

Residual Herbicides and Cover Crops Interactions for Soybean Weed Control

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Abstract

Residual herbicides and cover crops are important tools inside an integrated weed management program. The straw produced in crop rotation can interact 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 its reflection on weed control and soybean production. Were 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, independently of cover crop straw. 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 interaction. 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. Introduction

Soybean (*Glycine max* (L.) Merr.) is a important oilseed for human and animal nutrition, with 37.03 million hectares being cultivated in Brazil with production of up to 126 million tons of grain, produced in more than 58% of the country’s arable area (Companhia Nacional de Abastecimento [CONAB], 2020).

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 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, Böhn, 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 off season 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.

2. Method

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 climate of the region is Cfb, characterized without a defined dry season, cool summers and moderate winter with minimum annual average temperature between 17 °C and 18 °C. Average annual rainfall varies between 1,400 and 1,600 mm according to Köppen classification. Allic Oxisoil + Allic Inceptisol, with prominent A horizon and gently undulating relief. According to the analysis, the soil had the following chemical and physical characteristics: pH in CaCl₂, 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; cation exchange capacity (CTCpH7), 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; 350 g kg⁻¹ of clay, 210 g kg⁻¹ of silt and 440 g 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.

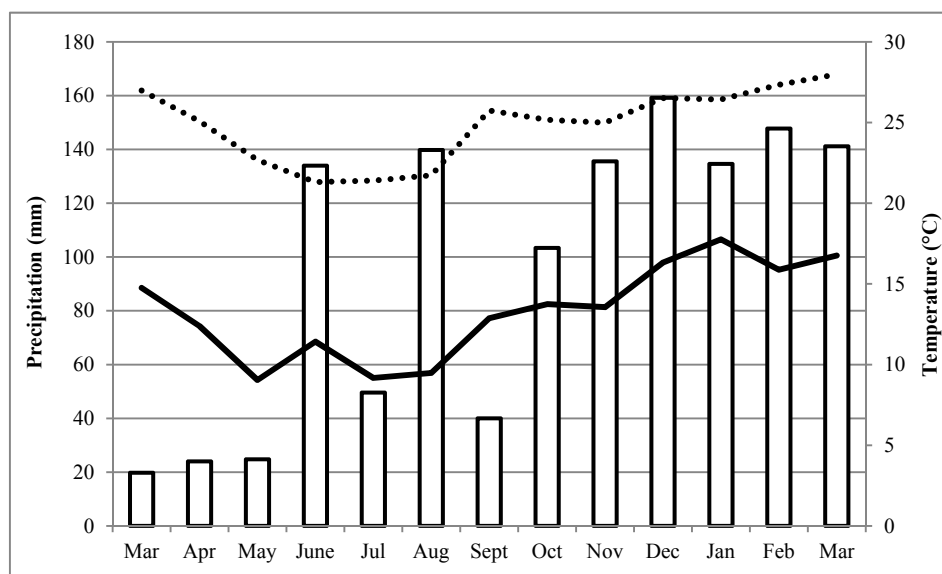


Figure 1. Average daily temperature and daily precipitation during the months of the experiment Fazenda Rio Grande (PR) 2020/2021

Four species of winter cover crops were established in this area on 25/06/2020: 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, followed by light harrowing. The seeds used in the experiment were purchased commercially.

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 covers were desiccated with 1,860 g ae ha⁻¹ of glyphosate (Glizmax Prime, 480 g ea L⁻¹, Dow AgroSciences, São Paulo, Brazil).

Residual herbicides were applied on the same day of soybean sowing (06/11/2020). The treatments applied were: no herbicide and hand weeding (weedy); no herbicide with hand weeding (check); 35.28 g ea ha⁻¹ of diclosulam (Spider® 840 WG, 840 g kg⁻¹, Dow AgroSciences Industrial Ltda-Barueri/SP); 600 g ea ha⁻¹ of sulfentrazone (Boral® 500 SC, 500 g L⁻¹, FMC Química do Brasil Ltda-Campinas/SP); 100 g ea ha⁻¹ of imazethapyr (Pivot®100 SL, 100 g L⁻¹, BASF S.A.-São Paulo/SP); 60 g ea ha⁻¹ of flumioxazin (Flumyzin 500, 500 g kg⁻¹, Sumitomo Chemical do Brasil Representações Ltda-SaoPaulo/SP); 1,440 g ea ha⁻¹ of s-metolachlor (Dual Gold 960 g L⁻¹, Syngenta Proteção de Cultivos Ltda-São Paulo/SP); 100 g ea ha⁻¹ of piroxasulfone (Yamato®SC 500 g L⁻¹, IHARABRAS S.A. Indústrias Químicas-Sorocaba/SP). Each plot had 2.5 m × 4 m (5 crop rows), with four replications, arranged in a split-plot design and two-level factorial experiment.

Applications were carried out using a backpack spray pressurized by CO₂ 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 of solution. The sown soybean cultivar was DM 53i54, which 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 350,000 plants per hectare with 0.45 m spacing between rows.

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 0.25 m² sampling. Samples were dried by heating in an oven with forced air circulation at 60 °C for 72 hours. For soybean, were evaluated in the two central lines of the plot the number of plants per linear meter at 28 days after emergence and the visual injury at 14 and 28 days after sowing (DAS), according to the European Weed Research Council (EWRC, 1964) rating scale (0 to 100%).

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 m² 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).

The soybean harvest was carried out on 13/03/2021. 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. Results

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.

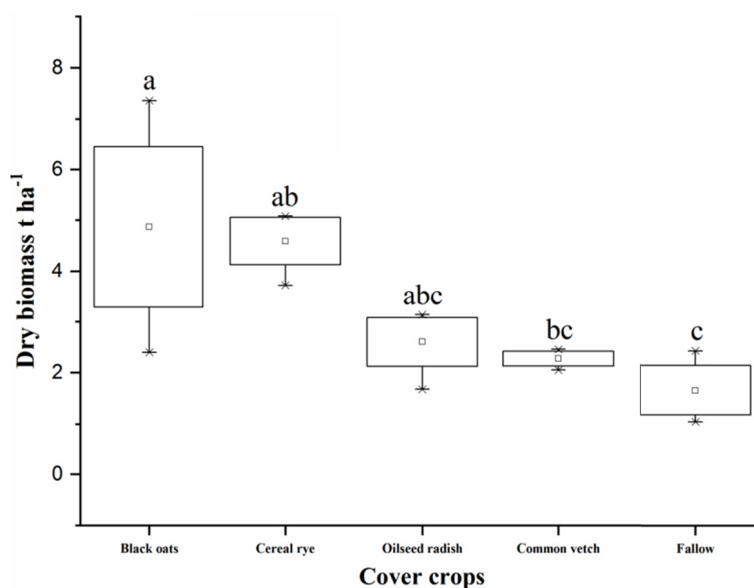


Figure 2. Cover crops dry biomass averages, in tons per hectare, at the time of soybean sowing. Significant differences are indicated by bars topped with different letters ($p \leq 0.05$)

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.

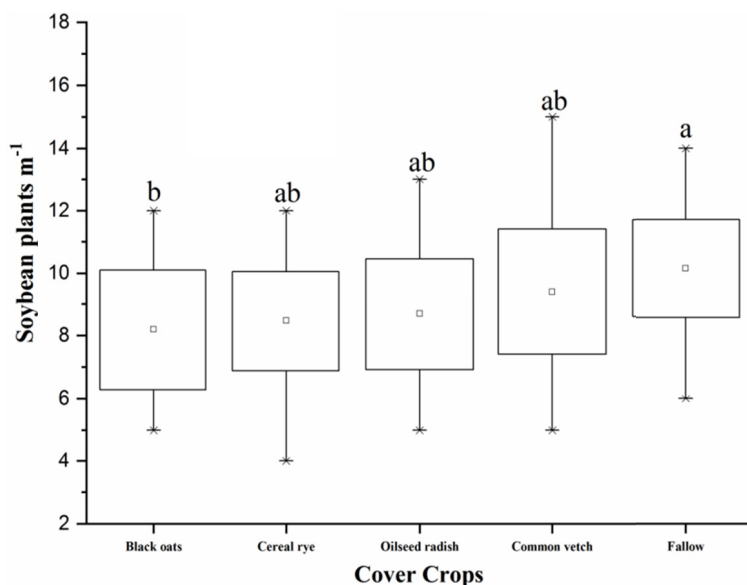


Figure 3. Number of soybean plants per linear meter at 28 days after emergence in different soil covers. Significant differences are indicated by bars topped with different letters ($p \leq 0.05$)

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 non-applied treatment (6.15 vs. 19.53 plants m²), values 68% lower. The herbicide imazethapyr, showed greater reductions (Figure 4) than those observed for the herbicides sulfentrazone, s-metolachlor and pyroxasulfone. For the coverings, the population was major reduced by black oat straw (10.96 vs. 19.53 plants m²), a reduction of 43% (Figure 5).

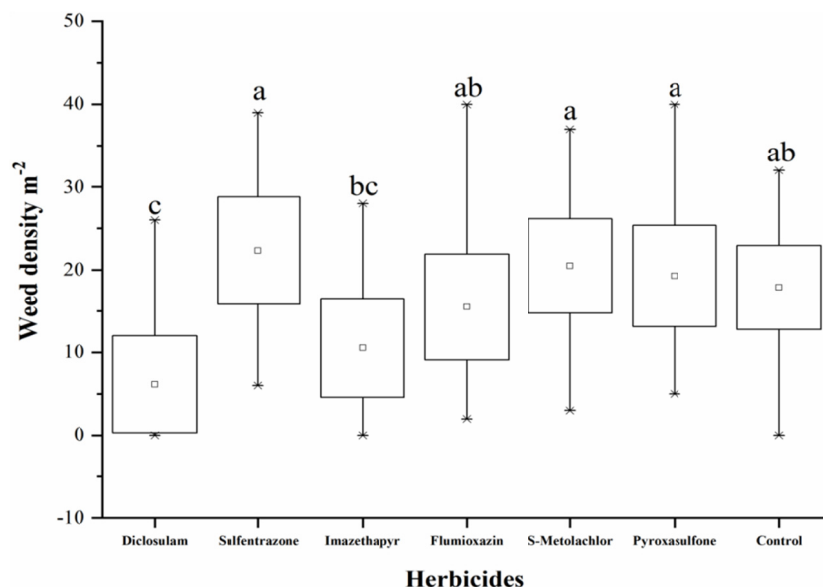


Figure 4. Effect of different herbicides on weed density per square meter at 42 days after soybean emergence. Significant differences are indicated by bars topped with different letters ($p \leq 0.05$)

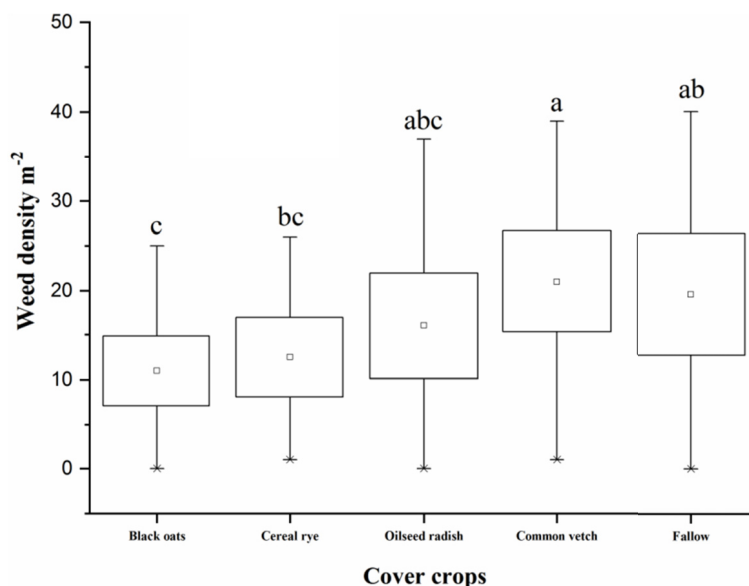


Figure 5. Effect of different cover crops on weed density per square meter at 42 days after soybean emergence. Significant differences are indicated by bars topped with different letters ($p \leq 0.05$)

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.

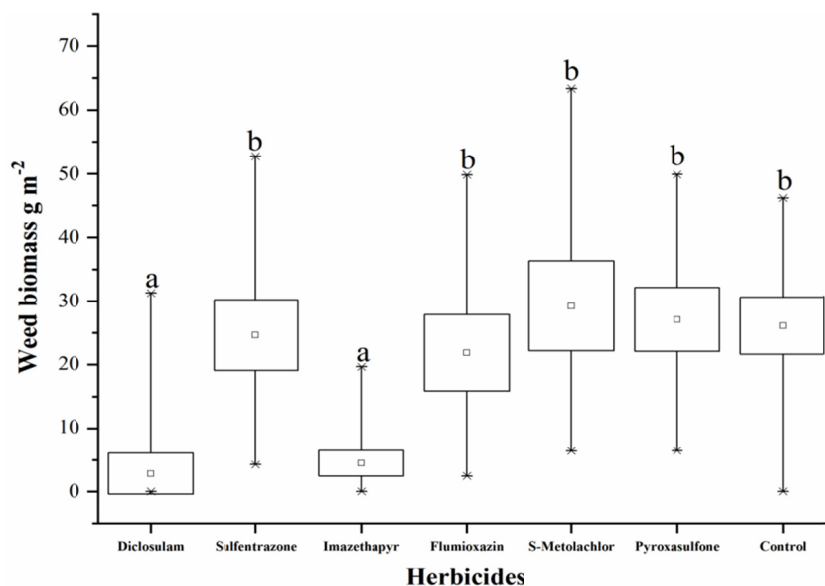


Figure 6. Effect of different herbicides on weed biomass per square meter at 42 days after soybean emergence. Significant differences are indicated by bars topped with different letters ($p \leq 0.05$)

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 m⁻², 12% lower compared to the fallow (22.43 g m⁻²).

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 album*), 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, regardless of the cover crop, that is, the levels of dry mass residue present at the time of application, greater control of weeds when compared to the others (Table 1). Imazethapyr, showed similar results to diclosulam, in coverings with black oat and oilseed radish.

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

Species	Herbicides								
	Check	Diclosulam	Sulfentrazone	Imazethapyr	Flumioxazin	S-Metolachlor	Pyroxasulfone	Weedy	
Black oat	100 Aa	74 ABb	21.2 ABc	62.5 Ab	17.5 Acd	5 Bde	2.5 Ade	0 Ae	
Cereal rye	100 Aa	58 Bb	33.7 Acd	40.0 Bc	22.5 Ade	23 Ade	7.5 Aef	0 Af	
Oilseed radish	100 Aa	69 ABb	16.2 BCc	63.8 Ab	8.7 Acd	0 Bd	0 Ad	0 Ad	
Common vetch	100 Aa	75 Ab	22.5 ABcd	35.0 BCc	11.3 Ade	0 Be	0 Ae	0 Ae	
Fallow	100 Aa	69 ABb	3.7 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 ($p \leq 0.05$).

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 imazetaphyr 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.

3.4 Soybean Yield

For soybean, symptoms of phytotoxicity can occur because residual herbicides application. Low symptoms were noted 14 days after applications (less than 5%), for sulfentrazone. 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 don't showed 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.

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

Species	Herbicides													
	Check	Diclosulam	Sulfentrazone	Imazethapyr	Flumioxazin	S-Metolachlor	Pyroxasulfone	Weedy						
Black oat	3366 Ab	2973 ABa	1941 CDbc	3287 Aab	2369 BCDA	2478 BCa	2420 BCDA	1820 Da						
Cereal rye	3832 Aab	3498 Aa	2579 Ba	3316 Aab	2537 Ba	2548 Ba	2540 Ba	1655 Ca						
Oilseedradish	4135 Aa	3064 Ba	2318 CDab	3746 Aa	1750 DEb	2659 BCa	2503 BCa	1575 Ea						
Common vetch	3255 Ab	3219 Aa	1611 Cc	2920 ABb	2453 Ba	2323 Ba	2490 Ba	1546 Ca						
Fallow	3828 Aab	3556 Aa	2094 DEabc	3354 ABab	2259 DEab	2639 CDa	2918 BCa	1679 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 ($p \leq 0.05$).

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 (1820 kg ha⁻¹) with the effect of application of herbicides in fallow. Values ranged from 2094 kg ha⁻¹ to 3556 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 1679 kg ha⁻¹.

4. Discussion

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 difficult sowing, because straw cutting and seeds/fertilizers depositions are affected (Trogello, José Modolo, Scarsi, & Dallacort, 2013).

Moderated cereal rye 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 et al., 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 no cover crops 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.

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 et al., 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., 2021).

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.

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. (2021), 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.

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 (1820 kg ha⁻¹) with the effect of application of herbicides in fallow. Values ranged from 2094 kg ha⁻¹ to 3556 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 1679 kg 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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References

- Agrofit, A. (2020). *Sistema de agrotóxicos fitossanitários*. Ministério da Agricultura, Pecuária e Abastecimento.
- Akobundu, I. O., Udensi, U. E., & Chikoye, D. (2000). Velvetbean (*Mucuna* spp.) suppresses speargrass (*Imperata cylindrica* (L.) Raeuschel) and increases maize yield. *International Journal of Pest Management*, 46(2), 103-108. <https://doi.org/10.1080/096708700227453>
- Almeida, F. S. (1991). *Efeitos alelopáticos de resíduos vegetais*. Área de Informação Da Sede-Artigo Em Periódico Indexado (ALICE).
- Blackshaw, R. E., Moyer, J. R., Doram, R. C., & Boswell, A. L. (2001). Yellow Sweetclover, Green Manure, and Its Residues Effectively Suppress Weeds during Fallow. *Weed Science*, 49(3), 406-413. [https://doi.org/10.1614/0043-1745\(2001\)049\[0406:YSGMAI\]2.0.CO;2](https://doi.org/10.1614/0043-1745(2001)049[0406:YSGMAI]2.0.CO;2)
- Bortolini, M. F., & Fortes, A. M. T. (2005). Efeitos alelopáticos sobre a germinação de sementes de soja (*Glycine max* L. Merrill). *Semina: Ciências Agrárias*, 26(1), 5. <https://doi.org/10.5433/1679-0359.2005v26n1p5>
- Brennan, E. B., & Smith, R. F. (2005). Winter Cover Crop Growth and Weed Suppression on the Central Coast of California. *Weed Technology*, 19(4), 1017-1024. <https://doi.org/10.1614/wt-04-246r1.1>
- Burgos, N. R., Talbert, R. E., & Mattice, J. D. (1999). Cultivar and age differences in the production of allelochemicals by *Secale cereale*. *Weed Science*, 47(5), 481-485. <https://doi.org/10.1017/s0043174500092146>
- Calegari, A. (2016). *Plantas de Cobertura -Manual Técnico* (Vol. 02). Instituto Agronômico do Paraná.
- Clark, S. L., Silva, P. V. da, Dayan, F. E., Nissen, S. J., & Sebastian, D. J. (2019). The Influence of Winter Annual Grass Litter on Herbicide Availability. *Weed Science*, 67(6), 702-709. <https://doi.org/10.1017/wsc.2019.45>
- CONAB. (2020). Acompanhamento da safra brasileira 2019/2020. *Acompanhamento da Safra Brasileira de Grãos, 2020*.
- Cornelius, C. D., & Bradley, K. W. (2017). Influence of Various Cover Crop Species on Winter and Summer Annual Weed Emergence in Soybean. *Weed Technology*, 31(4), 503-513. <https://doi.org/10.1017/wet.2017.23>
- Council, E. W. R. (1964). Report of the 3rd and 4th meetings of EWRC-Committee of Methods in Weed Research. *Weed Res.*, 4(1), 88. <https://doi.org/10.1111/j.1365-3180.1964.tb00275.x>
- Da Silva, P. V., Tronquini, S., Barbosa, G., Dias, R., Veiga, J., & Inácio, E. (2020). Eficácia de flumioxazin em *Euphorbia heterophylla* L. aplicado sobre diferentes tipos e quantidades de resíduos culturais e simulações de chuva. *Revista de Ciências Agrárias*, 43, 324-332. <https://doi.org/10.19084/rca.20815>

- Day, S., Calegari, A., Santos, A., Cremonesi, M., Maia, L., Demetrio, W., & Bartz, M. (2020). *Biodiversity management practices and benefits in Conservation Agriculture systems*. Burleigh Dodds Science Publishing. <https://doi.org/10.19103/AS.2019.0049.09>
- Denadai, M. S., De Mello, L. M. M., Chioderoli, C. A., & De Niro Gazola, R. (2016). Desiccation time of the spring sorghum as a predecessor crop for summer soybean and autumn bean in a no-tillage system. *Engenharia Agrícola*, 36(1), 94-101. <https://doi.org/10.1590/1809-4430-Eng.Agric.v36n1p94-101/2016>
- Ellenberg, D., & Mueller-Dombois, D. (1974). *Aims and methods of vegetation ecology*. Wiley New York.
- Essman, A. I., Loux, M. M., Lindsey, A. J., Dobbels, A. F., & Regnier, E. E. (2020). The effects of integrating a cereal rye cover crop with herbicides on glyphosate-resistant horseweed (*Conyza canadensis*) in no-till soybean. *Weed Science*, 68(5), 527-533. <https://doi.org/10.1017/wsc.2020.47>
- Fornarolli, D. A., Rodrigues, B. N., Lima, J. de, & Valério, M. A. (1998). Influência da cobertura morta no comportamento do herbicida atrazine. *Planta Daninha*, 16(2), 97-107. <https://doi.org/10.1590/s0100-83581998000200003>
- Grimmer, O. P., & Masiunas, J. B. (2004). Evaluation of Winter-killed Cover Crops Preceding Snap Pea. *HortTechnology Horttech*, 14(3), 349-355. <https://doi.org/10.21273/HORTTECH.14.3.0349>
- Heap, I. (2021). *The international survey of herbicide resistant weeds*. WeedScience.org.
- Heap, I., & Duke, S. O. (2018). Overview of glyphosate-resistant weeds worldwide. *Pest Management Science*, 74(5), 1040-1049. <https://doi.org/10.1002/ps.4760>
- Kan, Z. R., Ma, S. T., Liu, Q. Y., Liu, B. Y., Virk, A. L., Qi, J. Y., ... Zhang, H. L. (2020). Carbon sequestration and mineralization in soil aggregates under long-term conservation tillage in the North China Plain. *Catena*, 188(May 2020), 104428. <https://doi.org/10.1016/j.catena.2019.104428>
- Miyazaki, J., Bauer-Panskus, A., Bøhn, T., Reichenbecher, W., & Then, C. (2019). Insufficient risk assessment of herbicide-tolerant genetically engineered soybeans intended for import into the EU. *Environmental Sciences Europe*, 31(1), 92. <https://doi.org/10.1186/s12302-019-0274-1>
- Modolo, A., Zdziarski, A., Sgarbossa, M., Pagnoncelli, F., Trogello, E., & Dallacort, R. (2020). Plantabilidade e produtividade de milho sob palhada de aveia preta dessecada em diferentes épocas. *Revista Brasileira de Milho e Sorgo*, 18, 340-349. <https://doi.org/10.18512/1980-6477/rbms.v18n3p340-349>
- Moore, S. H. (1991). Uniformity of Plant Spacing Effect on Soybean Population Parameters. *Crop Science*, 31(4), 1049-1051. <https://doi.org/10.2135/cropsci1991.0011183X003100040041x>
- Nunes, U. R., Andrade Júnior, V. C., Silva, E. de B., Santos, N. F., Costa, H. A. O., & Ferreira, C. A. (2006). Produção de palhada de plantas de cobertura e rendimento do feijão em plantio direto. *Pesquisa Agropecuária Brasileira*, 41(6), 943-948. <https://doi.org/10.1590/s0100-204x2006000600007>
- Olofsdotter, M., Jensen, L. B., & Courtois, B. (2002). Improving crop competitive ability using allelopathy—An example from rice. *Plant Breeding*, 121(1), 1-9. <https://doi.org/10.1046/j.1439-0523.2002.00662.x>
- Peachey, R. E., William, R. D., & Mallory-Smith, C. (2004). Effect of No-Till or Conventional Planting and Cover Crops Residues on Weed Emergence in Vegetable Row Crop. *Weed Technology*, 18(4), 1023-1030. <https://doi.org/10.1614/WT-03-205R>
- Pires, J. L. F., Costa, J. A., & Thomas, A. L. (1998). Rendimento de grãos de soja influenciado pelo arranjo de plantas e níveis de adubação. *Pesquisa Agropecuária Gaúcha*, 4(2), 183-188. Retrieved from <http://revistapag.agricultura.rs.gov.br/ojs/index.php/revistapag/article/view/504>
- Reddy, K. N., Locke, M. A., Wagner, S. C., Zablutowicz, R. M., Gaston, L. A., & Smeda, R. J. (1995). Chlorimuron Ethyl Sorption and Desorption Kinetics in Soils and Herbicide-Desiccated Cover Crop Residues. *Journal of Agricultural and Food Chemistry*, 43(10), 2752-2757. <https://doi.org/10.1021/jf00058a038>
- Rizzardi, M. A., Rockenbach, A. P., & Schneider, T. (2020). Residual herbicides increase the period prior to interference in soybean cultivars. *Planta Daninha*, 38. <https://doi.org/10.1590/s0100-83582020380100091>
- Schramski, J. A., Sprague, C. L., & Renner, K. A. (2021). Integrating fall-planted cereal cover crops and preplant herbicides for glyphosate-resistant horseweed (*Conyza canadensis*) management in soybean. *Weed Technology*, 35(2), 234-241. <https://doi.org/10.1017/wet.2020.117>

- Silva, A. A., Vivian, R., & Oliveira Jr, R. S. (2007). Herbicidas: Comportamento no solo. *Tópicos Em Manejo de Plantas Daninhas* (pp. 189-248). Universidade Federal de Viçosa Viçosa, MG.
- Somerville, G. J., Powles, S. B., Walsh, M. J., & Renton, M. (2017). Why was resistance to shorter-acting pre-emergence herbicides slower to evolve? *Pest Management Science*, *73*(5), 844-851. <https://doi.org/10.1002/ps.4509>
- Sousa, R. O., & Ermani, P. R. (2016). *Manual de calagem e adubação para os estados do Rio Grande do Sul e de Santa Catarina*. Comissão de Química e Fertilidade Do Solo—RS/SC (Sociedade Brasileira de Ciência Do Solo—Núcleo Regional Sul): Santa Maria, Brazil.
- Stivers-Young, L. J. (1998). Growth, Nitrogen Accumulation, and Weed Suppression by Fall Cover Crops Following Early Harvest of Vegetables. *Hortscience*, *33*, 60-63.
- Team, R. C. (2020). *R: A Language and Environment for Statistical Computing*.
- Teasdale, J. R., & Daughtry, C. S. T. (1993). Weed Suppression by Live and Desiccated Hairy Vetch (*Vicia villosa*). *Weed Science*, *41*(2), 207-212. <https://doi.org/10.1017/S0043174500076074>
- Teasdale, J. R., & Mohler, C. L. (1993). Light Transmittance, Soil Temperature, and Soil Moisture under Residue of Hairy Vetch and Rye. *Agronomy Journal*, *85*(3), 673-680. <https://doi.org/10.2134/agronj1993.00021962008500030029x>
- Thomas, A. L., Costa, J. A., & Pires, J. L. (1998). Rendimento de grãos de soja afetado pelo espaçamento entre linhas e fertilidade do solo. *Ciência Rural*, *28*(4), 543-546. <https://doi.org/10.1590/s0103-84781998000400002>
- Trogello, E., José Modolo, A., Scarsi, M., & Dallacort, R. (2013). Manejos de cobertura, mecanismos sulcadores e velocidades de operação sobre a semeadura direta da cultura do milho. *Bragantia*, *72*(1), 101-109. <https://doi.org/10.1590/S0006-87052013005000016>
- Vieira, B. C., Luck, J. D., Amundsen, K. L., Werle, R., Gaines, T. A., & Kruger, G. R. (2020). Herbicide drift exposure leads to reduced herbicide sensitivity in *Amaranthus* spp. *Scientific Reports*, *10*(1), 2146. <https://doi.org/10.1038/s41598-020-59126-9>
- Whalen, D. M., Shergill, L. S., Kinne, L. P., Bish, M. D., & Bradley, K. W. (2020). Integration of residual herbicides with cover crop termination in soybean. *Weed Technology*, *34*(1), 11-18. <https://doi.org/10.1017/wet.2019.111>
- Wiggins, M. S., Hayes, R. M., & Steckel, L. E. (2016). Evaluating Cover Crops and Herbicides for Glyphosate-Resistant Palmer Amaranth (*Amaranthus palmeri*) Control in Cotton. *Weed Technology*, *30*(2), 415-422. <https://doi.org/10.1614/wt-d-15-00113.1>

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