The straw presence preceding soybean crop increases the persistence of residual herbicides

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Abstract: Background: There is little information on how different soil cover systems influence the residual effect of pre-emergent herbicides used in soybean cultivation in Brazil. **Objective:** The objective was to compare the persistence of different pre-emergent herbicides in a Latosolic Dystrophic Red Nitosol soil in the presence or absence of black oat straw on the soil surface. **Methods:** The herbicides used were chlorimuron-ethyl (40.0 g ai ha^{-1}), diclosulam (70.1 g ai ha^{-1}), flumioxazin (100.0 ai g ha^{-1}) and saflufenacil (70.0 g ai ha^{-1}). Soil samples were collected at 0, 5, 10, 15, 20, 32, 46 and 60 days after herbicide application. The bioavailability of the herbicides was evaluated in a greenhouse using cucumber plants as bioindicators. **Results:** Rainfall was necessary for the herbicides to go through the straw layer and reach the soil. Using straw, the half-life times for chlorimuron, diclosulam, flumioxazin and saflufenacil were 42, 61, 49 and 26 days, while without straw, they were 23, 45, 8 and 10 days, respectively. Conclusion: The presence of straw on the soil surface increased the persistence of herbicides in the soil.

Keywords: Herbicide dynamics; No-tillage; Conventional tillage; Dissipation constant; Straw transposition

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1. Introduction

Brazil is the second largest soybean producer in the world, totaling 117.89 million tons, and occupying an area of 34.77 million hectares in 2018 (Food and Agriculture Organization, 2020). The no-tillage system covers 33 million hectares in Brazil and the soybean crop was the most adapted to the no-tillage system, occupying more than 90% of the area in this system (Federação Brasileira do Sistema de Plantio Direto, 2021). The no-tillage system brings many benefits to Brazilian productive systems, such as reducing soil and water losses and bringing great savings in carbon, compared to systems with large soil disturbance. However, the cultivation of soybean under no-tillage system has become extremely dependent on the use of herbicides.

The use of herbicides in soybean fields in Brazil has been through significant changes along the years. Between the 1980s and the 2000s, when non-transgenic soybean cultivars were used, there was a predominance of the pre and post-emergent herbicides like Acetohydroxyacid Synthase (AHAS) and Acetyl Coa Carboxylase (ACCase) inhibitors. The intensive use of these herbicides led to the evolution of weed resistance cases between the 1990s and the 2000s (Adegas et al., 2017; Ovejero et al., 2019). The soybean cultivars resistant to glyphosate (Roundup Ready) were launched in 2005, and later on, other technologies were introduced providing farmers with different types of herbicide resistant cultivars.

There was a fast adoption of the glyphosate resistant soybean cultivars by Brazilian farmers, that was accompanied by the exclusive use of glyphosate in several operations through the year and the abandonment of consolidated weed management practices resulted in the evolution of weeds that became glyphosate tolerant or resistant (Adegas et al., 2017; Pazuch et al., 2017). The annual economic negative impact of the resistance of the main weeds to herbicides for soybean crops in Brazil in 2017 was estimated to be U$ 2.82 billion (Adegas et al., 2017).

To reduce weed infestations during the crop cycle and also act as a preventive measure against herbicide resistant weeds infestation, farmers has intensified the use of cover crops. Straw is a very useful tool for reducing weed infestations and black oats (*Avena strigosa* L.) are the main cover crop used in winter season in southern Brazil (Ziech et al., 2015), with an estimated area of 5 million ha (Federizzi et al., 2014). This winter grass has a dry biomass production during the cycle ranging between 1,532 and 6,000 kg per ha and a leaf/stem ratio ranging between 0.65 to 1.71 depending on the stage of development of the plants (Ziech et al., 2015; Dochwat et al., 2020). To cope with the increased infestation of resistant weeds, farmers are also implementing the rotation of herbicides with distinct mechanisms of action and with residual effect over weeds.

The herbicides chlorimuron-ethyl, diclosulam, flumioxazin are examples of broadleaves residual herbicides used for weed management in soybean in Brazil. The herbicide saflufenacil is recommended in broadleaves burndown operations in pre-sowing soybean, showing residual activity in soil (Badische Anilin- & Soda-Fabrik, 2008). The herbicides chlorimuron-ethyl and diclosulam are AHAS inhibitors, while flumioxazin and saflufenacil inhibit the enzyme protoporphyrinogen oxidase (PPO) (Oliveira Jr. et al., 2020).

Several environmental factors such as soil moisture, organic matter and soil texture can influence the efficacy of residual herbicides. Although mulching is an excellent tool in integrated weed management (Kadziene et al., 2020), the crop residues deposited on the soil affect the behavior of residual herbicides. These plant residues can create a barrier preventing the herbicides from reaching the soil or slowing this necessary movement (Carbonari et al., 2016). The performance of residual herbicides depends on their physicochemical characteristics and also on the amount and origin of the mulch, the rain or irrigation volume, and the length of time prior to the first rainfall event after application and of subsequent rainfall events. Additionally, it can also depend on other prevailing weather conditions during and after application (Carbonari et al., 2016).

The presence of crop residue on the surface has the ability to affect the dynamics of herbicides in the environment (Cavenaghi et al., 2007; Matos et al., 2016; Carbonari et al., 2016) and, therefore, could affect both weed control and phytotoxicity on succession crops. Undesired residual effects of herbicides used in soybean crops on succession crops have been reported (Artuzi, Contieiro, 2006; Dan et al., 2012; Szmigielski et al., 2009). The species used in crop succession must be carefully planned, in order to avoid problems caused by herbicide carryover, and for this, the ideal situation is that the residual effect of the herbicide should last until the senescence of the first planted crop (Mancuso et al., 2011).

There is still a lack of information available on how different soil cover systems affect the residual effect of pre-emergent herbicides used for soybean weed management in Brazil. This information is key for improvement of weed and weed resistance to herbicides management. Our hypothesis is that the straw present on the surface will modify the presence and the persistence of pre-emergent herbicides in the soil, explained by differences in herbicide transposition through straw. In this context, the objective of this study was to determine, in a comparative way, the persistence of the herbicides chlorimuron-ethyl, diclosulam, flumioxazin and saflufenacil applied in management systems with and without black oat straw on the surface of a Red Dystrophic Latosol.

2. Methodology

Field experiments and bioassays in greenhouse were installed in the experimental area of the Federal University of Technology (UTFPR) *Campus* Pato Branco (26°07'S and 52°41'W). The soil used in the experiments is classified as Red Dystrophic Latosol with 20, 60 and 20% sand, clay and silt, respectively. The soil organic matter content, pH and CTC were 48.92 g dm^{-3}; 4.97 and 12.98, respectively.

The field experiment was carried out in a randomized block design in 5 x 2 x 8 factorial scheme with four replications. The experimental units measured 3 x 3 m, with a 2.5 x 2.5 m usable area. The first factor comprised the herbicides chlorimuron-ethyl (40 g ha^{-1}), diclosulam (70.1 g ha^{-1}), flumioxazin (100.0 g ha^{-1}) and saflufenacil (70.0 g ha^{-1}) and a check without herbicide. The following commercial products were used: Classic®, 240 g chlorimuron kg^{-1}, Corteva; Spider®, 840 g diclosulam kg^{-1}, Corteva; Flumyzin®, 500 g flumioxazin kg^{-1}, Sumitomo; Heat®, 700 g saflufenacil kg^{-1}, Basf. The second factor was the presence or absence of the black oat straw on the soil surface. The third was represented by the periods of sample collection in experimental units (0, 5, 10, 15, 20, 32, 46 and 60 days after application).

The experimental area was under no-tillage system for ten years, with varied rotation and succession systems, in which oats or fodder turnip predominated in autumn/winter and millet or soybeans in the spring/summer period. The black oat (*Avena strigosa*) was only sown in the previously designated plots, on May, 25th. The remaining plots (treatments without straw) were kept free from the presence of weeds throughout the experimental period. Thirty days before the soybean sowing (October, 25th), when the oat plants were at the full bloom stage, the area was desiccated with Original DI® (glyphosate) in a 1,110 g e.a. ha^{-1} dose. The average dry mass produced by black oat in experimental units with straw at the time of sowing soybean was 4,700 kg ha^{-1}. The herbicides were applied on the same day of the soybean sowing using backpack equipment at 200 kPa constant pressure and 200 L ha^{-1} spray solution volume, with a 2.00 m wide bar containing 80.01 flat fan tips, 0.50m apart from each other.

The accumulated rainfall between herbicide application and the last soil sampling was 322 mm (Figure 1). In the period between 0 and 28 DAA, the rainfall was low and irregular. From the 28 DAA onwards, the rainfall was better distributed along time. The maximum, medium and minimum temperatures were normal for the period.

The soil sampling and bioassay procedures were adapted from the methodology used by Trezzi et al. (2013). Soil samples were collected at a 7cm depth from each field

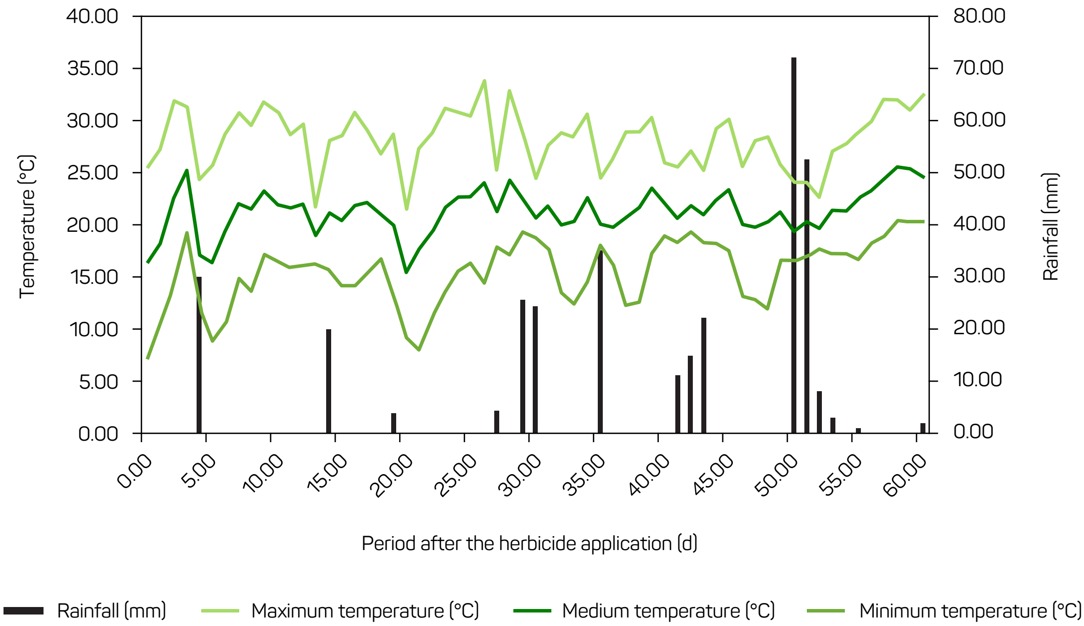

Figure 1 - Rainfall (mm) and maximum, medium and minimum temperatures (°C), during the period of sample collection for the herbicide persistence evaluation. UTFPR, Pato Branco-PR

experimental unit, immediately evenly turned over and placed in 300 cm^3 plastic pots at 0, 5, 10, 15, 20, 32, 46 and 60 days after herbicide application (DAA). The samples were stored at -26 °C until its use in the greenhouse bioassays. All samples collected in the pots, in all sampling periods, were defrosted at the same time, inside a greenhouse, over a 24-hour period for carrying out the persistence bioassay with cucumber seedlings.

Hybrid cucumber seeds Pioneer® 007557 were seeded in gerboxes containing two layers of blotting paper moistened with water for seed germination. The gerboxes were incubated in growth chamber at 25 °C with 12-hour photoperiod for 36 hours. This procedure aimed at the standardization of the seed radicle emission, and two of the germinated seeds (with visible radicle protrusion) were transplanted into each pot containing the sampled soil.

Plant height and phytotoxicity were measured at 7, 14 and 21 days after transplantation (DAT). The plant height was measured with a millimeter ruler from the base of the plant to the last leaf inflection point. At the end of the experiment, at 21 DAT, the fresh mass (FM) was determined by weighing the plants immediately after being cut. The plants were then taken to the drying oven at 60 °C until they reached constant weight dry shoot mass (FM) measurement.

The FM of cucumber over the sampling periods was fitted using equation 1:

$$y = a_0 + a1x + a2x^2 + a3x^3 \qquad \text{(Equation 1)}$$

The bioavailability of the herbicides chlorimuron-ethyl, diclosulam, flumioxazin and saflufenacil in the soil was verified through calibration curves obtained in the cucumber response-to-herbicide bioassay. The cucumber seedlings were grown in 300 cm^{-3} plastic pots. Eight doses of each herbicide were applied to the soil as previously described for the curve adjustment and calibration to determine its bioavailability (Table 1).

To obtain the bioavailability values, the equation linear segments were used, determined through the calibration curves. The bioavailability of the herbicides was calculated by employing the FM evaluations. Then, the FM values obtained from the persistence experiment were substituted in the equations to determine the proportion of herbicides bioavailable in the soil.

The response variable to determine the persistence of residual herbicides was the cucumber plant fresh mass (FM) due to the better adjustment of the regression model.

The persistence of the herbicides chlorimuron-ethyl, diclosulam, flumioxazin and saflufenacil was determined using the kinetics of herbicide dissipation equation (Paul, Clark, 1989):

$$(\ln([c_f]/[c_i] = - kt \qquad \text{(Equation 2)}$$

Where $[C_f]$ and $[C_i]$ correspond to the herbicide concentration indicated by the bioassay at the initial and final times, respectively; k is the herbicide dissipation rate in time; and t is time. To determine ti, the time after application when the greatest herbicide availability detected by the bioassay method was considered, and ci is the amount of herbicide detected as a function of ti.

Table 1 - Doses of herbicides in g i.a. ha^{-1} used to calibrate the curve for bioavailability determination

Saflufenacil	Diclosulam	Chlorimuron-ethyl	Flumioxazin
Doses (g i.a. ha^{-1})			
0.00	0.00	0.00	0.00
0.70	0.84	0.50	0.50
1.05	1.68	1.13	1.50
1.40	2.94	1.75	2.50
2.10	5.88	2.75	3.50
3.50	8.82	4.13	4.50
4.90	11.76	5.50	6.00
6.30	15.54	6.88	7.50

The herbicide half life ($t_{½}$) in the soil solution was calculated using equation 3.

$$t_{½}=0,693/k \qquad \text{(Equation 3)}$$

Where [C_i] was considered the date after the herbicide application when the maximum amount available in the soil solution was observed.

The data were converted into percentage in relation to the herbicide free treatment. The data were submitted to variance analysis using the F test, aided by the program Genes®. The treatment means were compared one to another using the confidence interval (CI) at 5% experimental error probability ($p \geq 0.05$). The adjustment of the calibration curves was carried out through polynomial regression, using the software SigmaPlot® version 10.0.

3. Results and discussion

3.1 Herbicide behavior on the straw

Regarding fresh matter (FM), evaluated at 21 DAT and normalized in relation to the check, statistical significance ($p < 0.05$) was observed only in the interactions Herbicide x Evaluation, Herbicide x Straw and Straw x Evaluation. No significance was found for the interaction of the three factors.

In the soil collection carried out immediately after the herbicide application, the cucumber FM reduction was seen to be more intense in the no straw system when compared to the system with straw (Figure 2). This indicates that the black oat straw acted as a barrier for the transposition of the herbicide into the soil. After the first rainfall 4 DAA (Figure 1) the herbicide probably reached the ground in sufficient concentration to reduce cucumber's FM.

The bioassay with cucumber plants indicates that the herbicide chlorimuron-ethyl went through the oat straw on the soil surface quickly. From the the thirty second day onwards, the cucumber FM reduction was more intense in the straw system (Figure 2A). The residual effect and the persistence of ionizable molecules of the herbicides such as chlorimuron (pKa = 4.2) in the environment depends on the clay and organic matter content in the soil as well as the soil pH (Milanova, Grigorov, 1996). The chlorimuron-ethyl solubility is considered high (450 mg L^{-1} under pH 6.5), which explains its ability to transpose the oat straw to reach the soil. Thus, the 30mm rainfall that occurred at 4 DAA was enough to move this herbicide from the straw to the soil (Figure 1). However, the results indicate that the herbicide chlorimuron-ethyl presented greater retention by the soil colloids than on the straw. Therefore, this result may explain the herbicide lower leaching, and why remained in the system for a longer period of time.

The herbicide diclosulam was released from the straw to the soil (Figure 2B) after a 25 mm accumulated rainfall up to 15 DAA (Figure 1). The diclosulam availability in the system with straw on the soil surface was similar in comparison to the no straw system (Figure 2B). The greatest FM reduction in the treatment with diclosulam was 55%, in the period between 5 and 15 DAA evaluation and no straw treatment. In the last soil sampling at 60 DAA, FM was reduced 49.6% and 31.5% in comparison to control in the treatments with and without straw, respectively. In a system with sugar cane straw on the soil, it was possible to observe by the chromatographic method that diclosulam needed approximately 50mm rainfall to reach a 65% transposition to the soil (Perim, 2014). After 140 DAA, the presence of diclosulam in the soil was still detectable, with or without straw (Perim, 2014). Due to the diclosulam high persistence in the soil, it presents potential to cause negative effects on successional crops.

The herbicide flumioxazin was greatly affected by the presence of oat straw on the soil surface (Figure 2C). According to the mathematical models adjusted for both regressions, only from the 17 DAA onwards the flumioxazin soil availability was lower in the straw system when compared to no straw. Out of the four herbicides used in this study, flumioxazin was the one presenting less solubility in water, with only 1.79 mg L^{-1} at 25 °C and 2.55 log Kow at 20 °C (Senseman, 2007). Therefore, the rainfall registered up to 17 DAA seems to have been insufficient to

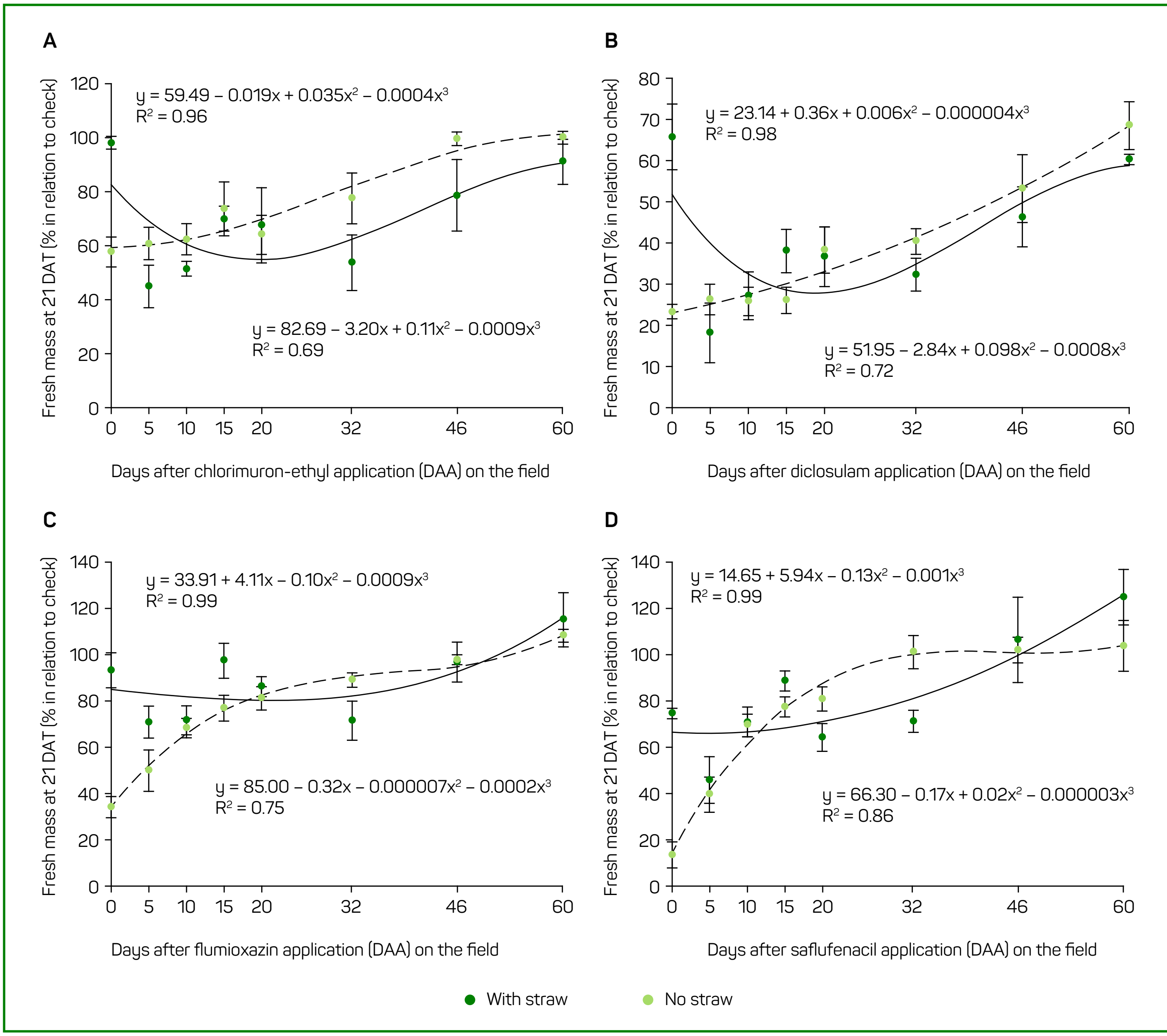

Figure 2 - Cucumber fresh plant mass (% in relation to check) evaluated 21 days after transplantation in soil treated with four different herbicides (A = Chlorimuron; B = Diclosulam; C = Flumioxazin; D = Saflufenacil) at eight sampling times (0, 5, 10, 15, 20, 32, 46 and 60 days after herbicide application on the field), in the presence and in the absence of black oat straw on the soil surface. Bars represent confidence intervals. UTFPR, Pato Branco

dislocate the herbicide from the straw to the soil, making it available to fulfill its role in the weed control (Figure 1). This result demonstrates its greater dependence on water to go through the straw.

The reduction of the effect of flumioxazin in samples taken 20 DAA in both systems (with and without straw) might be related to the high microbial degradation rate and the fast adsorption of flumioxazin molecules in the soil organic complex. The study carried out by Ferrell et al. (2003) revealed that around 80% of the flumioxazin molecules were adsorbed in 72 hours after application. Reports in the literature point out that millet plants sown in periods over 80 DAA of flumioxazin did not present intoxication symptoms (Dan et al., 2012). At 90 DAA, respectively 24.9, 14.4, 21.6 and 9.6% of the flumioxazin applied in four different soils in vineyards in Chile remained in the soil, and the final amount observed was inversely proportional to the rainfall recorded (Alister et al., 2008). Therefore, an increase in the rainfall events and reduction in the time between the herbicide application and the first heavy rain event should result in increased flumioxazin in the soil solution.

The herbicide saflufenacil, as well as flumioxazin, presented shorter periods of fresh plant mass reduction in cucumber (Figure 2D). From the evaluation at 32 DAA onwards, it was not possible to identify any reduction in the cucumber shoot mass in the treatment without black oat straw. In the treatment with straw, there is evidence that the herbicide was released to the soil after the rainfall (Figure 2D). Such behavior made the effects on the cucumber plants to be observed for a longer period, up to 46 DAA with a 29% reduction in FM in comparison to the check. In addition to the microbial degradation, the saflufenacil leaching to unsampled soil depth (up to 7 cm deep) might have contributed to the absence of effects from the 32 DAA onwards. In soils with pH 5.2 the highest saflufenacil concentration was found 15 cm from soil surface (Monquero et al., 2012), suggesting that in our condition (pH = 4.97) the herbicide might be leached deeper.

3.2 Calibration Curve from the fresh plant mass

To obtain the bioavailability values, we used the following calibration curves linear segments: between 0 to 2.75 g i.a. ha^{-1} for chlorimuron (Figure 3A); 0 to 2.94 g i.a. ha^{-1} for diclosulam (Figure 3B); 0 to 4.5 g i.a. ha^{-1} for flumioxazin (Figure 3C); and between 0 and 3.5 g i.a. ha^{-1} for saflufenacil (Figure 3D).

3.3 Bioavailability from the fresh plant mass

The herbicide chlorimuron-ethyl went through the straw and reached the soil 5 DAA, presenting greater bioavailability with straw in comparison to the treatment without soil cover (Figure 4A). The no straw treatment showed constant reduction in bioavailability throughout time, while in the soil with straw treatment, there were variations following rainfall events (Figure 1). The greater bioavailability of the herbicide chlorimuron-ethyl observed in the no straw treatment on the day of application can be

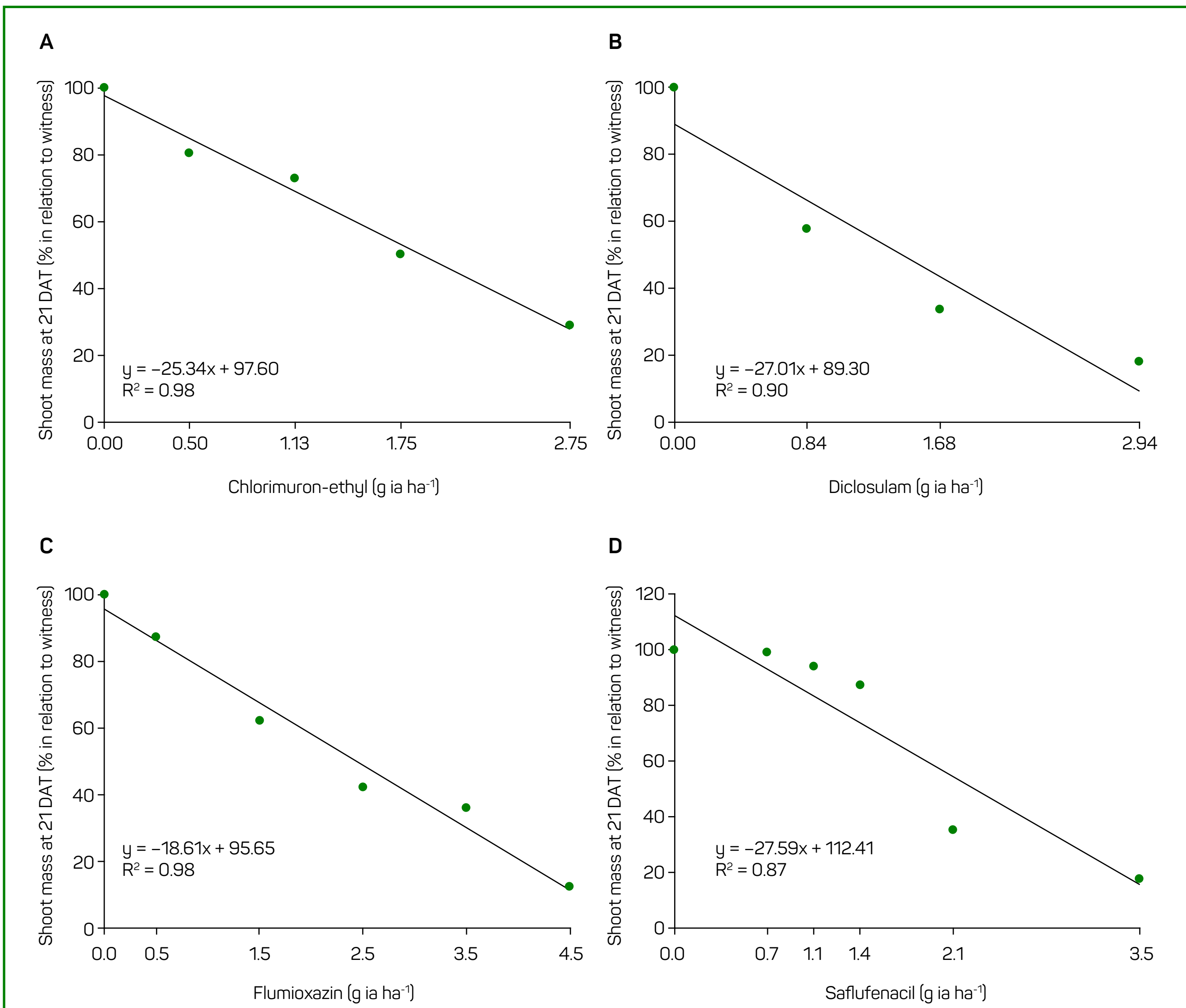

Figure 3 - Cucumber fresh plant mass (% in relation to check) as a function of the doses of the herbicides (A) Chlorimuron-ethyl, (B) Diclosulam, (C) Flumioxazin and (D) Saflufenacil, evaluated 21 days after transplantation (DAT). UTFPR, Pato Branco

explained by the absence of rain to leachate the herbicide from the straw to the soil.

In the first two rainfall recordings, chlorimuron-ethyl was leached from the straw to the soil (up to 15 DAA). In the no straw treatment 60 DAA (last evaluation), chlorimuron was no longer detected in the soil, while in the treatment with straw it was still detected. The greater bioavailability of chlorimuron-ethyl in the soil was detected at 5 DAA in the treatment with straw, representing 5.20% in relation to the applied dose. It was possible to identify that only 1.53% of the total chlorimuron-ethyl applied to the soil was still available 60 DAA. The major chlorimuron-ethyl cause of degradation in the soil is biological, thru bacterial degradation (Zhang et al., 2019).

Diclosulam remained in the black oat straw during the interval between the application and the first evaluation at 5 DAA (Figure 4B). After the first 30 mm rainfall recorded (Figure 1) the herbicide amount in the soil with straw was similar to the no straw treatment, which means it became slightly more available because the rain. In the last sample collected at 60 DAA, only 1.53% and 1.10% of the total diclosulam applied was detected, in the treatments with and without straw, respectively. In a Brazilian study, after 119 days of application of diclosulam in the soil, analysis by chromatographic method estimated dissipation rates of 73% and 62% in no-tillage and conventional tillage, respectively (Lavorenti et al., 2003).

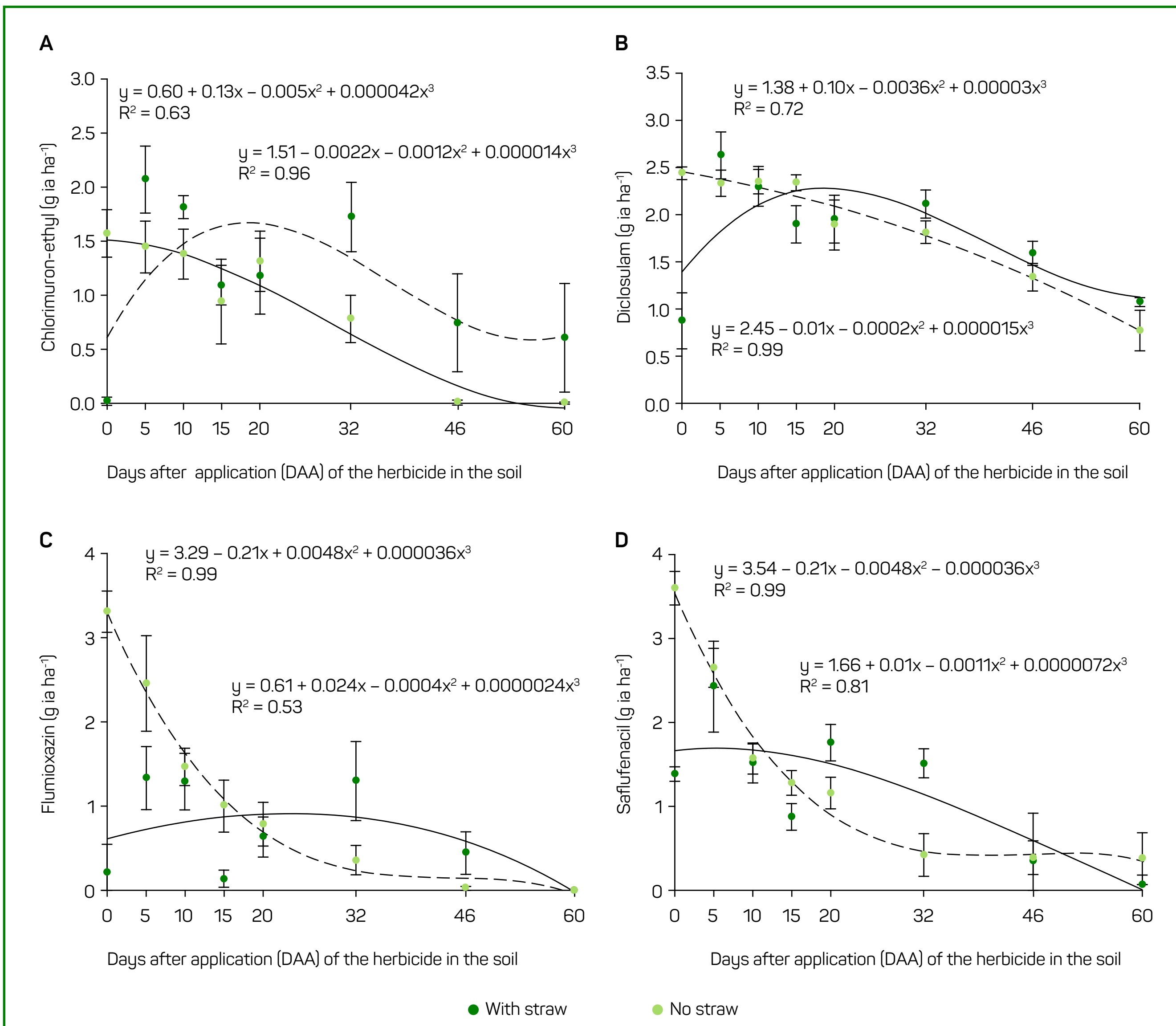

Figure 4 - Bioavailability of the herbicides chlorimuron-ethyl (A), diclosulam (B), flumioxazin (C) and saflufenacil (D), obtained through the variable fresh plant mass at 21 DAT of cucumber plants in soil samples up to 60 DAA of herbicides in the soil on the field. Bars represent confidence intervals. UTFPR, Pato Branco

The bioavailability of the herbicide flumioxazin was quite irregular with time, especially with straw (Figure 4C). The greater availability of this herbicide in the soil in the straw treatment occurred soon after the first rainfall at 5 DAA and also at 32 DAA (Figure 1). However, both lower than 1.50% of the total applied on the field. In the no straw system, approximately 3.31% of the herbicide was detected on the soil at the day of the application, and the availability was reduced gradually up to 45 DAA. The herbicide dislocation from the straw to the soil occurred in two periods that coincided with rainfall events recorded in the experiment, demonstrating dependence on the rain to increase its herbicide availability in the soil when there is straw covering soil. In the straw treatment, the herbicide availability was extended in comparison to the no straw (Figure 4 C). The flumioxazin have a high adherence to the residues (Silva, Monquero, 2013) mainly due to its high log kow (Vidal, 2002), and this causes a reduction in the amount of the herbicide that reaches the soil. According to Carbonari et al. (2019) only 35% of the flumioxazin transposed 15 t of eucalyptus residues and reached the soil after 10 mm of rain and it was necessary 150 mm of rain so that there was 58% transposition of the flumioxazin.

The saflufenacil bioavailability, in the no straw treatment on the day of application was 5.13% in relation to the initial dose applied on the field (Figure 4D). After 32 DAA, only traces of the product were detected in the soil. In the straw treatment, three peaks of bioavailability were detected, which coincided with rainfall events (Figure 1). In the evaluations at 46 and 60 DAA the bioavailability results between the straw treatments were similar.

Based on the data obtained in this work, chlorimuron-ethyl required a period between 46 and 60 DAA for its total dissipation in the no straw system, while 60 days weren't enough to dissipate 100% of this herbicide in the straw treatment. As for the herbicide diclosulam, the herbicide was still found in the soil in the systems with and without black oat straw on the soil surface 60 DAA. Because diclosulam percentages were higher than the remaining herbicides, exemplifies its high residual effect on the soil. The herbicide flumioxazin needed a period of 32 to 46 days to be completely dissipated from the soil layer under evaluation (5 cm) in the no straw treatment, while in the system with straw, the time required for complete dissipation was 46 to 60 days. Saflufenacil required a period of 32 to 46 days for its complete dissipation from soil in the no straw system, while with black oat straw the time required for complete dissipation was over 60 days. In general, the presence of black oat straw increased the residual effect of the herbicides in the soil.

The differences between the straw treatments can be explained by other factors beyond the initial physical obstacle for its movement to the soil solution. The straw influence the soil pH, which might impact herbicide ionization, thus interfering in the their adsorption to the soil organic and mineral colloids, changing degradation, persistence, and mainly their activity (Reddy et al., 1995b). In addition, the herbicide retention by the plant residues might minimize losses due to hydric erosion and leaching (Reddy et al., 1995a), slowing herbicide arrival to the soil. Thus, the herbicide residual activity may suffer additional variation according the amount of straw on the soil surface (Kadziene et al, 2020).

3.4 Kinetics of the herbicide dissipation in the soil

By using the herbicide bioavailability data along the time, calculated through the cucumber fresh mass data, evaluated on the 21st day after transplantation (DAT), it was possible to calculate the dissipation kinetics (Table 2) in the soil. The initial time (ti) represents the number of DAA in which there was high availability of the active ingredient and the initial concentration (ci) indicates the amount of the herbicide active ingredient available on the day ti.

Regarding the herbicide chlorimuron-ethyl, its dissipation constant (k) was seen to be lower with straw (0.0189) when compared to the no straw treatment (0.0303) (Table 2). The herbicide chlorimuron-ethyl half-life time was 41.67 and 22.88 for the treatments with black

Table 2 - Initial concentration (ci), dissipation constant (k) and half-life (t½) of the herbicides chlorimuron-ethyl, diclosulam, flumioxazin and saflufenacil in the presence and absence of black oat straw in the soil cover, by evaluating the fresh plant mass at 21 DAT. UTFPR, *Campus* Pato Branco

Herbicide	Soil cover	ti (days)	ci ± ep	k ± ep	R2	Half-life (t½) (days)
Chlorimuron-ethyl	With straw	5	1.894 ± 0.265	0.019 ± 0.008	0.79	41.67
	No straw	0	1.731 ± 0.219	0.030 ± 0.009	0.89	22.88
Diclosulam	With straw	5	2.484 ± 0.159	0.012 ± 0.003	0.90	60.90
	No straw	0	2.636 ± 0.128	0.015 ± 0.002	0.95	45.30
Flumioxazin	With straw	5	1.084 ± 0.396	0.016 ± 0.023	0.34	48.87
	No straw	0	3.598 ± 0.096	0.082 ± 0.004	0.99	8.44
Saflufenacil	With straw	5	2.149 ± 0.414	0.032 ± 0.015	0.82	26.39
	No straw	0	3.741 ± 0.207	0.069 ± 0.007	0.99	9.99

oat straw on the soil surface and without, respectively. This indicates that the straw increase the persistence of chlorimuron-ethyl in the soil.

Diclosulam presented a dissipation constant in the straw (0.0124) lower than that in the no straw treatment (0.0153). Thus the half-life times were 60.90 days for the treatment with straw and 45.30 days for the no straw treatment (Table 2). The half-life time of 67- days in no tillage system and 87 in the conventional system presented by Lavorenti et al. (2003) differed from our results. In Brazilian, Argentinian, and North American soils, the half-life of this herbicide tends to vary from 16 to 54 days (Yoder et al., 2000).

The flumioxazin data indicated greater difference between the straw treatments. The dissipation constant for the straw (0.0158) was lower than that of the no straw (0.0821) (Table 2). The half-life times (t½) were 48.87 and 8.44 days for straw and no straw, respectively, indicating that the black oat straw promoted herbicide residue in the soil. Data from the literature indicate that the flumioxazin half-life time is between 11.9 and 17.5 days (Taylor-Lovell et al., 2001).

Saflufenacil presented a lower dissipation constant with straw (0.0324) when compared to the no straw treatment (0.0694) (Table 2). The half-life values (t½) obtained were 26.39 for straw and 9.99 for no straw, being within the range from 7 to 35 days informed by the manufacturer (Badische Anilin- & Soda-Fabrik, 2008). The product efficacy (control) is kept at levels close to 80% even after 28 days of drought after application, however a sharp fall in the herbicide performance tends to occur after this period (Monquero et al., 2012). This data confirms the literature reports that indicate saflufenacil's persistence in the soil to be around 25 and 35 DAA (Diesel, 2013).

Our results showed an optimizing effect of straw oat on the pre-emergent herbicides agronomic performance. The use of cover crops is a major strategy for agricultural systems, protecting the soil and helping weed management (Kadziene et al., 2020). However, studies reinforce the importance of integrating the use of mulching with other weed management tools. Several studies highlight the existence of a complementary effect between the use of herbicides and mulching (Marchesan et al., 2016). To achieve this integrated control system, cover crops need to produce sufficient amount of straw covering the soil, which allow the maximization of its physical and allelopathic effects (Trezzi et al., 2016) combined with the use of herbicides that are able to migrate from the straw to the soil (Carbonari et al., 2016), both favoring weed suppression and control.

Although cover crops create a barrier preventing immediate direct contact of the herbicide with the soil, it allows the gradual release of herbicide in the soil solution, increasing its persistence. This is clear in this study when we compare the half-life of herbicides applied with and without straw (Table 2). Although not evaluated, the lower leaching in the straw system may be another factor increasing the half-life in no tillage systems. The use of undisturbed soil samples could produce different results compared to the present study, in which the samples were deformed, due to changes in hydraulic conductivity, density and macroporosity, which can favor the leaching of herbicides and, compromise the control of weeds (Ferri et al., 2002). However, in both systems (with and without straw), the soil samples were deformed, so that the main difference between the systems was the presence or not of straw on the soil surface. Thus, it is possible that among the various factors interfering with herbicide persistence, the gradual release of the herbicide present in the straw is more important than the highest rate of microbial degradation known to occur in no tillage systems or herbicide retention by straw.

4. Conclusions

The presence of straw on the soil surface increased the persistence of the herbicides chlorimuron-ethyl, diclosulam, flumioxazin and saflufenacil in the soil, when compared to the straw absence.

The ascending order of persistence in the soil, with and without straw, between evaluated herbicides was saflufenacil < flumioxazin < chlorimuron-ethyl < diclosulam.

Authors' contributions

FP: study design and execution of experiments, writing of the manuscript. MT: general coordination and design of the study, writing of the manuscript. AN: review of data and graphics and writing of the manuscript. HB: review of data and writing of the manuscript. FD: execution of experiments and statistical analysis of data. FP Jr.: statistical analysis of data.

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