Weed Science

www.cambridge.org/wsc

Research Article

Cite this article: de Castro Macedo G, Antonio Carbonari C, Domingues Velini E, Gimenes Cotrick Gomes GL, Alves de Matos AK, Batista de Castro E, Roma Burgos N (2020) Behavior of sulfentrazone in the soil as influenced by cover crop before no-till soybean planting. Weed Sci. **68**: 673–680. doi: 10.1017/wsc.2020.70

Received: 12 March 2020
Revised: 14 July 2020
Accepted: 11 September 2020
First published online: 22 September 2020

Associate Editor:
Timothy L. Grey, University of Georgia

Keywords:
Dystrophic Red Nitosol; glyphosate [*N*-(phosphonomethyl)glycine]; leaching; pearl millet (*Pennisetum glaucum* (L.) R. Brown); sorghum [*Sorghum bicolor* (L.) Moench ssp. *bicolor*]; sorption

Author for correspondence:
Gabrielle de Castro Macedo, University of Nebraska–Lincoln, West Central Research and Extension Center, 402 West State Farm Road, North Platte, NE, 69101.
(E-mail: gabriellecmacedo@gmail.com)

Behavior of sulfentrazone in the soil as influenced by cover crop before no-till soybean planting

Gabrielle de Castro Macedo[1], Caio Antonio Carbonari[2], Edivaldo Domingues Velini[3], Giovanna Larissa Gimenes Cotrick Gomes[4], Ana Karollyna Alves de Matos[4], Edicarlos Batista de Castro[1] and Nilda Roma Burgos[5]

[1]Postgraduate Student, Department of Plant Protection, Sao Paulo State University, Botucatu, Sao Paulo, Brazil; [2]Associate Professor, Department of Plant Production and Breeding, Sao Paulo State University, Botucatu, Sao Paulo, Brazil; [3]Titular Professor, Department of Plant Production and Breeding, Sao Paulo State University, Botucatu, Sao Paulo, Brazil; [4]Postgraduate Student, Department of Plant Production and Breeding, Sao Paulo State University, Botucatu, Sao Paulo, Brazil and [5]Professor, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA

Abstract

More than 80% of soybean [*Glycine max* (L.) Merr.] in Brazil is cultivated in no-till systems, and although cover crops benefit the soil, they may reduce the amount of residual herbicides reaching the soil, thereby decreasing herbicide efficacy. The objective of this study was to evaluate sulfentrazone applied alone, sequentially after glyphosate, and in a tank mixture with glyphosate before planting no-till soybean. Experiments were performed in two cover crop systems: (1) pearl millet [*Pennisetum glaucum* (L.) R. Br.] and (2) forage sorghum [*Sorghum bicolor* (L.) Moench ssp. *bicolor*]. The treatments tested were: glyphosate (720 g ae ha^{-1}) at 20 d before sowing (DBS) followed by sulfentrazone (600 g ai ha^{-1}) at 10 DBS; glyphosate + sulfentrazone (720 g ae ha^{-1} + 600 g ai ha^{-1}) for cover crop desiccation at 10 DBS; and sulfentrazone alone at 10 DBS without a cover crop. The accumulation of straw was 31% greater using sorghum rather than pearl millet. In the sorghum system, the concentration of sulfentrazone at 0 to 10 cm was 57% less with sequential application and 92% less with the tank mixture compared with the treatment without cover crop straw at 1 d after application (DAA). The same occurred in the pearl millet system, where the reduction was 33% and 80% for the sequential application and tank mixture, respectively. The absence of a cover crop resulted in greater sulfentrazone concentrations in the top layer of the soil when compared with the sequential application or tank mixture. At 31 and 53 DAA, the concentration of sulfentrazone at 10 to 20 and 20 to 40 cm did not differ among treatments. Precipitation of 90 mm was enough to remove the herbicide from the cover crop straw at 31 DAA when using sequential application. An additional 90-mm precipitation was necessary to promote the same result when using the tank mixture.

Introduction

No-till crop production in Brazil occupies more than 35 million hectares and continues to expand (FEBRAPDP 2013). About 85% of the total soybean [*Glycine max* (L.) Merr.] production area is no-till (EMATER 2014). The herbicide sulfentrazone, an inhibitor of protoporphyrinogen oxidase (PPO), is often used with glyphosate for preplant vegetation burndown in no-till soybean. In some cases, the use of glyphosate with PROTOX-inhibiting herbicides is synergistic, manifested in faster desiccation, reducing the time between preplant burndown and sowing (Jaremtchuk et al. 2008). The addition of a PROTOX inhibitor helps manage glyphosate-resistant weeds (Ashigh and Hall 2010; Shaner 2000), and its residual activity allows for application of POST herbicides later in the season (Jaremtchuk et al. 2008).

Sulfentrazone belongs to the chemical family of triazolinones and the PROTOX inhibitor group. It is a weak acid with a dissociation constant (pK_a) of 6.56 (Grey et al. 1997); water solubility of 110 mg L^{-1} (pH 6.0); vapor pressure of 1.07×10^{-7} Pa (25 C) (Shaner 2014); partition coefficient (K_{ow}) of 9.8 (pH 7.0); and a half-life of 110 to 280 d in soil depending on the local edaphoclimatic conditions. It is degraded primarily by soil microbes (FMC Corporation 1995; Grey et al. 1997; Hess 1993; Martinez et al. 2010; Shaner 2012; Tomlin 1994). Therefore, factors that favor high microbial population and activity also favor rapid degradation of sulfentrazone.

Despite broad adoption of mixing residual herbicides with nonselective herbicides for preplant burndown and application of PRE herbicides with glyphosate or following glyphosate application at planting, little is known about the dynamics of residual herbicides when applied

Table 1. Chemical characterization of the soil sorghum and pearl millet cover crop locations.[a]

Depth	pH	OM	P_{resin}[b]	Al^{3+}	$H^{+}Al$	K	Ca	Mg	SB	CEC	V%
Sorghum cover crop location											
cm	$CaCl_2$	g dm^{-3}	mg dm^{-3}	———mmol$_c$ dm^{-3}———							
10-20	4.9	26	19	1	44	4.6	33	14	52	96	54
20-40	4.9	21	8	1	40	3.3	28	12	43	83	52
Pearl millet cover crop location											
Depth	pH	OM	P_{resin}	Al^{3+}	$H^{+}Al$	K	Ca	Mg	SB	CEC	V%
cm	$CaCl_2$	g dm^{-3}	mg dm^{-3}	———mmol$_c$ dm^{-3}———							
10-20	4.7	22	13	1	44	9.2	32	13	54	98	55
20-40	4.5	17	8	3	57	3.9	27	10	40	97	42

[a]Abbreviations: OM, organic matter; SB, sum of bases; V%, base saturation.
[b]There are several methods to determine phosphorus content in soil. In the extraction procedure with the resin, P moves into solution and is then adsorbed by the resin, a porous synthetic material with positive charges, mimicking what happens with roots.

Table 2. Physical characterization of the soil in the sorghum and pearl millet cover crop locations.

Cover crop site	Depth	Granulometry					Texture
		Sand					
		Coarse	Fine	Total	Clay	Silt	
	—cm—	———g kg^{-1}———					
Sorghum	10–20	51	152	203	507	290	Clay
Sorghum	20–40	49	137	186	525	289	Clay
Pearl millet	10–20	48	145	193	529	278	Clay
Pearl millet	20–40	40	117	157	578	265	Clay

to soil covered with plant residue. Recent studies indicate that residual herbicides can be effectively integrated in conjunction with cover crop termination applications in preplant, but termination timing and biomass accumulation will affect the amount of sulfentrazone reaching the soil (Whalen et al. 2020).

The presence of plant residue on the soil surface can alter herbicide behavior (Selim et al. 2003) and reduce herbicide efficacy. Plant residue prevents deposition of herbicide to soil. Herbicide molecules retained on plant residue are exposed to various avenues of dissipation, including volatilization and degradation by sunlight (Johnson et al. 1989; Locke and Bryson 1997). The magnitude of these effects on herbicide molecules retained on plant residues depends on the occurrence of rain, which washes the herbicide into the soil, where it follows normal chemical dynamics in the soil environment (Banks and Robinson 1986; Ghadiri et al. 1984; Reddy et al. 1995).

In sugarcane (*Saccharum officnarum* L.), it was observed that more than 20% of the total sulfentrazone applied is retained in sugarcane straw (Carbonari et al. 2016). There is practically no information about the dynamics of sulfentrazone applied in no-till soybean, whether on crop stubble or on cover plants at the time of desiccation. The prevailing hypothesis is that applying herbicide on soil with plant residue cover results in reduced herbicide efficacy.

The objectives were to evaluate the behavior and spatial distribution of sulfentrazone in the soil when applied on pearl millet [*Pennisetum glaucum* (L.) R. Br.], sorghum [*Sorghum bicolor* (L.) Moench ssp. *bicolor*], or bare soil.

Materials and Methods

Experimental Area

Two experiments were performed between 2013 and 2014 at the Lageado Experimental Farm, São Paulo State University–UNESP, Botucatu Campus, Sao Paulo, Brazil. The forage sorghum area was located at 22.844°S, 48.425°W, and the millet area at 22.844°S, 48.424°W, at an altitude of 779 m. The soil of the experimental areas was Dystrophic Red Nitosol (EMBRAPA 2006). The soil physical and chemical characteristics are listed in Tables 1 and 2. The climatic conditions during the implementation of the experiments are shown in Figure 1.

Experimental Design and Cover Crop Establishment

Forage sorghum and pearl millet were chosen due their common use as cover crops in Brazilian Cerrado. The forage sorghum cover crop was planted at 9 kg ha^{-1} and the pearl millet cover crop at 15 kg ha^{-1} of seed, both in a no-till system. The cover crops were sown on October 7, 2013. The experimental design was a randomized complete block design with four treatments and four replications. Each plot was 7-m long and 2.5-m wide, with five crop rows spaced 0.5 m apart.

Three preplant burndown treatments were tested on each cover crop: (1) glyphosate (Roundup® Original, 480 g ai L^{-1}, Monsanto, km 159 Carlos Marcondes Road, Sao Jose dos Campos, Sao Paulo, Brazil) (720 g ae ha^{-1}) at 20 d before sowing (DBS) followed by sulfentrazone (Boral 500 SC®, FMC, 943 Bortolo Jose Ferro Street, Paulinia, Sao Paulo, Brazil) (600 g ai ha^{-1}) at 10 DBS; (2) glyphosate (720 g ae ha^{-1}) mixed with sulfentrazone (600 g ai ha^{-1}) at 10 DBS; and (3) sulfentrazone (600 g ai ha^{-1}) at 10 DBS on bare soil. All treatments were performed in an area with a no-till planting system. For the treatment without cover crop, the cover crop plants were removed from the plots with minimal soil disturbance by using a hoe before the spraying herbicides.

Application of Treatments, Soybean Sowing, and Data Collection

At 1 d before herbicide application (20 DBS), cover crop residue samples were collected from four 0.25-m^2 random sites per plot.

https://doi.org/10.1017/wsc.2020.70 Published online by Cambridge University Press

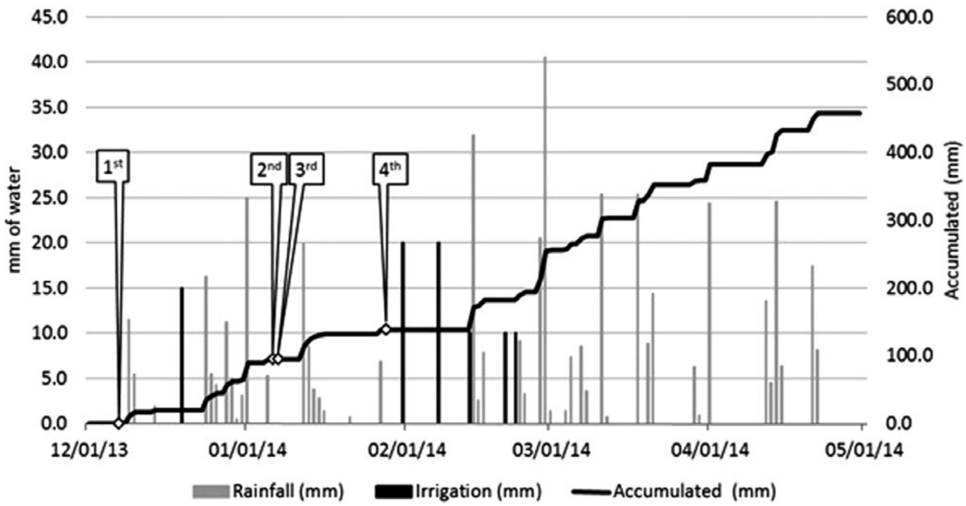

Figure 1. Precipitation, irrigation, and accumulation (mm) during the experiments. 1st: collection performed 1 d after the application of sulfentrazone; 2nd: collection performed 31 d after the application of sulfentrazone; 3rd: collection performed 32 d after the application of sulfentrazone; 4th: collection performed 53 d after the application of sulfentrazone.

No further biomass collection was made until all the termination treatments were applied and the cover crops were dead. At 9 d after the sulfentrazone application (DAA), 0.25-m² cover crop residue samples were collected per plot. The samples were stored in paper bags and dried in a forced-air circulation oven (60 C) until the samples reached constant mass. Total dry weights per plot were collected for data analysis.

The herbicides were applied using a CO_2-pressurized backpack sprayer operating at a pressure of 300 kPa and a spray volume of 200 L ha^{-1}. The sprayer was fitted with six flat-fan XR 11002 VS nozzles (TeeJet® Technologies, Spraying Systems, Wheaton, IL, USA) spaced 0.5 m apart.

Soybean 'BMX Potência' was planted in a no-till system on December 17, 2013, at 22 seeds m^{-1}, on rows spaced 0.45 m apart (Strieder et al. 2015). Soybean was managed following region-specific recommendations. The crop was sprinkler irrigated as needed.

To determine the concentration of sulfentrazone in the soil profile, soil samples were collected at three sites per plot to create a composite sample per collection time (1, 31, and 53 DAA). The first collection was performed only in the 0 to 10 cm layer, before the occurrence of rain. The samplings at 31 and 53 DAA of sulfentrazone occurred after 90 mm of precipitation had fallen between the first and second sampling and between the second and third sampling, with a total of 180 mm of precipitation between 1 and 53 DAA (Figure 1). At these timings, the samples were acquired at three depths: 0 to 10 cm, 10 to 20 cm, and 20 to 40 cm. An auger-type probe was used to collect the soil samples, and the samples were placed in plastic bags and stored at −20 C until processing.

The purpose of any herbicide application is to distribute the product as evenly as possible in the treated area. To evaluate this distribution, in addition to the collections to determine the dynamics of sulfentrazone release in the soil profile, a spatial collection was also carried out, aiming to demonstrate the uniformity of the concentration of the herbicide at different points within the experimental plot in the different pre-sowing management systems for soybeans. The soil sampling was conducted at 32 DAA of the herbicide by collecting samples at five points from each parcel, which yielded a total of 20 samples per treatment at a depth of 0 to 10 cm, and the samples were stored as described earlier.

To extract the available sulfentrazone from the soil solution, the samples were thawed and dried at 40 C. After the samples were homogenized, a 7-g subsample of dry soil was removed and placed in a 10-ml plastic cartridge containing porous polyethylene. Each soil-containing cartridge was saturated with 2.5-ml of deionized water and refrigerated (8 ± 3 C) for 24 h. Water was used to remove only the available sulfentrazone fraction in the soil solution. The cartridges were then centrifuged (Hettich Zentrifugen centrifuge, Föhrenstraße 12 78532, Tuttlingen, Germany) at 3,270 × *g* and 25 C for 10 min (Carbonari 2009). The soil-water extract was filtered using 3.0-ml plastic syringes with Millex® membrane filters (Millipore PVDF 13 mm × 0.45 μm, Merck Millipore, Tullagreen, Carrigtohill, County Cork, Ireland). The filtrate was transferred to 2.0-ml glass vials.

Sulfentrazone in the solution was quantified using high-performance liquid chromatography–mass spectroscopy with an HPLC column (Prominence UFLC, Shimadzu, Kyoto, Japan) coupled to a triple quadrupole mass spectrometer (3200 Q TRAP, Applied Biosystems, Foster City, CA, USA). A 50 × 4.60 mm C18 column with a 20-μl injection volume was used (Synergi 2.5-μ Hydro-RP 100 Å, Phenomenex, Torrance, CA, USA). The mobile phases used were 0.5% acetic acid in water (Phase A) and 0.5% acetic acid (Avantor Performance Materials, Center Valley, PA) in methanol (Avantor Performance Materials S.A., Xalostoc, Mexico) (Phase B), with a flow rate of 0.4 ml min^{-1}. The following sequence of mobile phase gradients was used: (1) 70% Phase A and 30% Phase B for 1 min; (2) 5% Phase A and 95% Phase B, 3 min; (3) 5% Phase A and 95% Phase B, 2 min; (4) 70% Phase A and 30% Phase B, 2 min; and (5) 70% Phase A and 30% Phase B, 2 min. The mass spectrometer was operated in the positive electrospray ionization mode. The sulfentrazone multiple reaction monitoring was optimized to 386.9, and confirmation was achieved through two-ion transition (110.2 and 146.1). A standard curve of serial dilutions of sulfentrazone analytical standard with a certified purity level of 99.8% (supplied by FMC) was used for quantification.

Data Analysis

For the cover crop dry mass data, 95% confidence intervals were established. The data for sulfentrazone concentration in the soil

https://doi.org/10.1017/wsc.2020.70 Published online by Cambridge University Press

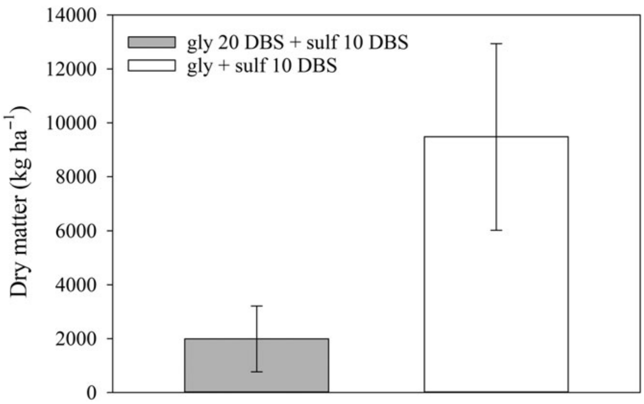

Figure 2. Average quantity of sorghum cover in the experimental areas at 70 d after sowing and at 9 d after the application of sulfentrazone. The sizes of the error bars are equal to the confidence interval ($P \leq 0.05$). DBS, days before sowing; gly 20 DBS + sulf 10 DBS = glyphosate 20 DBS + sulfentrazone 10 DBS; gly + sulf 10 DBS = glyphosate + sulfentrazone 10 DAS.

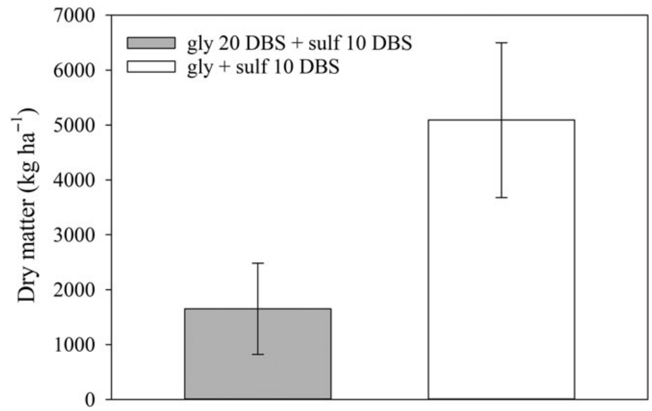

Figure 3. Average quantity of pearl millet cover in the experimental areas at 70 d after sowing and at 9 d after the application of sulfentrazone. The sizes of the error bars are equal to the confidence interval ($P \leq 0.05$). DBS, days before sowing; gly 20 DBS + sulf 10 DBS, glyphosate 20 DBS + sulfentrazone 10 DBS; gly + sulf 10 DBS, glyphosate + sulfentrazone 10 DAS.

were subjected to ANOVA by the *F*-test at 5% probability, and the treatment across depths means were compared using Tukey's test ($P \leq 0.05$). The data for the accumulated frequencies of the point availability of the herbicides were subjected to regression analysis using the Gompertz model in SAS (SAS Institute, Cary, NC) statistical software (Velini 1995):

$$F = \left[e^{a - e^{(-bc*x)}}\right] \quad [1]$$

where *F* represents the accumulated frequency of the availability of the herbicide as a percentage; *a* is the maximum asymptote of the curve, which was set to 4.60517; $e^a = 100$; the displacement of the curve along the *x* axis is represented by the modulus of the parameter *b*; and the parameter *c* is the slope or concavity of the curve relative to the accumulated frequency.

Results and Discussion

The Effect of Glyphosate and Sulfentrazone Preplant Burndown on Cover Crop Residue

The cover crop termination treatments affected the amount of residue present at soybean planting for both sorghum and pearl millet cover crops and also the amount of residue in the soil surface by the time of sulfentrazone application. The sequential application of glyphosate (20 DBS) followed by sulfentrazone (10 DBS) reduced the amount of sorghum residue on the soil surface to 1,999 kg ha^{-1} compared with 9,480 kg ha^{-1} obtained with the tank mixture of glyphosate plus sulfentrazone by 9 d after sulfentrazone application and resulted in a better kill of the sorghum cover crop (Figure 2). Less plant residue on the soil surface has several consequences, including greater deposition of sulfentrazone on the top layer of the soil, which can led to better weed control. Sulfentrazone has foliar activity in addition to being active in the soil; therefore any living plants would be controlled by its application. In addition to that, in the tank-mixture treatment, the cover crops had 10 additional growing days, which would help account for the greater biomass in this treatment.

As was observed with sorghum, the sequential application also resulted in less pearl millet straw on the soil compared with the tank mixture. In the pearl millet cover crop experiment, the amount of straw on the soil surface was 1,650 kg ha^{-1} in the sequential application of glyphosate and sulfentrazone and 5,090 kg ha^{-1} in the tank mixture (Figure 3). The presence of straw on the soil surface can affect the leaching of herbicides (Banks and Robinson 1982). Large amounts of herbicide may be retained in the straw, and rain or irrigation is needed to leach the herbicide from the straw to the soil to be effective on weeds. Correia et al. (2013) determined that 20 mm of simulated rainfall after sulfentrazone application on the straw was sufficient to ensure that the herbicide reached the soil and attained a good level of weed control.

Behavior of Sulfentrazone in No-Till Soybean with Sorghum Cover Crop

Plots treated with glyphosate followed by sulfentrazone had a greater concentration of sulfentrazone in the soil solution than those treated with a tank mixture of both herbicides, but less than the amount of sulfentrazone detected in the soil of plots with bare soil at 1 DAA (Table 3). Thus, it seems a greater amount of cover crop residue may reduce the deposition of sulfentrazone into the soil and, therefore, intercepted more of the applied herbicide (Table 3). Similar results were reported by Whalen et al. (2020), who found that biomass accumulation had an inverse relationship with sulfentrazone soil concentrations, with lower sulfentrazone concentration occurring where cover crop biomass was greatest.

At 31 DAA, sulfentrazone concentrations in the top soil layer soil solution (0 to 10 cm) were reduced compared with 1 DAA with the sequential application and bare-soil treatments. In contrast, the tank mixture resulted in increased concentration of sulfentrazone from 1 DAA to 31 DAA in the same soil layer. This demonstrated that the greater amount of sulfentrazone that was retained in the high cover crop biomass was then leached into the soil profile after a 1-mo period plus 90 mm of precipitation. The same pattern was observed at 53 DAA in the top soil layer (0 to 10 cm) when compared with the levels of sulfentrazone observed at 1 DAA, where sulfentrazone concentration in the soil solution decreased in the sequential application and bare soil after a 1-mo period plus 90 mm of precipitation. Meanwhile, the sulfentrazone concentration increased from 10.79 ng g^{-1} (1 DAA) to 24.78 ng g^{-1} (31 DAA) when glyphosate and sulfentrazone were applied in mixture (Table 3). Rainfall and irrigation play a key role in releasing the

https://doi.org/10.1017/wsc.2020.70 Published online by Cambridge University Press

Table 3. Concentrations of sulfentrazone in the soil at 1, 31, and 53 d after application (DAA) in the sorghum cover crop area.[a]

1 DAA			
	Sulfentrazone concentration in soil solution		
Depth	Glyphosate (20 DBS) + sulfentrazone (10 DBS)	Glyphosate + sulfentrazone (10 DBS)	Sulfentrazone (10 DBS)—bare soil
—cm—		ng g^{-1}	
0–10	56.30 b	10.79 b	131.96 a
F treatment		15.14**	
F block		0.31^{NS}	

31 DAA			
	Sulfentrazone concentration in soil solution		
Depth	Glyphosate (20 DBS) + sulfentrazone (10 DBS)	Glyphosate + sulfentrazone (10 DBS)	Sulfentrazone (10 DBS)—bare soil
—cm—		ng g^{-1}	
0–10	43.99 A	24.78 A	30.44 A
10–20	20.22 B	15.39 AB	17.67 AB
20–40	6.47 B	7.01 B	13.69 B
F treatment		1.60^{NS}	
F depth		15.11**	
F treatment*depth		1.24^{NS}	
F block		3.03^{NS}	

53 DAA			
	Sulfentrazone concentration in soil solution		
Depth	Glyphosate (20 DBS) + sulfentrazone (10 DBS)	Glyphosate + sulfentrazone (10 DBS)	Sulfentrazone (10 DBS)—bare soil
—cm—		ng g^{-1}	
0–10	24.57 A	20.70 A	27.7 A
10–20	9.38 B	6.99 B	12.88 B
20–40	8.87 B	1.93 B	5.96 B
F treatment		1.49^{NS}	
F depth		16.80**	
F treatment*depth		0.21^{NS}	
F block		1.74^{NS}	

[a]DBS, days before sowing. Averages followed by the same lowercase letter do not differ from each other for the treatments according to Tukey's test ($P \leq 0.05$). Averages followed by the same uppercase letter do not differ from each other for the depth according to the Tukey's test ($P \leq 0.05$). NS, nonsignificant ($P \leq 0.05$). *Significant ($P \leq 0.05$). **Significant ($P \leq 0.01$).

herbicide retained in the straw to the soil, which would improve weed control (Carbonari et al. 2016).

At 53 DAA, the concentration of sulfentrazone in the soil solution within the 10- to 20-cm depth decreased (for all treatments when compared with the concentrations observed at 31 DAA Table 3). At the 20- to 40-cm depth, the concentration in the soil solution increased with the sequential application and decreased in the tank mixture and bare-soil treatments (Table 3). The lower herbicide deposition into soil with a cover crop can reduce weed control. On the other hand, the cover crop residue itself can reduce the germination, emergence, and growth of weeds through physical impediment and/or allelopathy (Egley and Duke 1985; Gomes and Christoffoleti 2008). This may make up for any loss in herbicide activity and allow for the use of cover crops for soil conservation and supplemental weed control.

With sugarcane residue, it takes 20 mm of rain to wash off sulfentrazone from the crop biomass covering the soil (Carbonari et al. 2016). Therefore, more than enough rain or irrigation occurred in the current experiments to warrant the maximum release of sulfentrazone from the cover crop residues.

The main points of this study are that crop residue intercepts the herbicide, and the intercepted herbicide, with sufficient rain or irrigation, is leached into the soil within 2 mo. There is no evidence that soil moisture affects sulfentrazone degradation rate, although degradation happens faster at higher temperatures (Martinez et al. 2008) decreasing the time in which the herbicide is effective on weed control. Microbial degradation also plays an important role in sulfentrazone dissipation in the soil (Ohmes et al. 2000). The interception of herbicides by plant residues increases herbicide vulnerability to volatilization and photodecomposition before reaching the soil (Locke and Bryson 1997). This study also showed, indirectly, that sulfentrazone degradation by UV (while it is on the cover crop residue) is limited, because sulfentrazone concentration in the top soil layer increased with time after application (Shaner 2014). In other words, the largest proportion of herbicide molecule remained intact while on the residue, to be detected in larger concentrations with time in the soil. After the maximum leaching of sulfentrazone from cover crop residue into the soil had occurred, the difference in sulfentrazone concentration in soil solution no longer existed at any depth.

Regarding the spatial distribution of the herbicide in the plots (Figure 4; Table 4), the average availability of sulfentrazone in the soil solution was 21.52 ng g^{-1} for sequential applications, 17.57 ng g^{-1} with the tank mixture, and 42.63 ng g^{-1} in the absence of crop straw. The distribution of sulfentrazone concentration data in soil without cover crop showed less dispersion and less variability than the soils with cover crops according to the adjustments provided by the Gompertz model. The tank mixture of glyphosate and sulfentrazone, which was sprayed in the presence of the highest amount of biomass, also had the highest dispersion of

https://doi.org/10.1017/wsc.2020.70 Published online by Cambridge University Press

Table 4. Parameters from the Gompertz model and the averages, medians, and coefficients of variation (CV) from the data for the point distributions of sulfentrazone concentrations for the different modalities of application at the sorghum cover crop location.[a,b]

Model parameters		G[1] (20 DBS[3]) + S[2] (10 DBS)	G + S (10 DBS)	S (10 DBS)
Constants	a	4.60517	4.60517	4.60517
	b	−1.132517	−1.229123	−1.34277
	c	0.077544	0.115526	0.044517
F regression		1,584.76**	915.46**	1,475.43**
r^2		0.98	0.96	0.97
Average		21.52	17.57	42.63
Median		21.96	16.70	43.75
CV (%)		61.94	74.26	54.52

[a] Abbreviations: G, glyphosate; S, sulfentrazone; DBS, days before sowing.
[b] Gompertz model used: $f = a^{*}\exp\{-\exp[-(x-c)/b]\}$. a = maximum asymptote of the curve; b = displacement of the curve along the x axis; c = slope or concavity of the curve relative to the accumulated frequency. **Significant by the *F*-test ($P \leq 0.01$).

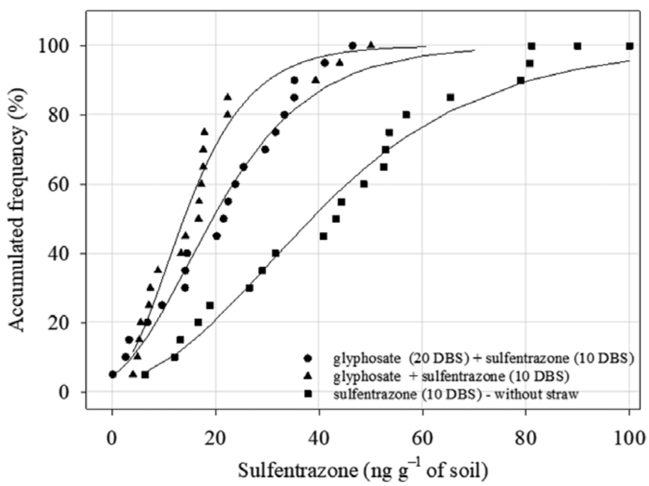

Figure 4. Accumulated frequencies of the point distributions of the sulfentrazone concentrations in the soils in the areas with sorghum cover. DBS, days before sowing.

sulfentrazone concentration data and variability. This result indicates that in addition to interfering with the average sulfentrazone concentrations at different soil depths, the cover crop and manner of burndown reduced the uniformity of spatial soil distribution of sulfentrazone. Not only was the availability of sulfentrazone in the top soil layer lower with cover crop residue, its dispersion around the mean across the soil profile was even greater relative to the bare soil. This variability in soil herbicide concentration in the presence of cover crop residue is another important point to consider in weed management using cover crops, as it would result in increased patchiness of weed distribution, which may be addressed with variable-rate herbicide application technology in large-scale farms when that becomes commercially viable.

Behavior of Sulfentrazone in No-Till Soybean with Pearl Millet Cover Crop

At 1 DAA, the sulfentrazone concentrations in the soil solution with the sequential application and in the bare-soil treatments were similar, whereas less herbicide was found with the tank-mixture application (Table 5). The amount of sulfentrazone in the soil solution that reached the top soil layer with pearl millet as cover crop was 52% greater with sequential application and 135% greater with the tank mixture when compared with the area with sorghum as the cover crop.

Sulfentrazone concentration in the soil solution decreased between soil collections for all treatments and all depths, reducing the differences among treatments throughout the time of the study. At 31 DAA, the sulfentrazone concentrations in the top 0 to 10 cm of soil were 37%, 16%, and 61% lower when compared with the concentrations in the first sampling, respectively, at the same depth. Similar dynamics occurred at 53 DAA, when the sulfentrazone concentrations declined by 75%, 27%, and 78% for the same treatments at 0 to 10 cm (Table 5).

At the 10- to 20-cm depth, the decline in sulfentrazone concentration between 31 and 53 DAA was 69% in the treatment with sequential applications, 53% with the tank mixture, and 47% in bare soil (Table 5). The decline in sulfentrazone between 31 and 53 DAA was also apparent at the 20- to 40-cm layer, with 72%, 25%, and 16% for sequential application, tank mixture, and without pearl millet cover crop, respectively (Table 5).

Using the Gompertz model, cumulative frequency curves of sulfentrazone concentration in the soil solution at different sampling times and depths were developed (Figure 5; Table 6). The average sulfentrazone concentration in the soil solution was 68.43 ng g^{-1} with sequential applications, 38.38 ng g^{-1} using the tank mixture, and 56. 91 ng g^{-1} in the absence of pearl millet, which again shows reduction in the availability of herbicide in the soil due to the presence of the cover crop, especiallyif plants are alive. Sulfentrazone application on bare soil and the application on partially dead cover (sequential to glyphosate) resulted in greater dispersion of data around the mean. In contrast to the sorghum cover crop experiment, the concentration of sulfentrazone in soil with pearl millet killed by sequential application of glyphosate and sulfentrazone was greater than in the bare soil. As in the sorghum experiment, the tank mixture of glyphosate and sulfentrazone on pearl millet cover crop at 10 DBS caused the greatest variation in the spatial soil distribution of sulfentrazone and the lowest average concentration of the herbicide.

Lessons Learned from the Two Cover Crop Experiments

Understanding how the cover crop alters the dynamics of sulfentrazone in the soil can support the adjustment of herbicide doses and management recommendations, ensuring that the quantity of herbicide in the soil is sufficient and herbicide distribution is uniform to achieve optimum weed control.

Less cover crop residue is expected to result in better herbicide activity than high cover crop residue. Less residue also facilitates planting of the main crop (i.e., soybean) and is expected to result in better crop establishment, although the yield effect is uncertain and depends on each crop–soil ecosystem (Forcella et al. 1994). Studies similar to the ones we are reporting here are needed to determine the optimum combination of cover crop residue and herbicide dose to achieve the best possible level of crop establishment, weed control, and soil conservation. The straw from the cover crops may improve weed control, but if the amount of mulch is competitive enough to suppress weeds, it may also be enough to interfere with crop growth and yield (Teasdale 1996). As reported by Whalen et al. (2020), growers can integrate residual herbicides with cover crops to eliminate an additional sprayer pass; however, applying the residual herbicide preplant in conjunction with the termination application provided higher overall weed control than an early residual herbicide application.

https://doi.org/10.1017/wsc.2020.70 Published online by Cambridge University Press

Table 5. Concentrations of sulfentrazone in the soil at 1, 31, and 53 d after application (DAA) in the pearl millet cover crop area.

	1 DAA		
	Sulfentrazone concentration in soil solution		
Depth	Glyphosate (20 DBS[a]) + sulfentrazone (10 DBS)	Glyphosate + sulfentrazone (10 DBS)	Sulfentrazone (10 DBS)—bare soil
—cm—		ng g^{-1}	
0–10	85.54 a	25.39 b	127.05 a
F treatment		14.34**	
F block		0.34^{NS}	

	31 DAA		
	Sulfentrazone concentration in soil solution		
Depth	Glyphosate (20 DBS) + sulfentrazone (10 DBS)	Glyphosate + sulfentrazone (10 DBS)	Sulfentrazone (10 DBS)—bare soil
—cm—		ng g^{-1}	
0–10	52.50 Aa	21.25 Ab	50.00 Aa
10–20	22.10 Bb	13.12 Bc	29.86 Ba
20–40	20.11 Ba	4.88 Cb	16.98 Ca
F treatment		61.85**	
F depth		103.11**	
F treatment*depth		7.05**	
F block		3.17*	

	53 DAA		
	Sulfentrazone concentration in soil solution		
Depth	Glyphosate (20 DBS) + sulfentrazone (10 DBS)	Glyphosate + sulfentrazone (10 DBS)	Sulfentrazone (10 DBS)—bare soil
—cm—		ng g^{-1}	
0–10	21.46 Aa	18.55 Aa	27.43 Aa
10–20	6.96 Bab	6.06 Bb	15.82 Ba
20–40	5.65 Bab	3.67 Bb	14.30 Ba
F treatment		8.48**	
F depth		20.22**	
F treatment*depth		0.08^{NS}	
F block		1.26^{NS}	

[a]DBS, days before sowing. Averages followed by the same lowercase letter do not differ from each other for the treatments according to Tukey's test (P ≤ 0.05). Averages followed by the same uppercase letter do not differ from each other for the depth according to the Tukey's test (P ≤ 0.05). NS, nonsignificant (P ≤ 0.05). *Significant (P ≤ 0.05). **Significant (P ≤ 0.01).

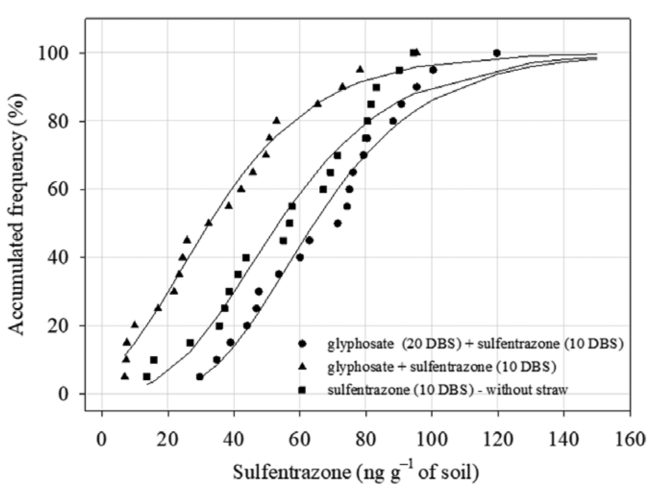

Figure 5. Accumulated frequencies of the point distributions of the sulfentrazone concentrations in the soils in the areas with pearl millet cover. DBS, days before sowing.

Table 6. Gompertz model parameters and the averages, medians, and coefficients of variation (CV) for the data from the point distributions of the sulfentrazone concentrations for the different modalities of application at the pearl millet cover crop location.[a,b]

Model parameters		G(20 DBS) + S (10 DBS)	G + S (10 DBS)	S (10 DBS)
Constants	a	4.60517	4.60517	4.60517
	b	−2.396569	−1.0851	−1.842336
	c	0.043005	0.044795	0.041371
F regression		1,348.61**	2,873.66**	1,067.51**
r^2		0.97	0.99	0.96
Average		68.43	38.38	56.91
Median		72.86	35.33	57.21
CV (%)		35.158	66.49	43.12

[a] Abbreviations: G, glyphosate; S, sulfentrazone; DBS, days before sowing.
[b] Gompertz model used: $f = a*\exp\{-\exp[-(x-c)/b]\}$. a = maximum asymptote of the curve; b = displacement of the curve along the x axis; c = slope or concavity of the curve relative to the accumulated frequency. **Significant by the *F*-test (P ≤ 0.01).

The herbicide behavior dynamic was the same with both pearl millet and sorghum cover crops. The initial sulfentrazone concentration in the soil solution in the area with sorghum cover was lower than in the area with pearl millet at the 0- to 10-cm depth, because sorghum biomass was greater than that of pearl millet. Regardless of cover crop species, the plant residue retained a large proportion of the herbicide. The sulfentrazone leached deeper into the soil profile and its concentration diminished with time. In both

https://doi.org/10.1017/wsc.2020.70 Published online by Cambridge University Press

studies, a portion of the herbicide eventually leached to the 20- to 40-cm layer, where it was not needed.

Cover crops affected the dynamics of spatial distribution and dissipation of herbicide in soil. The amount of sulfentrazone herbicide intercepted by the cover crop residue increased with the amount of biomass. Live cover crop intercepted more herbicide than partially dead cover crop. Live cover crop caused the highest variability in horizontal and vertical distribution of sulfentrazone in soil, and this variability increased with the amount of biomass.

Managing cover crops with a sequential application of glyphosate followed by sulfentrazone is better than with a tank mixture of both herbicides, because partial desiccation with glyphosate allows more sulfentrazone to be deposited directly on the soil.

Acknowledgments. The authors thank the Brazilian Federal Agency for the Support and Evaluation of Graduate Education (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior–CAPES) for their financial assistance. No conflicts of interest have been declared.

References

Ashigh J, Hall JC (2010) Bases for interactions between saflufenacil and glyphosate in plants. J Agric Food Chem 58:7335–7343

Banks PA, Robinson EL (1982) The influence of straw mulch on the soil reception and persistence of metribuzin. Weed Sci 30:164–168

Banks PA, Robinson EL (1986) Soil reception and activity of acetochlor, alachlor, and metolachlor as affected by wheat (*Triticum aestivum*) straw and irrigation. Weed Sci 34:607–611

Carbonari CA (2009) Effects of the Straw in the Amicarbazone Availability in Soil Solution in Cultivated Areas with Sugarcane. Ph.D dissertation. Botucatu, Sao Paulo: São Paulo State University. 101 p

Carbonari CA, Gomes GLGC, Trindade MLB, Silva JRM, Velini ED (2016) Dynamics of sulfentrazone applied to sugarcane crop residues. Weed Sci 64:201–206

Correia NM, Camilo EH, Santos EA (2013) Sulfentrazone efficiency on *Ipomoea hederifolia* and *Ipomoea quamoclit* as influenced by rain and sugarcane straw. Planta Daninha 31:165–174

Egley GH, Duke SO, ed (1985) Physiology of Weed Seed Dormancy and Germination. 1st ed. Volume 1. Boca Raton, FL: CRC Press. Pp 27–64

[EMBRAPA] Empresa Brasileira de Pesquisa Agropecuária (2006) Centro Nacional de Pesquisa de Solos—Sistema brasileiro de classificação de solos. Rio de Janeiro, RJ: Empresa Brasileira de Pesquisa Agropecuária. 306 p

[FEBRAPDP] Federação Brasileira de Plantio Direto na Cobertura morta (2013) Federação Brasileira de Plantio Direto e Irrigação. http://www.febrapdp.org.br. Accessed: June 10, 2015

FMC Corporation (1995) Technical Bulletin of Sulfentrazone. Philadelphia: FMC. 6 p

Forcella F, Buhler, DD, McGiffen, ME (1994) Pest management and crop residues. Pages 173–189 *in* Hatfield JL, Stewart BA, eds. Crops Residue Management. Boca Raton, FL: Lewis Publishers

Ghadiri H, Shea PJ, Wicks GA (1984) Interception and retention of atrazine by wheat (Triticum aestivum L.) stubble. Weed Sci 32:24–27

Gomes FG Jr, Christoffoleti PJ (2008) Weed biology and management in no-tillage areas. Planta Daninha 26:789–798

Grey TL, Walker RH, Hancock HG (1997) Sulfentrazone adsorption and mobility as affected by soil and pH. Weed Sci 45:733–738

Hess DF (1993) Herbicide effects on plant structure, physiology, and biochemistry. Pages 13–34 *in* Altman J, ed. Pesticide Interactions in Crop Production. London: CRC Press

[EMATER] Instituto Paranaense de Assistência Técnica e Extensão Rural (2014) Evolução do Sistema de Plantio Direto no Paraná. Curitiba, PR: Instituto Paranaense de Assistência Técnica e Extensão Rural. 4 p

Jaremtchuck CC, Constantin J, Oliveira Júnior RS, Biffe DF, Alonso DG, Arantes JGZ (2008) Effect of burndown management on desiccation speed, initial weed emergence, development and yield of soybean. Acta Sci Agron 30:449–455

Johnson MD, Wyse DL, Lueschen WE (1989) The influence of herbicide formulation on wed control in four tillage systems. Weed Sci 37:239–249

Locke MA, Bryson CT (1997) Herbicide-soil interaction in reduced tillage and plant residue management systems. Weed Sci 45:307–320

Martinez CO, Silva CMMS, Fay EF, Maia AHN, Abakerli RB, Durrant LR (2008) Degradation of the herbicide sulfentrazone in a Brazilian Typic Hapludox soil. Soil Biol Biochem 40:879–886

Martinez CO, Silva CMMS, Fay EF, Maia AHN, Abakerli RB, Durrant LR (2010) Microbial degradation of sulfentrazone in a Brazilian Rhodic Hapludox soil. Braz J Microbiol 41:209–217

Ohmes GA, Hayes RM, Mueller TC (2000) Sulfentrazone dissipation in a Tennessee soil. Weed Technol 14:100–105

Reddy KN, Locke MA, Wagner SC, Zablotowicz RM, Gaston LA, Smeda RJ (1995) Chlorimuron ethyl sorption and desorption kinetics in soils and herbicide-desiccated cover crop residues. J Agric Food Chem 45:2752–2757

Selim HM, Zhou L, Zhu H (2003) Herbicide retention in soil as affected by sugarcane mulch residue. J Environ Qual 32:1445–1454

Shaner DL (2000) The impact of glyphosate-tolerant crops on the use of other herbicides and on resistance management. Pest Manage Sci 56:320–326

Shaner DL (2012) Field dissipation of sulfentrazone and pendimethalin in Colorado. Weed Technol 26:633–637

Shaner DL, ed (2014) Herbicide Handbook. 10th ed. Lawrence, KS: Allen Press. 513 p

Strieder ML, Pires JLF, Constamilan LM (2015) Rendimento de grãos de soja em diferentes espaçamentos entre linhas, na safra 2014/15. Passo Fundo, RS: Embrapa Trigo. Pp 19–24

Teasdale, JR (1996) Contributions of cover crops to weed management in sustainable agricultural systems. J Prod Agric 9:475–479.

Tomlin C, ed (1994) Pesticide Manual. 10th ed. Cambridge: British Crop Protection Council and the Royal Society of Chemistry. 1341 p

Velini ED (1995) Estudos e desenvolvimento de métodos experimentais e amostrais adaptados à matologia. Ph.D dissertation. Jaboticabal, Sao Paulo: São Paulo State University. 250 p

Whalen DM, Shergill LS, Kinne LP, Bish MD, Bradley KW (2020) Integration of residual herbicides with cover crop termination in soybean. Weed Technol 34:11–18