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Interval between the application of metsulfuron-methyl and sowing soybean in different production environments[1]

Intervalo entre a aplicação de metsulfuron-methyl e semeadura da soja em diferentes ambientes de produção

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ABSTRACT - The persistence of herbicides in the soil is extremely important for controlling weeds during the critical period of weed interference, and for determining which substitute crops might be sown. The aim of this study was to evaluate the effect of metsulfuron-methyl when applied at different times in relation to sowing soybean, seeking to determine a safe interval between its application and sowing the legume under different conditions of soil and climate. Two experiments were conducted, one in the district of Campo Mourão in the state of Paraná (PR) (2014/15 crop) and the other in Curitibanos in the state of Santa Catarina (SC) (2015/16 crop). Both experiments were carried out in a randomised block design with four replications. The treatments were arranged in a 2 x 6 + 1 factorial scheme, where factor A represented two doses of metsulfuron-methyl (1.98 and 3.96 g ha^{-1}), and factor B six different intervals between applying the metsulfuron-methyl and sowing the soybean (0, 15, 30, 45, 60 and 75 days after application - DAA), in addition to a control without the application of herbicide, to serve as a standard for comparison. The following were evaluated: percentage phytotoxicity, plant height, stand, number of pods per plant, 100-grain weight and productivity. A difference was seen in the persistence of metsulfuron-methyl for the experiments in Campo Mourão PR, and Curitibanos SC, and was greater for Campo Mourão. The safe interval between applying the metsulfuron-methyl and sowing the soybean was 17 days for the experiment in Curitibanos and 40 days for Campo Mourão. Precipitation volume, pH and organic matter are the main factors to possibly have influenced this interval.

Key words: Carryover. Sulphonylurea. Phytotoxicity. Productivity. *Glycine max*.

RESUMO - A persistência dos herbicidas no solo é extremamente importante para proporcionar controle de plantas daninhas durante o período crítico de interferência e determinar quais culturas poderão ser implantadas nos cultivos sucedâneos. Desta forma, objetivou-se avaliar o efeito do metsulfuron-methyl aplicado em diferentes períodos em relação a semeadura da soja, buscando-se determinar o intervalo de tempo seguro entre a sua aplicação e a semeadura desta leguminosa, em diferentes condições edafoclimáticas. Foram conduzidos dois experimentos, sendo um no município de Campo Mourão-PR (safra 2014/15) e outro em Curitibanos-SC (safra 2015/16). Ambos experimentos foram conduzidos em delineamento experimental de blocos casualizados, com quatro repetições. Os tratamentos foram dispostos em esquema fatorial 2 x 6 + 1, onde o fator A representou duas doses de metsulfuron-methyl (1,98 e 3,96 g ha^{-1}) e o fator B seis épocas entre a aplicação do metsulfuron-methyl e a semeadura da soja (0, 15, 30, 45, 60 e 75 dias após a aplicação - DAA), além de uma testemunha sem a aplicação do herbicida, para servir como padrão de comparação. Avaliou-se a porcentagem de fitointoxicação, altura de plantas, estande, número de vagens por planta, massa de 100 grãos e produtividade. Notou-se diferença na persistência do metsulfuron-methyl para os experimentos de Campo Mourão-PR e Curitibanos-SC, sendo maior para o primeiro município. O intervalo seguro entre a aplicação do metsulfuron-methyl e a semeadura da soja foi de 17 dias para o experimento de Curitibanos-SC e de 40 dias para Campo Mourão-PR. O volume de precipitação, o pH e a matéria orgânica são os principais fatores que podem ter influenciado na duração deste intervalo.

Palavras-chave: *Carryover.* Sulfonilureia. Fitointoxicação. Produtividade. *Glycine max*.

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INTRODUCTION

The persistence of herbicides is extremely important for controlling weeds during the critical period of weed interference, and for determining which substitute crops might be sown. The persistence time of the herbicide in the soil can vary according to the chemical structure of the molecule, and the soil and climate conditions, factors that affect the sorption, leaching, and microbial and chemical decomposition of the herbicide (GUERRA *et al*., 2011; INOUE *et al*., 2008), and consequently influence the development of sensitive crops that can be used for succession sowing (DAN *et al*., 2011, 2012; GRAY; BRAXTON; RICHBURG, 2012; MANCUSO; NEGRISOLI; PERIN, 2011).

Metsulfuron-methyl is an herbicide of variable persistence in the soil. It acts in inhibiting the enzyme acetolactate synthase (ALS), and belongs to the group of sulfonylureas. It is recommended in winter cereals, rice, pasture, coffee and sugar cane (RODRIGUES; ALMEIDA, 2011), its use has been widened to include autumn weed management, such as *Conyza* spp (MOREIRA *et al*., 2010; PAULA *et al*., 2011), especially in southern Brazil. It is characterised by high biological activity, being effective at very low doses, and by its broad spectrum of action (VARGAS; ROMAN, 2005).

The physical and chemical characteristics of this herbicide are: weak acid, with a pKa of 3.3, a Kow of 1.0 (pH 5.0) and 0.018 (pH 7.0), and solubility in water of 548 mg L^{-1} (pH 5.0) and 2790 mg L^{-1} (pH 7.0) (RODRIGUES; ALMEIDA, 2011). The sorption of metsulfuron-methyl in soils of different depths correlated negatively with the soil pH and positively with the organic matter content, with pH considered the dominant factor in controlling adsorption for most of the studied soils (DUTTA *et al*., 2015; WALKER; COTTERILL; WELCH, 1989; WANG *et al*., 2010; ZANINE *et al*., 2009).

The presence of metsulfuron-methyl residue in the soil can compromise productivity in the sunflower, cotton, maize, soybean and beans (RODRIGUES; ALMEIDA, 2011), and it is necessary to observe a safe interval between applying the herbicide and sowing the crop.

Previous studies have shown that there was no effect on dry matter in maize when sown in soil that received an application of metsulfuron-methyl 30 days before sowing and a daily irrigation of 5 mm following the application (CARVALHO *et al*., 2015). Conversely, Santos *et al*. (2009) concluded that metsulfuron-methyl affected initial development in three maize hybrids, even with an interval of 90 days between the application and sowing. However, in these studies, the authors evaluated the development of maize up to 14 and 20 days after emergence respectively, and it is not possible to come to any conclusion as to the effects on crop productivity.

There are no studies in the literature that evaluate the effect of metsulfuron-methyl residue on soybean. However, due to the increased use of this herbicide during the off-season, especially for managing species that are resistant to glyphosate, such studies are necessary. Therefore, the aim of this work was to evaluate the effect of metsulfuron-methyl applied at different intervals relative to sowing soybean, seeking to determine a safe interval between applying the herbicide and the sowing the soybean under different conditions of soil and climate.

MATERIAL AND METHODS

Two experiments were conducted for different seasons and locations, one in the district of Campo Mourão PR, between August 2014 and March 2015, and the other in Curitibanos SC, between September 2015 and April 2016, both in Brazil. The first experiment was located at 52º22’40’’ W and 23º59’34’’ S, at an altitude of 580 m. According to Köppen, the climate in the region is classified as type Cfa (subtropical humid mesothermal, with hot summers and infrequent frosts). The soil is classified as a dystrophic Red Latosol of very clayey texture (EMBRAPA, 2013), consisting of 760 g kg^{-1} clay, 110 g kg^{-1} silt, 130 g kg^{-1} sand, 24.00 g dm^{-3} organic matter, and a pH ($CaCl_2$) of 4.94 (analysis of the 0-20 cm layer).

The second experiment was conducted at 50°31’78” W and 27°16’94” S, at an altitude of 980 m. According to Köppen, the climate is classified as type Cfb (always humid temperate, with mild summers and dry winters with frequent frosts). The soil is a Haplic Cambisol of clayey texture (EMBRAPA, 2013), with 534 g kg^{-1} clay, 392 g kg^{-1} silt, 74 g kg^{-1} sand, 49.59 g dm^{-3} organic matter, and a pH ($CaCl_2$) of 5.9 (analysis of the 0-20 cm layer).

In each experiment, the experimental units were represented by plots of 2.8 x 4.0 m (11.2 m^2), with the three central rows considered the working area, disregarding 0.5 m from the end of each row (4.08 m^2), for a total area of 582.4 m^2.

In Campo Mourão and Curitibanos, the soybean cultivars NS 5959 IPRO (breeder Nidera Seeds, indeterminate growth habit, maturity group 5.9) and NA5909 RG (breeder Nidera Seeds, indeterminate growth habit, maturity group 6.2) were sown on 29 October 2014 and 20 November 2015 respectively, at a population of 320,000 plants ha^{-1} and spacing between rows of 0.45 m at each location.

Both experiments were conducted in a randomised block design with four replications. The treatments were arranged in a 2 x 6 + 1 factorial scheme, where factor A represented two doses of metsulfuron-methyl (1.98 and 3.96 g ha^{-1}), and factor B six different intervals between applying the metsulfuron-methyl and sowing the soybean (0, 15, 30, 45, 60 and 75 days after application - DAA), in addition to a control without the application of herbicide, to serve as a standard for comparison.

The metsulfuron-methyl was applied at intervals of 15 days, giving a total of six applications per experiment (Figure 1). After the last application, the soybean was sown in each plot, thereby obtaining six different intervals between applying the metsulfuron-methyl and sowing the legume (0, 15, 30, 45, 60 and 75 DAA). This procedure was adopted in order to minimise experimental error, since the soybean plants developed under the same environmental conditions, regardless of the treatment.

For each application, a precision backpack sprayer was used, pressurised with CO_2 and equipped with a bar containing XR11002 fan nozzles, spaced 0.5 m apart, at a pressure of 207000 Pa and a displacement speed of 1.0 m s^{-1}, giving an application rate of 200 L ha^{-1}. The climate conditions at the time of each application were obtained by means of a digital thermo-hygro-anemometer. In Campo Mourão, the temperature varied between 24 and 32 °C, the relative humidity between 47 and 65%, and the winds between 0.06 and 0.8 m s^{-1}. In Curitibanos, the temperature varied between 20.4 and 26.8 °C, the relative humidity between 51 and 71%, and the winds from 0 to 0.55 m s^{-1}.

Precipitation data and the mean minimum and maximum temperatures during the experimental period in Campo Mourão and Curitibanos are shown in Figures 1a and 1b respectively. The data for Campo Mourão were obtained from the weather station of the National Institute of Meteorology – INMET, and for Curitibanos from the weather station at the Federal University of Santa Catarina, located 200 m from the experiment.

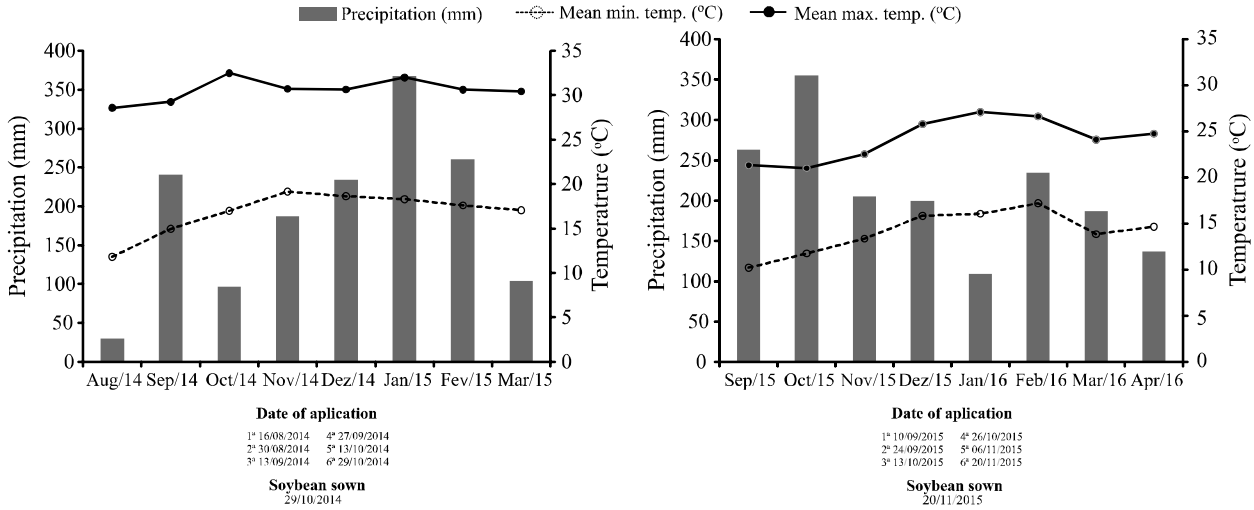
Throughout each experiment, pests and diseases were controlled following the technical recommendations for soybean cultivation (EMBRAPA, 2011). For weed control in each experiment, two applications of glyphosate (720 g ha^{-1} acid equivalent) were given when the soybean was at stage V2 and V4.

Evaluations of percentage phytotoxicity in the soybean plants were made visually 30 days after emergence (DAE) when scores from 0 to 100 were assigned, where 0 represents the absence of symptoms and 100 the death of the plant. Plant height was evaluated at 30 DAE, measuring five randomly chosen plants in each plot from the base of the plant to the last trifoliate leaf with the aid of a rule graduated in centimetres.

Before harvesting the soybean, the plant stand (counted in two rows of 2 linear metres per plot) and number of pods per plant (in five randomly chosen plants per plot) were evaluated. Following the harvest, the 100-grain weight (four replications) and productivity were also determined, corrected for a humidity of 130 g kg^{-1}.

The percentage reduction in each characteristic was calculated for the treatments with metsulfuron-methyl relative to the control without herbicide. The

Figure 1 - Mean monthly precipitation (mm) and minimum and maximum temperature (°C) during the experimental period, in Campo Mourão PR, 2014/15 crop (a) and Curitibanos SC, 2015/16 crop (b)



data for percentage reduction were subjected to analysis of variance ($p<0.05$) followed by regression analysis ($p<0.05$), with the coefficient of determination and biological significance considered when choosing the model. The established criteria were met by the non-linear exponential model (equation 1).

$$y = \alpha * exp(-b * x) \quad (1)$$

where: y represents the estimate for the variable in question, a is the maximum inhibition, b is the constant rate of decline and x is the sowing interval relative to the application of metsulfuron-methyl.

RESULTS AND DISCUSSION

In both experiments, the symptoms of phytotoxicity seen in the soybean plants were characterised by growth inhibition and intense chlorosis, similar to the symptoms seen by Alonso, Oliveira Junior and Constantin (2013) after sowing soybean in soil treated with metsulfuron-methyl.

A difference was seen in the persistence of metsulfuron-methyl between the experiments in Campo Mourão and Curitibanos. The persistence was greater in Campo Mourão.

For the experiment carried out in Campo Mourão, it was found that the soybean plants in the 2014/15 crop showed levels of phytotoxicity greater than 5% when the sowing interval was 63 and 74 days, at metsulfuron-methyl doses of 1.98 and 3.96 g ha^{-1} respectively. The symptoms were more intense the greater the dose of herbicide and the shorter the interval between application and sowing (Figure 2a). Carvalho *et al*. (2015) also found that shorter intervals between applying metsulfuron-methyl (3.96 g ha^{-1}) and sowing maize resulted in an increase in phytotoxicity, with the maize plants developing normally only when sowing occurred 90 days after applying the herbicide. Santos *et al*. (2009), studying the sensitivity of maize hybrids sown in soil with an application of 3.6 and 7.2 g ha^{-1} metsulfuron-methyl, found a reduction in shoot and root dry matter for plants sown up to 60 days after application.

In Curitibanos, symptoms of phytotoxicity were seen only when the interval between application and sowing was shorter than 8 days, regardless of the tested dosage. When application and sowing occurred on the same day, damage of 71.25% and 83.25% was seen at doses of 1.98 and 3.96 g ha^{-1} metsulfuron-methyl respectively (Figure 2b).

In Campo Mourão, it was found that growth in the soybean plants was delayed when the interval between sowing and the application of 1.98 and 3.96 g ha^{-1} metsulfuron-methyl was less than 63 or 68 days respectively. For the doses under test, it can be seen that, for intervals of up to 30 days, the reduction in height was more intense at the dose of 3.96 g ha^{-1}, from then, on the percentage reduction was similar for both doses (Figure 3a). In Curitibanos, no difference was seen between the doses of metsulfuron-methyl for height reduction in the soybean plants, so the mean value of the tested doses was used. Significant reductions in the height of the soybean plants were seen only when application and sowing took place at intervals of less than 11 days (Figure 3b).

In Campo Mourão, the soybean stand was reduced compared to the control for both of the doses under test,

Figure 2 - Percentage phytotoxicity in soybean plants relative to the control 30 days after emergence (DAE), for different intervals (days) between the application of two doses of metsulfuron-methyl and sowing the soybean, in Campo Mourão PR, 2014/15 crop (a) and Curitibanos SC, 2015/16 crop (b)

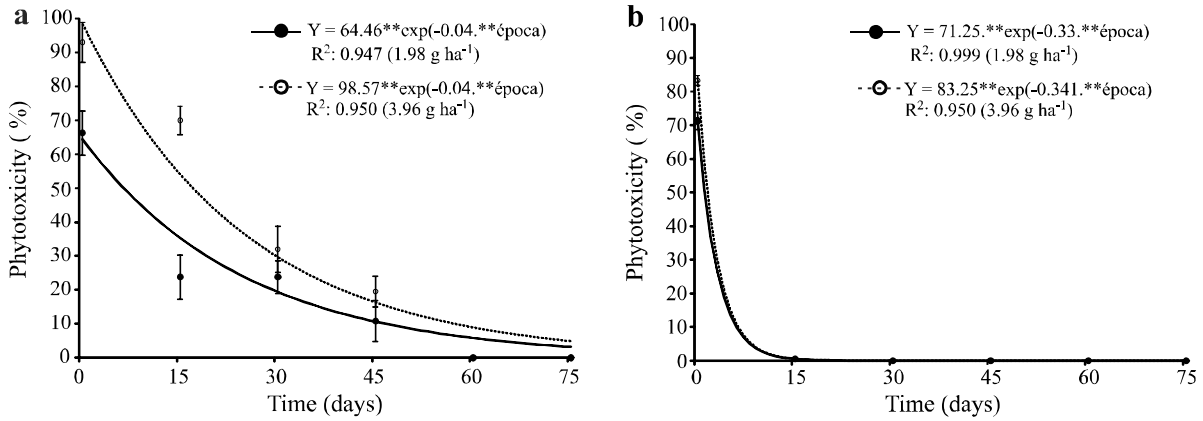
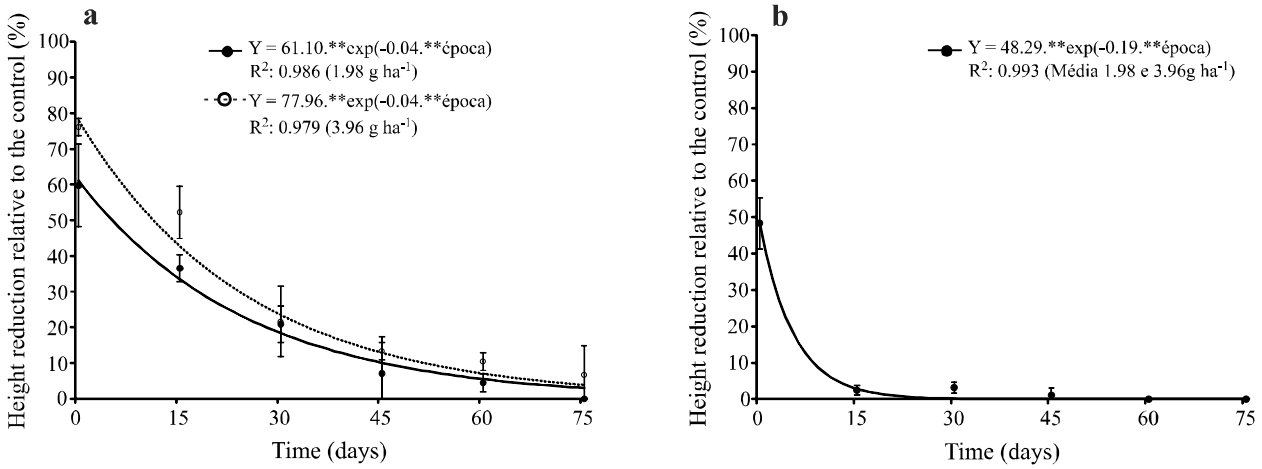


Figure 3 - Percentage reduction in the height of soybean plants relative to the control 30 days after emergence (DAE), for different intervals (days) between the application of two doses of metsulfuron-methyl and sowing the soybean, in Campo Mourão PR, harvest 2014/15 (a) and Curitibanos SC, 2015/16 crop (b)



when the interval between application and sowing was less than 73 days. The strength of the reduction differed between the tested doses when the interval was up to 39 days, from then on there was no significant difference between the doses (Figure 4a). In Curitibanos, there was no difference in soybean stand at the doses of 1.98 or 3.96 g ha^{-1} metsulfuron-methyl, with the 17-day interval between application and sowing being sufficient for there to be no reduction in this agronomic characteristic (Figure 4b).

The number of soybean pods grown in Campo Mourão decreased compared to the control at intervals of less than 65 days. When the interval between application and sowing was up to 30 days, a greater percentage reduction in this variable was seen at the dose of 3.96 g ha^{-1}. From then on, no differences were seen between the doses under test (Figure 5a). For the 100-grain weight (Campo Mourão), a difference was seen relative to the control, only when the interval between application and sowing was shorter than 11 or 16 days, at the doses of 1.98 and 3.96 g ha^{-1} respectively (Figure 5b).

The doses and application intervals under evaluation did not affect the number of pods per plant or 100-grain weight for the experiment in Curitibanos (data not shown).

Figure 4 - Percentage reduction in soybean stand relative to the control, for different intervals (days) between the application of two doses of metsulfuron-methyl and sowing the soybean, in Campo Mourão PR, 2014/15 crop (a) and Curitibanos SC, 2015/16 crop (b)

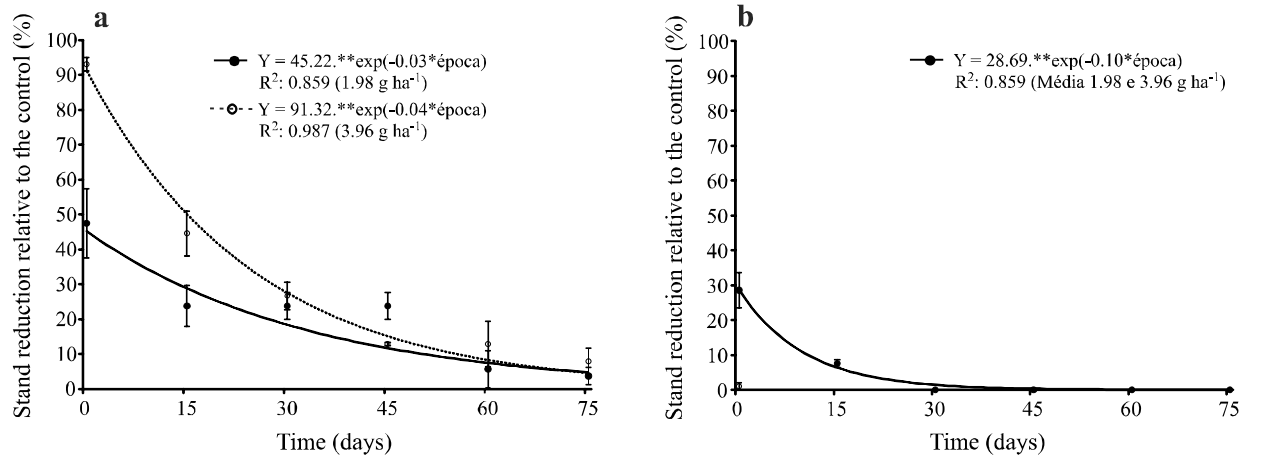


Figure 5 - Percentage reduction in the number of pods per plant (a) and 100-grain weight (b) in soybean relative to the control, for different intervals (days) between the application of two doses of metsulfuron-methyl and sowing the soybean, in Campo Mourão PR, 2014/15 crop

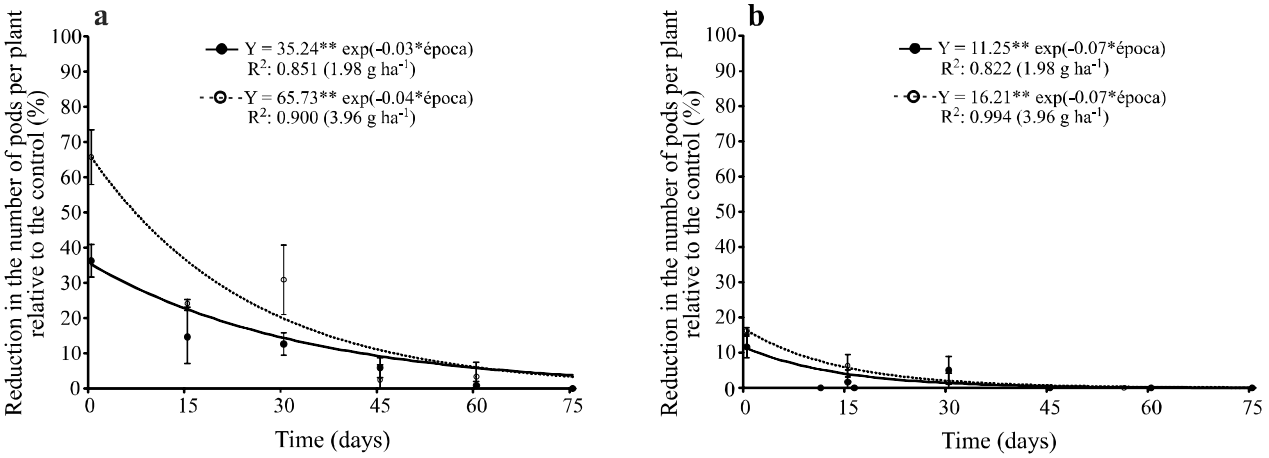
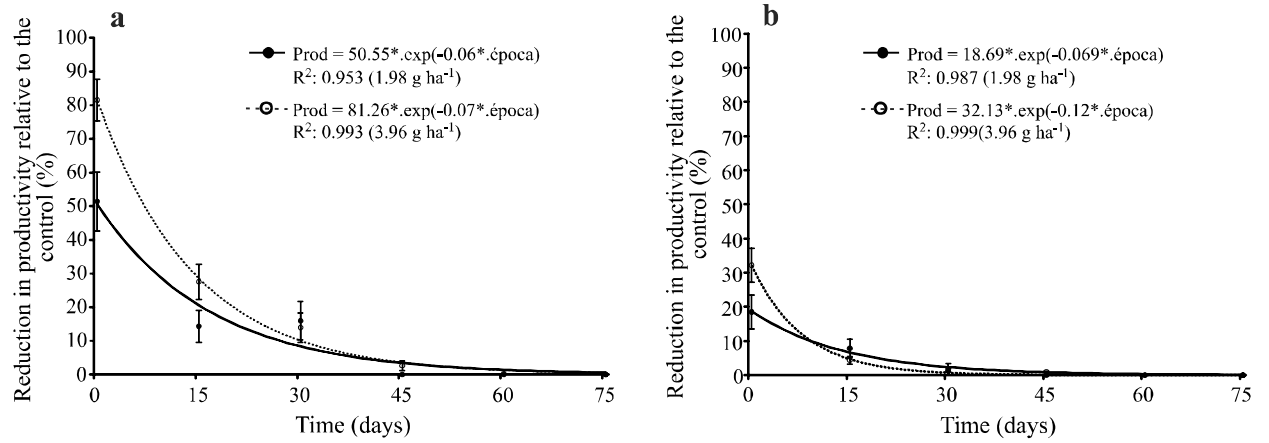


Figure 6 shows the percentage reduction in soybean productivity relative to the control for the experiments conducted in Campo Mourão (a) and Curitibanos (b). According to the model fitted to the experiment in Campo Mourão, in order for the reduction in productivity not to exceed 5% at the doses of 1.98 and 3.96 g ha^{-1} metsulfuron-methyl, an interval of 39 and 40 days respectively is necessary between applying the herbicide and sowing the soybean (Figure 6a), while in Curitibanos, 19 and 15 days were necessary at the doses of 1.98 and 3.96 g ha^{-1}respectively (Figure 6b).

In the district of Campo Mourão (2014/15 crop), during the 39 and 40 days prior to sowing there was an accumulated precipitation of 161.8 and 193.1 mm respectively (Figure 1a). While in Curitibanos (2015/16 crop), during the 19 and 15 days preceding sowing, the respective accumulated precipitation was 150.8 and 118.2 mm (Figure 1b). It is important to point out that during the 2015/16 crop, the district of Curitibanos had precipitation volumes above the historical average due to the 'El Niño' phenomenon, which may have contributed to the rapid dissipation of the herbicide in the soil through leaching.

Analysing the results of the two experiments, it is found that the time the metsulfuron-methyl remained active in the soil in sufficient quantity to reduce productivity in the soybean fluctuated greatly, being on average 39.5

Figure 6 - Percentage reduction in soybean productivity relative to the control, for different intervals (days) between the application of two doses of metsulfuron-methyl and sowing the soybean, in Campo Mourão PR, 2014/15 crop (a) and Curitibanos SC, 2015/16 crop (b)



days for the district of Campo Mourão and 17 days for Curitibanos. However, when considering the amount of precipitation that occurred at the two locations (Figure 1), it can be seen that these values did not vary much, with an average of 177.5 and 134.5 mm for Campo Mourão and Curitibanos respectively. It is therefore assumed that these precipitation volumes were sufficient to cause herbicide transport throughout the soil profile, as the herbicide is very mobile in the soil (AZCARATE; MONTOYA; KOSKINEN, 2015; ZANINE *et al*., 2009).

Carvalho *et al*. (2015) found that a daily irrigation of 5 mm after the application of 3.96 g ha^{-1} metsulfuron-methyl was enough for the dry matter in maize plants sown 30 days after the application not to be affected. These authors concluded that dissipation of the herbicide was directly influenced by water availability, due to the solubility of the molecule and the time available for microbial degradation in the soil, results similar to those seen in the present experiments.

What may have contributed to the lower persistence of the metsulfuron-methyl in the experiment conducted in Curitibanos, was the pH of the soil. According to Sondhia (2008, 2009), an increase in soil pH makes this herbicide more mobile, leaching to greater depths and not available for absorption by the root system. The pH of the soil at Curitibanos was around 1.0 pH greater than that of the soil at Campo Mourão, suggesting that the herbicide became more soluble.

In addition to solubility, soil pH affects dissociation of the herbicide metsulfuron-methyl, as it is a weak acid with a pKa of 3.3. As such, soils where the pH is higher than the pKa have a predominance of herbicide molecules in dissociated (anionic) form, making the herbicide less prone to sorption in the soil and more susceptible to leaching. As the soil at Curitibanos had a higher pH than that of Campo Mourão, it is assumed that there were a greater number of molecules in anionic form, which favoured loss of the herbicide through leaching due to the large precipitation volume in this municipality following the applications, resulting in less persistence and a shorter safe interval between the application and sowing the soybean. Other authors have also found that, due to the rise in the amount of anionic species in solution, the sorption of metsulfuron-methyl is reduced with increases in the soil pH (ABDULLAH; SINNAKAKANI; TAHIR, 2001; SHONDIA, 2008, 2009).

The organic carbon content of the soil is another factor that may have contributed to the shorter safe interval between applying the metsulfuron-methyl and sowing the soybean in Curitibanos, as it presented approximately twice the amount (49.59 g dm^{-3}) found in Campo Mourão (24.00 g dm^{-3}). A large part of the applied herbicide would therefore be linked to these colloids and not available to the root system of the crop. This argument is reinforced by the results of Walker, Cotterill and Welch (1989) and Zanine *et al*. (2009), who describe the sorption of metsulfuron-methyl as being positively correlated with the organic carbon content of the soil, where sorption occurs through strong bonds that indicate the low desorption capacity of these molecules (ABDULLAH; SINNAKAKANI; TAHIR, 2001; AZCARATE; MONTOYA; KOSKINEN, 2015; DUTTA *et al*., 2015; SINGH; SINGH, 2012).

Sondhia (2008), studying the persistence of metsulfuron-methyl in soil with 35.47% clay, 8.00 g dm^{-3} organic carbon and a pH of 7.2, found that the concentration of the herbicide 30 days after the application of 3, 4, 5 and 8 g ha^{-1} was 0.009, 0.018, 0.012 and 0.024 μg g^{-1} of soil respectively. However, 60 days after application, metsulfuron-methyl residue was not found, being below the detection limit (<0.001 μg g^{-1}) for doses of between 3 to 5 g ha^{-1}.

In short, it appears that the safe interval between applying the metsulfuron-methyl and sowing the soybean varied with the soil and climate conditions.

CONCLUSION

The safe interval between applying the metsulfuron-methyl and sowing the soybean was 17 days for the experiment in Curitibanos and 40 days for Campo Mourão. Precipitation volume, pH and organic matter are the main factors that can influence the determination of this interval.

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