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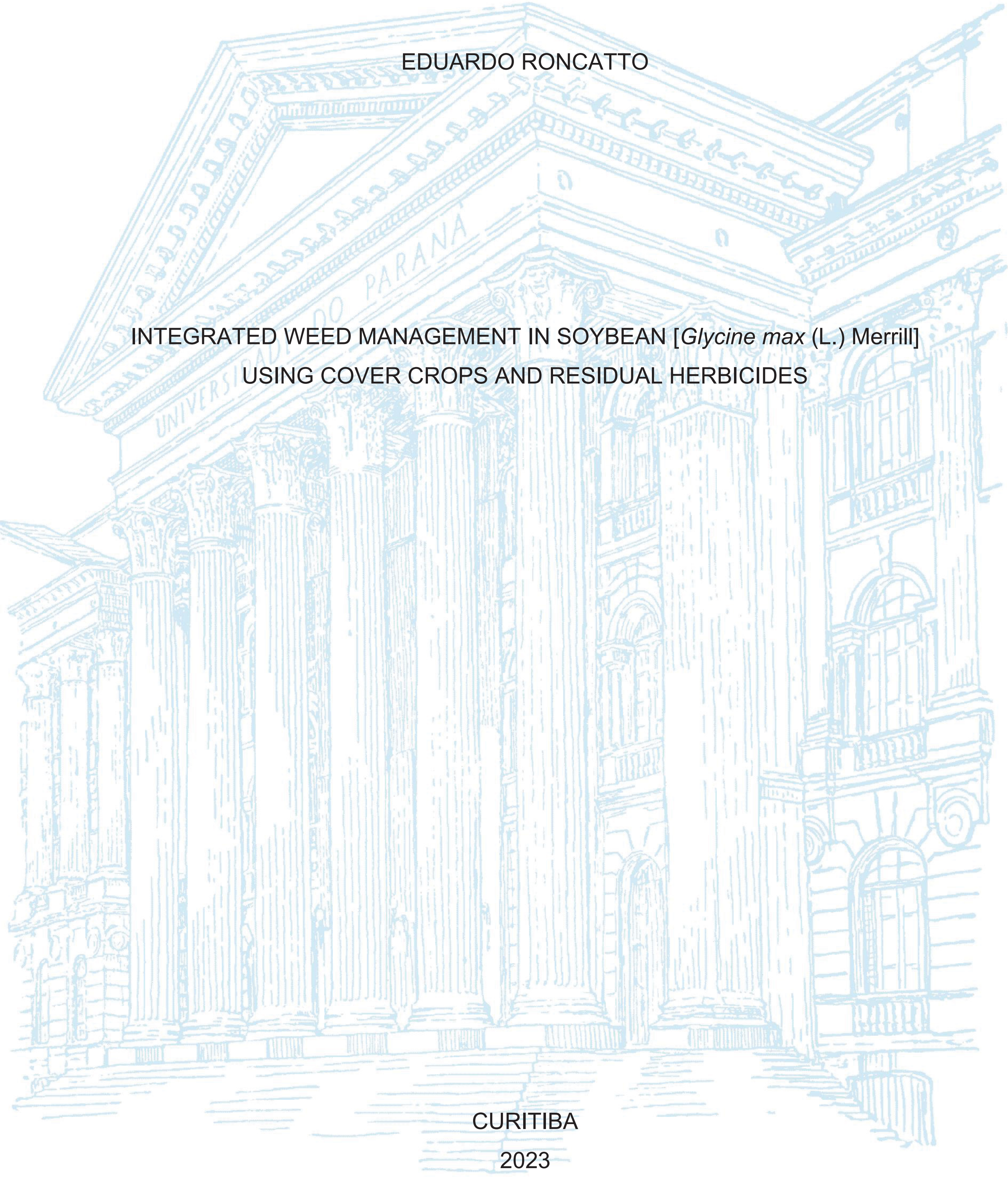

EDUARDO RONCATTO

INTEGRATED WEED MANAGEMENT IN SOYBEAN [*Glycine max* (L.) Merrill] USING COVER CROPS AND RESIDUAL HERBICIDES

CURITIBA
2023

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Tese apresentada ao curso de Pós-Graduação em Agronomia, Área de Concentração em Produção Vegetal, Setor de Ciências Agrárias, Universidade Federal do Paraná, como requisito parcial à obtenção do título de Doutor em Ciências.

Orientador: Prof. Dr. Arthur Arrobas Martins Barroso

Coorientador:Prof. Dr. Alfredo Junior Paiola Albrecht

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TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação AGRONOMIA (PRODUÇÃO VEGETAL) da Universidade Federal do Paraná foram convocados para realizar a arguição da tese de Doutorado de **EDUARDO RONCATTO** intitulada: **INTEGRATED WEED MANAGEMENT IN SOYBEAN [*Glycine max* (L.) Merrill] USING COVER CROPS AND RESIDUAL HERBICIDES**, sob orientação do Prof. Dr. ARTHUR ARROBAS MARTINS BARROSO, que após terem inquirido o aluno e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.

A outorga do título de doutor está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

CURITIBA, 10 de Março de 2023.

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Aos meus amados pais,
Dedico.

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BIOGRAFIA DO AUTOR

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Em março de 2023 concluiu o doutorado, com apresentação da tese INTEGRATED WEED MANAGEMENT IN SOYBEAN [Glycine max (L.) Merrill] USING COVER CROPS AND RESIDUAL HERBICIDES tendo como orientador o Prof. Dr. Arthur Arrobas Martins Barroso e coorientador o Prof. Dr. Alfredo Junior Paiola Albrecht.

CANÇÃO DO TAMOIO

Não chores, meu filho;
Não chores, que a vida
É luta renhida: Viver é lutar.
A vida é combate,
Que os fracos abate,
Que os fortes, os bravos,
Só pode exaltar.

Um dia vivemos!
O homem que é forte
Não teme da morte;
Só teme fugir;
No arco que entesa
Tem certa uma presa,
Quer seja tapuia,
Condor ou tapir.

O forte, o cobarde
Seus feitos inveja
De o ver na peleja
Garboso e feroz;
E os tímidos velhos
Nos graves conselhos,
Curvadas as frontes,
Escutam-lhe a voz!

Domina, se vive;
Se morre, descansa
Dos seus na lembrança,
Na voz do porvir.
Não cures da vida!
Sê bravo, sê forte!
Não fujas da morte,
Que a morte há de vir!

E pois que és meu filho,
Meus brios reveste;
Tamoio nasceste,
Valente serás.
Sê duro guerreiro,
Robusto, fragueiro,
Brasão dos tamoios
Na guerra e na paz.

Teu grito de guerra
Retumbe aos ouvidos
D'imigos transidos
Por vil comoção;
E tremam d'ouví-lo
Pior que o sibilo
Das setas ligeiras,
Pior que o trovão.

E a mãe nestas tabas,
Querendo calados
Os filhos criados
Na lei do terror;
Teu nome lhes diga,
Que a gente inimiga
Talvez não escute
Sem pranto, sem dor!

Porém se a fortuna,
Traindo teus passos,
Te arroja nos laços
Do inimigo falaz!
Na última hora
Teus feitos memora,
Tranqüilo nos gestos,
Impávido, audaz.

E cai como o tronco
Do raio tocado,
Partido, rojado
Por larga extensão;
Assim morre o forte!
No passo da morte
Triunfa, conquista
Mais alto brasão.

As armas ensaia,
Penetra na vida:
Pesada ou querida,
Viver é lutar.
Se o duro combate
Os fracos abate,
Aos fortes, aos bravos,
Só pode exaltar.

(Antônio Gonçalves Dias)

RESUMO

O manejo integrado de plantas daninhas, baseado em um modelo de agricultura ambientalmente equilibrada e sustentável, é eficaz no controle de espécies de plantas daninhas identificadas nos cultivos de grãos. No entanto, sua eficiência pode variar de acordo com os métodos de controle combinados e o ambiente de produção onde ocorre a interferência. Além disso, são incipientes os estudos discutindo a utilização do controle cultural e o uso de herbicidas residuais em diferentes ambientes no sul do Brasil. O objetivo deste trabalho foi investigar os benefícios proporcionados pelo uso de herbicidas residuais e plantas de cobertura dentro de um programa integrado de manejo de plantas daninhas na cultura da soja. O Capítulo I abordou a dinâmica de interação entre seis herbicidas residuais aplicados em quatro culturas de cobertura de inverno e seu efeito no controle de plantas daninhas na cultura da soja. Foram avaliadas a produção de biomassa das coberturas, a redução de massa seca e densidade de plantas daninhas causada pelas coberturas, o controle dos herbicidas pré-emergentes aplicados no verão e a produtividade da soja. A combinação entre culturas de cobertura de inverno e herbicidas pré-emergentes se mostrou eficiente para o controle de plantas daninhas no verão. O Capítulo II avaliou os efeitos do aumento do Período Anterior à Interferência (PAI) na produtividade da soja pela mistura de diferentes herbicidas residuais e suas implicações no manejo de plantas daninhas. Dois experimentos foram conduzidos em 2021/2022, um em sistema de preparo convencional e outro em sistema de plantio direto, ambos com períodos crescentes de convivência soja/infestantes e aplicação de misturas de herbicidas pré-emergentes após a semeadura. Após a determinação da produtividade em cada intervalo de interferência os dados foram comparados por regressões não lineares para determinação do início do Período Crítico de Prevenção a Interferência. A aplicação de herbicidas residuais garantiu a produtividade da soja em até 57% e aumentou o PAI de oito a quarenta dias, dependendo das misturas dos pré-emergentes e das perdas aceitáveis de 2, 5 e 10 %. O capítulo III teve como objetivo avaliar a eficiência de supressão de plantas daninhas na soja pelo cultivo de culturas de coberturas isoladas ou em mistura. Os tratamentos consistiram no cultivo de quatro espécies solteiras e quatro misturas entre as espécies, com ou sem aplicação de glifosato em pós-emergência. Foram avaliadas a produção de biomassa das coberturas de inverno e seu efeito na supressão de plantas daninhas no verão, além da produtividade da soja. Neste experimento a maior quantidade de massa seca produzida pelas espécies isoladas não contribuiu para o aumento da supressão da infestação observada. A produtividade da soja foi maior em ambiente com coberturas isoladas e aplicação de glifosato em pós-emergência. O emprego do MIPD contribui para tornar o ambiente produtivo mais estável e diversificado. A utilização de culturas de cobertura no inverno promove a supressão de plantas daninhas, reduzindo seus caracteres de massa seca e densidade, o que implica em manejo facilitado no cultivo de verão. A utilização de herbicidas pré-emergentes na soja reduz os fluxos de emergência em estádios iniciais da soja, aumenta o PAI e possibilita a rotação de mecanismos de ação, reduzindo a pressão de seleção causada pelo uso repetido do glifosato.

Palavras-chave: Manejo integrado, culturas de cobertura, herbicidas residuais

ABSTRACT

Integrated weed management, based on an environmentally balanced and sustainable agriculture model, is effective in controlling weed species identified in grain crops. However, their efficiency may vary depending on the combined control methods and the production environment where the interference occurs. Furthermore, studies discussing the use of cultural control and the use of residual herbicides in different environments in southern Brazil are incipient. This thesis aimed to investigate the benefits provided by the use of residual herbicides and cover crops within an integrated weed management program in soybean crops. Chapter I addressed the dynamics of interaction between six residual herbicides applied to four winter cover crops and their effect on weed control in soybean. Coverage biomass production, reduction in dry mass and weed density caused by cover crops, control of pre-emergent herbicides applied in summer and soybean yield were evaluated. The combination of winter cover crops and pre-emergent herbicides proved to be efficient for controlling weeds in summer. Chapter II evaluated the effects of increasing the Period Prior to Interference (PPI) on soybean productivity by mixing different residual herbicides and its implications for weed management. Two experiments were carried out in 2021/2022, one in a conventional tillage system and the other in a no-tillage system, both with increasing periods of soybean/weed coexistence and application of pre-emergent herbicide mixtures after sowing. After determining the productivity in each interference interval, the data were compared by non-linear regressions to determine the beginning of CWCP. The application of residual herbicides ensured soybean productivity by up to 57% and increased the PPI from eight to forty days, depending on the mixtures of pre-emergents and acceptable losses of 2, 5 and 10%. Chapter III aimed to evaluate the efficiency of weed suppression in soybean by growing cover crops alone or in mixture. Treatments consisted of growing four single species and four mixtures between species, with or without post-emergence glyphosate application. The biomass production of the winter covers and its effect on the suppression of weeds in the summer, in addition to soybean productivity, were evaluated. In this experiment, the greater amount of dry mass produced by the isolated species did not contribute to the increase in the suppression of the observed infestation. Soybean productivity was higher in an environment with isolated coverings and post-emergence glyphosate application. The use of MIPD contributes to making the productive environment more stable and diversified. The use of cover crops in winter promotes the suppression of weeds, reducing their dry mass and density characteristics, which implies easier management in summer cultivation. The use of pre-emergent herbicides in soybeans reduces emergence fluxes in early stages of soybeans, increases the AIP and enables the rotation of action mechanisms, reducing the selection pressure caused by the repeated use of glyphosate.

Keywords: Integrated management, cover crops, residual herbicides

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SUMMARY

GENERAL INTRODUCTION

The reduction in the availability of new crop lands suitable for food production, accompanied by population growth and its growing demand for food and energy, is a recurring theme in the debate on world food security. According to the United Nations (UN) the current world population is 8 billion people and will be approximately 9.7 billion inhabitants in 2050 (United Nations Department Of Economic And Social Affairs, 2022).

From an economic point of view, Brazil's agricultural production capacity maintains its positive trade balance. Products such as soybeans, coffee, sugar, corn, cotton, orange juice and beef made the country one of the world's largest exporters, in addition to making it self-sufficient (OECD, 2022). However, the intensification of production puts pressure on the use of natural resources and increases the risks of environmental impact. From this, new studies seek ways to mitigate environmental impacts through new technologies, management solutions and sustainable production.

Currently, corn and soybean production in Brazil is dependent on the application of pesticides, which represent 31% of the total production cost. Of the 421 thousand tons of phytosanitary products imported in 2021, 44% corresponds to the volume of herbicides (CAFFAGNI, 2022), which, if not used, compromise grain production, since weeds reduce the productivity of soybeans and corn, for example.

In this sense, the Integrated Weed Management (IWM) presents itself as a solution based on the integration of control methods, where the production system is less dependent on the application of herbicides, which can mitigate its use and reduce production costs. Through different control methods, an unfavorable environment for weeds is created, reducing their interference in grain production(KORRES et al., 2019; MONTEIRO; SANTOS, 2022).

The repeated use of the same molecules repeatedly caused selection pressure on plant populations and made this tool unusable for some species. There are currently 515 herbicide-resistant species in the world, with resistance to 21 of the

31 known sites of action (Heap, 2023). The projection for discovering new mechanisms of action by 2050 is not favorable, therefore, there is a need to safeguard the efficiency of molecules already used by adopting integrative solutions (DUKE; DAYAN, 2022).

The cultural control of weeds carried out with the cultivation of cover crops can mitigate the use of herbicides. Cover crops cultivated in the off-season can reduce the growth and development of weeds in this period, in addition, the accumulated plant biomass can contribute to the suppression of infestation in the subsequent crop, due to its ability to intercept light or release compounds that inhibit the germination of weeds (ROSE, T. J. et al., 2022; SINGH et al., 2022). The suppression efficiency depends on a number of factors such as biomass production and characteristics of each species. The cultivation of mixtures of cover species also favors the suppression of weeds, in addition to adding benefits to the chemical, physical and biological characteristics of the soil (REISS; DRINKWATER, 2022).

Considering that: (1) IWM is essential for weed management and for maintaining herbicide efficiency; (2) The interaction between residual herbicides and cover crops needs to be better understood, considering different cover species, physical-chemical characteristics of herbicides and soil; (3) Isolated or mixed cover crops promote different levels of weed suppression in winter. This thesis aimed to investigate the benefits provided by the use of residual herbicides and cover crops within an integrated weed management program.

Chapter I addressed the dynamics of interaction between residual herbicides applied on different winter cover crops and their effect on weed suppression in soybean crops.

Chapter II evaluated the effects of increasing the Period Prior to Interference on soybean productivity by mixing different residual herbicides and their implications for weed management.

Chapter III demonstrated how growing cover crops alone or in mixtures can provide significant levels of weed suppression during soybean cultivation.

CHAPTER I

RESIDUAL HERBICIDES AND COVER CROPS INTERACTIONS FOR SOYBEAN WEED CONTROL[1]

[1] This manuscript is presented according to the Journal of Agricultural Science guidelines

RESIDUAL HERBICIDES AND COVER CROPS INTERACTIONS FOR SOYBEAN WEED CONTROL

ABSTRACT

Residual herbicides and cover crops are important tools inside an integrated weed management program. The straw produced in crop rotation can interacts with herbicides. The aim of this study was to evaluate the interaction of diclosulam, sulfentrazone, imazethapyr, flumioxazin, s-metolachlor and pyroxasulfone with black oat, cereal rye, common vetch and oilseed radish cover crops and your reflection on weed control and soybean production. Was evaluated the biomass production of cover crops and its influence on the soybean population. A phytosociological survey of the weed community was carried out, further evaluating the control provided by the herbicides and its effects on soybean productivity. Diclosulam was the more efficient herbicide tested, reducing both weed density and biomass (68% and 89%, respectively) compared to the fallow. The best control levels for the population identified were provided by the combination of the herbicides diclosulam with black oat, radish or fallow. We observed that herbicide efficacy in this case was more related with control spectrum than with herbicide-straw interation. This research demonstrates that the integration of cover crops and residual herbicides is efficient in the suppression and control of weeds in the soybean crop in the no-tillage system.

Keywords: Black oat, diclosulam, pre-emergent herbicides, integrated weed management

1.1 INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) is an important oilseed for human and animal nutrition, with 40.4 million hectares being cultivated in Brazil with production of up to 141 million tons of grain, produced in more than 58% of the country’s arable area (United States Department of Agriculture [USDA] 2022).

Is currently cultivated in the no-tillage system (NTS) which has as fundamental precepts the permanent vegetation cover and the seeding on the plant biomass of the predecessor crop. The success of the no-tillage system in tropical and subtropical environments is due to the cultivation of cover species combined with the use of the herbicide glyphosate for its desiccation (Day et al., 2020; Kan et al., 2020)

The advent of transgenic RR (RoundUp Ready) soybean made it possible to control weeds with glyphosate also in crop post-emergence. However, the repeated use of the herbicide ended up selecting resistant weeds, which led to an increase of 149.14% in the use of herbicides between 2007 and 2014 in Brazil (Agrofit, 2020), in addition to the increase in environmental problems such as the drift of herbicides to non-target areas (Vieira et al., 2020).

The worldwide demand for the production of food without specific patterns of chemical residues and the recent cases of limitation and prohibition of the use of glyphosate in countries in Europe and Latin America, also place Brazil at the center of the discussion on reducing the use of pesticides in food production on a global scale (Miyazaki, Bauer-Panskus, Bøhn, Reichenbecher, & Then, 2019).

In this sense, the cultivation of cover species to maintain no-till also contributes to mitigating the use of herbicides. The establishment of cover crops is an excellent alternative for reducing the density and biomass accumulation of the weed community in the autumn and winter period and in summer crops as weeds and crops compete for light, water and nutrients (Akobundu et al., 2000; Blackshaw et al., 2001; Brennan & Smith, 2005; Grimmer & Masiunas, 2004; Peachey et al., 2004; Stivers-Young, 1998). In addition, cover crops are responsible for the interception and absorption of light that acts on the germination of weed seeds and, in some cases, their suppression by allelopathy (Teasdale & Daughtry, 1993).

Rotating mechanisms of action by using residual herbicides can also reduce glyphosate use within a management program, as well as new cases of resistance (Heap & Duke, 2018). When applied at the time of seeding, pre-emergent herbicides promote a prolonged control of weeds in the early stages of the crop, increasing the period prior to interference (PPI) (Rizzardi, Rockenbach, & Schneider, 2020).

Studies show that the use of pre-emergence herbicides in conjunction with cover crop cultivation within a weed management program can be effective in reducing interference in early summer (Cornelius & Bradley, 2017; Wiggins, Hayes, & Steckel, 2016).

The cover straw cultivated in the winter promotes soil shading and contributes to the reduction of weed species germination, on the other hand, this physical barrier can also reduce the efficiency of herbicides, since they have solubility characteristics that depend on a certain amount of water to break the straw and reach the ground (Da Silva et al., 2020). Higher straw densities can mitigate herbicide transposition, increasing the possibility of degradation (Fornarolli, Rodrigues, Lima, & Valério, 1998; Reddy et al., 1995).

Under these conditions, research is needed that point to the development of sustainable and economically viable production systems, focusing on the search for integrative solutions for different weed control methods, from the establishment of cover crops in winter to the end of the cycle of summer culture. The objective of this work was to evaluate the efficacy of weed control, soybean selectivity from residual herbicides interacting without and with cover crops straw.

1.2 MATERIAL AND METHODS

1.2.1 Location and description of treatments

This experiment was carried out during the 2020/2021 season at Gralha Azul Experimental Farm, at Pontifical Catholic University of Paraná - PUCPR, located at Fazenda Rio Grande, Paraná, Brazil (25°39'9.65"S; 49°16'50.66"W). The region has a Cfb climate according to Köppen classification, with Allic Oxisoil + Allic Inceptisoil, with prominent A horizon and gently undulating relief. According to the analysis, the soil had the following chemical and physical characteristics: pH in $CaCl_2$, 4.8; Ca, 4.23 cmol dm^{-3}; Mg, 2.54 cmol dm^{-3}; Al, 0.2 cmol dm^{-3}; H+Al, 7.42 cmol dm^{-3}; CTC pH7, 14.38 cmol dm^{-3}; SMP, 5.3; P, 8.12 mg dm^{-3}; K, 0.19 cmol dm^{-3}; base saturation (V%) of 48.4%; Soil organic matter (SOM), 42.13 g dm^{-3}; 350g kg^{-1} of clay, 210 g kg^{-1} of silt and 440g kg^{-1} of sand.

The accumulation of precipitation during the experiment was 1250 mm, with low precipitation accumulated in the summer months. After fertilization with mineral N, a precipitation of 20 mm was observed, that contributed to dissolve the fertilizer. A precipitation of 18 mm was also observed five days after the summer sowing, which contributed to a good germination and emergence of the soybean, also favoring the action of pre-emergent herbicides applied on the day of sowing. Figure 1 shows precipitation and temperature data during the conduct of the experiment.

Four species of winter cover crops were established in this area: black oat (*Avena strigosa* S.), cereal rye (*Secale cereal* L.), common vetch (*Vicia sativa* L.), oilseed radish (*Raphanus sativus* var. *Oleiferus*) plus a control treatment (fallow without cultivation). Sowing densities were: 66 kg ha^{-1} for black oat, 84 kg ha^{-1} for cereal rye, 96 kg ha^{-1} for common vetch and 20 kg ha^{-1} for oilseed radish, defined according to the technical manual of plants cover (Calegari, 2016). Seeding was carried out by broadcast seeder, followed by light harrowing. The seeds used in the experiment were purchased commercially.

During the winter cover cycle, maintenance nitrogen fertilization (150 kg of nitrogen per hectare in form of urea 45%) was carried out for each treatment as recommended in the fertilizer and liming guidelines for the states of Rio Grande do Sul and Santa Catarina (Sousa & Ermani, 2016). After a period of 110 days from sowing (june to october), the covers were desiccated with 1,860 g ae ha^{-1} of glyphosate (Glizmax Prime, 480 g ea L^{-1}, Dow AgroSciences, São Paulo, Brazil).

The treatments applied were: no herbicide and hand weeding (weedy); no herbicide with hand weeding (check); 35.28 g i a ha^{-1} of diclosulam (Spider® 840WG, 840 g kg^{-1}, Dow AgroSciences Industrial Ltda - Barueri/SP); 600 g i a ha^{-1} of sulfentrazone (Boral® 500 SC, 500 g L^{-1}, FMC Química do BrasilLtda - Campinas/SP); 100 g ea ha^{-1}of imazethapyr (Pivot®100 SL, 100g L^{-1}, BASF S.A. - São Paulo/SP); 60 g i a ha^{-1} of flumioxazin (Flumyzin 500, 500 g kg^{-1}, Sumitomo Chemical do Brasil Representações Ltda – SaoPaulo-SP); 1,440g i a ha^{-1} of s-metolachlor (Dual Gold 960g L^{-1},Syngenta Proteção de Cultivos Ltda. - São Paulo/SP);100 g i a ha^{-1}of pyroxasulfone (Yamato®SC 500g L^{-1}, IHARABRAS S.A. Indústrias Químicas - Sorocaba/SP). Each plot had 2,5m x 4m (5 crop rows), with four replications, arranged in a split-plot design and factorial scheme experiment.

The applications were carried out on the day of soybean sowing, using a backpack spray pressurized by CO_2 at a constant pressure of 3 kPa, equipped with an one-meter application bar equipped with two tips and AIXR110015 nozzles (TeeJet Technologies, Wheaton, IL), regulated to deliver 200 L ha^{-1}. The soybean cultivar DM 53i54 was sown on November 25th, has an indeterminate growth habit, average cycle of 125 days in the state of Paraná and belongs to maturity group 5.4, showing stability and high yield potential in a subtropical climate. The sowing density was 350 thousand plants per hectare with 0.45m spacing between rows.

1.2.2 Data collection and analysis

In order to measure the accumulation of dry mass provided by the cover crops during the winter and the amount of straw at the time of sowing, the plant cover was collected before desiccation with the aid of a 0.062 m² frame, in four replications, totaling 0.25m sampling. Samples were dried by heating in an oven with forced air circulation at 60°C for 72 hours. For soy, was evaluated the number of plants per linear meter and the visual phytotoxicity herbicide according to the European Weed Research Council (EWRC, 1964) at 28 days after emergence, considering two central lines of the plot.

At 42 days after soybean emergence (DAE), a visual evaluation of weed control was performed following a scale from 0% to 100%, where 0% represented no control and 100% the absence of weeds. On the same date, with the aid of a 0.25 m^2 frame, the phytosociological evaluation of the weed community was carried out to determine the phytosociological descriptors (density, dry mass and frequency of the species present), applied to the study of the horizontal structure of plant communities, with further calculation of the relative importance of species in treatments without residual herbicide with manual weeding (Ellenberg & Mueller-Dombois, 1974).

At the end of the soybean cycle (114 days), the harvest was carried out, where the three central lines of the plot were cut into three linear meters, totaling a sampling of 4.05 m². The samples were threshed with a soybean thresher, thus obtaining the average productivity of the plots. With grain moisture corrected to 13%, it was possible to determine the soybean yield per hectare (kg ha^{-1}) by extrapolation. Data were subjected to analysis of variance using the F test ($p \leq 0.05$). In cases of significance, the means were compared by the Tukey test ($p \leq 0.05$) using the R statistical software (R Core Team, 2020).

1.3 RESULTS

1.3.1 Cover crop biomass

The biomass production by cover crops show no significant differences between black oat, cereal rye and oilseed radish at the time of soybean sowing (Figure 2). The lowest biomass accumulation was observed in fallow (1.665 ton ha^{-1}), differing from black oat and cereal rye. Black oat produced more dry matter than common vetch. Overall, cereals produced 75% more biomass when compared to oilseed radish and common vetch covers.

Analyzing the effect of cover crop straw on sowing quality and the final stand of soybean plants (Figure 3), it was observed that the greater accumulation of black oat biomass altered the dynamics of seed emergence, causing a reduction in the amount of viable plants per linear meter.

1.3.2 Weed Suppression

There was no significant interaction between the factors cover crops and herbicides, however, analyzing the factors separately, significant differences were observed in the effect of herbicides and cover crops on weed density. It was observed that only diclosulam reduced weed density compared to the untreated check (6.15 x 19.53 plants m^2), values 68% lower. The herbicide imazethapyr showed greater reductions than those observed for the herbicides sulfentrazone, s-metolachlor and pyroxasulfone (Figure 4). For the coverings, the population was major reduced by black oat straw (10.96 x 19.53 plants m^2), a reduction of 43% (Figure 5).

Weed dry mass (Figure 6) was altered only by the use of herbicides. The greatest effect of reducing plant development was caused by the herbicides diclosulam (2.83 g m^2) and imazethapyr (4.48 g m^2), both ALS inhibitors, which reduced by 89 and 82% weed biomass compared to the control (26.09 g m^2).In contrast, sulfentrazone, s-metolachlor, pyroxasulfone and flumioxazin did not reduce weed development.

No significant differences were observed in the effect of cover crops on weed density, however, the reduction in dry mass provided by the different cover crops average was 19.57 g m², 12% lower compared to the fallow (22.43 g m²).

1.3.3 Weed control

Weed community present in the experiment was composed mostly of dicotyledonous plants (96%), distributed in eight species and six families, with a predominance of wild radish plants (*Raphanus raphanistrum*) 84,5%, followed by Hairy beggarticks (*Bidens pilosa*), Common lambsquarters (*Chenopodium giganteum*), Black oats (*Avena strigosa*), Cereal rye (*Secale cereal*), Hairy fleabane (*Conyza spp.*), Tropic ageratum (*Ageratum conyzoides*) and Brazil pusley (*Richardia brasiliensis*), totaling 100%.

For the visual control of herbicides, there was an interaction between the analyzed factors and a significant difference between the averages of the treatments. Several herbicides analyzed showed very low control, such as s-metolachlor (5.6%), pyroxasulfone (3%) and flumioxazin (13.51%), including that observed in fallow, demonstrating that this behavior is linked to control inefficiency for the observed species and not the interference of the cover crop in the movement of the herbicide to its target. The herbicide diclosulam promoted greater control of weeds when compared to the others regardless of the cover crop (Table 1). Imazethapyr, showed similar results to diclosulam, in coverings with black oat and oilseed radish.

Cover crops did not modify the observed efficacy of diclosulam, flumioxazin, and pyroxasulfone. Black oat improved the observed efficacy of sulfentrazone and imazetaphyr. Cereal rye cover improved the observed efficacy of imazethapyr and s-metolachlor. Common vetch cover improved the observed efficacy of imazetaphyr.

The herbicide flumioxazin (enzyme protopor-phyrinogen oxidase inhibitor, PROTOX) was not efficient in controlling the weed population, however, it was superior when compared to the efficacy of the herbicides s-metolachlor and pyroxasulfone.

1.3.4 Soybean yield

For soybean, symptoms of phytotoxicity can occur because residual herbicides application. Low symptoms were noted 14 days after sulfentrazone application (less than 5%). After 28 days, no further damage to crop development was observed (data not shown). For average soybean yield, a significant interaction of the effect of herbicides with the different winter coverings was observed.

In the unfolding of the herbicide factor, the treatment without winter covering with the applications of imazethapyr and diclosulam increased soybean yield. Flumioxazin and sulfentrazone applications had no effect. The application of diclosulam and imazetaphyr did not show differences from a fallow condition (Table 2). In black oat, the crop that most reduced the presence and development of weeds, the treatments with diclosulam and imazethapyr had higher yields. The same was observed for cereal rye and common vetch. For oilseed radish only treatment with imazethapyr reduced weed development.

Comparing the chemical and cultural method, the yield obtained by using cover crops as the only method of weed suppression was not sufficient to guarantee higher yields. The summation effect of chemical control can be observed when comparing the isolated effect of black oat crop (1 820.99 kg ha^{-1}) with the effect of application of herbicides in fallow. Values ranged from 2 094.44 kg ha^{-1} to 3 556.00 kg ha^{-1} (treatments with sulfentrazone and diclosulam, respectively). The worst situation observed was in fallow without application of residual herbicide, reaching soybean yield of 1 679.01 kg ha^{-1}.

1.4 DISCUSSION

1.4.1 Cover crop biomass

The establishment of winter cover crops is essential in maintaining the no-tillage system, enhancing soil healthy in addition to reducing weed emergence in the early stages of the crop. According to (Nunes et al., 2006), the ideal minimum amount of biomass for ground cover in the no-tillage system should be 6.0 ton ha^{-1} near what was observed for black oat. On the other hand, excess of straw can make sowing difficult, because straw cutting and seeds/fertilizers depositions are affected (Trogello, José Modolo, Scarsi, & Dallacort, 2013).

Moderated cereal rye seeding densities, as 67 kg ha^{-1}, do not affect the soybean stand, however, seeding densities varying between 100-135 kg ha^{-1}, can cause a reduction in the soybean population up to 4% (Essman, Loux, Lindsey, Dobbels, & Regnier, 2020; Schramski, Sprague, & Renner, 2021). Our results support these observations, since the sowing density of cereal rye used in this experiment was 84 kg ha^{-1}, with no differences in soybean emergence compared to the fallow treatment.

According to Modolo et al. (2020), the exacerbated accumulation of biomass can negatively affect the number of plants per hectare, reducing the successor crop's productivity. In this sense, actions such as the reduction of nitrogen fertilization of the covers and early desiccation can be interesting management alternatives to avoid a substantial increase in biomass in years with greater precipitation.

1.4.2 Weed Suppression

The production systems are much diversified and vary according to their location, altitude, soil and relief. The same happens in the establishment of weed communities. Although there was no significant interaction of the factors, both the cover crops and the herbicides decreased the density and dry mass of weeds growing with soybean. The use of residual herbicides has been one of the main methods of annual weed control, and is one of the main recommendations for the management of herbicide resistance (Somerville, Powles, Walsh, & Renton, 2017).

Previous research shows that the application of residual herbicides in combination with cover crops residues can provide farmers adequate weed control at the end of the season (Cornelius & Bradley, 2017; Wiggins, Hayes, & Steckel, 2016), because the use of coverings during winter reduces the incidence of light on the soil, reducing the temperature range, reducing the germination rate of some weed species (Teasdale & Mohler, 1993). In addition to promoting a change in edaphoclimatic conditions, biomass residues have the ability to suppress weed growth by releasing allelopathic compounds that act as growth inhibitors in the weed rooting zone (Burgos, Talbert, & Mattice, 1999; Olofsdotter, Jensen, & Courtois, 2002).

According to Brennan and Smith (2005), the amount of cover crop biomass determines the level of plant suppression, as greater amounts of residues provide greater suppression. However, the suppression exclusively by the cultivation of winter covers varies from year to year, because the production of dry mass is influenced by particular conditions of each environment, such as fertility, average rainfall and average temperature during its cycle and weed community, basically composed by soil seedbank (Schramski et al., 2020).

Even with the average dry mass reduction of the herbicides diclosulam and imazethapyr being higher than the average of the effect of all the coverings, we cannot say that the herbicides were more efficient than the coverings for weed suppression in this case, because coverages such as common vetch and oilseed radish caused higher density reduction and dry mass when compared to the herbicide sulfentrazone, for example. In this case, soybean yield and economic return should be considered.

1.4.3 Weed control

For visual control, there was a significant interaction between herbicide and cover factors, showing synergism of some combinations, demonstrating the importance of adopting weed management programs that include control methods both in winter and in summer. The same result was observed by Whalen et al., (2020), where they concluded that the use of pre-emergence herbicides in conjunction with cover crops is more efficient in controlling weeds when compared to management only with herbicides in the summer. Wiggins et al., (2016) found that rye, hairy vetch (*Vicia villosa*), clover (*Trifolium*) or winter wheat (*Triticum aestivum*) in combination with a residual herbicide resulted in 87% control of pigweed (*Amaranthus albus*), with a control of 65% being observed where cover crops did not receive added residual herbicide effect. The main characteristic of residual herbicides is their prolonged action on the soil seed bank, reducing germination and seedling emergence. After its application, the residual herbicide control efficiency decreases over time, because in contact with the environment, the molecule can be subject to photodegradation, volatilization, chemical and biological degradation and sorption processes (Silva et al., 2007).

Schramski et al. (2020), observed 99% control of horseweed (*Conyza spp.*) when using the mixed herbicides glyphosate + 2,4-D + flumioxazin + metribuzin, regardless of the presence of plant cover, however, even with the efficiency of control by herbicides, the author emphasizes the need for a crop cover in order to reduce horseweed biomass and obtain better control with the application of a post-emergence herbicide only.

The herbicide action dynamics can change due to precipitation conditions, however, there was no observation of the negative influence of cover on the chemical control of weeds, since there were no water limitations after the application of the herbicides in this work. An accumulated precipitation of 18 mm was observed up to five days after application (Figure 7), enough to reduce the possibilities of adsorption of molecules on the straw and facilitate the concentration of the herbicide in the solution (Clark et al., 2019; Da Silva et al., 2020).

The inferior control performances of the herbicides s-metolachlor, pyroxasulfone and sulfentrazone in this case, occurred due to the predominance of wild radish plants in the experiment, as these herbicides act mainly in the control of monocotyledonous and are not recommended for the two species with highest relative importance identified (Agrofit, 2020).

It is worth mentioning that there are already cases of wild radish resistance to ALS-inhibiting herbicides in Brazil and multiple resistance in Australia (Heap, 2021), in this case, the better performance of ALS inhibitors herbicides could be compromised by the presence of biotypes resistant to this mechanism of action.

1.4.4 Soybean yield

For average soybean yield, a significant interaction of the effect of herbicides with the different winter coverings was observed. Such behavior was also observed by Schramski et al. (2020), when soybean yield varied between 52-145% higher only using residual herbicides, and between 19-75% higher only using cover crops.

The yield obtained in the treatment characterized by the absence of weeds and residual herbicides confirms that the volume of biomass produced by cover crops did not change yield, even though, previously observed, affected soybean seed emergence. Such a difference in the plant stand is a factor that can be compensated for, as soybean plants can modify their individual development to compensate for empty row spaces (Moore, 1991; Pires et al., 1998; Thomas et al., 1998).

Cover species such as sorghum (*Sorghum bicolor L.*) cause soybean suppression by releasing allelopathic compounds with yield effects (Denadai, De Mello, Chioderoli, & De Niro Gazola, 2016), however, for Almeida (1991), allelopathic compounds released by cereal rye, oilseed radish and oat (*Avena sativa*) roots do not interfere in the germination percentage of soybean seeds. Bortolini and Fortes., (2005), studying allelopathy caused by cover crops, concluded that root exudates from black oat and hairy vetch plants do not reduce soybean seed germination.

Comparing the chemical and cultural method, the yield obtained by using cover crops as the only method of weed suppression was not sufficient to guarantee higher yields. The summation effect of chemical control can be observed when comparing the isolated effect of black oat crop (1 820.99 kg ha^{-1}) with the effect of application of herbicides in fallow. Values ranged from 2 094.44 kg ha^{-1} to 3 556.00 kg ha^{-1} (treatments with sulfentrazone and diclosulam, respectively). The worst situation observed was in fallow without application of residual herbicide, reaching soybean yield of 1 679.01kg ha^{-1}. This research confirms the results of other studies that have shown the ability of winter cover crops to reduce weed density and dry mass, but reinforces that residual herbicides are still essential in the management program (Cornelius & Bradley, 2017; Essman et al., 2020).

The effect of cover crops plus straw interactions is an important management alternative that should be increasingly explored due to the use of more than a single control method. The interaction of the herbicide with the straw and the soil is a complex process, each herbicide has particularities regarding its physical/chemical factors, and the variation in coverage makes it even more difficult to study their relationships. More studies should be carried out considering the herbicide dynamics in different weed communities.

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1.6 APPENDIX

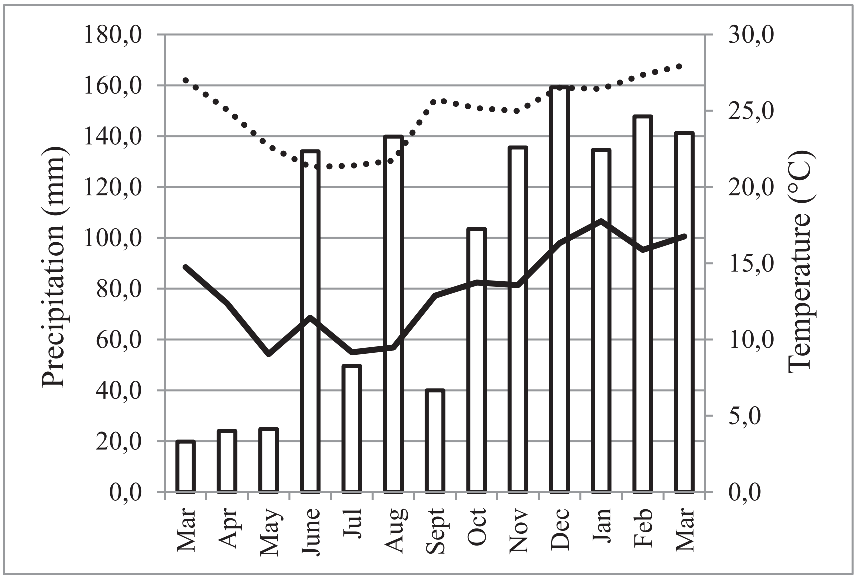

Figure 1. Average daily temperature and daily precipitation during the months of the experiment Fazenda Rio Grande (PR) 2020/2021.

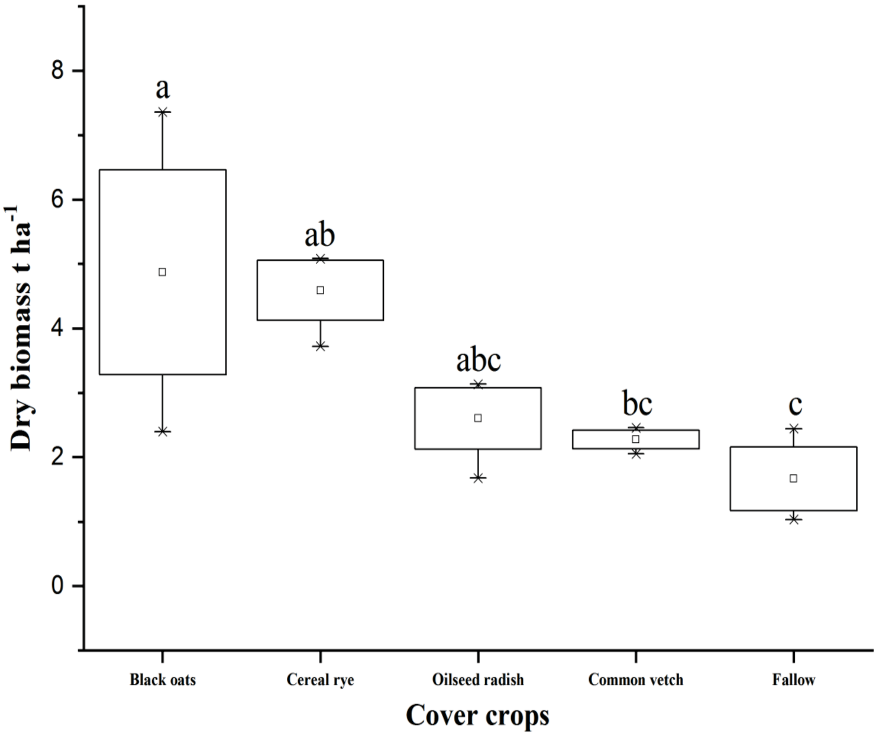

Figure 2. Cover crops dry mass averages, in tons per hectare, at the time of soybean sowing. Significant differences are indicated by bars topped with different letters . (p ≤ 0.05).

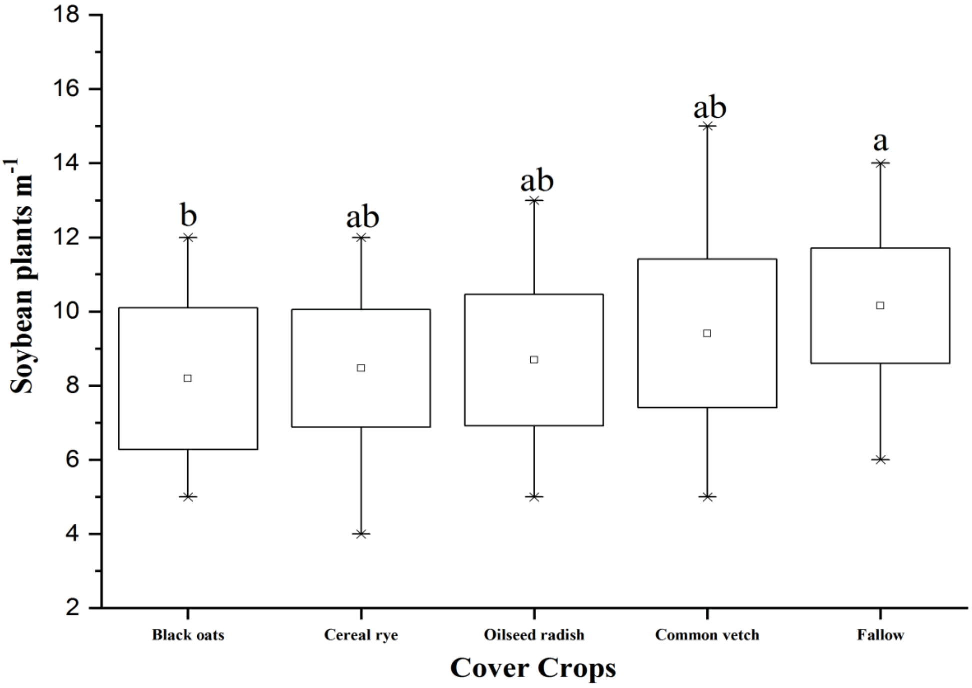

Figure 3. Number of soybean plants per linear meter at 28 days after emergence in different soil covers. Significant differences are indicated by bars topped with different letters . (p ≤ 0.05).

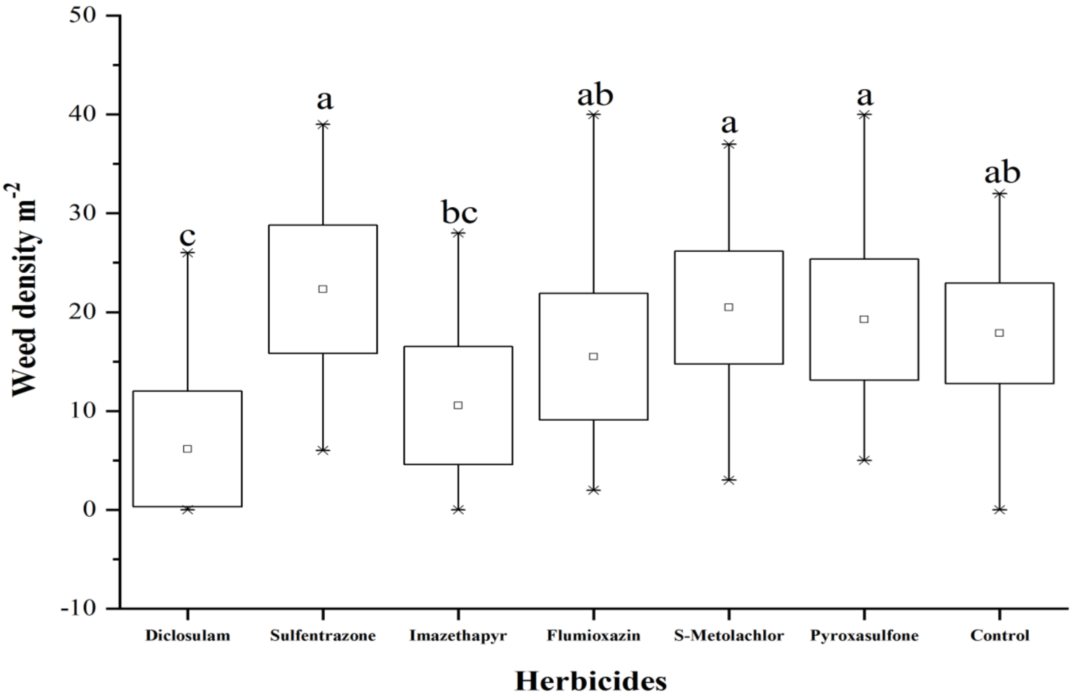

Figure 4. Effect of different herbicides on weed density per square meter at 42 days after soybean emergence. Significant differences are indicated by bars topped with different letters . (p ≤ 0.05).

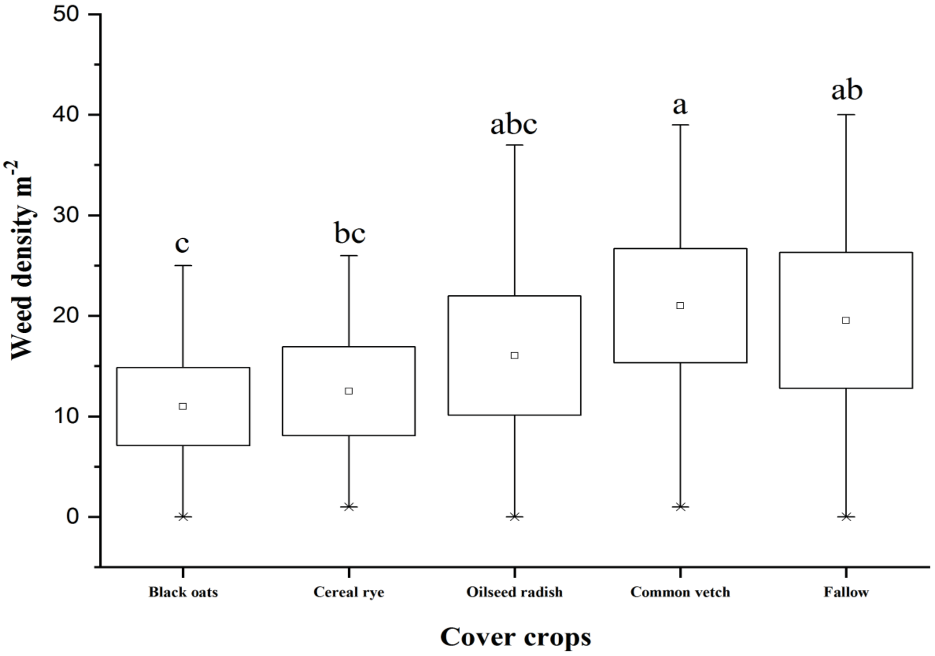

Figure 5. Effect of different cover crops on weed density per square meter at 42 days after soybean emergence. Significant differences are indicated by bars topped with different letters . ($p \leq 0.05$).

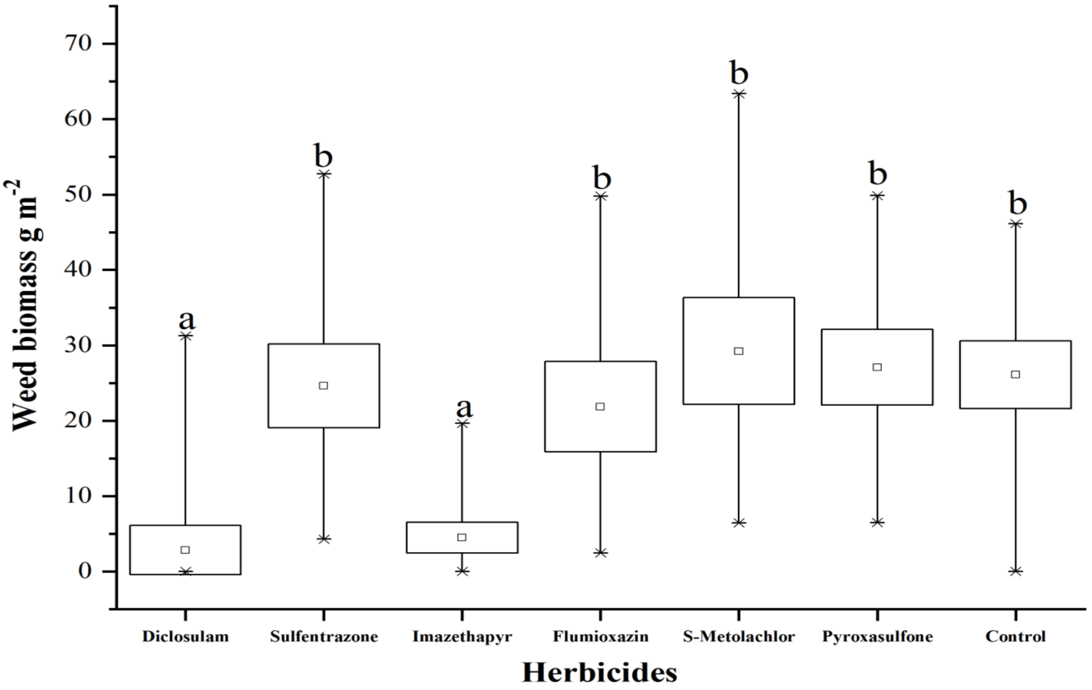

Figure 6. Effect of different herbicideson weed biomass per square meter at 42 days after soybean emergence. Significant differences are indicated by bars topped with different letters . ($p \leq 0.05$).

Table 1. Weed control (%) at forty-two days after soybean emergence sowed under different cover crops. Fazenda Rio Grande (PR), 2021.

	Herbicides							
species	check	diclosulam	sulfentrazone	imazethapyr	flumioxazin	s-metolachlor	pyroxasulfone	weedy
Black oat	100 Aa	74 ABb	21.25 ABc	62.5 Ab	17.5 Acd	5 Bde	2.5 Ade	0 Ae
Cereal rye	100 Aa	58 Bb	33.75 Acd	40.0 Bc	22.5 Ade	23 Ade	7.5 Aef	0 Af
Oilseed radish	100 Aa	69 ABb	16.25 BCc	63.8 Ab	8.75 Acd	0 Bd	0 Ad	0 Ad
Common vetch	100 Aa	75 Ab	22.50 ABcd	35.0 BCc	11.3 Ade	0 Be	0 Ae	0 Ae
Fallow	100 Aa	69 ABb	3.75 Cd	21.3 Cc	7.5 Acd	0 Bd	5 Ad	0 Ad

Note. Averages in the same column followed by distinct capital letters and in the row followed by differ lowercase letters differ by Tukey test (p≤0.05).

Table 2. Effect of cover crops and residual herbicides on grains final productivity (kg ha^{-1}) in the soybean. Fazenda Rio Grande (PR), 2021.

	Herbicides							
Species	check	diclosulam	sulfentrazone	imazethapyr	flumioxazin	s-metolachlor	pyroxasulfone	weedy
Black oat	3 366.67 Ab	2 973.46 ABa	1 941.98 CDbc	3 287.04 Aab	2 369.76 BCDa	2 478.4 BCa	2 420.99 BCDa	1 820.99 Da
Cereal rye	3 832.72 Aab	3 498.15 Aa	2 579.63 Ba	3 316.05 Aab	2 537.66 Ba	2 548.15 Ba	2 540.13 Ba	1 655.56 Ca
Oilseedradish	4 135.19 Aa	3 064.2 Ba	2 318.52 CDab	3 746.92 Aa	1 750 DEb	2 659.88 BCa	2 503.09 BCa	1 575.93 Ea
Common vetch	3 255.56 Ab	3 219.75 Aa	1 611.73 Cc	2 920.99 ABb	2 453.09 Ba	2 323.46 Ba	2 490.13 Ba	1 546.3 Ca
Fallow	3 828.4 Aab	3 556.79 Aa	2 094.44 DEabc	3 354.32 ABab	2 259.26 DEab	2 639.51 CDa	2 918.52 BCa	1 679.01 Ea

Note. Averages in the same row followed by distinct capital letters and in the column followed by differ lowercase letters differ by Tukey test (p≤0.05).

CHAPTER II

INCREASING THE PERIOD PRIOR TO INTERFERENCE IN SOYBEAN BY MIXING RESIDUAL HERBICIDES [1]

[1] This manuscript is presented according to the Advances in Weed Science Journal guidelines

INCREASING THE PERIOD PRIOR TO INTERFERENCE IN SOYBEAN BY MIXING RESIDUAL HERBICIDES

HIGHLIGHTS

-Pre-emergent herbicide mixtures reduce weed interference and enhances soybean yield.

-Pre-emergent herbicides mixtures with residual weed control can delay the critical period of weed control up to 40 days.

-Pre-emergent herbicide mixtures combining ALS, PROTOX and VLCFA inhibitors can be safe for soybean development.

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 start 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, diuron + sulfentrazone were applied, in addition to the treatment without pre-emergence herbicide. Soybean yield was evaluated at grain maturity, and data compared by non-linear regressions to CPWC determination.

Results: The application of residual herbicides can ensure soybean yields 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.

2.1 INTRODUCTION

The presence of weeds can cause competition for crop essential resources, such as water, light, nutrient absorption and space occupation. Soybean 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, 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´s 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 (SIAGRO, 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's 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.

2.2 MATERIAL AND METHODS

2.2.1 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.

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.

2.2.2 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. The sub-plot factors were 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 m^2). 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 CO2 at a constant pressure of 2 PSI, 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.

2.2.3 Data collection and analysis

Three linear meters of soybean were hand harvested from the two middle rows of each plot (4.05 m^2) and then threshed to determine yield. Yields were reported at 13% moisture. A three-parameter Weibull model of the drc package (Ritz and 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).

2.3 RESULTS AND DISCUSSION

At PUCPR, weed community was composed mostly of dicotyledonous plants (96%), 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. No differences were found in soybean yield for the different periods of weed removal and for both conditions (with and without pre-emergent herbicides). It seems that the absence of straw in this system, favored the local weed community, major formed by radish, which caused 21% 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.

2.3.1 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 sum of 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, and many weed species have germination period that extend even in advanced periods of crop development. 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 and 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.

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 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% 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 (t1/2) 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.

2.3.2 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.

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, 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.

2.3.3 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; Somerville et al. 2017). 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 aet al., 2021; Schramski et al., 2021).

2.4 CONCLUSIONS

The use of the mixture of two pre-emergent herbicides can delay the beginning 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.

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2.6 FIGURES AND TABLES

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		4.23	4.02
Mg		2.54	0.89
Al	cmol dm^{-3}	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		8.12	7.18
V%	g dm^{-3}	48.4	43.16
SOM		42.13	22.59
clay		35	66.25
silt	g 100 g^{-1}	21	18.75
sand		44	15.00

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 lowercase letter vertically or by a capital letter horizontally do not differ from each other (Tukey, $p \leq 0.05$)

Table 3. The beginning of the critical period of weed control (CPWC) 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

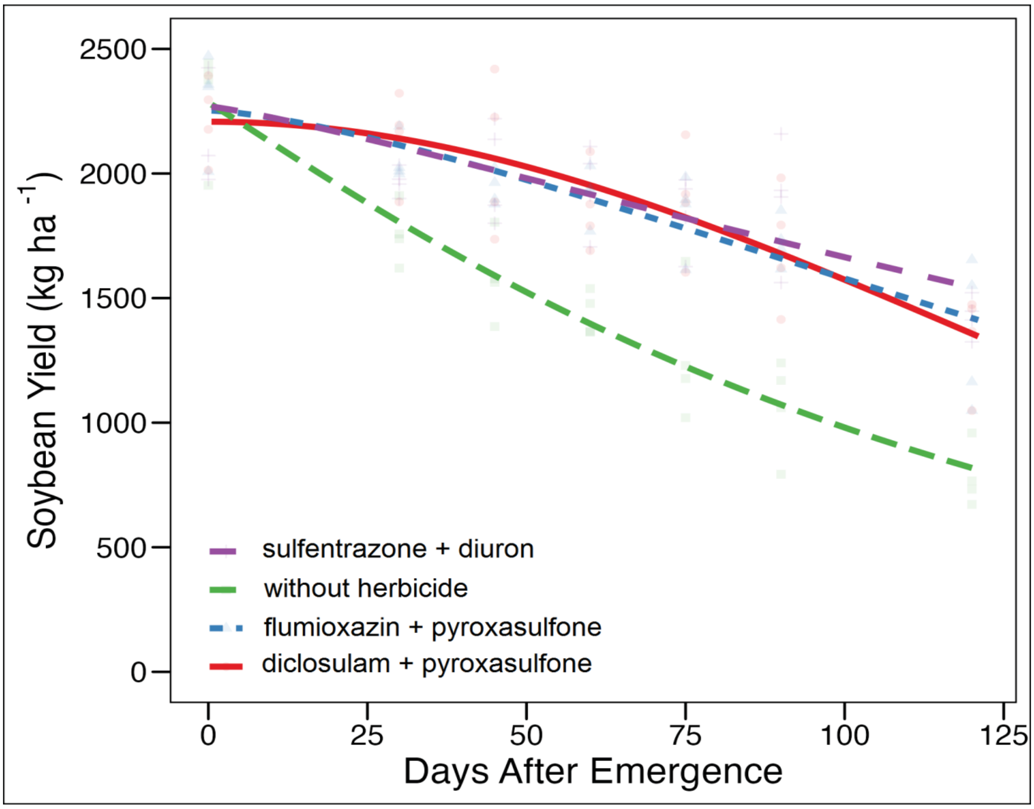

Figure 1. Loss of soybean productivity as a function of the increase in days of coexistence with weeds and the application of different treatments with pre-emergent herbicides at sowing. Equation: $y = d\ exp(-\ exp(b(log(x) - e)))$

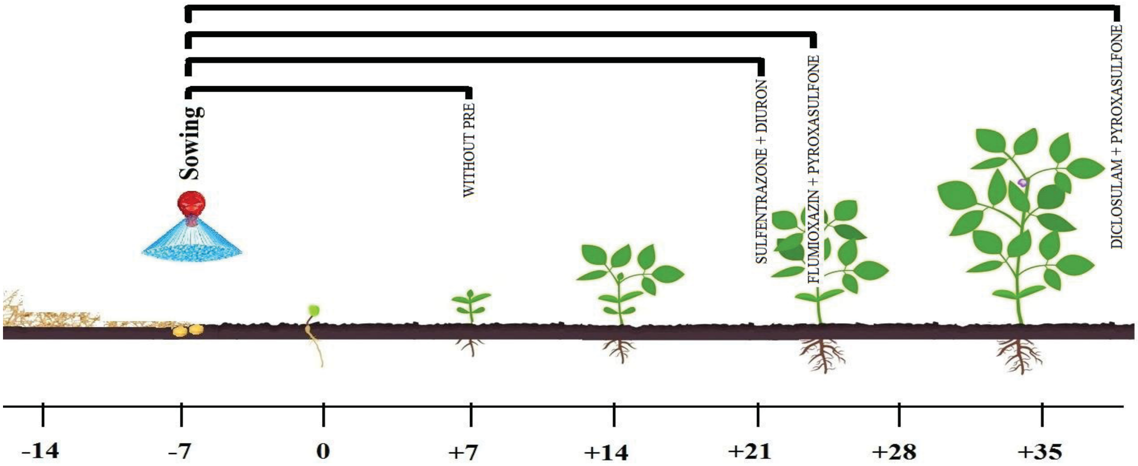

Figure 2. The beginning of the critical period of weed control - CPWC, with and without the using pre-emergent herbicide mixtures, considering acceptable losses of 5% at soybean yield.

CHAPTER III

WEED SUPPRESSION BY COVER CROP MONOCULTURES AND MIXTURES

WEED SUPPRESSION BY COVER CROP MONOCULTURES AND MIXTURES

Abstract: The cultivation of isolated cover crops for weed suppression during the winter is known, however, information on the use of species mixtures for weed suppression is still contradictory. The objective of this work was to determine the level of weed suppression in soybeans by growing cover crops alone or in mixtures during the winter period. Two experiments were conducted in the 2020/2021 and 2021/2022 growing seasons in different locations. Treatments consisted of cultivation of isolated species (ryegrass, black oat, cereal rye and vetch) and species mixtures (black oat + ryegrass + oilseed radish; black oat + cereal rye + vetch; black oat + oilseed radish + vetch and ryegrass + black oat + cereal rye + oilseed radish + vetch), in addition to the fallow treatment, all with and without post-emergence glyphosate application. Dry mass production of cover crops, its influence on spring dry mass and weed density reductions and soybean yield were evaluated. The effect of isolated and mixed cultures on the dry mass of weeds was the same, providing an average reduction of 62,4% compared to fallow in both locations. The mixture of black oat + cereal rye + vetch provided the highest reduction in weed density (68%) at site 1. The greater amount of dry biomass produced by the isolated species did not contribute to the increase in the suppression of the observed infestation. Soybean productivity was higher in an environment with isolated cover crops and post-emergence glyphosate application.

Keywords: crop diversification, blends, interspecific interaction.

Resumo: O cultivo de culturas de cobertura isoladas para supressão de plantas daninhas durante o inverno é conhecido, entretanto, as informações sobre o emprego de misturas de espécies para a supressão ainda são contraditórias. O objetivo deste trabalho foi determinar o nível de supressão de plantas daninhas na cultura da soja pelo cultivo de culturas de cobertura isoladas ou em misturas no período de inverno. Dois experimentos foram conduzidos nas safras 2020/2021 e 2021/2022 em localidades distintas. Os tratamentos consistiram em cultivo de espécies isoladas (azevém, aveia, centeio, ervilhaca) e misturas de espécies (aveia + azevém + nabo; aveia+ centeio + ervilhaca; aveia + nabo + ervilhaca; azevém + aveia + centeio + nabo + ervilhaca), além do tratamento com pousio, todos com e sem aplicação de glyphosate em pós-emergência Foi avaliada a produção de massa seca das culturas de cobertura, sua influência nas reduções de massa seca e densidade de plantas daninhas de primavera e na produtividade da soja. O efeito das coberturas isoladas e suas misturas sobre a massa seca de plantas daninhas foi o mesmo, proporcionando uma redução média de 62,4% comparada ao pousio em ambos os locais. A mistura de aveia preta + centeio + ervilhaca proporcionou a maior redução na densidade de plantas daninhas (68%) no local 1. A maior quantidade de massa seca produzida pelas espécies isoladas não contribuiu para o aumento da supressão da infestação observada. A produtividade da soja foi maior em ambiente com coberturas isoladas e aplicação de glifosato em pós-emergência.

Palavras-chave: diversificação de culturas, misturas, interação interespecífica.

3.1 INTRODUCTION

The use of cover crops within no-tillage system (NTS) is recognized for providing soil protection, maintenance and retention of moisture, temperature reduction, nutrient cycling and reduction of soil compaction (Delgado et al., 2021). Among the many direct benefits provided by the use of vegetation covers, we can also consider weed suppression (Smith, Warren, & Cordeau, 2020).

The presence of cover species in the off-season allows for a reduction in weed germination, growth and development during this period due to the competition for environmental resources (Kruidhof et al., 2008) Furthermore, its suppressive effect extends to the subsequent crop, since biomass residues limit weed germination and growth in early soybean stages (Koehler-Cole et al., 2020). This suppression strategy is widespread in organic cropping systems, where cover crop residues are used to suppress weeds after harvest, in conventional crops, this suppressive effect can even mitigate the post-emergence application of herbicides (Wallace, Curran, & Mortensen, 2019).

In the long term, the adequate cultivation of cover species can prevent the accumulation of populations and facilitate weed management. The straw layer produced on the soil surface acts as a physical barrier, limiting the light penetration, reducing seed germination and new emergence flows of positive photoblastic species (Teasdale & Daughtry, 1993). In addition to the physical impediment, the reduction in germination can also occur due to the action of allelopathic exudates released by the roots or in the decomposition of the aerial part of cover crops such as oats, cereal rye and ryegrass (Mennan, Jabran, Zandstra, & Pala, 2020). Species of the Brassicaceae family can also interfere with weed growth through direct competition and the release of allelopathic compounds, mainly isothiocyanate, which is toxic to plants and inhibits seed germination (Haramoto & Gallandt, 2005; Petersen et al. 2001; Bell & Muller, 1973).

In general, the suppressive capacity of the species stems from the functional traits of its taxonomic group. Species of the Poaceae family, for example, have fast growth and are more efficient in nitrogen absorption when compared to species of the Fabaceae family, therefore, they tend to suppress weeds more easily (Finney, White, & Kaye, 2016).

Single cover crops are widely recommended within the NTS, however, the need for increasingly personalized management where the particular characteristics of each production environment are taken into account, have encouraged the use of mixtures of cover species to meet more specific objectives. Some leguminous species such as vetch promote biological nitrogen fixation (Blesh, VanDusen, & Brainard, 2019). Other species have the ability to decompress the soil, as is the case of the oilseed radish, in addition to releasing nutrients such as sulfur from the decomposition of its plant biomass. By combining different species it is also possible to increase or decrease the C:N ratio of plant biomass, which allows for a longer or shorter period of soil cover and weed suppression (Reiss & Drinkwater, 2022).

The survival ability of the species in off-season periods is also an important characteristic, since climatic conditions can interfere with its development and alter its suppressive effect (Bechini, 2022). However, equalizing the benefits of each species within a combination is important, because different habits and growth rates can create temporal asynchrony in the growth dynamics of species and cause a negative effect on weed suppression.

The rationale for adopting mixtures of cover species is related to greater functionality and stability within the system compared to communities with few species. In this case, the use and recycling of available natural resources are more dynamic due to greater diversity, in addition, more diverse communities may have greater levels of stability over time compared to less diverse communities (MacLaren, Swanepoel, Bennett, Wright, & Dehnen-Schmutz, 2019; Weisser et al., 2017). However, studies investigating the use of mixtures and isolated coverings for weed suppression show contrasting results, since the results are strongly influenced by the cultivation environment (Baraibar, Hunter, Schipanski, Hamilton, & Mortensen, 2018). Given these uncertainties, the present work aimed to investigate the effect of cover crops grown alone or in mixtures on the suppression of weed populations and their relation to soybean productivity.

3.2 MATERIAL AND METHODS

3.2.1 Area and sowing

Field studies were conducted and repeated at the 2020-2021 and 2021-2022 growing seasons, one at the Pontifical Catholic University of Paraná, PUCPR (25°39'9.65"S; 49°16'50.66"W) and other at Fernandes Pinheiro - Paraná - Brazil (25°37'19.8"S; - 50°29'39.2"W). According to the Koppen classification, both areas have a Cfb climate with uniform rainfall throughout the year, without dry seasons with frost in winter. At PUCPR (site 1) soil had the following chemical and physical characteristics: pH in $CaCl_2$, 4.8; Ca, 4.23 cmol dm^{-3}; Mg, 2.54 cmol dm^{-3}; Al, 0.2 cmol dm^{-3}; H+Al, 7.42 cmol dm^{-3}; CTC pH7, 14.38 cmol dm^{-3}; P, 8.12 mg dm^{-3}; K, 0.19 cmol dm^{-3}; base saturation (V%) of 48.4%; soil organic matter (SOM), 42.13 g dm^{-3}, area previously occupied by millet. At Fernandes Pinheiro (site 2) soil had the following chemical and physical characteristics: pH in $CaCl_2$, 4.7; Ca, 6,0 cmol dm^{-3}; Mg, 2,5 cmol dm^{-3}; Al, 0.8 cmol dm^{-3}; H+Al, 7.5 cmol dm^{-3}; CTC pH7, 15,87 cmol dm^{-3}; P, 12,1 mg dm^{-3}; K, 0.1 cmol dm^{-3}; base saturation (V%) of 42.5%; soil organic matter (SOM), 40,0 g dm^{-3}, area previously occupied by soybean.

At PUCPR, soybean sowing (DM 54i52 IPRO) took place in a no-tillage system, sowing 15 seeds per linear meter spaced between rows in 0.45 m, totalizing 333,333 seeds per hectare. At Fernandes Pinheiro, soybean sowing (DM 53i54 IPRO) also took place in a no-tillage system, sowing 14 seeds per linear meter spaced between rows in 0.45 m, totalizing 311.108 seeds per hectare. At PUCPR, soil was fertilized at sowing with 14 kg ha^{-1} of nitrogen and with 70 kg ha^{-1} of phosphorus and potassium, whereas at Fernandes Pinheiro, fertilization was performed with 90 kg $ha^{-1}$of phosphorus and with 90 kg ha^{-1} of potassium at sowing.

The weed community present at site 1 was composed mostly of eudicotyledonous plants (96%), with a predominance of wild radish (*Raphanus raphanistrum L*) (84.5%). Weed community present at site 2 was also mostly comprised of eudicotyledonous species, with a predominance of *Cardiaca arvensis* L. (83,9%) and *Borreria latifolia* (9,3%). In both locations, we considered the natural population of weeds, without manual sowing.

3.2.2 Treatments and experimental design

Each plot had an area of 2,5m x 4m (5 crop rows), with four replications, arranged in a split-plot design and factorial scheme experiment. Treatments consisted of isolated or mixed cover crops sowed previous soybean. Monocultures of four cover crops were used: ryegrass (*Lolium multiflorum)* black oat (*Avena strigosa* S.), cereal rye (*Secale cereal* L.) and vetch (*Vicia sativa* L.) In addition, these species were combined into four mixes of three species and one mix of five species plus fallow treatment (Table 1). Sowing densities were defined according to the technical manual of plants cover (Calegari, 2016). Seeding was carried out by broadcast, followed by light harrowing. The seeds used in the experiment were purchased commercially.

Table 1. Composition of the cover crops isolated and mixtures sowed before soybean, percent of species and seeding rates for each species.

Treatment ID	Species	Specie (%)	Seeding rate (kg ha^{-1})
fallow	-	-	-
ryegrass	ryegrass	100	30
black oat	black oat	100	66
cereal rye	cereal rye	100	84
vetch	vetch	100	96
mixture 1	black oat	33,3	22
	ryegrass	33,3	10
	oilseed radish	33,3	6,8
mixture 2	black oat	33,3	22
	cereal rye	33,3	28
	vetch	33,3	32
mixture 3	black oat	33,3	22
	oilseed radish	33,3	6,8
	vetch	33,3	32
mixture 4	black oat	20	13,2
	ryegrass	20	6
	cereal rye	20	16,8
	oilseed radish	20	4,08
	vetch	20	19,2

During the winter cover cycle, nitrogen fertilization (150 kg of nitrogen per hectare in form of urea 45%) was carried out for each treatment as recommended in the fertilizer and liming guidelines for the states of Rio Grande do Sul and Santa Catarina (Sousa & Ermani, 2016). After a period of 110 days from sowing, the cover crops were desiccated with 1,860 g ae ha^{-1} of glyphosate-dimetylammonium (Glizmax Prime, 480 g ea L^{-1}, Dow AgroSciences, São Paulo, Brazil). After 30 days of desiccation, soybean was sown.

3.2.3 Data collection and analysis

In order to measure the accumulation of dry mass provided by the cover crops over the winter and the amount of straw at soybean sowing, plant cover was collected before desiccation with the aid of a 0.062 m² frame, in four replications, totaling 0.25m sampling. Samples were dried in an oven with forced air circulation at 60°C for 72 hours and dry mass obtained.

At 42 days after soybean emergence (DAE), with the aid of a 0.25 m^2 frame, the phytosociological evaluation of the weed community was carried out to determine the phytosociological descriptors (density, dry mass and frequency of the species present), applied to the study of the horizontal structure of plant communities in treatments without residual herbicide with manual weeding (Ellenberg & Mueller-Dombois, 1974).

At the end of the soybean cycle (114 days), harvest was carried out, where the three central lines of the plot were cut into three linear meters, totaling a sampling of 4.05 m². The samples were threshed with a soybean thresher, thus obtaining the average productivity of the plots. With grain moisture corrected to 13%, it was possible to determine the soybean yield per hectare (kg ha^{-1}) by extrapolation. Data were subjected to analysis of variance using the F test ($p \leq 0.05$). In cases of significance, the means were compared by the Tukey test ($p \leq 0.05$) using the R statistical software (R Core Team, 2020).

3.3 RESULTS AND DISCUSSION

3.3.1 Cover crops dry biomass

There was a significant interaction between environment and coverage factors. A significant difference between the mean production of each isolated species or mixture at site 1 was observed, with greater dry mass production provided by black oat cover (Table 2). In the same environment, the lowest dry biomass productions were for vetch coverings, mixture 3 and fallow management. In site 2 the production of dry biomass by coverings was statistically equal, with an average of 3.009 kg ha^{-1}.

Table 2. Dry biomass (kg ha^{-1}) of different cover crops at the time of soybean sowing.

Treatment ID	Treatment	Site 1 dry biomass (kg ha^{-1})		Site 2 dry biomass (kg ha^{-1})	
ryegrass	ryegrass	3.257	Abc	2.811	Aa
black oat	black oat	5.291	Aa	2.977	Ba
cereal rye	cereal rye	5.003	Aab	3.234	Ba
vetch	vetch	2.303	Ac	3.238	Aa
fallow	fallow	2.737	Ac	2.893	Aa
mixture 1	black oat + ryegrass + oilseed radish	3.289	Abc	2.183	Aa
mixture 2	black oat + cereal rye + vetch	3.092	Abc	3.524	Aa
mixture 3	black oat + oilseed radish + vetch	2.424	Ac	3.350	Aa
mixture 4	ryegrass + black oat + cereal rye + oilseed radish + vetch	2.741	Ac	2.874	Aa

Note. Averages in the same column followed by distinct lowercase letters and in the row followed by differ capital letters differ by Tukey test ($p \leq 0.05$).

Greater mass production by black oat and cereal rye covers are not necessarily related to greater weed suppression. The dry biomass data of weeds in site 1 indicate that the greatest suppression was due to the cultivation of mixture 3, which produced only 2424 kg ha^{-1} of straw. In the same location, dry mass production by rye cover crops and mixtures 1 and 2 reduced weed dry mass equally. These results corroborate studies by MacLaren et al (2019), as they demonstrate that greater amounts of dry mass do not necessarily reduce the dry biomass of weeds. Such results differ from Adeux et al (2021) where the highest dry mass production of *Brassica juncea* (L.) Czern. resulted in suppression superior to treatments with lower biomass production of *Vicia villosa* and *Trifolium squarrosum*.

3.3.2 Weed dry biomass

With no significant interaction between the factors, the dry mass of weeds was altered by the experimental site and by the interference of cover crops. The average dry biomass in site 1 was 24.10 g m², while the weed dry biomass observed in site 2 was only 6.34 g m². The greatest effect of weed dry mass suppression was caused by the mixtures and the isolated cultivation of black oat and vetch (Table 3). Mixture 1, vetch, black oat and ryegrass had less effect, which resembled fallow. The smallest suppression observed, caused by ryegrass, was the result of the reseeding of the species between its desiccation and soybean sowing.

Table 3. Effect of different cover crops on weed biomass per square meter at 42 days after soybean emergence.

Treatment ID	Species	Weed dry biomass ($g m^2$)
ryegrass	ryegrass	30,70 A
black oat	black oat	15,14 AB
cereal rye	cereal rye	9,61 B
vetch	vetch	15,02 AB
fallow	fallow	29,29 A
mixture 1	black oat + ryegrass + oilseed radish	14,37 AB
mixture 2	black oat + cereal rye + vetch	7,88 B
mixture 3	black oat + oilseed radish + vetch	5,84 B
mixture 4	ryegrass + black oat + cereal rye + oilseed radish + vetch	9,16 B

Note. Averages in the same column followed by distinct capital letters differ by Tukey test ($p \leq 0.05$).

The mixture of species together with a cover composed exclusively of a legume increased weed suppression from 55 to 67% compared to single species, results similar to those observed in other works where the mixture of grass monocultures and mixtures provided a reduction in weed mass greater than leguminous monocultures during the winter (Baraibar et al., 2018; MacLaren et al., 2019). One of the explanations is given by the improvement of environmental variables in the establishment of crops that favor the competitiveness of the covers (Baraibar et al., 2018).

The similarity between the levels of suppression between single and mixed toppings can be explained by the use of cereals in the composition of the mixture. According (Dorn, Jossi, & van der Heijden, 2015), the dry biomass of 1.500 kg ha^{-1} of cereal rye has the same suppressive capacity as the dry biomass of 3,500 kg ha^{-1} of black oat dry biomass due to its fast growth and fast soil cover. Furthermore, Smith et al (2014), suggest that suppression may result from the presence of one or more species within the cultivated mixture, usually grasses with high growth capacity and competition. Baraibar et al., 2018, observed that mixtures containing 20% grass species caused similar levels of weed suppression in the winter period.

The reduction of weed biomass provided by the use of cover crops during the winter ranged from 48 to 80%. These results suggest that the establishment of single species or in mixtures is important for the reduction of weed biomass during the period, taking into account the cycle of each species and the time of desiccation for the non-occurrence of reseeding in the spring. In addition, climatological conditions should favor the growth and development of cover crops in winter, mainly in early stages, in order to promote rapid canopy establishment and weed suppression by interfering with light quality. Greater weed biomass reduction also implies greater ease of infestation control with post-emergent herbicides in spring and less reproduction of herbicide-resistant species.

3.3.3 Weed density

Density was affected by locations and cover crops, with significant interaction between factors. At site 1, an average density of 16 plants m^2 was observed, higher than at site 2. The suppressive effect of the covers was significantly different only in the black oat + cereal rye + vetch composition, reducing weed density by 68% in site 1 (Table 4).

Table 4. Weed density per square meter at 42 days after soybean emergence.

		Site 1	Site 2
Treatment ID	Treatment	weed density (plants m^2)	
ryegrass	ryegrass	32 Aa	1 Bb
black oat	black oat	13 Abc	1 Bb
cereal rye	cereal rye	13 Abc	1 Bb
vetch	vetch	19 Aabc	1 Bb
fallow	fallow	26 Aab	23 Aa
mixture 1	black oat + ryegrass + oilseed radish	16 Aabc	1 Bb
mixture 2	black oat + cereal rye + vetch	5 Ac	1 Ab
mixture 3	black oat + oilseed radish + vetch	14 Abc	7 Ab
mixture 4	ryegrass + black oat + cereal rye + oilseed radish + vetch	7 Abc	2 Ab

Note. Averages in the same column followed by distinct lowercase letters and in the row followed by differ capital letters differ by Tukey test ($p \leq 0.05$).

The weed community at site 1 was mostly composed of eudicotyledonous plants (96%), with a predominance of wild radish (*Raphanus raphanistrum L*) (84.5%). This species is negative photoblastic, therefore its germination was little affected by the shading of the coverings, on the other hand, the quality of the light interfered significantly in the development and production of biomass of the species, independent of the cover specie (Reeves, Code, & Piggin, 1981).

In site 2 the predominance of positive photoblastic species affected the density. The community composed only of eudicotyledonous species, with a predominance of *Cardiaca arvensis* L. (83,9%) and *Borreria latifolia* (9,3%) had its density reduced by the presence of straw. The lower amount of weeds present in cultivation with the crop decreases the chances of selection of resistant plants, as the quantity and variety of genes present are lower. In addition, lower densities represent fewer plants reproducing in an eventual failure of control (Martins, Chamma, Dias, & Christoffoleti, 2010).

3.3.4 Soybean productivity

For soybean productivity (Table 5), there was a significant interaction between environment and coverage factors. For site 1, higher yields are related to single cover cropping followed by post-emergence weed management. The performance of the mixtures is also favored by the management with glyphosate, however, without the post-emergence management, the highest yields were ensured by the cultivation of the species in mixture. Comparing the productivity averages at site 2, there was no statistically significant difference.

Table 5. Effect of cover crops and post application on soybean productivity.

Treatment ID	Weed control	Soybean Grain Yield (kg ha^{-1})	
		Site 1	Site 2
fallow	Weedy	1679 Ae	1969 Aa
fallow	Weed-free	3828 Aab	1820 Ba
ryegrass	Weedy	1610 Ae	2006 Aa
ryegrass	Weed-free	4189 Aa	1949 Ba
black oat	Weedy	1821 Ade	2147 Aa
black oat	Weed-free	3367 Aabc	1829 Ba
cereal rye	Weedy	1656 Ae	2076 Aa
cereal rye	Weed-free	3833 Aab	1999 Ba
vetch	Weedy	1546 Ae	1694 Aa
vetch	Weed-free	3256 Aabc	1874 Ba
mixture 1	Weedy	2823 Ac	1964 Ba
mixture 1	Weed-free	3022 Abc	2217 Ba
mixture 2	Weedy	2623 Acd	1573 Ba
mixture 2	Weed-free	2693 Acd	1788 Ba
mixture 3	Weedy	2694 Acd	1559 Ba
mixture 3	Weed-free	2922 Abc	1445 Ba
mixture 4	Weedy	2704 Acd	1678 Ba
mixture 4	Weed-free	2946 Abc	1724 Ba

Note. Averages in the same column followed by distinct lowercase letters and in the row followed by differ capital letters differ by Tukey test ($p \leq 0.05$).

Although it is difficult to measure the relative contribution of each species in the suppression of weeds, it is likely that the allelopathic effects of ryegrass (Mennan et al., 2020) have contributed to the suppression of other species present in the area, ensuring greater productivity. The use of single vetch provided lower yields in scenarios with glyphosate and its absence, which can also be explained by the production of allelopathic compounds, where the increase in suppression by the species does not correspond to the increase in crop productivity (Reiss et al., 2022).

The single coverings of black oats, cereal rye and vetch provided productivity equal to mixtures 1, 3 and 4 with the application of glyphosate in post-emergence. In a scenario where there is no second intervention, there was greater productivity in the treatments with the cover mix, except for black oat, which provided a statistically equal mean productivity for the four mixtures, which may be related to lower variability in production and total dry biomass.

The use of cover crops as the only method of weed suppression was not enough to guarantee higher yields in this study, even with dry biomass production of cover crops above 2500 kg ha^{-1} and reductions of 48% and 68% in dry mass and weed density respectively. The sum effect of the chemical control can be observed when comparing the isolated effect of the ryegrass crop (1610 kg ha^{-1}) with the effect of the post-emergence glyphosate application (4189 kg ha^{-1}).

3.4 CONCLUSIONS

The cultivation of cover crops in winter reduced the density and dry mass of weeds in the soybean crop, however, reductions provided by isolated coverings were equal to the reductions obtained with the cultivation of species in mixture.

The difference in the dry mass production of the cover crops did not cause a difference in the level of weed suppression, showing that the higher dry mass production of the cover crops does not necessarily cause greater weed suppression.

Yield was affected by different coverages and post-emergence glyphosate application. The mixed species provided equal productivity with or without post-emergence application.

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FINAL CONSIDERATIONS

This thesis sought to investigate the benefits of integrating cultural and chemical methods in weed management, contributing to the scientific production related to MIPD in different soybean production environments.

The combination of different methods promoted an integrative and beneficial solution at several points. In addition to the benefits of ecological services provided by the use of cover crops such as improved soil structure, greater retention of water, organic matter and soil fertility (O'CONNELL et al., 2015; WHITE et al., 2017), their cultivation implied also in the suppression of weeds by interspecific competition, release of allelopathic compounds and physical control by shading or smothering weed seedlings, benefits also observed by other authors (BARAIBAR et al., 2018; DORN; JOSSI; HEIJDEN, VAN DER, 2015; SMITH; WARREN; CORDEAU, 2020).

The use of pre-emergent herbicides acts in complementarity with the cultivation of cover crops, as it reaches the soil without straw cover, helping to control positive photoblastic species as long as there are favorable conditions (precipitation and soil moisture) for their mobility and phytotoxic action. Among other important factors in the integration of these two control methods are: reduction in the selection pressure of resistant species by using different mechanisms of action; reduction in seed production and smaller increase in the seed bank; ease of post-emergence control due to reduced density and dry mass of weeds by cover crops; increase in PPI, reducing the level of weed interference in productivity.

Considering the results of the thesis on the use of pre-emerging herbicides in soybeans, new studies must be carried out taking into account the differences in the productive environments, mainly edaphoclimatic differences that interfere in the efficiency of the molecules. The physicochemical particularities of soil herbicides make their recommendation more careful and technical.

On the dynamics of weed suppression by mixing different coverages, other aspects need to be explored: individual suppression level of each species used in the mixture; effects of species mixtures on light quality and weed development; level of suppression in environments with unfavorable climate and soil conditions and/or for longer periods.

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