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Shortening critical period of weed control at soybean by residual herbicide mixtures

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Abstract: Background: Weed interference in the early stages of soybean development can compromise its yield. The use of herbicides with residual effects at the time of sowing is an alternative to reduce weed density and emergence time, consequently, the damage caused by their interference. Therefore, weed development can be reduced, which can result in easier post-emergence control. The combination of herbicide modes of action extends the spectrum of control and delays herbicide resistance evolution.

Objective: This work aimed to determine the onset of the critical period of weed control (CPWC) from the application of residual herbicides mixtures at soybean sowing.

Methods: Two experiments were carried out in 2021/2022, the first in a conventional tillage system with increasing periods of soybean/weeds coexistence (14, 28, 42, and 56 days after crop emergence). The second experiment consisted of a no-tillage system with soybean/weeds coexistence for 30, 45, 60, 75, and 90 days after crop emergence. On the day of soybean sowing, mixtures of the herbicides diclosulam + pyroxasulfone, flumioxazin + pyroxasulfone and diuron + sulfentrazone were applied, in addition to the untreated check. Soybean yield was evaluated evaluated upon harvest and data compared by non-linear regressions to CPWC determination.

Results: The application of residual herbicides can allowing reduces losses relative to the untreated control by up to 57%. CPWC beginning can be extended from eight to forty days, depending on mixes and acceptable losses.

Conclusions: The use of the mixture of residual herbicides are a good option for weed interference reduction for soybean crop.

Keywords: Pyroxasulfone; Weed interference; Pre-emergent control; Weed seedbank

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1. Introduction

The presence of weeds can cause competition for crop essential resources, such as water, light, nutrient absorption and space occupation. Soybean (*Glycine max* (L.) Merrill) yield, for example, can be reduced by up to 86–92% when coexisting with a community with *green foxtail* and *waterhemp* predominance (Knezevic et al., 2019). Weed interference is accentuated in the beginning of the cycle and will generally end with crop canopy closure. The "window" between these periods is defined as the critical period for weed control – CPWC (Rüdell et al., 2021; Knezevic et al., 2002), a period calculated by days, years or stage of growth, where the adoption of control methods is recommended (Tursun et al., 2016).

The degree and the duration of interference are influenced by the community, density and distribution of weeds, edaphoclimatic, and cultural factors, such as crop cultivars, and sowing dates (Zandoná et al., 2018; Knezevic et al., 2002). In soybean, CPWC values ranged from 13 to 27 days after emergence (DAE) for a shorter cycle cultivar and from 14 to 76 for a longer cycle cultivar (Tavares et al., 2012). For instance, in the presence of southern crabgrass (*Digitaria ciliaris)*, soybean must remain free from the presence of weeds in the period between 23 and 50 DAE (Agostinetto et al., 2014).

Thinking in a way to reduce the CPWC, it is possible to use residual herbicides, that will provide longer weed germination control, ensuring greater development opportunities for the crop and even a greater flexibility in time for a post-emergence application (Perkins et al., 2021; Barnes et al., 2019). If some plants emerge, they will be less developed, facilitating their post-emergence control (Pavlovic et al., 2018). The residual herbicides will delay the beginning of CPWC, for example, where diclosulam and flumioxazin applied at sowing of the soybean cultivar NA5909RG increased the beginning of CPWC to 42 and 35 DAE respectively. This increase was also observed in the soybean cultivar P95R51, with CPWC starting at 28 DAE (V4 soybean stage of growth) for both herbicides tested, compared with 14 DAE (V2 soybean stage of growth) without application (Rizzardi et al., 2020). Furthermore, residual herbicides can be a source of mechanisms of action rotation, reducing the selection pressure for resistant plants (Chahal et al., 2018).

Even with all the aforementioned benefits, the use of residual herbicides in the weed management program is still reduced. In the state of Paraná, for example, only 15% of soybean producers carry out pre-emergent applications (Agência de Defesa Agropecuária do Paraná, 2022), since the use of these products requires knowledge about their interaction with the soil and straw, carryover or residual effect and especially their selectivity for the crop, what is enhanced in conditions of herbicides mixtures. Therefore, this work aimed to evaluate the influence of the application of pre-emergent herbicides in a mixture of different mechanisms of action in soybean on the interference of weeds and crop yield by calculating the CPWC start.

2. Material and Methods

2.1 Site and plant description

Field studies were conducted in 2020/2021 growing season, one at the Pontifical Catholic University of Paraná, PUCPR at Fazenda Rio Grande, Paraná, Brazil (25°39'9.65"S; 49°16'50.66"W) and other at the Federal University of Paraná, UFPR in Palotina, Paraná, Brazil (24º26'79"S; 53º80'82"W). The PUCPR experimental area presents a Cfb Koeppen climate type (uniform rainfall throughout the year, without dry seasons, with frosts at winter), and the UFPR field has a Cfb Koeppen climate type (higher temperatures in the summer, with a dry winter period, but without frosts). At PUCPR, mean maximum and minimum temperature throughout the evaluated period were 24.9 and 13.3 °C with 1,253.8 mm of rain. At UFPR, mean maximum and minimum temperature were 32.80 and 19.48 °C with 985.20 mm of rain.

Table 1- Soil analysis for both sites (experiments) conduced

Soil analyzis		PUCPR - Site 1	UFPR - Site 2
pH	$CaCl_2$	4.8	4.7
Ca	cmol dm^{-3}	4.23	4.02
Mg		2.54	0.89
Al		0.2	0.17
H+Al		7.42	6.69
K		0.19	0.17
CTC	pH 7	14.38	11.77
SMP	mg dm^{-3}	5.3	5.08
P	g dm^{-3}	8.12	7.18
V%		48.4	43.16
SOM		42.13	22.59
clay	g 100 g^{-1}	35	66.25
silt		21	18.75
sand		44	15.00

Soil fertility from both areas were similar with different textures (Table 1). At PUCPR, soybean sowing (DM 54i52 IPRO, 5.4 maturity group, with medium ramification and high demanding in soil fertility) was carried out in a conventional tillage system, sowing 15 seeds per linear meter spaced between rows in 0.45 m, aiming an initial population of 333,333 plants per hectare. At UFPR, soybean sowing (M5947 IPRO, 5.9 maturity group, with high ramification and high demanding in soil fertility) took place in a no tillage system after maize cultivation, sowing 12 seed per linear meter spaced between rows in 0.45m, aiming an initial population of 266,666 plants per hectare. At PUCPR, soil was fertilized at sowing with 14 kg ha^{-1} of nitrogen and 70 kg ha^{-1} of phosphorus and potassium. At UFPR, fertilization was conducted with 5 kg ha^{-1} of nitrogen and 50 kg ha^{-1} phosphorus and potassium at sowing.

2.2 Treatments and experimental design

Experiments were conducted in a split-plot design with four replications. Pre-emergence herbicide treatments applied at soybean sowing were the main plot factor arranged in four replicates, whereas sub-plot factors consisted of weed removal timing by hand weeding after herbicide application/soybean sowing: no weed control (weedy), season-long weed control (check), weed removal at 14, 28, 42, and 56 days after soybean sowing for PUCPR and no weed control (weedy), season-long weed control (check), weed removal at 30, 45, 60, 75, and 90 days after soybean sowing for UFPR.

Each sub-plot size was 2.5 m x 4 m (10 m²). Treatments at PUCPR were: 35 g i a ha^{-1} diclosulan + 100 g i a ha^{-1} of pyroxasulfone; 90 g i a ha^{-1} of pyroxasulfone + 60 g i a ha^{-1} of flumyoxazin and untreated check. At UFPR, treatments were: 245 g i a ha^{-1} of sulfentrazone + 490 g i a ha^{-1} of diuron, 90 g i a ha^{-1} of pyroxasulfone + 60 g i a ha^{-1} of flumyoxazin, 29,4 g i a ha^{-1} diclosulan + 100 g i a ha^{-1} of pyroxasulfone and untreated check.

Herbicide applications were performed using a backpack spray pressurized by CO_2 at a constant pressure of 13,7 kPa, equipped with a one-meter application bar equipped with two AIXR110015 nozzles (TeeJet Technologies, Wheaton, IL), regulated to deliver 200 L ha^{-1} of solution. Plots were maintained weed-free for the remainder of the season through 1,440 g ea ha^{-1} glyphosate (Glizmax Prime, 480 g ea L^{-1}, Dow AgroSciences, São Paulo, Brazil) application on the day of weed removal event at PUCPR and with handy weeding at UFPR.

2.3 Data collection and analysis

Three linear meters of soybean were hand harvested from the two middle rows of each plot (4.05 m²) and then threshed to determine yield. Yields were reported at 13% moisture. A three-parameter Weibull model of the drc package (Ritz, Strebig, 2016) described the relationship between soybean yield and weed removal timings (in days after soybean emergence) using the equation:

$$y = d\, exp(-\, exp(b(log(x) - e)))$$

Where Y is the yield (kg ha^{-1}); d is the upper limit (soybean yield); x is the day after soybean emergence; e is the day after soybean emergence at the inflection point, and b is the slope of the curve around the inflection point. The equation was choose after using the mselect function to find the lower AIC (akaike information criterion). The beginning of CWCP, in days after soybean emergence, were calculated using the ED function of the drc package, considering soybean yield loss of 2, 5 and 10%. Data from soybean yield obtained from the check and weedy treatments was compared by an ANOVA, and using the Tukey test at 5% ($p < 0.05$). Data from the two experimental areas were analyzed separately, due to greater weed suppression and greater straw production in the no-till system and greater interference from the weed community in the conventional tillage system. Data analyses were performed in R (R Development Core Team 2022).

3. Results and Discussion

At PUCPR, weed community was composed mostly of dicotyledonous plants (96.0%), distributed in eight species and six families, with a predominance of wild radish plants (84.5%), followed by hairy beggarticks, common lambsquarters, black oats, cereal rye, hairy fleabane, tropic ageratum and Brazil pusley. There was no significant interaction between herbicide factors and coexistence periods (with and without pre-emergent herbicides). It seems that the absence of straw in system, favored the local weed community, major formed by radish, which caused 21.0% soybean yield reduction comparing weedy and weed-free treatments even with the residual sprayed herbicides (data not showed). Considering that no pre-emergent herbicide efficacy difference was observed at different weed removal treatments, data did not fit to regressions and it was not possible to determinate the CPWC, the objective of this worf, so this area results will not be analyzed here.

For UFPR, weed community was composed of monocotyledonous plants, distributed in two species and two families, with a predominance of bengal dayflower (82.7%), followed by sourgrass (17.3%). At both locations, we considered the natural population of weeds, without manual sowing. So our first result is that our mixtures texted were more efficient controlling grasses than dicotyledonous species. Because of this, a significant difference among herbicides treatments were observed, so CPWC was established. In this area, a soybean yield reduction of 66% was observed, highlighting a higher weed pressure than PUCPR.

3.1 Soybean yield loss

Analyzing soybean yields for UFPR, we observed that not using a weed control method resulted in a mean yield of 782 kg ha^{-1}, 43% lower than the average of treatments with exclusive application of pre-emergent herbicides (1,372 kg ha^{-1}). However, comparing all treatments yield with the total weed control, we assume that another intervention would be necessary (Table 2). This intervention will depend on the characteristics of the weed community, such as species fluxes and weed emergence densities. In other studies, the control provided by straw and application of pre-emergent herbicides was enough to ensure maximum soybean productivity, even without other interventions in the post-emergence of the crop. In this area, with a weed community mostly composed of monocot species, no (Duarte et al., 2021; Roncatto et al., 2022).

The weed-free treatment resulted in productivity of 2,295 kg ha^{-1}, not statistically different to the treatments with the application of pre-emergent followed by handy weeding, evidencing that the mixture of herbicides, in this case, did not cause damage to the development and soybean productivity. When comparing the average yields given by the effect of weeding on herbicide treatments, we observed that there was an average increase in productivity of 66.12% when weeding was performed as a complement to weed management. This difference is since the control effect of the residual herbicide is decreasing over time. This could be explained by some weed species able to germinate near or after the end of a pre-emergent herbicides soil residual effect. Considering the variability of weed traits, there are species able to manifest several flows during the crop growing season, such as *Brassica carinata*, *Raphanus raphanistrum*, *Oenothera laciniata*, and *Anthemis cotula* (Piskackova, Leon, 2022). In this study, the success in the control of *D. insularis* and *C. benghalensis* by pre-emergent herbicides can also be attributed because the control happened for germinating seedlings and the annual growing cycle of the weeds.

In general, the application of residual herbicides in crops prior to soybean reduces the risk of injuries and crop yield losses. However, applications carried out at the time of sowing require attention, since each active ingredients has distinct physicochemical characteristics that increase

Table 2 - Soybean yield (kg ha^{-1}) submitted to the application of different pre-emergent treatments with or without supplementation of control (weedy or check)

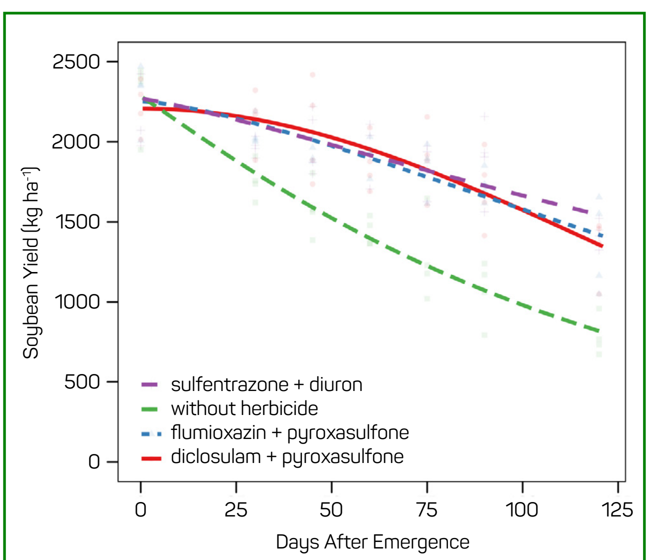
Herbicides	Soybean yield (kg ha^{-1})	
	weedy	check
without herbicide	782 Bb	2.295 Aa
diclosulam + pyroxasulfone	1.336 Ba	2.219 Aa
flumioxazin + pyroxasulfone	1.354 Ba	2.296 Aa
diuron + sulfentrazone	1.426 Ba	2.322 Aa

Averages followed by the same capital letter vertically or by a lowercase letter horizontally do not differ from each other (Tukey, p ≤ 0.05) or decrease its permanence in each environment (Grint et al., 2022). Different levels of phytotoxicity in soybean caused by the use of pre-emergent herbicides at the time of sowing are found in the literature, ranging from 12.0% by the application of sulfentrazone + diuron (Galon et al., 2022), reduction of soybean canopy area by 1.5% by the application of sulfentrazone (Arsenijevic et al., 2021) and an eleven-day delay in canopy closure with application of flumioxazin + metribuzin + pyroxasulfone when compared to treatment without pre-emergence herbicide (Arsenijevic et al., 2022). However, all these authors reported that injuries caused by herbicides in the early stages did not affect grain yield at the end of the cycle, in accordance with the results of this experiment.

The residual herbicide selectivity and its phytotoxic potential for the crop are influenced by more or less favorable environmental conditions for its degradation, defined mainly by the half-life of the active ingredient ($t_{1/2}$) and the sensitivity of each species (Curran, 2016). According to Walsh et al. (2014), soybean selectivity for pre-emergent herbicides in early stages also depends on environmental conditions from sowing to crop emergence, because even with higher doses of sulfentrazone, the herbicide can be leached or degraded before causing phytotoxicity in the crop.

3.2 Critical time for weed removal

At UFPR, pre-emergent herbicides provided weed emergence and development control at the soybean early stages of growth, increasing in all cases the start of CPWC (Figure 1). At PUCPR, herbicides did not change the control of the weed community in the evaluated periods, thus, the productivity data did not fit the Weibull Model, and CPWC could not be determined.



Equation: $y = d\ exp(-\ exp(b(log(x) - e)))$

Figure 1 - Loss of soybean productivity as a function of the increase in days of coexistence with weeds and the application of different treatments with pre-emergent herbicides at sowing

The CPWC without the use of herbicides (Table 3) was shorter than where residual control took place. In the use of sulfentrazone + diuron mixture, for example, the farmer can have more 8 to 26 days to stablish a post emergent control. In the mixture of flumioxazin + pyroxasulfone from 11 to 28 days and in the mixture between diclosulam + pyroxasulfone from 22 to 41 days (Figure 2). It is noticed that with the increase of the tolerance of losses, bigger were the differences among the established CPWC.

Other studies established similar interference periods as a result of the application of pre-emergent mixtures at soybean sowing. Knezevic et al. (2019) found variable CPWC from 28 to 66 days after the application of saflufenacil + imazethapyr + pyroxasulfone. Pre-emergent herbicides also shortened the CPWC in other crops. In maize, the application of saflufenacil + dimethenamid-P + pyroxasulfone decreased CPWC in 26 days (Ulusoy et al., 2021), atrazine + s-metolachlor in 53 days in popcorn (Barnes et al., 2019), and in beans (*Phaseolus vulgaris*), with a reduction of 47 days by the application of the mixture of pendimethalin + dimethenamid-P (Beiermann et al., 2022).

Applying a residual herbicide at the time of soybean sowing can reduce seed bank germination and seedling emergence. These periods can last up to 42 days under ideal conditions of rain and organic matter (Rizzardi et al., 2020). However, in conditions of high infestation and greater species diversity, the use of two active principles with different characteristics is an alternative to increase the spectrum of controlled species, since areas with higher density and emergence of weeds have their CPWC in advance compared to areas with lower density and lower emergence flows (Jeschke et al., 2011, Soltani et al., 2017). Studies demonstrating that the mixture of two pre-emergent herbicides with different physicochemical characteristics can ensure weed control in less favorable environmental conditions are incipient since most works with pre-emergent herbicide mixtures do not evaluate this possibility.

Table 3 - Periods Prior to Interference (days after emergence) resulting from the application of different pre-emergent herbicides on soybean

Herbicides	Acceptable loss levels		
	2%	5%	10%
without herbicide	2	7	14
diuron+sulfentrazone	10	22	40
flumioxazin+pyroxasulfone	13	25	42
diclosulam +pyroxasulfone	24	38	55
CV %	53,8	51,1	49,5

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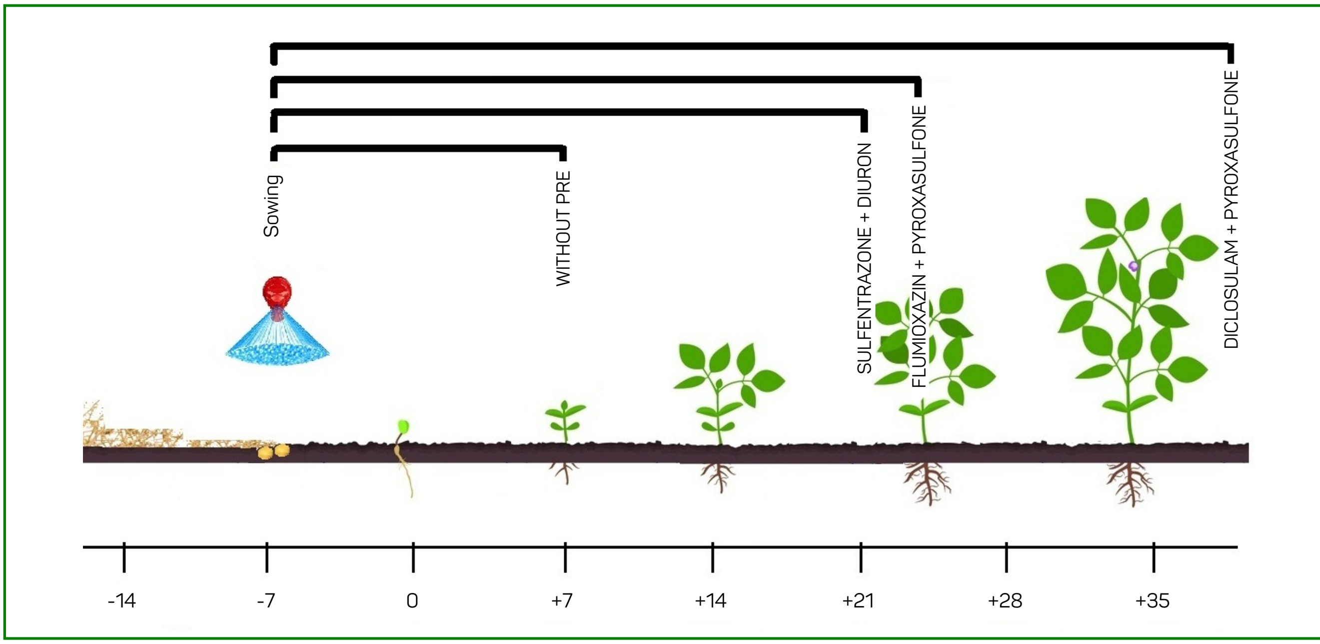

Figure 2 - The beginning of the critical period of weed control - CPWC, with and without the using pre-emergent herbicide mixtures, considering acceptable losses of 5% iat soybean yield

3.3 Management implications

The use of pre-emergence herbicides with residual action promotes a longer time window without the need for post-emergence herbicide application, which may reduce the use of glyphosate herbicide in tolerant soybeans depending on the canopy closing speed (Duarte e et al., 2021). On the other hand, when there is no application of residual herbicides at the time of sowing, the crop is subject to weed interference at early stages, which can reduce its stand by 58%, compromising its productivity (Knezevic et al., 2019). Although the application of pre-emergent herbicides can cause phytotoxicity in soybeans at early stages, reducing their photosynthetic area and delaying canopy closure, in some cases their effect remains beneficial, since the canopy area is also reduced when there is no application of pre-emergent herbicides by interference (DeWerff et al., 2014).

In addition to suppressing new weed emergence periods, residual herbicides play a key role in resistance management, especially when mixed, as the use of different mechanisms of action, increases the spectrum of control of different species (Knezevic et al., 2019). In this study, we used four mechanisms of action, protoporphyrinogen oxidase inhibitor herbicides, acetolactate synthase inhibitors, inhibitors of photosystem II and very-long-chain fatty acids inhibitors, which include the control of two main genera of soybean weeds, *Conyza* and *Digitaria*.

Another important factor contributing to the successful use of pre-emergent herbicides within the resistance management program is the possibility of year-round applications, as much in autumn/winter management where the risk to the subsequent crop is reduced (Bond et al., 2022), as in the beginning of the summer growing season (Cantu et al., 2021; Schramski et al., 2021).

4. Conclusions

The use of the mixture of two pre-emergent herbicides can delay the onset of CPWC in soybean without causing damage to its development and productivity. The variation obtained in days are a result of weed community at the area, crop sowing system and herbicide mechanism of action. Considering 5% acceptable losses, soybean can growth more than a month without weeds.

Author's contributions

ER, BDN, RGS and CBWB: carried out the experiment. ER: wrote the manuscript with support from AAMB and AJPA. ER and AAMB: conceived the original idea. AAMB: supervised the project.

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