83.7	-	62.5	-	7.0	-	0.7	+	0.0	+
2,4-D + glyphosate + sulfentrazone	78.2	-	73.0	-	43.7	-	6.0	-	1.3	+
2,4-D + sulfentrazone	91.5	-	75.5	-	34.3	-	0.0	+	0.0	+
Glyphosate + saflufenacil + fluroxypyr	9.2	-	8.2	+	1.7	+	0.0	+	0.0	+
Glyphosate + [imazapic+imazapyr] + fluroxypyr	50.0	-	46.7	-	31.5	-	1.0	+	0.0	+
Glyphosate + dicamba + saflufenacil	100.0	-	98.0	-	89.0	-	80.0	-	9.8	-
Glyphosate + saflufenacil + [imazapic+imazapyr]	69.7	-	68.3	-	33.7	-	4.7	-	2.0	+
Fluroxypyr	68.7	-	63.3	-	7.0	-	0.5	+	0.0	+
Check	0.0	+	0.0	+	0.0	+	0.0	+	0.0	+
CV (%)	6.1		8.4		11.3		25.5		103.5	
MSD	8.0		9.9		5.9		3.6		2.1	

DAS: days after sowing; Dunnet test ($p\leq0.01$); Equal signs between the treatment and the control indicate similarity between the treatments.

saflufenacil + fluroxypyr treatments showed less than 10% intoxication of the soybean plants, not differing from the control without application.

For soybean sown at 60 DAA, the herbicidal treatments that promoted intoxication, but did not differ from the control without application were: 2,4-D, 2,4-D + glyphosate, 2,4-D + glyphosate + saflufenacil and glyphosate + saflufenacil + fluroxypyr. In the sowing performed at 90 DAA, the treatments 2,4-D + [imazapic + imazapyr], 2,4-D + glyphosate + sulfentrazone, glyphosate + dicamba + saflufenacil and glyphosate + saflufenacil + [imazapic + imazapyr] promoted plant poisoning significantly higher than the control without application, with emphasis on the treatment glyphosate + dicamba + saflufenacil, which caused 80% visual phytointoxication in plants sown at 90 days, also affecting soybean plants even when sown at 120 DAA.

In general, most treatments affected soybean height when sowing was carried out up to 60 days (Table 4). The only treatment that did not affect soybean growth under any conditions was glyphosate + saflufenacil + fluroxypyr. For sowing at 30 days, in addition to this treatment, treatment with 2,4-D no longer affected the height of the soybean. The treatment that had a significant effect on soybean height for a longer period (90 days) was glyphosate + dicamba + saflufenacil. Only at sowing of 120 days there was no effect of all herbicide treatments on the relative height of the soybean. The application of dicamba provides a reduction in the height of soybean plants, and in association with glyphosate there is an increase in the levels of intoxication (Robinson et al., 2013). The authors related the reduction in height mainly to the reduction of the leaf area and shortening of nodes of the main trunk, due to the reduction of photosynthesis, which is highly correlated with soybean yield.

The application of herbicide treatments reduced the dry weight of soybean plants, especially when the interval between application and sowing was less than or equal to 60 days, in most herbicide treatments (Table 5). There was a reduction in dry weight in all treatments that received herbicides when soybeans were sown at 0 DAA. For sowing at 30 days, treatments 2,4-D, 2,4-D + glyphosate + saflufenacil and glyphosate + saflufenacil + fluroxypyr no longer affected the dry weight of soybean plants and did not differ from the control without application. When soybean was sown at 60 days, in addition to the treatments already mentioned, the treatments 2,4-D + glyphosate and 2,4-D + glyphosate + saflufenacil + [imazapic + imazapyr] also did not affect the dry weight of the soybean plants. The treatment that had a significant effect on the dry weight of soybean plants for a longer period (90 days) was glyphosate + dicamba + saflufenacil. Only when sowing at 120 days was there no effect of all herbicide treatments on the relative dry mass of soybeans.

Based on the data obtained, the safety interval (SI) was estimated for soybean sowing after application "A" of herbicide treatments (Table 6). The adjusted curves are shown in Figure 2 and the adjusted

Table 4 - Relative height (percentage in relation to the control without herbicide) of soybean plants in plantations at 0, 30, 60, 90 and 120 days after application (application A) of herbicide treatments

Treatment (application A)	Relative height (%) of soybean plants at 30 DAS									
	0 Days		30 Days		60 Days		90 Days		120 Days	
2,4-D	77.2	-	98.8	+	94.7	+	94.7	+	98.6	+
2,4-D + glyphosate	27.1	-	22.9	-	93.4	+	94.0	+	100.0	+
2,4-D + saflufenacil	7.1	-	9.1	-	49.2	-	96.3	+	99.7	+
2,4-D + [imazapic+imazapyr]	4.9	-	12.7	-	49.8	-	96.8	+	94.2	+
2,4-D + glyphosate + saflufenacil	73.2	-	63.8	-	100.0	+	95.4	+	92.6	+
2,4-D + glyphosate + [imazapic + imazapyr]	30.8	-	45.3	-	56.6	-	92.9	+	99.3	+
2,4-D + glyphosate + saflufenacil + [imazapic+imazapyr]	33.3	-	41.9	-	92.3	+	96.9	+	97.5	+
2,4-D + glyphosate + sulfentrazone	28.3	-	39.2	-	58.4	-	98.4	+	96.9	+
2,4-D + sulfentrazone	8.7	-	30.1	-	59.2	-	100.0	+	90.4	+
Glyphosate + saflufenacil + fluroxypyr	84.1	+	94.7	+	98.9	+	92.7	+	97.7	+
Glyphosate + [imazapic+imazapyr] + fluroxypyr	52.0	-	53.0	-	67.1	-	90.0	+	89.8	+
Glyphosate + dicamba + saflufenacil	0.0	-	1.3	-	10.7	-	43.2	-	100.0	+
Glyphosate + saflufenacil + [imazapic+imazapyr]	39.5	-	51.9	-	71.3	-	91.1	+	90.7	+
Fluroxypyr	36.4	-	51.9	-	91.0	+	93.1	+	97.7	+
Check	100.0	+	100.0	+	100.0	+	100.0	+	100.0	+
CV (%)	25.1		18.8		8.2		6.4		7.1	
MSD	21.2		18.6		12.5		12.3		14.2	

DAS: days after sowing; Dunnet test (p≤0.01); Equal signs between the treatment and the control indicate similarity between the treatments.

Table 5 - Relative dry mass (percentage in relation to the control without herbicide) of soybean plants in sowing carried out at 0, 30, 60, 90 and 120 days after application (application A) of the herbicide treatments

Treatment (application A)	Relative dry mass (%) of soybean plants at 30 DAS									
	0 Days		30 Days		60 Days		90 Days		120 Days	
2,4-D	77.3	-	100.0	+	100.0	+	100.0	+	98.6	+
2,4-D + glyphosate	29.9	-	41.2	-	97.3	+	99.5	+	96.0	+
2,4-D + saflufenacil	20.3	-	23.5	-	79.9	-	96.2	+	95.6	+
2,4-D + [imazapic+imazapyr]	17.2	-	30.2	-	68.9	-	100.0	+	97.2	+
2,4-D + glyphosate + saflufenacil	64.4	-	83.3	+	99.2	+	97.6	+	92.4	+
2,4-D + glyphosate + [imazapic + imazapyr]	40.6	-	61.3	-	72.3	-	97.2	+	96.5	+
2,4-D + glyphosate + saflufenacil + [imazapic+imazapyr]	42.6	-	47.1	-	98.4	+	100.0	+	94.8	+
2,4-D + glyphosate + sulfentrazone	35.1	-	55.5	-	75.9	-	99.9	+	93.1	+
2,4-D + sulfentrazone	12.2	-	44.1	-	68.6	-	100.0	+	93.4	+
Glyphosate + saflufenacil + fluroxypyr	75.6	-	97.7	+	100.0	+	96.2	+	92.7	+
Glyphosate + [imazapic+imazapyr] + fluroxypyr	62.4	-	65.2	-	83.1	-	96.6	+	97.8	+
Glyphosate + dicamba + saflufenacil	0.0	-	2.5	-	13.1	-	58.3	-	95.1	+
Glyphosate + saflufenacil + [imazapic+imazapyr]	47.8	-	72.7	-	75.3	-	100.0	+	94.8	+
Fluroxypyr	47.4	-	73.2	-	98.2	+	97.3	+	98.2	+
Check	100.0	+	100.0	+	100.0	+	100.0	+	100.0	+
CV (%)	23.5		20.4		8.1		7.3		6.1	
MSD	22.0		25.3		13.8		14.6		12.1	

DAS: days after sowing; Dunnet test ($p \leq 0.01$); Equal signs between the treatment and the control indicate similarity between the treatments.

Table 6 - Estimated safety interval based on phytointoxication data, relative height and relative dry weight after a single application of herbicide treatments (A), aiming at soybean sowing

Treatment (application A)	Safety interval (SI) for soybeans (days after sowing)[(1)]		
	Phytointoxication	Height	Dry mass
2,4-D	17	2	**28**
2,4-D + glyphosate	51	52	**54**
2,4-D + saflufenacil	73	**85**	52
2,4-D + [imazapic + imazapyr]	79	**89**	85
2,4-D + glyphosate + saflufenacil	49	**71**	42
2,4-D + glyphosate +[imazapic + imazapyr]	74	**100**	91
2,4-D + glyphosate + saflufenacil + [imazapic + imazapyr]	55	**74**	71
2,4-D + glyphosate + sulfentrazone	83	**96**	85
2,4-D + sulfentrazone	83	**92**	85
Glyphosate + saflufenacil + fluroxypyr	0	8	**10**
Glyphosate + [imazapic + imazapyr] + fluroxypyr	71	**108**	83
Glyphosate + dicamba + saflufenacil	**120**	115	113
Glyphosate + saflufenacil + [imazapic + imazapyr]	79	76	**82**
Fluroxypyr	56	**103**	89
Check	-	-	-

[(1)] In bold the highest estimated value for SI, considering the three response variables evaluated.

equations used in the regressions are shown in Table 11. Considering the maximum tolerances proposed in this work (10% reduction compared to the control without herbicide) and the curves adjusted in Figure 2, the SI's were calculated for a single application of treatments (Table 6). The lowest SI for soybean sowing was observed in the treatments with glyphosate + saflufenacil + fluroxypyr (10 days) and with 2,4-D (28 days). On the other hand, the longest carryover treatment was that with glyphosate + dicamba + saflufenacil.

There was a significant interaction between herbicide treatments and soybean sowing time when two sequential applications (A/B) of the treatments were performed. The results of % visual phytotoxicity in soybean plants are shown in Table 7.

When two sequential applications of the herbicide treatments were performed, the results of phytointoxication were observed to be similar to those presented in the experiment with a single application of the treatments (A). However, the levels of intoxication of soybean plants, especially when sown on the second application day (0 days), were higher in most treatments, with total plant death in six of the fourteen herbicide treatments tested.

At sowing at 0 DAA, all herbicides showed significantly higher poisoning of soybean plants than

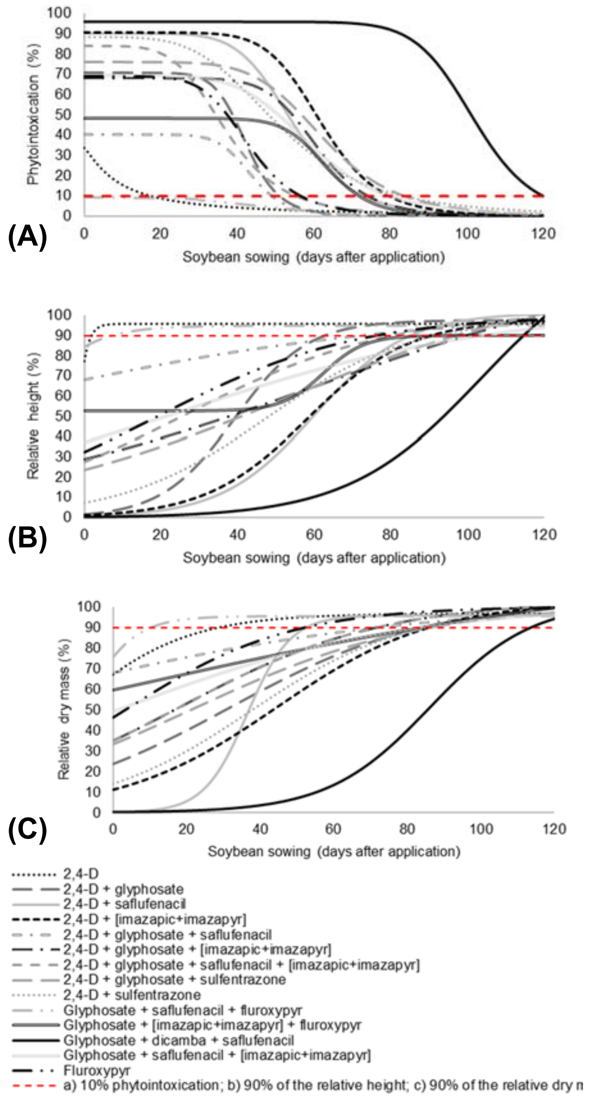

Figure 2 - Phytointoxication (A), relative height (B) and relative dry weight (C) of soybean plants sown at 0, 30, 60, 90 and 120 days after a single application (application A) of the herbicide treatments used in the control of cotton stalks. Santo Antônio de Posse, SP, 2014.

treatment without herbicide. When the soybean was sown at 30 days, the treatment with 2,4-D showed only 4.7% of intoxication, not differing from the control. At 60 days, in addition to 2,4-D, treatments 2,4-D + glyphosate, 2,4-D + glyphosate + saflufenacil and glyphosate + saflufenacil + fluroxypyr also showed similar results to the control without herbicide. On the other hand, at 90 days, only soybean sown where 2,4-D + glyphosate + saflufenacil + [imazapic + imazpyr], 2,4-D + glyphosate + sulfentrazone and glyphosate + dicamba + saflufenacil were applied presented phytointoxication higher than the control without herbicide (≥14.7%). The only treatment that still showed relevant phytointoxication (29%) when soy was sown at 120 days was glyphosate + dicamba + saflufenacil.

Only the treatment with 2,4-D showed a relative height of the soybean similar to the control without herbicide in the first two sowing seasons (0 and 30 days) (Table 8). For sowing performed at 60 days, also three other treatments (2,4-D + glyphosate; 2,4-D + glyphosate + saflufenacil; glyphosate + saflufenacil + fluroxypyr; glyphosate + [imazapic + imazapyr] + fluroxypyr) did not present more effects on soybean growth. For sowing at 90 days, the only treatment that had lower soybean height was glyphosate + dicamba + saflufenacil, whereas at 120 days there was no longer any negative effect from the treatments.

The data of relative dry weight of soybean plants in the sowing carried out after the second sequential application (0, 30, 60, 90 and 120 days) were similar to those obtained for relative height (Table 9). For sowing at 0 and 30 days, only the 2,4-D treatment presented a similar dry weight to the control without application. The treatments that showed sufficient residual activity to affect the soybean dry mass for a longer period were 2,4-D + glyphosate + sulfentrazone and glyphosate + dicamba + saflufenacil, which had a significant effect up to 90 days. At 120 days, only the glyphosate + dicamba + saflufenacil treatment affected the soybean dry weight and differed from the control without herbicide. The safety interval (SI) estimated after two sequential applications of the herbicide treatments evaluated in this work for soybean sowing is shown in Table 10 and was based on the equations in Figure 3, whose equations are shown in Table 11. It is observed that with two sequential applications (A/B) the SI for most treatments increased in relation to the estimated for the single application (A) shown in Table 6. The shortest SI calculated was 19 days for 2,4-D and 47 days for glyphosate + saflufenacil + fluroxypyr. The treatment containing dicamba showed SI longer than 120 days, which makes its use in the control of cotton stalks unviable if the objective is to grow soybeans in the next harvest.

There was a significant difference in visual intoxication provided by the application of the 2,4-D and 2,4-D + glyphosate herbicide treatments, suggesting that when mixed (2,4-D + glyphosate) there is an increase in intoxication and a prolongation of injury symptoms on soybean plants. The safety interval for sowing soybeans after the application of 2,4-D is estimated to be at least ten days (Osipe, 2015). The symptoms observed resulting from the application of 2,4-D + glyphosate were shrinking of the leaf blade, thickening of the base of

Table 7 - Phytointoxication of soybean plants sown at 0, 30, 60, 90 and 120 days after two sequential applications (A/B) of herbicide treatments

Treatment (application A/B)	Phytointoxication (%) of soybean plants at 14 DAS				
	0 Days	30 Days	60 Days	90 Days	120 Days
2,4-D	32.7 -	4.7 +	1.7 +	0.0 +	0.0 +
2,4-D + glyphosate	51.7 -	37.0 -	5.5 +	1.7 +	0.0 +
2,4-D + saflufenacil	100.0 -	64.0 -	9.7 -	4.2 +	0.0 +
2,4-D + [imazapic+imazapyr]	92.0 -	71.2 -	39.5 -	1.7 +	0.0 +
2,4-D + glyphosate + saflufenacil	100.0 -	42.5 -	4.7 +	0.0 +	0.0 +
2,4-D + glyphosate + [imazapic + imazapyr]	76.7 -	48.5 -	37.0 -	4.7 +	0.0 +
2,4-D + glyphosate + saflufenacil + [imazapic+imazapyr]	100.0 -	53.5 -	45.0 -	14.7 -	3.0 +
2,4-D + glyphosate + sulfentrazone	100.0 -	84.0 -	58.7 -	23.0 -	3.0 +
2,4-D + sulfentrazone	100.0 -	81.2 -	36.0 -	4.0 +	2.0 +
Glyphosate + saflufenacil + fluroxypyr	66.0 -	31.2 -	5.5 +	0.0 +	0.0 +
Glyphosate + [imazapic+imazapyr] + fluroxypyr	64.0 -	42.7 -	29.7 -	0.0 +	0.0 +
Glyphosate + dicamba + saflufenacil	100.0 -	100.0 -	72.0 -	57.7 -	29.0 -
Glyphosate + saflufenacil + [imazapic+imazapyr]	53.2 -	44.2 -	33.0 -	4.2 +	1.7 +
Fluroxypyr	89.2 -	54.7 -	25.0 -	3.5 +	0.0 +
Check	0.0 +	0.0 +	0.0 +	0.0 +	0.0 +
CV (%)	7.7	4.5	9.9	24.9	47.8
MSD	12.2	4.7	5.6	4.8	3.1

DAS: days after sowing; Dunnet test (p≤0.01); Equal signs between the treatment and the control indicate similarity between the treatments.

Table 8 - Relative height (percentage in relation to the control without herbicide) of soybean plants in plantations at 0, 30, 60, 90 and 120 after two sequential applications (A/B) of herbicide treatments

Treatment (application A/B)	Relative height (%) of soybean plants at 30 DAS				
	0 Days	30 Days	60 Days	90 Days	120 Days
2,4-D	100.0 +	100.0 +	100.0 +	90.2 +	98.9 +
2,4-D + glyphosate	56.0 -	75.0 -	95.8 +	97.0 +	99.0 +
2,4-D + saflufenacil	0.0 -	48.7 -	83.1 -	93.1 +	100.0 +
2,4-D + [imazapic+imazapyr]	41.4 -	48.4 -	68.9 -	91.8 +	96.0 +
2,4-D + glyphosate + saflufenacil	0.0 -	74.8 -	93.2 +	100.0 +	100.0 +
2,4-D + glyphosate + [imazapic + imazapyr]	61.4 -	69.8 -	77.1 -	96.0 +	100.0 +
2,4-D + glyphosate + saflufenacil + [imazapic+imazapyr]	0.0 -	52.3 -	72.4 -	96.3 +	99.0 +
2,4-D + glyphosate + sulfentrazone	0.0 -	39.8 -	67.4 -	85.9 +	100.0 +
2,4-D + sulfentrazone	0.0 -	47.3 -	57.5 -	93.1 +	100.0 +
Glyphosate + saflufenacil + fluroxypyr	66.2 -	81.0 -	96.5 +	90.1 +	100.0 +
Glyphosate + [imazapic+imazapyr] + fluroxypyr	85.7 -	76.0 -	94.9 +	89.9 +	100.0 +
Glyphosate + dicamba + saflufenacil	0.0 -	0.0 -	44.8 -	66.1 -	86.1 +
Glyphosate + saflufenacil + [imazapic+imazapyr]	81.7 -	71.5 -	76.6 -	96.5 +	100.0 +
Fluroxypyr	0.0 -	57.6 -	79.8 -	89.9 +	100.0 +
Check	100.0 +	100.0 +	100.0 +	100.0 +	100.0 +
CV (%)	10.7	9.9	5.3	8.1	9.1
MSD	9.7	13.4	9.0	15.4	19.3

DAS: days after sowing; Dunnet test (p≤0.01); Equal signs between the treatment and the control indicate similarity between the treatments.

Table 9 - Relative dry weight (percentage in relation to the control without herbicide) of soybean plants in plantations at 0, 30, 60, 90 and 120 days after two sequential applications (A B) of herbicide treatments

Treatment (application A/B)	Relative dry mass (%) of soybean plants at 30 DAS				
	0 Days	30 Days	60 Days	90 Days	120 Days
2,4-D	90.8 +	100.0 +	100.0 +	100.0 +	100.0 +
2,4-D + glyphosate	84.3 -	85.4 -	98.1 +	96.8 +	100.0 +
2,4-D + saflufenacil	0.0 -	49.8 -	87.8 -	100.0 +	100.0 +
2,4-D + [imazapic+imazapyr]	34.3 -	50.2 -	78.2 -	98.3 +	100.0 +
2,4-D + glyphosate + saflufenacil	0.0 -	77.6 -	97.5 +	100.0 +	100.0 +
2,4-D + glyphosate + [imazapic + imazapyr]	53.2 -	77.5 -	87.8 -	100.0 +	100.0 +
2,4-D + glyphosate + saflufenacil + [imazapic+imazapyr]	0.0 -	77.5 -	86.3 -	99.6 +	89.8 +
2,4-D + glyphosate + sulfentrazone	0.0 -	47.1 -	64.6 -	84.0 -	100.0 +
2,4-D + sulfentrazone	0.0 -	48.6 -	78.2 -	98.4 +	98.4 +
Glyphosate + saflufenacil + fluroxypyr	63.3 -	83.1 -	100.0 +	99.8 +	100.0 +
Glyphosate + [imazapic+imazapyr] + fluroxypyr	61.1 -	74.5 -	100.0 +	100.0 +	100.0 +
Glyphosate + dicamba + saflufenacil	0.0 -	0.0 -	55.3 -	82.2 -	81.2 -
Glyphosate + saflufenacil + [imazapic+imazapyr]	66.5 -	74.3 -	83.9 -	95.8 +	99.4 +
Fluroxypyr	0.0 -	61.7 -	85.4 -	99.8 +	100.0 +
Check	100.0 +	100.0 +	100.0 +	100.0 +	100.0 +
CV (%)	16.5	9.4	6.5	7.4	8.6
MSD	12.7	13.2	11.9	15.1	17.9

DAS: days after sowing; Dunnet test (p≤0.01); Equal signs between the treatment and the control indicate similarity between the treatments.

Table 10 - Estimated safety interval based on phytointoxication data, relative height and relative dry weight after two sequential applications of the herbicide treatments (A/B) evaluated in this work, aiming at soybean sowing

Treatment (application A/B)	Safety interval (SI) for soybean (days after sowing)[(1)]		
	Phytointoxication	Height	Dry mass
2,4-D	**19**	0	0
2,4-D + glyphosate	51	**54**	34
2,4-D + saflufenacil	**91**	74	62
2,4-D + [imazapic + imazapyr]	84	**90**	76
2,4-D + glyphosate + saflufenacil	**52**	49	39
2,4-D + glyphosate + [imazapic + imazapyr]	**92**	82	59
2,4-D + glyphosate + saflufenacil + [imazapic + imazapyr]	**101**	86	61
2,4-D + glyphosate + sulfentrazone	**106**	97	94
2,4-D + sulfentrazone	83	**90**	77
Glyphosate + saflufenacil + fluroxypyr	**47**	30	39
Glyphosate + [imazapic + imazapyr] + fluroxypyr	**57**	52	50
Glyphosate + dicamba + saflufenacil	**>120**	**>120**	**>120**
Glyphosate + saflufenacil + [imazapic + imazapyr]	79	**86**	76
Fluroxypyr	80	**86**	67
Check	-	-	-

(1) In bold the highest estimated value for SI, considering the three response variables evaluated.

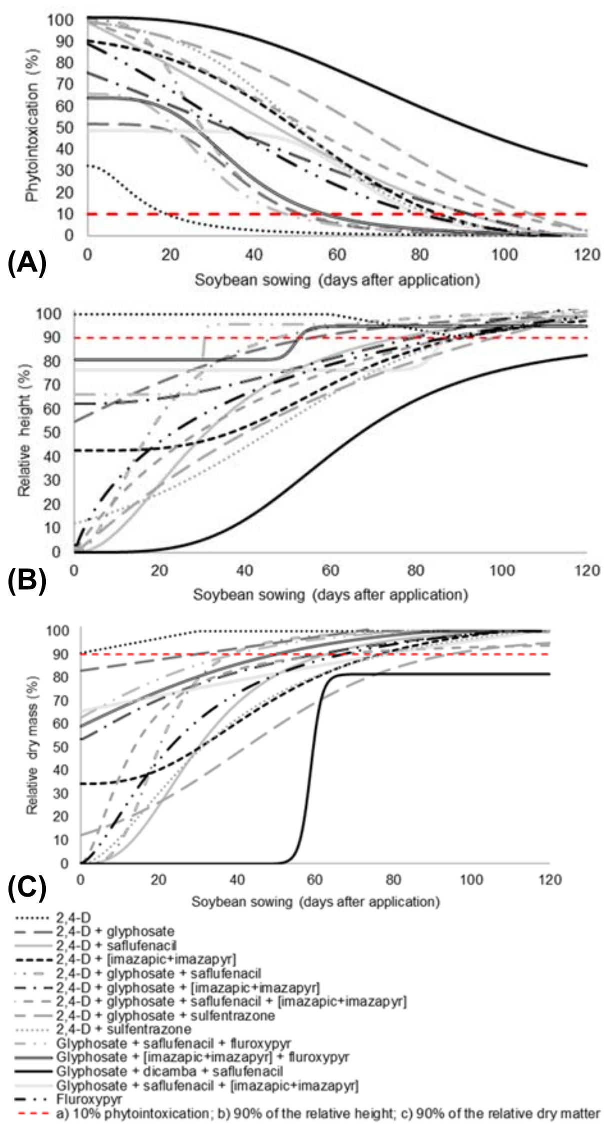

Figure 3 - Phytointoxication (A), relative height (B) and relative dry mass (C) of soybean plants sown at 0, 30, 60, 90 and 120 days after sequential application (application A/B) of the herbicide treatments used in the control of cotton stalks. Santo Antônio de Posse, SP, 2014.

the stem, chlorosis of the stem and reduction in the size of the plants, symptoms characteristic of auxin mimics, the symptoms being only dissipated when sowing was carried out after 54 days (Tables 6 and 10).

A possible explanation is the effect of some by-product that remained active in the soil from the interaction between the two herbicides, which may have provided an increase in the residual of the 2,4-D herbicide. Furthermore, microbial degradation is the key process in the degradation of most herbicides in the soil, being valid for both glyphosate (Andrighetti et al., 2014) and 2,4-D (Araújo and Orlanda, 2014). When these herbicides are applied in combination, there may be a possible overload of the soil microbiota, which slows down the degradation of the herbicides and provides greater persistence, mainly of 2,4-D; which can affect sowed soybean plants at different times after application.

The presence of herbicides with residual activity in the mixtures, widely used in pre-emergence applications, such as [imazapic + imazapyr] and sulfentrazone, also affected soy in succession. Imazapic and imazapyr belong to the chemical group of imidazolinones and are characterized by low-dose efficacy and long persistence in the soil, influenced by soil properties, such as pH, humidity, organic matter content and still present limited biodegradation when under anaerobic conditions (Shaner, 2014).

Monquero et al. (2010) when evaluating the persistence of imazapyr in different pH ranges and leaching at different depths of the soil profile, found greater persistence of this product in the upper layers of the soil when at pH 4.7, negatively affecting

Table 11 - Equations adjusted to estimate the safety interval for sowing the soybean crop after the herbicide application to control cotton stalks

Treatment (application A)	Equation used to estimate the safety interval (SI)		
	Phytointoxication	Relative height	Relative dry mass
2,4-D	$\hat{Y}$=33.74/(1+((x/8.9)^1.25))	$\hat{Y}$=95.82/(1+EXP(-(x-(-2.09))/1.46))	$\hat{Y}$=96.92/(1+EXP(-(x-(-13.23))/16.23))
2.4-D + glyphosate	$\hat{Y}$=70.75/(1+((x/42.42)^9.84))	$\hat{Y}$=97.62/(1+EXP(-(x-(39.13))/9.53))	$\hat{Y}$=102.81/(1+EXP(-(x-(32))/26.79))
2.4-D + saflufenacil	$\hat{Y}$=90.05/(1+((x/54.89))^7.23)	$\hat{Y}$=101.17/(1+EXP(-(x-60)/12.11))	$\hat{Y}$=96.08/(1+EXP(-(x-(36.49))/5.89))
2.4-D + [imazapic + imazapyr]	$\hat{Y}$=90.34/(1+((x/62.22)^8.37))	$\hat{Y}$=98.11/(1+EXP(-(x-58.26)/13.35))	$\hat{Y}$=103.02/(1+EXP(-(x-(44.73))/21.25))
2.4-D + glyphosate + saflufenacil	$\hat{Y}$=40.24/(1+((x/43.7)^9.75))	$\hat{Y}$=103.37/(1+EXP(-(x-(-37.27))/57.64))	$\hat{Y}$=103.37/(1+EXP(-(x-(-37.27))/57.64))
2.4-D + glyphosate +[imazapic + imazapyr]	$\hat{Y}$=67.96/(1+((x/60.94)^8.98))	$\hat{Y}$=12.51/(1+EXP(-(x-(60.5))/48))	$\hat{Y}$=103.17/(1+EXP(-(x-(18.44))/27.51))
2.4-D + glyphosate + saflufenacil + [imazapic + imazapyr]	$\hat{Y}$=83.74/(1+((x/37.18)^5.02))	$\hat{Y}$=101.76/(1+EXP(-(x-26.43)/26.63))	$\hat{Y}$=103.17/(1+EXP(-(x-(18.44))/27.51))
2.4-D + glyphosate + sulfentrazone	$\hat{Y}$=75.96/(1+((x/62.74)^6.58))	$\hat{Y}$=118.48/(1+EXP(-(x-52.89)/38.06))	$\hat{Y}$=101.19/(1+EXP(-(x-(21.74))/30.92))
2.4-D + sulfentrazone	$\hat{Y}$=88.19/(1+((x/51.25)^4.27))	$\hat{Y}$=98.76/(1+EXP(-(x-47.63)/18.99))	$\hat{Y}$=99.12/(1+EXP(-(x-(37.47))/20.84))
Glyphosate + saflufenacil + fluroxypyr	-	$\hat{Y}$=94.78/(1+EXP(-(x-(-17.9))/8.67))	$\hat{Y}$=95.48/(1+EXP(-(x-(-9.42))/7.04))
Glyphosate + [imazapic + imazapyr] + fluroxypyr	$\hat{Y}$=48.38/(1+((x/63.5)^10.97))	$\hat{Y}$=52.47+37.54/(1+EXP(-(x-62.36)/5.37))	$\hat{Y}$=120.9/(1+EXP(-(x-(2.54))/76.16))
Glyphosate + dicamba + saflufenacil	$\hat{Y}$=95.72/(1+((x/101.78)^13.15))	$\hat{Y}$=137.35/(1+EXP(-(x-(103.45))/17.37))	$\hat{Y}$=102.6/(1+EXP(-(x-(86.18))/13.83))
Glyphosate + saflufenacil + [imazapic + imazapyr]	$\hat{Y}$=69.55/(1+((x/59.37)^6.05))	$\hat{Y}$=103.37/(1+EXP(-(x-(24.18))/41.92))	$\hat{Y}$=100.69/(1+EXP(-(x-(1.97))/38.11))
Fluroxypyr	$\hat{Y}$=68.74/(1+((x/43.27)^6.66))	$\hat{Y}$=100.15/(1+EXP(-(x-(19.33))/25.92))	$\hat{Y}$=100.19/(1+EXP(-(x-(3.45))/22.39))
Check	-	-	-
Treatment (application A/B)			
2.4-D	$\hat{Y}$=32.74/(1+((x/13.14)^2.13))	-	-
2.4-D + glyphosate	$\hat{Y}$=51.76/(1+((x/37.04)^4.34))	$\hat{Y}$=100.58/(1+EXP(-(x+5.16)/27.94))	$\hat{Y}$=82.9343+0.2417*x+(-0.0008*x)^2
2.4-D + saflufenacil	$\hat{Y}$=-14.36+(156.8/(1+EXP(-(x-33.12)/-34.45)))	$\hat{Y}$=106.28/(1+((x/32.5)^-2.03))	$\hat{Y}$=104/(1+((x/31)^-2.64))
2.4-D + [imazapic + imazapyr]	$\hat{Y}$=-5.11+(100.55/(1+EXP(-(x-53.46)/-17.89)))	$\hat{Y}$=42.7+(59.66/(1+((x/62.45)^-3.61)))	$\hat{Y}$=34.56+(73.89/(1+((x/50.31)^-2.64)))
2.4-D + glyphosate + saflufenacil	$\hat{Y}$=99.98/(1+((x/27.53)^3.48))	$\hat{Y}$=103.65/(1+((x/18.01)^-1.96))	$\hat{Y}$=100.48/(1+((x/20.18)^-3.33))
2.4-D + glyphosate +[imazapic + imazapyr]	$\hat{Y}$=-20.7+(147.82/(1+EXP(-(x-29.35)/-46.68)))	$\hat{Y}$=62.42+(59.3/(1+((x/83.9)^-2.24)))	$\hat{Y}$=53.32+(64.22/(1+((x/47.32)^-1.17)))
2.4-D + glyphosate + saflufenacil + [imazapic + imazapyr]	$\hat{Y}$=-8.21+(130.29/(1+EXP(-(x-46.89)/-29.94)))	$\hat{Y}$=155.95/(1+((x/62.95)^-0.95))	$\hat{Y}$=96.22/(1+((x/13.08)^-1.69))
2.4-D + glyphosate + sulfentrazone	$\hat{Y}$=-10.77+(117.62/(1+EXP(-(x-68.04)/-25.32)))	$\hat{Y}$=179.82/(1+((x/97.32)^-1.06))	$\hat{Y}$=97.24/(1+EXP(-(x-40.96)/21.1))
2.4-D + sulfentrazone	$\hat{Y}$=-0.44+(103.32/(1+EXP(-(x-50.36)/-14.78)))	$\hat{Y}$=104.51/(1+EXP(-(x-47.12)/23.42))	$\hat{Y}$=112.74/(1+((x/35.48)^-1.74))
Glyphosate + saflufenacil + fluroxypyr	$\hat{Y}$=65.98/(1+((x/29.14)^3.5))	$\hat{Y}$=66.23+(29.33/(1+((x/29.99)^-89.99)))	$\hat{Y}$=102.01/(1+EXP(-(x+11.882)/25.33))
Glyphosate + [imazapic + imazapyr] + fluroxypyr	$\hat{Y}$=63.91/(1+((x/36.41)^3.71))	$\hat{Y}$=80.89+(14.09/(1+(x/51.64)^-36.95))	$\hat{Y}$=104.31/(1+EXP(-(x+8.62)/31.75))
Glyphosate + dicamba + saflufenacil	$\hat{Y}$=101.3/(1+((x/91.28)^2.74))	$\hat{Y}$=90.41/(1+((x/63.05)^-3.75))	$\hat{Y}$=81.77/(1+EXP(-(x-58.94)/1.42))
Glyphosate + saflufenacil + [imazapic + imazapyr]	$\hat{Y}$=48.89/(1+((x/66.2)^7.21))	$\hat{Y}$=76.65+(23.35/(1+((x/86)^-38.7)))	$\hat{Y}$=127.53/(1+EXP(-(x+5.74)/95.4))
Fluroxypyr	$\hat{Y}$=-4.611+(125.99/(1+EXP(-(x-27.57)/-25.88)))	$\hat{Y}$=149.59/(1+((x/52.45)^-0.82))	$\hat{Y}$=111.39/(1+((x/26.18)^-1.53))
Check	-	-	-

(-) not adjusted.

bioindicator plants for periods of up to 210 days, while at pH 6.0 this effect dissipated in the soil profile, going down in depth affecting the bioindicator plants in up to 150 days.

Sulfentrazone, also an herbicide with residual activity, has greater persistence in the soil than other herbicides such as glyphosat and 2,4-D, which increases the risk of affecting crops in succession, as observed in this work. The sulfentrazone half-life in soil is estimated to be between 110 and 280 days, varying according to local edaphoclimatic conditions (Vivian et al., 2006). Some authors report that the toxicity of sulfentrazone to soybean varieties is closely related to the speed with which the herbicide is metabolized, and that factors such as pH and soil texture can also influence selectivity (Arruda et al., 1999; Zobiole et al., 2007)

Although dicamba is an auxin-mimicking herbicide such as 2,4-D, it can be seen in this work that the residual effect of dicamba prevailed over any mixture containing the 2,4-D herbicide. The dicamba has higher water solubility, lower K_{ow} value (octanol-water partition coefficient) and lower sorption value to soil (K_d) or organic matter (K_{oc}), which may imply greater availability of the herbicide in the solution of the consequently, greater residual activity (Villaverde et al., 2008; Rodrigues e Almeida, 2018; Osipe et al., 2014), which may have contributed to the onset of injuries up to 120 days after the application of the glyphosate + mixture dicamba + saflufenacil, regardless of whether the single or sequential application of the herbicide treatment was carried out.

4 Conclusions

As this work was conducted, it was concluded that the single application and the sequential application of the glyphosate + dicamba + saflufenacil treatment has great carryover potential for soybean crops, with the safety interval for sowing the crop exceeding 120 days after application. The treatments 2,4-D, 2,4-D + glyphosate, glyphosate + saflufenacil + fluroxypyr had the shortest safety intervals, even when in sequential application. The treatment with application of 2,4-D alone showed the lowest carryover potential for soybean.

The results obtained in this work may have overestimated the safety interval for some herbicides. This is due to the fact that the conduction of the experiments was carried out in a greenhouse, simulating a possible condition that occurs in the field. In this way, the results provide a carryover indicator that can assist in the adoption of management strategies for cotton stalks when the objective is to cultivate soybean in succession.

5 Contributions

ACF: designed and performed the experiments, analyzed the data, interpreted the results, and drafted the manuscript. JC, WDM, and RSOJr: designed the experiments and revised the manuscript.

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