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Sweet Sorghum Establishment after Application of Residual Herbicides

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Abstract *— Imazethapyr, sulfentrazone, clomazone, diclosulam, trifloxysulfuron-sodium and trifluralin are residual herbicides commonly used for weed control in soybean or sugarcane crops. The sorghum crop implanted succeeding sugarcane, can be affected by the carryover effect of these herbicides. In this context, we aim with this work to evaluate the minimum period between application of herbicides with residual effect (imazethapyr, sulfentrazone, clomazone, diclosulam, trifluralin and trifloxysulfuron-sodium) and the planting of sorghum so that there is no impairment in growth and establishment of this crop due to the herbicide carryover effect. The experiment was installed in randomized blocks design with four replications, under field conditions. The herbicides were applied to the previously tillaged soil, with sorghum being planted 0, 14, 28, 42, 56 and 70 days after herbicide application (DAA). The percentage of germination was evaluated daily from planting, and 7, 14, 21 and 28 days after emergence (DAE) of each planting, the phytotoxicity was evaluated. Thirty five DAE of each planting season, ten plants were collected per plot for measurement of leaf area, fresh and dry mass of plants, leaves and stems. The minimum time interval for planting sorghum after application of these herbicides varies, but imazethapyr is highlighted by causing high and durable toxicity to sorghum even when planting sorghum after 70 days of its application.*

Keywords *— Phytotoxicity,* **Sorghum bicolor,** ***pre-emergence.***

I. INTRODUCTION

The different types of sorghum (grain, forage and saccharine) are cultivated in different regions of the world and have wide adaptability to environmental conditions, especially under water deficiency, establishing themselves in more varied environments than other commercial species (Francisco, 2016). In addition, research on sorghum in Brazil has been boosted in recent years, mainly due to its applicability to ethanol production in situations or regions of the country where sugarcane may either not present high yields, or is not available for processing, since the entire sugarcane-based alcohol and sugar industry structure is suitable also for sorghum processing (Almodares & Hadi, 2009). Thus, sorghum has increasingly become an option for cultivation in Brazil, mainly in succession to soybeans (Dan et al., 2010).

Sugarcane makes an average of five to six successive crops, demanding a plantation reform after this period (Durães, 2011), for a new cropping cycle. Sorghum, with a short cycle – 90 - 130 days from emergence to harvest, is ideal for complementing ethanol production during the sugarcane off-season, or when sugarcane is still with low sugar concentration, allowing to extend the period of use of the ethanol production plants in up to three months (Almodares & Hadi, 2009). It should be noted that sorghum requires less fertilizer amounts, and stores sugars in its stems at different times, compared to sugarcane (Lourenço et al., 2007). In addition, it may also be suitable in an integrated system of rural property exploitation, aiming at self-sufficiency in energy, together with other activities focused on agricultural production (Souza et al., 2005).

Weed control is essential in cash crops due to competition for environmental resources such as water, light, nutrients and physical space (Silva et al., 2007). In contemporary agriculture, herbicides stand out as one of the main tools for weed control, being its use economically viable (Inoue et al., 2011). However, herbicides that have a long residual effect in soils may not be degraded during the main crop cycle, leaving residues that harm the germination and development of succeeding crops (Werle et al., 2017). Several authors report effects of residual herbicides to succeeding crops, as for rice (Avila et al., 2010; Pinto et al., 2011), cotton (Grichar et al., 2004), maize (Ulbrich et al., 2005; Artuzi e Contieiro, 2006), sunflower (Merotto Jr; Vidal, 2001; Brighenti et al., 2002),

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sorghum (Silva et al., 1999; Dan et al., 2010) and millet (Dan et al., 2011).

The impact of herbicide residues (carryover effect) on crops grown succession depends on several factors, among them the natural susceptibility of the planted species, the herbicide half-life and the environmental conditions that affect the herbicide degradation rate in soil (Silva et al., 2007). Imazethapyr, sulfentrazone, clomazone, diclosulam, trifluralin and trifloxysulfuron-sodium are herbicides commonly used in soybean or sugarcane cultivation (Monquero, 2014), where sorghum can be planted in succession; all these compounds are considered at least moderately soil persistent (IUPAC, 2018). With the possibility of growing sorghum in succession to these crops, it is a priority to study the residual effect of these molecules and their potential to cause damage to the establishment of sorghum planted in succession.

II. OBJECTIVE

In this context, we aimed with this work to evaluate the minimum period between the application of the residual herbicides imazethapyr, sulfentrazone, clomazone, diclosulam, trifluralin and trifloxysulfuron-sodium, and the planting of sorghum so that there is no damage to the growth and establishment of this crop.

III. MATERIAL AND METHODS

The experiment was installed in field conditions on a Red Dystroferric Latosol with 60% clay, in the experimental area of Embrapa Agropecuária Oeste, Dourados-MS, Brazil, in the 2013/2014 cropping season. We used the strip-plot experimental design, comprising a factorial scheme 7 x 6, with four replications.

Factor A (horizontal bands) was represented by the treatments: Test (T-01); Clomazone 1.25 $kg_{a.i.}$ ha^{-1} (T-02); Trifloxysulfuron-sodium 0.0075 $kg_{a.i.}$ ha^{-1} (T-03); Trifluralin 2.4 $kg_{a.i.}$ ha^{-1} (T-04); Diclosulam 0.042 $kg_{a.i.}$ ha^{-1} (T-05); Imazethapyr 0.15 $kg_{a.i.}$ ha^{-1} (T-06); and Sulfentrazone 0.6 $kg_{a.i.}$ ha^{-1} (T-07). Factor B (vertical bands) was composed by sorghum planting, variety BRS 511, at intervals of 0, 14, 28, 42, 56 and 70 days after application (DAA) of the herbicides. These intervals were chosen in order to identify the minimum period required between the application of these herbicides and the implementation of the sorghum crop in a way that does not hinder its growth and development. The physico-chemical characteristics of the screened herbicides are listed in Table 1.

Table.1: physico-chemical properties of the herbicides used in the present study.

Herbicide	Solubility mg L^{-1}	K_{oc} mL g^{-1}	Half-life (days)	Persistence
Clomazone	1102	300	26-167	Moderated
Trifloxysulfuron sodium	25700	306	45-80	Moderated
Trifluralin	0.221	15800	81-356	Persistent
Diclosulam	6.32	90	14-80	Moderated
Imazethapyr	1400	52	14-290	Moderated
Sulfentrazone	780	43	121-302	Highly persistent

Planting was accomplished manually, where 3 cm deep furrows were opened in rows spaced at 0.45 m, and 7 seeds m^{-1} were uniformly deposited, resulting in an approximate final density of 150,000 plants ha^{-1} (15 plants m^{-2}). The area was tillaged with plowing and harrowing, previously fertilized according to soil analysis and technical recommendations for the crop (May et al., 2012). The area had no history of application of residual herbicides for five years prior to the installation of the experiment. Soil characteristics are listed in Table 2.

Table.2: chemical soil analysis in two depthscollected in the area where the experiment wa sinstalled.

Soil Depth	pH	Al	K	Ca	Mg	CTC
cm	H_2O	----------		$cmol_c$ dm^{-3}		----------
0 - 5	6.50	0.07	1.16	8.23	3.35	15.9
5 - 15	5.40	0.74	0.43	4.59	2.06	15.8
Soil Depth	**M.O**	**P[1]**	**Fe**	**Mn**	**Zn**	**Cu**
cm	g kg^{-1}	----------		mg dm^{-3}		----------
0 - 5	38.9	48.5	22.2	134.2	2.9	13.6
5 - 15	26.8	30.2	28.3	69.6	1.8	17.6

Herbicide application and the first planting season were accomplished on Oct. 18, 2013. For this, we used a CO_2-pressurized backpack sprayer, connected to a bar equipped with nozzles 110.02 working at the recommended pressure, delivering 120 L ha^{-1} of herbicide solution. The application was done at early morning, right after the planting of the first season. The soil was about 80% of field capacity by the time of the application. Basic

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temperature and rain data for the period of the experiment are supplied at Figure 1.

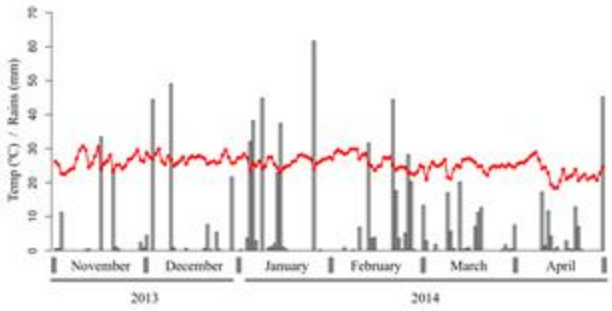

Fig.1: mean daily rainfall (mm - ▇) and temperature (ºC - ——) along the experimental period.

Phytotoxicity evaluations were performed 7, 14, 21 and 28 days after emergence (DAE), through visual symptoms measured on a scale varying from 0 to 100, where zero represents no symptoms and 100% the death of the plants. The emergence was evaluated by daily counting in a previously marked section of 3 m of planting row in each replication, daily from 0 to 14 days after planting (DAP), being considered as "emerged" seedlings with height equal or superior to 1 cm. Thirty DAE, in each planting season and for each herbicide treatment, the fresh and dry mass of of shoot, leaves and stems of sorghum plants were evaluated. At 103 DAE, plant height, fresh and dry mass and density were assessed.

The data set was submitted to analysis of variance in the statistical software R (R Core Team, 2012), being explored by 3D response surfaces, and linear or non-linear regressions, according to the significances. For percentage of emergence and phytotoxicity, the Gaussian equation was used to obtain the response surfaces, as follows:

$$Z = ae^{-0,5\left[\left(\frac{x-x_0}{b}\right)^2+\left(\frac{y-yo}{c}\right)^2\right]} \quad (1)$$

IV. RESULTS AND DISCUSSION

The average daily air temperature during the conduction of the experiment ranged from 15 to 25 °C, and at least 16 rainfall events with considerable volume were observed (Figure 1), demonstrating good conditions for conducting the experiment.

The regression parameters for all treatments are summarized at Table 3. The number of emerged plants (Z axis) was modeled according to the sorghum planting interval after herbicide application (X axis) and the period in days after each planting (Y axis), by using Gaussian response surfaces (Figure 2). For all herbicide treatments the percentage of emergence increased until the eighth day after planting, reaching the apex between the eighth and the tenth day; due to unfavorable environmental conditions and pest attacks there was a decrease in the number of plants after the tenth day. It can also be observed that all herbicides affected the number of emerged plants, and the lower the interval between herbicide application and planting, the lower the sorghum germination. When sorghum was planted at the day of the application, for example, there were 15 seeds germinated at the control plot, while for the herbicide treatments, only about 10 seedlings were present. Diclosulam was the least impacting herbicide on sorghum in concomitant planting/application, with approximately 13 seeds in a 3m row (Figure 3).

Table.3: components of the Gaussian equation (X_0, Y_0, a, b, c), significance (P), adjustment coefficient (R2) and mean residual square (MRS), as function of treatment.

	Treatment						
	T01	**T02**	**T03**	**T04**	**T05**	**T06**	**T07**
X0	-6948	58,6	57,2	66,5	1580	46,8	47,5
Y0	10,1	10,1	10,1	10,4	10,3	10	10,2
a	77,5	18,1	16,2	17,1	119	17	18,4
b	3949	56,9	66,4	70,1	756	50,7	51,2
c	4,55	4,4	4,4	4,52	4,4	4,42	4,5
R2	0,67	0,66	0,66	0,71	0,74	0,68	0,67
P	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01
MRS	41,76	118,5	103,1	38,82	35,2	37,04	122,4

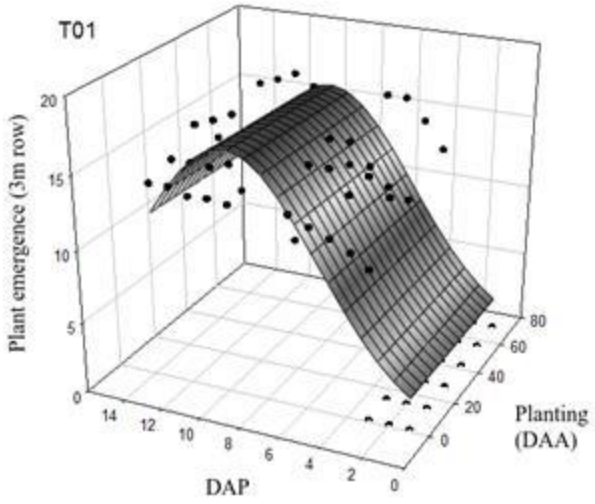

Fig.2: plant emergence in 3m in a planting row, for the control treatment with no herbicide, as function of the sorghum planting season (days after herbicide application in the other treatments – DAA), and days after each planting.

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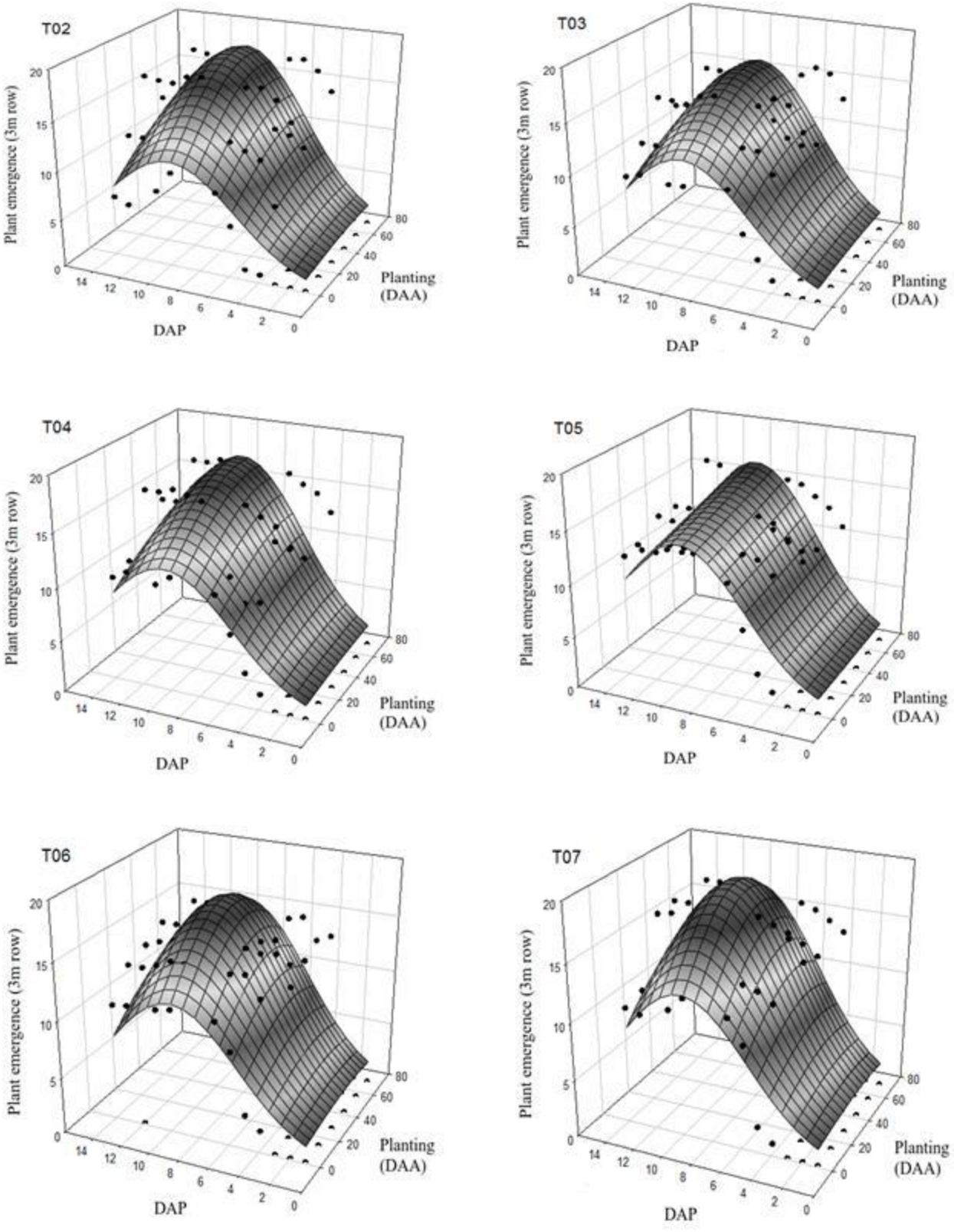

Fig.3: plant emergence in 3m in a planting row, for herbicide treatments, as function of the sorghum planting season (days after herbicide application - DAA), and days

Although all herbicides used in this experiment are considered to be at least moderately persistent in soil (Table 1), the response surfaces show that in the last planting season, 70 DAA, herbicide interference on

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germination (Figure 3) decreased considerably and all treatments were similar to the control plot (Figure 2).The treatment T-02 (clomazone), T-04 (trifluralin) and T-07 (sulfentrazone) were the ones that most affected the emergence of sorghum seedlings. Maladão et al. (2013) reported that only 1/4 of the commercial dose of sulfentrazone was sufficient to significantly reduce the emergence of sorghum. According to Stougaard et al. (1990) and Brighenti et al. (2002), diclosulam (T-05) and sulfentrazone (T-06) present long residual effect and they may, depending on climatic and soil conditions, cause damage to crops planted in succession. Vencill (2002) also observed that trifluralin has physical and chemical characteristics that allow it to persist in soil for a certain period of time, as observed in this work. Machado et al. (2016) verified 46% and 50% toxicity and stand reduction in sorghum planted soon after application of trifluralin and clomazone, respectively.

Although there was seed germination in treatments where the herbicides were applied, many of these plants showed toxicity symptoms, which was higher when the planting was carried out closer to the herbicide application date (Figure 3). Each herbicide presented a different percentage of toxicity in sorghum that is native to its molecule; that is, the natural differential level of tolerance to a specific treatment. Thus, 35 DAE the first planting season, all herbicides - except trifluralin (T-04), scored toxicity levels above 70%. By considering the response surfaces altogether, it can be seen that in each planting season the degree of phytotoxicity increases throughout the evaluation period.

Trifluralin also presented a shorter period of influence on sorghum development, compared to the other herbicides(Figure 3). Most of the herbicides tend not to cause significant phytotoxicity to sorghum when it is planted after 70 DAA of the herbicides (40 DAA for trifluralin). However, Imazethapyr at the end of the evaluations still presented an average 8% of phytotoxicity on sorghum plants, suggesting that the safety interval is above the range evaluated and that more studies are needed for this herbicide.

ALS-inhibiting herbicides (trifloxysulfuron-sodium, diclosulam and imazethapyr) had similar behavior, with persistent symptoms and toxicity above 80% in the first planting season, with the greatest symptoms reported 14 DAE of each planting season (Figure 4). The main symptoms were intense chlorosis, striae, followed by necrosis, reduction of growth rate and even plant death. Similar symptoms were observed by Ulbrich et al. (2005), Dan et al. (2010) and Dan et al. (2011) when assessing the effects of imidazolinones on corn, sorghum and millet, respectively.

PROTOX-inhibiting (sulfentrazone) and carotenoid biosynthesis inhibiting (clomazone) herbicides, were highly harmful to sorghum; seedlings that were able to emerge already presented more than 40% phytotoxicity 7 DAE (Figure 4), in agreement with data reported by Machado et al. (2016). Maladão et al. (2013) also observed high impact of sulfentrazone in *Sorghum bicolor*.

Fresh and dry mass of the plants, leaves and stems that were able to emerge, were smaller in plantings closer to the application of the herbicides (Figures 5; 6), corroborating with the data of phytotoxicity (Figure 4). These variables are closely linked to the dissipation of herbicides from soil, which strongly affects soil persistence. Persistence corresponds to the time when a herbicide remains active in soil, which is of fundamental importance in weed management (Karam, 2005). However, more persistent herbicides, if they are not selective to the crop, can cause losses as reduced fresh and dry mass, leaf area and productivity.

It was observed (Figures 5; 6) that all herbicides caused damage to the sorghum. For the first planting season (same day of herbicides application), the dry mass measured 35 DAE, corresponded to approximately 2 - 5 g plant^{-1} in all treatments; for the planting performed 60 DAA, dry mass was superior to 15 g plant^{-1}, also 35 DAE.

Treatments with clomazone, trifloxysulfuron-sodium, trifluralin, diclosulam and sulfentrazone were statistically equal, so for better comprehension, they were grouped for the variables fresh and dry shoot mass, leaf and stem dry mass, and leaf area. There was reduction in all these variables, for imazethapyr at the 70 DAA planting compared to the control treatment; this corroborates the phytotoxicity data, although this herbicide did not differ statistically from the other treatments. This is also in agreement with results by Dan et al. (2012), who reported reductions in maize shoot growth when using 0.1 kg ha^{-1} imazethapyr, even when planting it 97 DAA.

For the same variables, no differences were observed between the control and the herbicide treatments at the 70 DAA planting. However, Dan et al. (2010) found negative effects of diclosulam on sorghum plants grown in succession to soybean in the Brazilian Cerrado (savanna-like biome) region.

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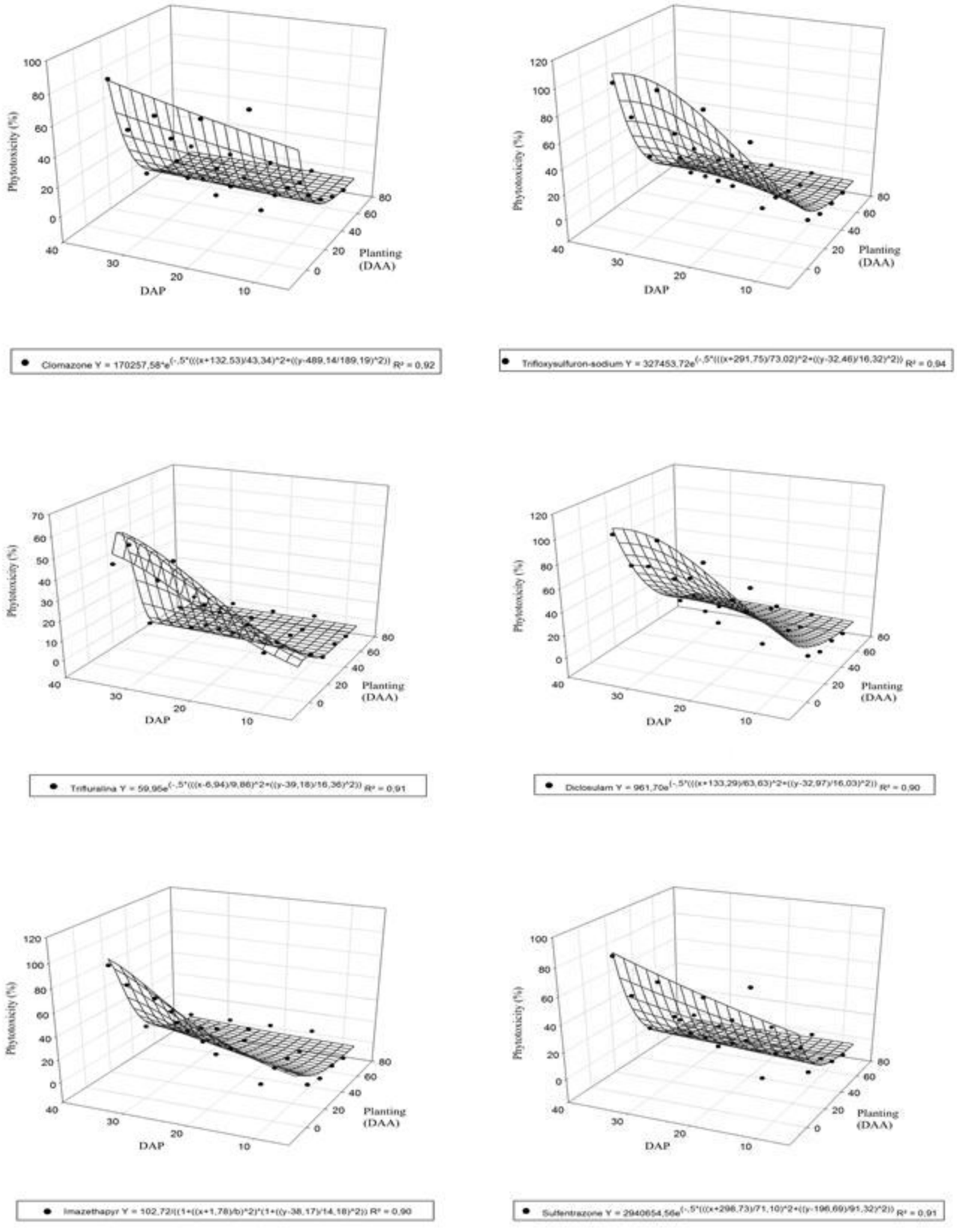

Fig.4: toxicity of sorghum plants (%), for herbicide treatments, as function of the sorghum planting season (days after herbicide application - DAA), and days after each planting (DAP).

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Therefore, innumerable factors are responsible for the residual activity of a given herbicide in soil. Among these, the physico-chemical and microbiological soil traits, besides the regional edaphoclimatic conditions, are highlighted (Oliveira Jr et al., 1999). As example, one could report to results presented by Artuzi and Contiero (2006), that did not observe negative effects on maize, planted succeeding soybeans where imazethapyr (0.1 kg ha^{-1}) was applied, in Eutrophic Red Latosol. On the other hand, Dan et al. (2011) reported negative effects on the yield of millet grown succeeding soybeans, where imazethapyr (0.1 kg ha^{-1}) and diclosulam (0.035 kg ha^{-1}) were applied to Dystroferric Red Latosol. According to Cole et al. (2017), another factor to be highlighted is the great variation of sensitivity herbicides intrinsic to the genetic variability among sorghumgenotypes.

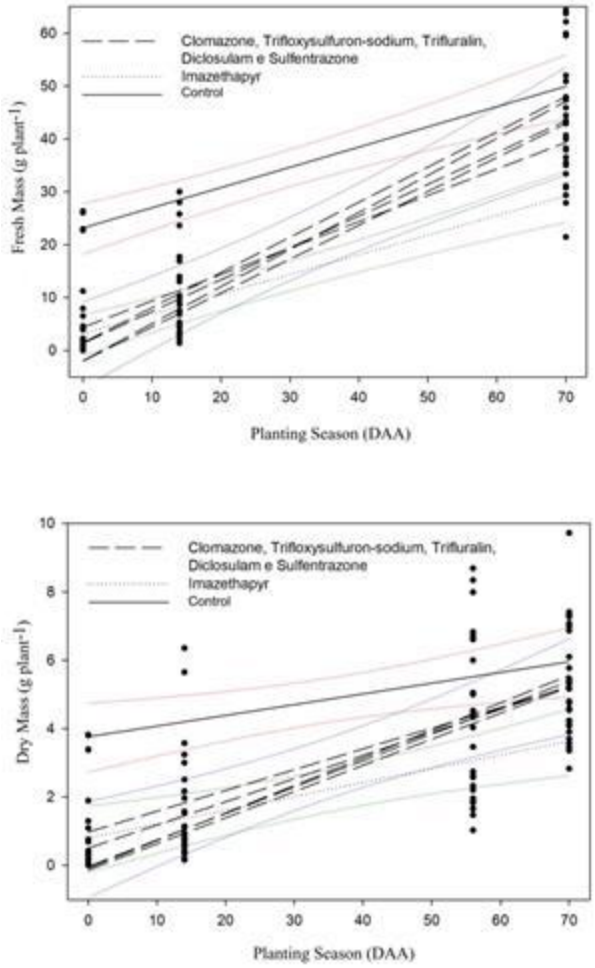

Fig.5: fresh and dry mass of saccharine sorghum plants, cv. BRS 506, as function of planting in days after application (DAA), under treatment with clomazone, trifloxysulfuron-sodium, trifluralin, diclosulam, imazethapyr or sulfentrazone.

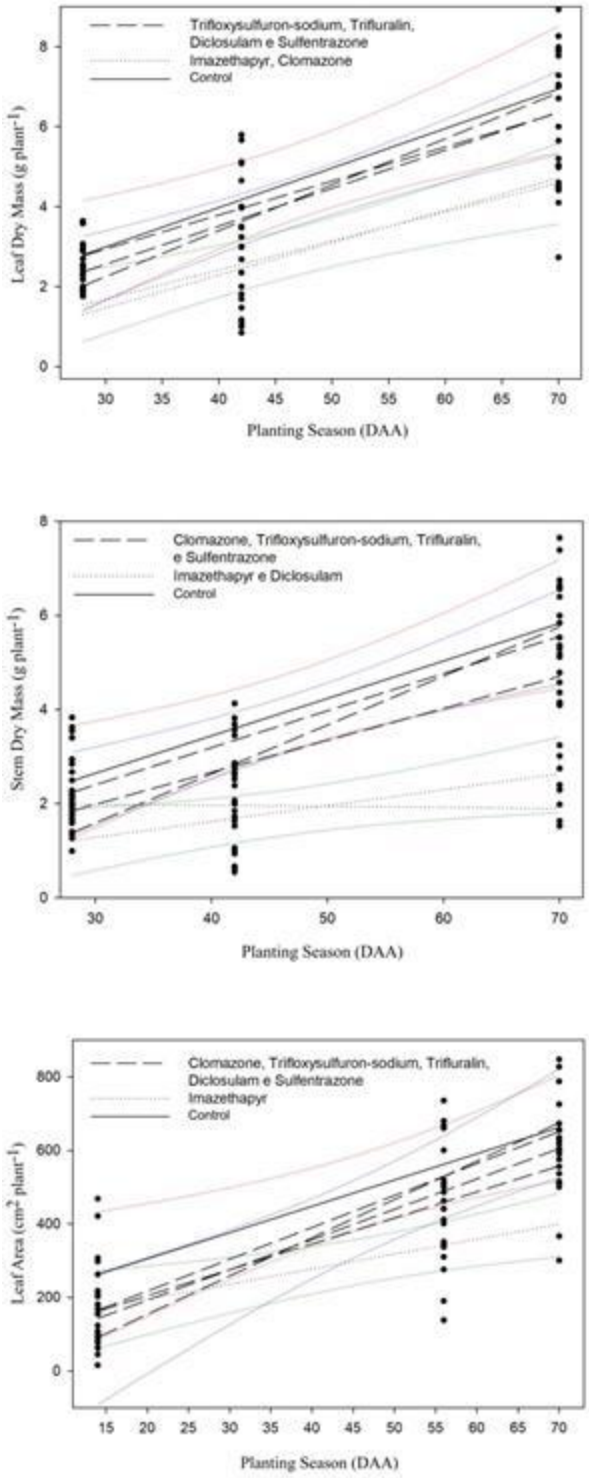

Fig.6: dry mass of leaves and stems, and leaf area, of saccharine sorghum plants, cv. BRS 506, as function of planting in days after application (DAA), under treatment with clomazone, trifloxysulfuron-sodium, trifluralin, diclosulam, imazethapyr or sulfentrazone.

The best planting time for sorghum, after application of residual herbicides, varies for each compound, being the toxicity as smaller as longer the time between the

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application of such herbicides and sorghum planting. Thus, sorghum can be considered an alternative in areas previously managed with clomazone (2.5 L ha^{-1}), trifloxysulfuron-sodium (30 g ha^{-1}), trifluralin (4.0 L ha^{-1}) and sulfentrazone (1.2 L ha^{-1}) since they are applied at the beginning of the cycle of the preceding crop, confering at least 70 days between its application and sorghum planting. On the other hand, attention should be given to areas applied with imazethapyr and diclosulam, where the carryover effect is potentially damaging even after 70 days after its application.

V. CONCLUSIONS

The best planting time for sorghum, after application of residual herbicides, varies for each compound, being the toxicity as smaller as longer the time between the application of such herbicides and sorghum planting. Thus, sorghum can be considered an alternative in areas previously managed with clomazone (2.5 L ha^{-1}), trifloxysulfuron-sodium (30 g ha^{-1}), trifluralin (4.0 L ha^{-1}) and sulfentrazone (1.2 L ha^{-1}) since they are applied at the beginning of the cycle of the preceding crop, confering at least 70 days between its application and sorghum planting. On the other hand, attention should be given to areas applied with imazethapyr and diclosulam, where the carryover effect is potentially damaging even after 70 days after its application.

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