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Response of soybean cultivars with different maturation times to pre-emergence herbicides

Resposta de cultivares de soja com diferentes grupos de maturação a herbicidas aplicados em pré-emergência

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Highlights

The phytotoxicity of herbicides was low not exceeding 11%.
In Lages, there was no effect of herbicides.
In Curitibanos there was an effect of herbicides mainly the application of diclosulam.

Abstract

Herbicide selectivity is the basis for chemical control of weeds; however, it depends on the interactions between herbicide, crop, and edaphoclimatic conditions. The objective of this work was to evaluate the selectivity of herbicides applied at the pre-emergence stage of soybean cultivars with different maturation times grown in different locations. The experiment was conducted under field conditions, in two crop seasons (2019/2020 and 2020/2021), in Lages and Curitibanos, state of Santa Catarina, Brazil. A randomized block experimental design was used, with treatments organized in 4×3 (2019/2020) and 4×4 (2020/2021) factorial arrangements, with four replications. The treatments consisted of interactions between four soybean cultivars: BMX Raio IPRO® (Raio), BMX Zeus IPRO® (Zeus), MONSOY 5947 IPRO® (Monsoy), and BMX Fibra IPRO® (Fibra) and three or four herbicide treatments: control with no herbicides, sulfentrazone + diuron, and diclosulam in 2019/2020; and control with no herbicide, sulfentrazone + diuron,

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diclosulam, and pyroxasulfone + flumioxazin in 2020/2021. The plots were evaluated for phytotoxicity of herbicides, canopy closure, plant height, stand of plants, number of pods per plant, one-thousand grain weight, and grain yield. The phytotoxicity of herbicides on the soybean plants was mild, under 11%, regardless of the cultivar and growth location. The soybean plants fully recovered from the injuries at 14 days after herbicide application. In Curitibanos, the cultivar Zeus presented higher grain yield in both crop seasons. The herbicide factor showed that sulfentrazone + diuron and diclosulam decreased the grain yield of the cultivars Raio and Zeus in 2019/2020. In the following crop season, only the cultivar Raio presented decreases in grain yield due to the application of diclosulam and pyroxasulfone + flumioxazin. In Lages, the soybean cultivar factor affected the grain yield; the cultivars Monsoy and Fibra were the most productive.
Key words: Phytotoxicity. Glycine max. Yield. Selectivity.

Resumo

A seletividade de herbicidas é a base para o controle químico de plantas daninhas, entretanto, esta depende da interação entre o herbicida, a cultura e as condições edafoclimáticas. O objetivo desta pesquisa foi avaliar a seletividade de herbicidas aplicados em pré-emergência de cultivares de soja de ciclos contrastantes, em diferentes regiões de Santa Catarina. O experimento foi conduzido em condições de campo, em duas safras (2019/2020 e 2020/2021), nos municípios de Lages e Curitibanos, Santa Cataria, Brasil. O delineamento experimental utilizado foi de blocos ao acaso com tratamentos organizados em esquema fatorial 4 x 3 (2019/2020) e 4 x 4 (2020/2021), com quatro repetições. Os tratamentos resultaram da interação de quatro cultivares de soja: BMX Raio IPRO® (Raio), BMX Zeus IPRO® (Zeus), MONSOY 5947 IPRO® (Monsoy) e BMX Fibra IPRO® (Fibra), com três tratamentos: testemunha sem herbicida, sulfentrazone + diuron e diclosulam em 2019/2020; e testemunha sem herbicida, sulfentrazone + diuron, diclosulam e pyroxasulfone + flumioxazin em 2020/21. As avaliações realizadas foram fitointoxicação, fechamento de entrelinhas, altura de plantas, estande, número de vagens por planta, peso de mil grãos e produtividade de grãos. A fitointoxicação das plantas de soja foi leve, não ultrapassando os 11% independente da cultivar e do município. A soja se recuperou totalmente das injúrias aos 14 dias após a aplicação (DAA). Em Curitibanos, a cultivar Zeus apresentou maior produtividade de grãos nas duas safras. Para o fator herbicida observou-se que a mistura sulfentrazone + diuron e diclosulam reduziram a produtividade das cultivares Raio e Zeus em 2019/2020. Na safra seguinte, apenas a cultivar Raio teve a produtividade reduzida com a aplicação de diclosulam e pyroxasulfone + flumioxazin. Em Lages houve diferença na produtividade de grãos apenas para o fator cultivares de soja, onde as cultivares Monsoy e Fibra foram as mais produtivas.
Palavras-chave: Fitointoxicação. Glycine max. Produtividade. Seletividade.

Introduction

Soybean (*Glycine max* L.) has a high socioeconomic value in the Brazilian and international markets (Souza et al., 2019). It is the most grown grain species in agricultural areas in Brazil, with more than 40.8 million hectares and a production of more than 122.4 million Mg of grains in the 2021/2022 crop season (Companhia Nacional de Abastecimento [CONAB], 2022). Agriculture has been growing in the last years, which is a result of technological investments that have made it possible to obtain high yields. However, there are factors that negatively affect these yields; one of the current concerns in agriculture is the losses caused by the effect of weeds on crops (Vasconcelos et al., 2012).

Weeds compete with crops for essential resources for their growth, such as water, light, nutrients, and pollinators, limiting the production potential of crops and leading to a broad use of chemical control to prevent their interference (Salomão et al., 2020). According to Silva et al. (2008), the competition between soybean plants and weeds for environmental resources is often reported as direct cause of weed interference, mainly when they are not adequately controlled, decreasing grain yields in up to 82%.

The effect of chemical control using herbicides can be harmful to soybean plants under certain conditions, causing injuries and, consequently, decreasing grain yield (Alonso et al., 2010). According to Belfry et al. (2015), the extension and intensity of phytotoxicity of herbicides vary depending on edaphoclimatic conditions, such as rainfall, soil carbon content, texture, pH, level of susceptibility of soybean cultivars to herbicides, and herbicide application time.

The application of pre-emergence herbicides became a very used tool to reduce the effect of weeds and manage weed species of difficult control or with history of resistance (Constantin et al., 2007). Some pre-emergence herbicides, such as sulfentrazone and diclosulam, are described as selective for soybean crops; however, sulfentrazone can affect the growth and yield of some cultivars (Belfry et al., 2016), and diclosulam, which is selective when applied to clayey soils (Gazola et al., 2016), can reduce grain yield when applied in soils that have a compacted surface.

Early-maturation soybean cultivars are more susceptible to herbicides than medium- or long-cycle cultivars (Fornazza et al., 2019). Commonly, shorter-cycle cultivars are more affected by stresses, as they present less time for recovery (Lamego et al., 2004; Nordby et al., 2007). According to Zobiole et al. (2010), herbicide applications to very early-maturation soybean cultivars has caused concerns regarding selectivity, raising the hypothesis that very early-maturation soybean cultivars are more susceptible to herbicides (Raimondi et al., 2017).

Thus, the objective of this work was to evaluate the selectivity of herbicides applied at the pre-emergence stage of soybean cultivars, with different maturation times, grown in Lages and Curitibanos, state of Santa Catarina, Brazil.

Materials and Methods

Site description

The experiment was conducted under field conditions, in two consecutive crop seasons, from November 2019 to April 2021, arranged in two experimental areas: Lages (27°47′34″S, 50°18′05″W, and altitude of 904 m) and Curitibanos (27°16′44″S, 50°34′57″W, and altitude of 987 m), in the state of Santa Catarina, Brazil. The soil of the experimental area in Lages was classified as a Typic Dystrudept (Santos et al., 2018) and the chemical analysis of the 0-0.2 m soil layer showed a pH in water of 5.9; 600 g kg^{-1} of clay; 29 g kg^{-1} of organic matter (OM); 10.2 mg dm^{-3} of phosphorus (P); 97 mg dm^{-3} of potassium (K); 0.4 cmolc dm^{-3} of aluminum (Al); 9.99 cmolc dm^{-3} of cation exchange capacity (CEC), and 58.1% base saturation (BS). The soil in Curitibanos was classified as a Typic Dystrudept (Santos et al., 2018), and the chemical analysis of the 0-0.2 m soil layer showed a pH in water of 6.0; 525 g kg^{-1} of clay; 52.5 g kg^{-1} of OM; 17.3 mg dm^{-3} of P; 78 mg dm^{-3} of K; 0.0 cmolc dm^{-3} of Al; 21.32 cmolc dm^{-3} of CEC, and 76.74% BS. Rainfall depths (mm) and mean temperatures (°C) were monitored during the conduction of the experiments in both crop seasons and the results are shown Figures 1 and 2 (Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina [EPAGRI], 2021).

Experimental design and treatments

A randomized block experimental design was used, with treatments organized in 4×3 (2019/2020) and 4×4 (2020/2021) factorial arrangements, with four replications. The treatments consisted of interactions between four soybean cultivars: BMX Raio IPRO® (Raio; maturation group 5.0), BMX Zeus IPRO® (Zeus; maturation group 5.5), MONSOY 5947 IPRO® (Monsoy; maturation group 5.9), and BMX Fibra IPRO® (Fibra; maturation group 6.3) and three or four herbicide treatments. The herbicide treatments were: control with no herbicide, sulfentrazone + diuron, and diclosulam in the 2019/2020 crop season; and control with no herbicide, sulfentrazone + diuron, diclosulam, and pyroxasulfone + flumioxazin in the 2020/2021 crop season. The mixture sulfentrazone + diuron was applied at the rates of 245 + 490 g a.i. ha^{-1} (Stone SC at 1.4 L c.p. ha^{-1}); diclosulam was applied at the rate of 33.6 g a.i. ha-1 (Spider 840 WG at 40 g c.p. ha^{-1}); and pyroxasulfone + flumioxazin was applied at the rates of 120 + 80 g a.i. ha^{-1} (Kyojin SC at 0.4 L c.p. ha^{-1}). The plots consisted of five 5-meter sowing rows, totaling an area of 10 m^2.

The herbicide applications were carried out using a CO_2-pressurized backpack sprayer equipped with four AD110.02 tips, under a constant pressure of 208 kPa, monitored with a pressure gauge on the spray boom, and running at speed of 1.0 m s^{-1} to apply a rate equivalent to 200 L ha^{-1}. The weather conditions at the time of application of the treatments were monitored using a digital thermo-hygro-anemometer; the applications were carried out under the following conditions: air temperature below 30 °C, relative air humidity above 55%, wind speed of 3 to 5 km h^{-1}, and wet soil.

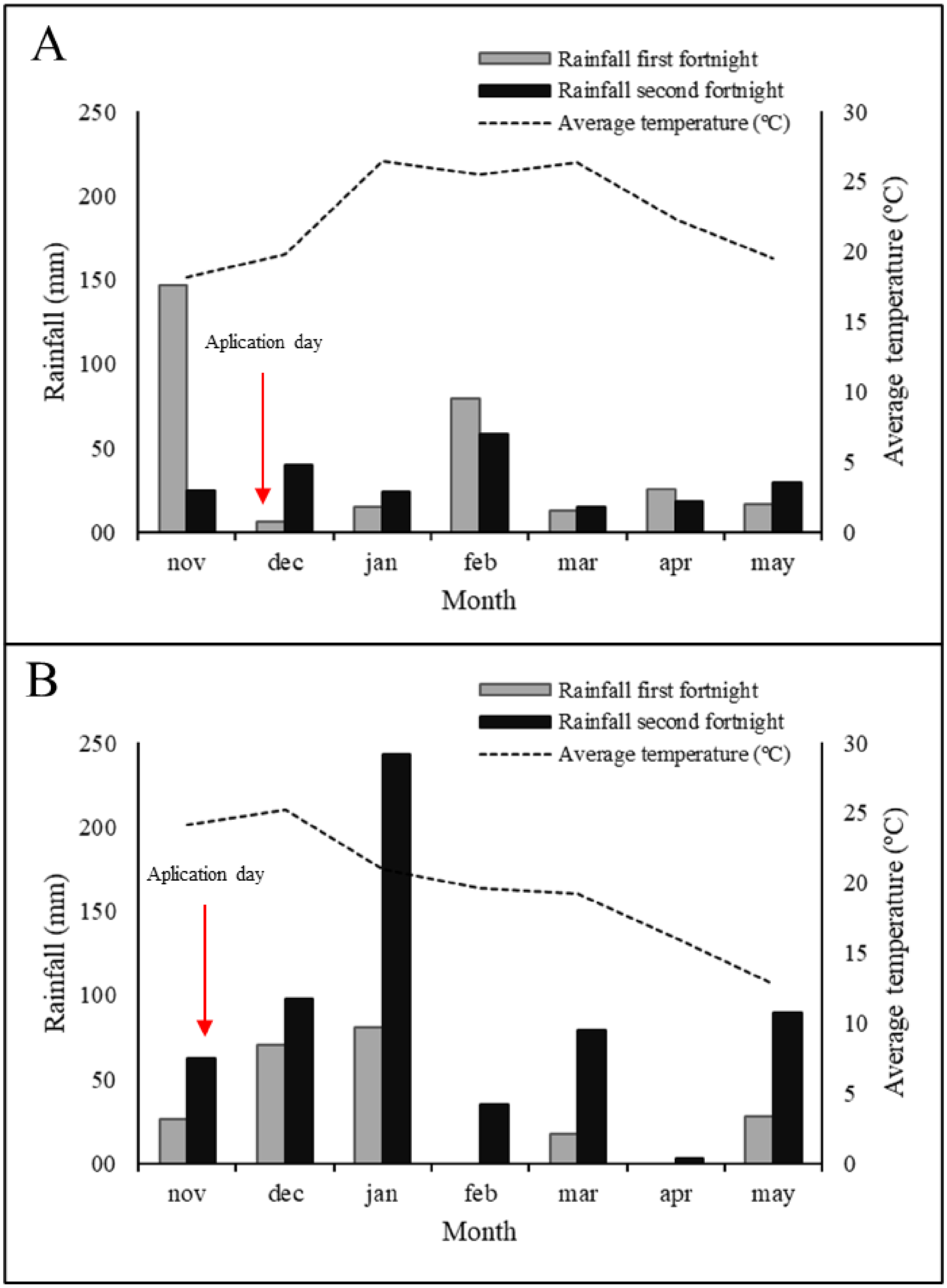

Figure 1. Rainfall depths and average temperatures in Lages, SC, Brazil, during the 2019/2020 (A) and 2020/2021 (B) soybean crop seasons.

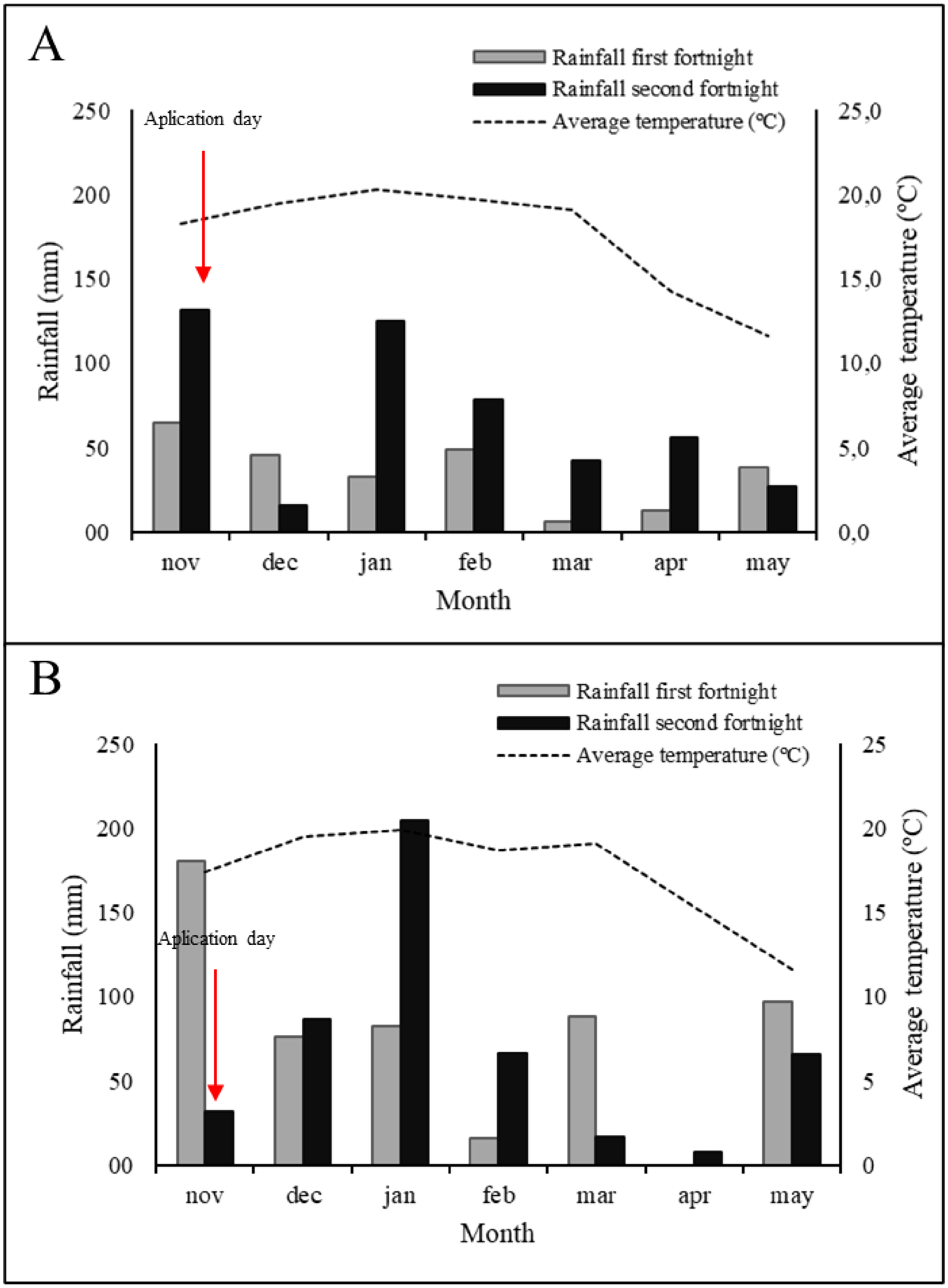

Figure 2. Rainfall depths and temperatures in Curitibanos, SC, Brazil, during the 2019/2020 (A) and 2020/2021 (B) soybean crop seasons.

Soybean sowing and management

Soybean seeds were sown between the second fortnight of November and the first fortnight of December (according to the weather conditions), with spacing of 0.40 m and sowing density of 14 seeds per linear meter. Soil fertilizers were applied following technical recommendations for soybean crops in the state of Santa Catarina (Sociedade Brasileira de Ciência do Solo [SBCS], 2016). The crops were grown under no-tillage system, with burndown management at 15 days before sowing. In the experiment of Curitibanos, oat was the previous cover crop and produced 6 t ha^{-1} of straw in both crop seasons and in Lages the cover crop that was growing previously was the ryegrass, that accumulated of 2 to 4 t ha^{-1} of straw. The effect of weeds was prevented through the application of the herbicide glyphosate (720 g a.i. ha^{-1}). Pest and disease managements were carried out with chemical control, using pesticides recommended for soybean crops and approved by the Brazilian Ministry of Agriculture, Livestock, and Food Supply.

Data Collection

The phytotoxicity of the herbicides was evaluated using a visual scale of grades that varies from 0 to 100%, in which 0 represents absence of symptoms and 100 represents the death of the plant (Kuva et al., 2016). The evaluations were carried out at 7, 14, and 28 days after application of the treatments (DAA). The canopy closure was evaluated at 52 DAA, using a visual scale from 0% to 100%, in which 0% represents no canopy closure and 100% represents total canopy closure.

Stand of plants and number of pods per plant were evaluated at the soybean pre-harvest: the stand of plants was represented by the mean number of plants per meter in four meters of three plant rows; and the number of pods per plant was represented by the mean of 10 plants per plot.

Plants in an area of 4.8 m^2 were harvested at the end of the crop cycle to determine grain yield and one-thousand grain weight. One-thousand grain weight was determined by counting one thousand grains with the aid of a seed counter, considering their initial weight and the weight of grains dried in an oven at temperature of 65 °C for 7 days; the grain moisture was corrected to 13%.

Data analysis

The experiments were similar in each crop season, and the difference between them was the growth location; thus, a joint data analysis was carried out. Similar physical factors, such as crop management, growing season, and agricultural year, were considered, as well as the order of magnitude of residual mean squares of individual analyses (Banzatto & Kronka, 2008).

The interaction between treatments and growth locations was significant for all variables in both crop seasons; thus, the analysis was carried out separately for each experiment. All means were compared by the Tukey's test ($p<0.05$).

Results and Discussion

In the 2019/2020 crop season, the application of diclosulam presented phytotoxicity at 7 DAA for the four soybean cultivars evaluated, regardless of the growth location; the intensity of symptoms was low, not exceeding 10.3% (Table 1). In Curitibanos, the cultivar Zeus presented phytotoxicity symptoms for sulfentrazone + diuron (Table 1). The plants fully recovered from 14 DAA onwards (data not shown). In the 2020/2021 crop season, the treatments with diclosulam, sulfentrazone + diuron, and pyroxasulfone + flumioxazin caused phytotoxicity to all cultivars in Curitibanos at 7 DAA. In Lages, the phytotoxicity symptoms were mild (≤4.0%) and found only for diclosulam and pyroxasulfone + flumioxazin, regardless of the cultivar. In the subsequent evaluations, phytotoxicity symptoms were not visually perceptible (data not shown).

According to Fornazza et al. (2019) reported phytotoxicity symptoms ranging from 5.1% to 7.0% at 15 DAA for diclosulam (25.2 g a.i. ha^{-1}) applied at pre-emergence, regardless of variations in soil and rainfall; and soybean cultivars treated with sulfentrazone (300 g a.i. ha^{-1}) presented phytotoxicity symptoms from 3.4% to 29.0%. The injuries were lower than related by Dalazen et al. (2020), that finding injury in soybean reaching 45% with diclosulam (75.6 g ha^{-1}), the researchers related that injury reduced twhen happen a rain precipitation was lower and less frequent, the rainfall contributed with incorporation and leaching of herbicide and reduced the diclosulam phytoxicity.

The intensity of phytotoxicity caused by sulfentrazone is highly correlated with the percentages of carbon and clay in the soil; more clayey soils present lower phytotoxicity (Szmigielski et al., 2009). The soils in Curitibanos and Lages presented high clay content (525 and 600 g kg^{-1}, respectively) and organic matter content (52.5 and 29.0 g kg^{-1}, respectively), which may have contributed to the low phytotoxicity of the treatments. Taylor-Lovell et al. (2001) reported injuries ranging from 4% to 61% after application of sulfentrazone (112, 224, and 446 g a.i. ha^{-1}) to 15 soybean cultivars; the highest injuries were found, in general, for the rate of 446 g a.i. ha^{-1}; however, the wet soil and low temperature conditions after the herbicide application were different those found in the present study, the rainfall distribution was regular during the soybean growing in both season in Lages and Curitibanos, however the total rainfall was superior in Curitibanos. Despite the low phytotoxicity found in Curitibanos, the applications of diclosulam in both crop seasons, sulfentrazone + diuron in the 2019/2020 crop season, and pyroxasulfone + flumioxazin in the 2020/2021 crop season affected the grain yield of the cultivar Raio, which had the earliest maturation. These results are consistent with those reported by Mahoney et al. (2014), who found injuries in long-cycle soybean cultivars, caused by sulfentrazone, until 151 days after emergence (physiological maturity), but with no decreases in grain yield.

Table 1
Phytotoxicity of herbicides and canopy closure in the 2019/2020 and 2020/2021 crop seasons, in Curitibanos and Lages, SC, Brazil

Phytotoxicity at 7 days after application (%)								
2019/2020								
Herbicide	Curitibanos				Lages			
	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	0.0 Ab	0.0 Ac	0.0 Ab	0.0 Ab	0.0	0.0	0.0	0.0
Dicl	5.5 Aa	6.0 Ab	6.0 Aa	5.5 Aa	10.3	5.0	4.5	5.0
Sulf + Diur	0.0 Bb	7.7 Aa	0.0 Bb	0.0 Bb	0.0	0.0	0.0	0.0
VC (%)	27.1				-			
2020/2021								
Herbicide	Curitibanos				Lages			
	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	0.0 Ab	0.0 Ab	0.0 Ab	0.0 Ab	0.0	0.0	0.0	0.0
Dicl	3.3 Ab	3.5 Aa	3.0 Aa	5.0 Aab	1.3	0.0	2.0	1.5
Sulf + Diur	6.5 Aa	3.5 Ba	4.5 ABa	3.5 Bb	0.0	0.0	0.0	0.0
Pyro + Flum	6.5 Aa	3.5 Ba	4.0 Ba	7.3 Aa	4.0	2.3	3.0	3.8
VC (%)	36.7				-			
Canopy closure at 52 days after application (%)								
2019/2020								
Herbicide	Curitibanos				Lages			
	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	100	100	100	100	68 Bab	80 Ba	98 Aa	93 Aa
Dicl	100	100	100	100	62 Cb	78 Ba	95 Aa	96 Aa
Sulf + Diur	100	100	100	100	73 Ba	85 Ba	100 Aa	98 Aa
VC (%)	-				7.3			
2020/2021								
Herbicide	Curitibanos				Lages			
	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	86 Aa	70 Bab	80 Aa	80 Aa	91 Aa	57 Ba	80 Ba	100 Aa
Dicl	70 ABb	63 Bb	76 Aa	75 Aa	75 ABa	53 Ba	91 Aa	100 Aa
Sulf + Diur	75 Ab	74 Aa	78 Aa	76 Aa	75 ABa	70 Ba	96 ABa	100 Aa
Pyro + Flum	71 Ab	74 Aa	76 Aa	79 Aa	72 ABa	60 Ba	100 Aa	98 Aa
VC (%)	6.9				18.9			

Means followed by the same lowercase letter in the columns, or uppercase letter in the rows, are not different from each other by the Tukey's test ($p>0.05$). Control = without treatment with herbicide; Dicl = diclosulam at 33.6 g a.i. ha^{-1}; Sulf + Diur = sulfentrazone + diuron at 245 + 490 g a.i. ha^{-1}; and Pyro + Flum = pyroxasulfone + flumioxazin at 120 + 80 g a.i. ha^{-1}. Raio = BMX Raio IPRO®, Zeus = BMX Zeus IPRO®, Monsoy = MONSOY 5947 IPRO®, and Fibra = BMX Fibra IPRO®.

The canopy closure was total for all evaluated cultivars in Curitibanos in the 2019/2020 crop season, regardless of the treatment applied. In the 2020/2021 crop season, the canopy closure was affected by the herbicides only for earlier-maturation cultivars; all herbicides reduced the canopy closure in the cultivar Raio and only diclosulam affected the cultivar Zeus. In Lages, in the 2019/2020 crop season, only the herbicide diclosulam affected the canopy closure of the cultivar Raio (Table 1). In the 2020/2021 crop season, the herbicides did not reduce the canopy closure of the soybean cultivars. In Lages, late-maturation cultivars (Monsoy and Fibra) presented better canopy closured, regardless of the crop season (Table 1).

The stand of plants at the pre-harvest of the 2019/2020 crop season presented differences between treatments only for the experiment in Lages and for the cultivar Fibra (Table 2); the applications of diclosulam and sulfentrazone + diuron decreased the stand of plants. In the 2020/2021 crop season, the application of herbicides decreased the stand of plants only for the cultivar Raio: for the mixture of pyroxasulfone + flumioxazin, in Curitibanos; and for the herbicide diclosulam, in Lages (Table 2). In the 2020/2021 crop season, the stand of plants of the cultivar Zeus was below that expected in both experiments, due to physiological seed quality problems. The application of herbicides was harmful to soybean growth only in the 2019/2020 crop season in Curitibanos: the herbicide diclosulam decreased the plant height of the cultivar Zeus, and the mixture sulfentrazone + diuron decreased the plant height of the cultivar Raio (Table 2). The longer-cycle cultivars (Monsoy and Fibra) presented higher heights, regardless of the crop season and growth location, and their heights were not affected by the herbicides (Table 2).

The application of the pre-emergence herbicides did not affect the number of pods per plant in the 2019/2020 crop season in any of the cultivars. The longer-cycle cultivars (Monsoy and Fibra) presented, in general, a higher number of pods per plant (Table 3). In Lages, there was no difference between cultivars and herbicides. In the 2020/2021 crop season, in both growth locations, the cultivars presented no differences in number of pods per plant, which was not affected by the application of the pre-emergence herbicides (Table 3).

Table 2
Stand of plants and plant height at pre-harvest in the 2019/2020 and 2020/2021 crop seasons, in Curitibanos and Lages, SC, Brazil

Stand of plants at pre-harvest (plants m^{-1})								
2019/2020								
Herbicide	Curitibanos				Lages			
	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	9.7 Ba	9.6 Ba	10.4 Aa	11.5 Aa	9.0 Ba	9.7 Ba	11.6 ABa	13.6 Aa
Dicl	10.5 Aa	8.6 Ba	11.2 Aa	11.1 Aa	8.0 Ba	8.7 ABa	11.5 Aa	10.5 ABb
Sulf + Diur	10.5 Aa	9.6 Aa	11.1 Aa	10.8 Aa	8.9 BCa	7.9 Ca	11.5 ABa	11.8 Aab
VC (%)	9.0				14.6			
2020/2021								
Herbicide	Curitibanos				Lages			
	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	10.5 Aa	8.0 Ba	9.9 Aa	10.8 Aa	10.5 Aa	5.4 Ca	7.2 BCa	9.1 Aba
Dicl	10.6 Aa	7.5 Ba	10.8 Aa	10.0 Aa	7.4 ABb	5.3 Ba	9.2 Aa	8.4 Aa
Sulf + Diur	9.5 Aab	7.6 Ba	10.3 Aa	10.5 Aa	9.0 Aab	5.1 Ba	8.0 Aa	8.6 Aa
Pyro + Flum	8.5 BCb	7.3 Ca	9.3 ABa	11.0 Aa	8.2 Aab	5.0 Ba	8.1 Aa	8.4 Aa
VC (%)	10.1				17.8			
Plant height at pre-harvest (cm)								
2019/2020								
Herbicide	Curitibanos				Lages			
	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	71 Ba	78 Ba	107 Aa	106 Aa	69 Ba	75 Ba	101 Aa	102 Aa
Dicl	70 Ba	73 Ba	99 Ab	98 Aa	71 Ba	71 Ba	93 Aa	97 Aa
Sulf + Diur	62 Cb	75 Ba	100 Aab	100 Aa	65 Ba	71 Ba	97 Aa	102 Aa
VC (%)	5.3				6.0			
2020/2021								
Herbicide	Curitibanos				Lages			
	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	79 Ba	82 Bab	119 Aa	114 Aa	80 BCa	77 Ca	94 ABa	105 Aa
Dicl	73 Ca	76 Cb	119 Aa	108 Ba	76 Ca	80 BCa	96 ABa	99 Aa
Sulf + Diur	80 Ca	85 Ca	122 Aa	109 Ba	75 Ba	82 Ba	101 Aa	107 Aa
Pyro + Flum	77 Ba	80 Bab	120 Aa	109 Ba	73 Ba	75 Ba	108 Aa	98 Aa
VC (%)	4.3				10.0			

Means followed by the same lowercase letter in the columns, or uppercase letter in the rows, are not different from each other by the Tukey's test ($p>0.05$). Control = without treatment with herbicide; Dicl = diclosulam at 33.6 g a.i. ha^{-1}; Sulf + Diur = sulfentrazone + diuron at 245 + 490 g a.i. ha^{-1}; and Pyro + Flum = pyroxasulfone + flumioxazin at 120 + 80 g a.i. ha^{-1}. Raio = BMX Raio IPRO®, Zeus = BMX Zeus IPRO®, Monsoy = MONSOY 5947 IPRO®, and Fibra = BMX Fibra IPRO®.

Table 3
Number of pods per plant, one-thousand grain weight, and grain yield of soybean cultivars grown in the 2019/2020 and 2020/2021 crop seasons, in Curitibanos and Lages, SC, Brazil

Number of pods per plant								
2019/2020								
Herbicide	Curitibanos				Lages			
	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	66 Ba	67 Ba	81 Ba	103 Aa	31 Aa	31 Aa	40 Aa	47 Aa
Dicl	69 ABa	60 Ba	87 Aa	84 Aab	41 Aa	37 Aa	36 Aa	45 Aa
Sulf + Diur	64 Ba	66 Ba	99 Aa	78 ABb	39 Aa	38 Aa	39 Aa	51 Aa
VC (%)	14.9				20.6			
2020/2021								
Herbicide	Curitibanos				Lages			
	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	67 Aa	67 Aa	71 Aa	68 Aa	39 Bb	56 ABb	50 Aba	59 Aa
Dicl	53 Aa	66 Aa	64 Aa	67 Aa	49 Aab	63 Ab	50 Aa	57 Aa
Sulf + Diur	58 Ba	63 ABa	59 Ba	76 Aa	46 Bab	81 Aa	58 Ba	63 Aa
Pyro + Flum	63 Aa	67 Aa	68 Aa	78 Aa	58 ABa	68 Aab	48 Ba	56 ABa
VC (%)	12.9				16.8			
One-thousand grain weight (g)								
2019/2020								
Herbicide	Curitibanos				Lages			
	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	211 Ba	242 Aa	169 Ca	165 Ca	181 Aa	187 Aa	148 Ba	154 Ba
Dicl	198 Bb	232 Aab	165 Ca	160 Ca	178 Aa	195 Aa	152 Ba	148 Ba
Sulf + Diur	200 Bab	226 Ab	167 Ca	171 Ca	187 Aa	190 Aa	148 Ba	154 Ba
VC (%)	3.7				5.4			
2020/2021								
Herbicide	Curitibanos				Lages			
	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	198 Ba	250 Aa	200 Ba	176 Cab	207 Aa	184 Aba	143 Ba	143 Ba
Dicl	156 Cb	263 Aa	186 Ba	178 Ba	164 ABa	201 Aa	163 ABa	148 Ba
Sulf + Diur	208 Ba	259 Aa	201 Ba	166 Cab	157 Aa	161 Aa	158 Aa	142 Aa
Pyro + Flum	162 Cb	257 Aa	194 Ba	158 Cb	160 Aa	189 Aa	165 Aa	160 Aa
VC (%)	5.1				16.8			

continue...

continuation...

Herbicide	Grain yield (kg ha^{-1})							
	2019/2020							
	Curitibanos				Lages			
	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	4678 Ba	5619 Aa	4598 Ba	5053 ABa	3272 Aa	3451 Aa	4273 Aa	4532 Aa
Dicl	4243 Aab	4755 Ab	4770 Aa	4424 Aa	3268 Aa	3601 Aa	3890 Aa	3666 Aa
Sulf + Diur	3831 Ab	4278 Ab	4431 Aa	4384 Aa	3992 Aa	3377 Aa	4099 Aa	3960 Aa
VC (%)	9.7				18.2			
	2020/2021							
	Curitibanos				Lages			
Herbicide	Raio	Zeus	Monsoy	Fibra	Raio	Zeus	Monsoy	Fibra
Control	5206 Ba	6403 Aa	5325 Ba	5271 Ba	3396 ABa	2786 Ba	3946 Aa	4068 Aa
Dicl	3456 Bb	6187 Aa	5639 Aa	5215 Aa	2973 Ba	2348 Ba	4549 Aa	4351 Aa
Sulf + Diur	4992 Ba	6093 Aa	5334 ABa	4971 Ba	2664 Ba	2473 Ba	4466 Aa	4267 Aa
Pyro + Flum	3707 Cb	6054 Aa	5285 ABa	4515 BCa	2816 Ba	2328 Ba	4515 Aa	4430 Aa
VC (%)	9.9				12.1			

Means followed by the same lowercase letter in the columns, or uppercase letter in the rows, are not different from each other by the Tukey's test ($p>0.05$). Control = without treatment with herbicide; Dicl = diclosulam at 33.6 g a.i. ha^{-1}; Sulf + Diur = sulfentrazone + diuron at 245 + 490 g a.i. ha^{-1}; and Pyro + Flum = pyroxasulfone + flumioxazin at 120 + 80 g a.i. ha^{-1}. Raio = BMX Raio IPRO®, Zeus = BMX Zeus IPRO®, Monsoy = MONSOY 5947 IPRO®, and Fibra = BMX Fibra IPRO®.

The interaction between the factors was significant for one-thousand grain weight in Curitibanos; the cultivar Zeus presented the highest one-thousand grain weight in the 2019/2020 crop season, and the one-thousand grain weight of the cultivars Zeus and Raio was affected by the herbicides diclosulam and sulfentrazone + diuron. In the 2020/2021 crop season, the cultivar Zeus also presented the highest one-thousand grain weight, whereas the cultivar Raio presented a decrease due to the application of diclosulam and pyroxasulfone + flumioxazin, and the cultivar Fibra presented a decrease due to the application of sulfentrazone + diuron and pyroxasulfone + flumioxazin (Table 3). Regarding the experiment in Lages, in 2019/2020, the early-maturation cultivars Raio and Zeus presented the highest one-thousand grain weight; in the following crop season (2020/2021), the cultivars presented, in general, no significant differences and no significant effect of the factor herbicide; and the cultivar Fibra presented the lowest one-thousand grain weight.

In Curitibanos, the cultivar Zeus presented the highest grain yield in both crop seasons (Table 3). However, the application of herbicides decreased the grain yield of the cultivars Raio and Zeus in the 2019/2020 crop season. In the following crop season (2020/2021), only the grain yield of the cultivar Raio decreased due to the application of diclosulam and pyroxasulfone

+ flumioxazin in Curitibanos (Table 3). In Lages, in both crop seasons, the herbicide treatments did not affect grain yield. In the 2019/2020 crop season, the cultivars presented no differences to each other. In the following crop season, late-maturation cultivars (Monsoy and Fibra) presented the highest grain yields (Table 3). The grain yields of all cultivars were higher in Curitibanos, regardless of the herbicide applications (Table 3). In Curitibanos, the initial hypothesis that herbicides affect grain yield of early-maturation cultivars was confirmed, which was more evident for the application of diclosulam in both crop seasons. In Lages, there was no effect of herbicides, but longer-cycle cultivars were more productive.

The yield potential of soybean cultivars as a function of crop locations (different production environments) showed that Curitibanos is the most favorable (Figure 2) to achieve high grain yields, showing practically a constant temperature. In general, in Curitibanos presented both lower temperature and higher rainfall volume than Lages, in both growing seasons, whereas Lages (Figure 1) presented a more restrictive environment for the crop, with decreases in grain yield in the summer crop season. Therefore, the differences in grain yield as a function of application of pre-emergence herbicides were not evident, probably because the effect of stress caused by the environment, like lower temperature and higher rainfall volume in Curitibanos, was greater than the effect of the herbicides. In Curitibanos, the herbicide diclosulam had significant effect because it presents a long residual period in the soil. Segundo R. S. Oliveira et al. (2002) found a residual control of 42 days for Pennisetum typhoideum with application of diclosulam at the rates of 30, 35, and 40 g a.i. ha^{-1}. Also, according to Dalazen et al. (2020), crop injury reduction can be related with increase herbicide degradation and percolation in the soil profile, due to higher rainfall volume. Microbiological activity related with herbicide degradation is potentialized in higher hydric availability (Reddy & Locke, 1998). Moreover, sulfentrazone showed higher soil percolation with rain increase, reaching 40 cm deep in sandy soils (Monquero et al., 2010).

According to Fornazza et al., (2019), the combined application of diclosulam at pre-emergence and bentazon (720 g a.i. ha-1) or glyphosate (900 g a.i. ha-1) at post-emergence resulted in lower soybean grain yield, with losses from 10% to 8%. In addition, Gazola et al. (2021) found that diclosulam and sulfentrazone should be applied at least 14 days before sowing to avoid damages to soybean plants. The variations in the results, under field conditions, found in the present study were due to correlations between the dynamics of pre-emergence herbicide application, local edaphoclimatic conditions, and genotypes used (Lima et al., 2011). A. M. Oliveira et al. (2017) reported that diclosulam-based treatments (33.6 g a.i. ha^{-1}) maintained high levels of control of fleabane (Conyza spp.) for 75 days between crop seasons, which reinforces the high persistence of this herbicide.

In Lages, the latest-maturation cultivars presented the highest grain yields. Almeida et al. (2013) reported that the soybean vegetative period is essential for plant formation and definition of the crop production potential, as the formation of leaves and the whole apparatus required for production of photoassimilates occurs at this stage. They also reported that the number of days for flowering is determinant for establishing the cycle of a cultivar, as early-maturation cultivars present shorter vegetative stages than late-cycle ones, which explains the different yields of the cultivars in Lages. Walsh et al. (2015) evaluated the effect of sulfentrazone on soybean crops and found no injuries or losses in grain yield caused by herbicide application after sowing in different locations in Canada.

Barros et al. (2005) conducted an experiment in Jataí, GO, Brazil, evaluating different soybean genotypes in a sandy soil subjected to application of diclosulam and sulfentrazone at pre-emergence; they found that sulfentrazone caused significant decreases in plant height for the evaluated genotypes and that diclosulam caused visible phytotoxicity symptoms in early-maturation cultivars, as also found in the present study. Osipe et al. (2014) evaluated the selectivity of diclosulam and sulfentrazone for soybean crops and found that the herbicides did not affect grain yield. Dalazen et al. (2020) observed that sulfentrazone caused injury of 7%, but this abiotic stress not affected by soybean grain yield; for diclosulam the injury was higher and reaching 15%, however the grain yield was not reduced too.

The early- and late-maturation cultivars presented little phytotoxicity symptoms after the herbicide treatments, presenting fast recovery. However, the cultivar Zeus differed significantly, presenting higher percentage of phytotoxicity symptoms in plants subjected to the treatment with sulfentrazone + diuron in the 2019/2020 crop season. The application of the herbicides pyroxasulfone + flumioxazin in the 2020/2021 crop season, in Curitibanos, caused phytotoxicity to the cultivars Raio and Fibra, although they have different cycles.

Regarding the mechanism of action of the herbicides, the phytotoxicity found in the cultivar Zeus confirms that the mixture of protox-inhibiting and photosystem II-inhibiting herbicides is not recommended for the climate conditions of the evaluated region, the higher pluviometry available and mild temperature aswell as the mixture of long-chain fat acid biosynthesis-inhibiting and protox-inhibiting herbicides.

Conclusions

The phytotoxicity of herbicides was mild and transitory, not exceeding 11%, and was imperceptible at 14 days after application, regardless of the soybean cultivar and growth location. The hypothesis that herbicides affect grain yield of early-maturation soybean cultivars was confirmed only in Curitibanos, where it was more evident for the application of diclosulam and for the cultivar Raio, in both crop seasons. In Lages, there was no effect of herbicides, but longer-cycle cultivars (Monsoy and Fibra) were more productive.

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