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# Planting into a living cover crop alters preemergence herbicide dynamics and can reduce soybean yield

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## Research Article

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## Abstract

Cereal rye cover crop (cereal rye) and preemergence (PRE) herbicides are becoming common practices for managing herbicide-resistant weeds in soybean production. Adopting these two practices in combination raises concerns regarding herbicide fate in soil, given that the cereal rye biomass can intercept the herbicide spray solution, preventing it from reaching the soil. Delaying cereal rye termination until soybean planting (planting green) optimizes biomass accumulation but might also increase PRE interception. To better understand the dynamics between cereal rye and PRE herbicides, a field experiment was conducted to evaluate two soil management practices (tillage and no-till) and two cereal rye termination practices in the planting-green system (glyphosate [1,260 g ae ha$^{-1}$] and roller-crimper) on the spray deposition and fate of PRE herbicides and soybean yield. The spray deposition was assessed by placing water-sensitive paper cards on the soil surface before spraying the PRE herbicides (sulfentrazone [153 g ai ha$^{-1}$] + *S*-metolachlor [1,379 g ai ha$^{-1}$]). Herbicide concentration in soil (0 to 7.6 cm) was quantified 25 d after treatment (DAT). The presence of no-till stubble and cereal rye biomass reduced the spray coverage compared to tillage at PRE application, which reflected in a reduction in the concentration of both herbicides in soil 25 DAT. Soybean yield was reduced in all three years when the cereal rye was terminated with a roller-crimper but only reduced in one year when terminated with glyphosate. Our findings indicate that mainly cereal rye biomass reduced the concentration of PRE herbicides in the soil due to the interception of the spray solution during application. Although higher cereal rye biomass accumulation can provide better weed suppression according to the literature, farmers should be aware that the biomass can lower the concentration of PRE herbicides reaching the soil, thus intensifying field scouting to ensure that weed control is not being negatively affected.

## Introduction

With the rapid increase in herbicide-resistant weeds across the United States, weed management recommendations have shifted toward more diversified farming systems (Heap 2023; Norsworthy et al. 2012). Farmers have increased their interest in adopting cover crops for weed suppression and preemergence (PRE) herbicides for weed control (Price et al. 2012). However, combining cover crops and soil-residual herbicides applied PRE brings new challenges and questions to the cropping system because farmers are used to spraying PRE herbicides under conventional tillage and no-tillage conditions, but not necessarily with the presence of a living cover crop. The presence of cover crop biomass adds a physical barrier over the soil, raising concerns regarding herbicide interception by the cover crop residue and PRE weed control effectiveness.

Adopting effective PRE herbicides allows farmers to control weeds as they emerge, thus minimizing weed competition with cash crops. It also provides more flexibility for postemergence (POST) applications, often reducing the need for an early in-crop POST herbicide application (Knezevic et al. 2019; Lopes-Ovejero et al. 2013; Perkins et al. 2021). On the other hand, the adoption of no-till practices associated with cover crops is a broader weed management approach that provides several ecosystem services in addition to weed control, such as reducing soil erosion, nitrogen leaching, and phosphorus loss; increasing soil organic carbon; and improving soil health (Appelgate et al. 2017; Blanco-Canqui et al. 2015; Kaspar and Singer 2011; Kaspar et al. 2012). Moreover, from a weed management perspective, the primary goal of a cover crop is to suppress weed emergence and development by competing with weeds for space, light, water, and other resources (Hayden et al. 2012; Reddy 2003).

Cereal rye cover crop (hereafter referred to as cereal rye) is the most common cover crop species adopted by farmers in the U.S. Midwest, mainly because of its winter hardiness and potential for large biomass accumulation in the spring, which maximizes weed suppression and agronomic services (Bowman et al. 2022; Palhano et al. 2018). Cereal rye is commonly seeded after cash crop (e.g., corn [*Zea mays* L.]) harvest in the fall and terminated prior to or at cash crop (e.g., soybean) planting in the following spring (Bowman et al. 2022). The cereal rye termination in conventional systems is frequently achieved chemically with glyphosate (Cornelius and Bradley 2017) or mechanically using a roller-crimper, a practice mostly adopted in organic systems (Keene et al. 2017). Termination timing is an important aspect of this system because it affects cereal rye biomass accumulation. In temperate regions like Wisconsin, where low growing degree days accumulation is a limiting factor for cover crop growth, terminating cereal rye early in the season before cash crop establishment can lead to low and insufficient biomass accumulation for effective weed suppression. To overcome this challenge, research has investigated the potential of the planting-green system in soybean production, which consists of terminating the cereal rye at or after cash crop establishment to optimize biomass accumulation for better weed suppression and agronomic services (Reed et al. 2019).

Despite the benefits of cereal rye for weed management, the soil coverage produced by its biomass can impact the fate of PRE herbicides and challenge the herbicides' ability to reach the soil and provide proper weed control. Previous research indicated that the cover crop residue present on the soil surface could retain the herbicide spray solution (Ghadiri et al. 1984; Whalen et al. 2020). Furthermore, an herbicide's ability to infiltrate through cover crop biomass is influenced by several factors and is mainly related to the herbicide's properties (i.e., water solubility, *Kow*, and *Koc*) and weather conditions, especially rainfall after application (Khalil et al. 2019; Selim et al. 2003). However, most of the research in this area has investigated this interaction using dead crop residue, and limited information is available on living cereal rye biomass in the planting-green system. Thereby, given the dynamics between cover crops and PRE herbicides, the goal of this study was to investigate the impacts of soil and cereal rye management practices on spray deposition, the fate of PRE herbicides, and soybean yield. We hypothesized that, regardless of the termination method, cereal rye can reduce the number of herbicide spray droplets reaching the soil during PRE application and lead to a lower herbicide concentration in the soil but does not affect soybean yield compared to conventional tillage and no-tillage.

## Materials and Methods

### Experimental Design and Treatments

A field study was conducted at the University of Wisconsin–Madison Arlington Agricultural Research Station near Arlington, WI (43.30°N, 89.36°W) in 2020, 2021, and 2022. The study was established following a randomized complete block design with four replications. Each experimental unit consisted of a plot 6 × 30.5 m in an area with a Plano Silt Loam soil (fine-silty, mixed, superactive, mesic, Typic Argiudoll) where soybean was grown the previous year. Treatments consisted of four different soil and cover crop management practices: (1) soil tilled conventionally with a field cultivator at study establishment (tillage), (2) no-tillage (no-till), (3) no-tillage fall-planted cereal rye chemically terminated with glyphosate at study establishment (glyphosate), and (4) no-tillage fall-planted cereal rye mechanically terminated with a roller-crimper and chemically with glyphosate (except in 2020) at study establishment (roller).

### Cereal Rye Establishment and Termination

For all experimental years, cereal rye was established in the fall of the previous year following soybean harvest with a 19-cm row spacing (13 rows) no-till grain drill (Yetter Farm Equipment, Colchester, IL, USA) at a depth of 2.5 cm (Table 1). Termination and soybean planting were performed when cereal rye reached the anthesis stage (Zadoks growth stage 60; Zadoks et al. 1974) following the aforementioned methods. The chemical termination was accomplished with glyphosate (Roundup PowerMAX®; Bayer CropScience, St. Louis, MO, USA) sprayed POST at 1,260 g ae $ha^{-1}$ (AMS added at 2,200 g $ha^{-1}$). Moreover, glyphosate was sprayed at the same rate to the no-till plots as burndown to control weeds present at the time of study establishment and POST over the entire experimental area when weeds reached 10 cm in height to keep the study weed-free. The mechanical termination was performed with a 4.5-m-wide roller-crimper (I&J Manufacturing, Gordonville, PA, USA) weighing 1,600 kg (1,088 kg roller plus 512 kg of water added as extra weight) rear-mounted to the tractor and rolled parallel to the cereal rye and soybean planting direction at a speed of 4.8 km $h^{-1}$. In 2020, only the roller-crimper was adopted to terminate the cereal rye at the study establishment in the roller treatment, but in 2021 and 2022, glyphosate was sprayed after rolling to complement the mechanical termination. At cereal rye termination/study establishment, three cereal rye biomass subsamples of 0.1 $m^{-2}$ were randomly collected from each plot by clipping the plants at the soil surface and dried to constant weight at 65 C to determine the aboveground cereal rye biomass in megagrams per hectare. The same was done in the no-till treatment by collecting the soybean stubble present on the field at the time of study establishment (Table 1).

### PRE Herbicide Application and Soybean Establishment

A commercial premix (Authority Elite®; FMC, Philadelphia, PA, USA) of sulfentrazone (153.2 g ai $ha^{-1}$) plus *S*-metolachlor (1,379 g ai $ha^{-1}$) was sprayed PRE with a tractor-mounted sprayer equipped with a 6-m boom containing 12 AIXR 11002 flat-fan nozzles (TeeJet® Technologies, Denver, CO, USA) calibrated to deliver 93.5 L $ha^{-1}$ of spray solution at a pressure of 193 kPa and a speed of 7.0 km $h^{-1}$ (Table 2). In 2020, the PRE herbicides were applied separately from glyphosate for cereal rye termination (two separate passes on the same day; spray deposition data were collected during the PRE application), but in 2021 and 2022, a single pass containing the PRE herbicides and glyphosate was deployed to better simulate what a farmer would do. The spray boom was adjusted 50 cm above the ground in the tillage, no-till, roller, and glyphosate (only in 2020) treatments and ~20 cm above the cereal rye canopy in the glyphosate treatment in 2021 and 2022 because of the higher cereal rye plant height in these years (Table 1). Soybean was planted on the same day after the application of the PRE herbicides and the spray deposition data collection. The crop was established using a four-row no-till planter MaxEmerge™ XP (John Deere, Moline, IL, USA) adjusted to place seeds at 2.5-cm depth on 76-cm row spacing and 341,725 seeds $ha^{-1}$ (Table 1).

**Table 1.** Cereal rye and soybean planting date, soil properties, and crop residue collected at the study establishment (cereal rye biomass and soybean stubble) in 2020, 2021, and 2022.[a]

| | Planting date | | Soil properties | | | | | Crop residue | |
|---|---|---|---|---|---|---|---|---|---|
| Year | Cereal rye[b] | Soybean[c] | OM | Sand | Silt | Clay | pH | Cereal rye[d] | No-till stubble |
| | | | % | | | | $H_2O$ | Mg ha$^{-1}$ | |
| 2020 | 5 Nov 2019 | 4 Jun 2020 | 3.0 | 24.0 | 52.0 | 24.0 | 6.4 | 5.2 (78 cm) | 2.9 |
| 2021 | 22 Sep 2020 | 25 May 2021 | 3.3 | 12.0 | 64.0 | 24.0 | 5.8 | 12.2 (148 cm) | 3.4 |
| 2022 | 24 Sep 2021 | 10 Jun 2022 | 3.0 | 20.0 | 59.0 | 21.0 | 6.7 | 9.3 (132 cm) | 1.8 |

[a] Abbreviation: OM, soil organic matter.

[b] Cereal rye variety Guardian Winter Rye, La Crosse Seed seeded at 67.3 kg ha$^{-1}$ in 2019 and at 87.5 kg ha$^{-1}$ in 2020 and 2021.

[c] Soybean variety S20-E3 in 2020 and S20-LLGT27 in 2021 and 2022, all seeded at 341,725 seeds ha$^{-1}$.

[d] Average plant heights at termination are in parentheses.

**Table 2.** Environmental conditions during preemergence herbicide application of each experimental year.

| | | Wind speed | | | | |
|---|---|---|---|---|---|---|
| Year | Date | Min. | Max. | Average | Air temperature | Relative humidity |
| | | km h$^{-1}$ | | | C | % |
| 2020 | 4 Jun 2020 | 10.1 | 17.0 | 12.2 | 27.9 | 59.5 |
| 2021 | 25 May 2021 | 22.0 | 28.0 | 25.0 | 29.4 | 51.4 |
| 2022 | 10 Jun 2022 | 2.8 | 8.5 | 6.8 | 24.8 | 61.9 |

## Data Collection

### Spray Deposition

Before spraying the PRE herbicides, six water-sensitive cards measuring 5.1 × 7.6 cm (SpotOn® paper; Innoquest, Woodstock, IL, USA) were placed in each plot at the soil level to assess the spray deposition pattern of each treatment (Figure 1). The cards were placed ~4 m apart along the plot's length and 1 m from the plot's right-side border to avoid disturbance from the tractor tracks during application. The tractor traveled all plots in the same direction, so all cards were sprayed by the same boom section to keep the application consistent. For plots with cereal rye biomass or soybean stubble, cards were carefully placed between cereal rye rows or underneath the soybean residue to simulate the natural interception from biomass/crop residue. Once each plot was sprayed, the six cards were immediately retrieved, placed inside plastic bags, and stored in a cooler at room temperature. The water-sensitive cards were then photographed using an 18.0-megapixel DSLR camera (Canon Rebel T6®; Canon, Melville, NY, USA), and the photos were analyzed using the computer program Gotas (Chaim et al. 2006) to determine the density of droplets per square centimeter and the percentage of spray coverage.

### Herbicide Concentration in the Soil

At 25 d after treatment (DAT), three soil cores (6 cm in diameter × 7.6 cm in depth) were collected from each plot using a handheld soil sampler (Flora Guard, Brampton, ON, Canada). The subsamples were homogenized and yielded a single soil sample per plot that was analyzed for sulfentrazone and metolachlor (ng g$^{-1}$ soil). Samples were immediately frozen at −10 C and shipped overnight to South Dakota Agricultural Laboratories (Brookings, SD) for analysis. Soil samples were air-dried and then thoroughly homogenized to ensure that the sample was representative of the entire soil sample. The soil was passed through a 2-mm No. 10 sieve (Gilson Company, Lewis Center, OH, USA) to remove any large particles or debris that may interfere with the analysis. A 50-g soil sample was weighed, placed in a 250-mL polyethylene screw-top bottle (Fisher Scientific, Pittsburgh, PA, USA), and blended with 100 mL of an 80/20 methanol/water solution to extract the target analytes from the soil matrix. The soil slurry was refluxed for 2 h, and 4 mL of the extract was removed with a syringe and filtered through a 0.45-µm filter (Fisher Scientific) into an LC-MS/MS vial for analysis. The extract was analyzed via LC-MS/MS in positive mode using a TSQ Quantum Access Max Thermo Scientific (Thermo Fisher Scientific, Waltham, MA, USA) LC-MS/MS system. For metolachlor, the mobile phase consisted of a mixture of acetonitrile and buffered water, whereas for sulfentrazone, the mobile phase consisted of a mixture of methanol and buffered water. Separation of the analytes was achieved using a Phenomenex C18 Thermo Scientific column (4.6 × 50 × 1.8 µm column; Thermo Fisher Scientific) at a temperature of 40 C. The injection volume was 2 µL, and the flow rate was 0.5 mL min$^{-1}$. These parameters were optimized to provide good chromatographic separation and efficient ionization of the analytes. Samples were quantified using chromatographic areas via a regression equation generated by a standard curve. This involves measuring the peak area of the analyte of interest in the sample and comparing it to a standard curve constructed using known concentrations of the analyte. The use of a standard curve helps to ensure accurate and precise quantification of the analyte in the sample.

### Soybean Yield

The two soybean center rows of each plot were harvested with a plot combine (Almaco, Nevada, IA, USA) at physiological maturity, and grain yield was estimated in kg ha$^{-1}$ at 13% moisture content. Besides the soybean yield for all three years, yield component data were also collected in 2021 and 2022. Soybean stand (plants m$^{-1}$) was recorded by counting the number of plants from 2 m of the two center rows of each plot. A 500-g sample was collected from the grain harvested with the combine, and three 100-seed subsamples were manually counted to determine the 100-seed weight (g$^{-1}$). Six plants from the two center rows were randomly harvested, and the number of beans per pod and pods per plant were counted.

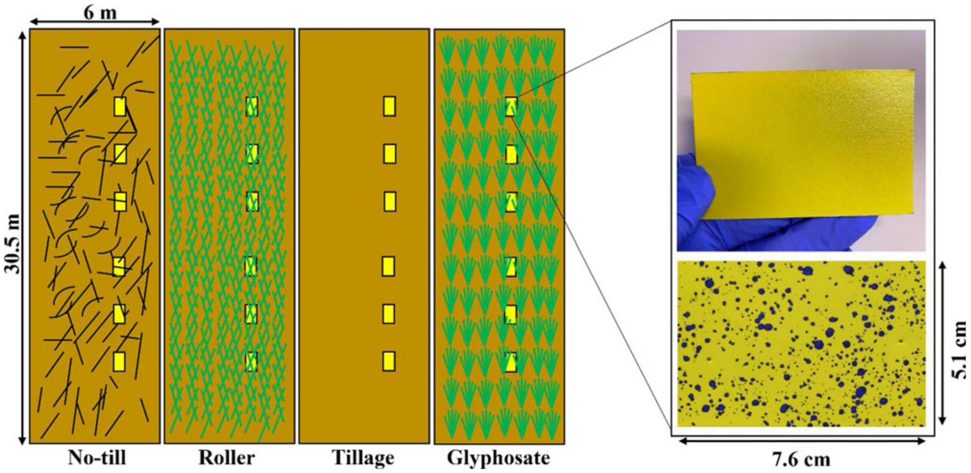

**Figure 1.** Layout of the study's methodology to evaluate spray deposition. Each experimental unit measured 6 × 30.5 m, and the water-sensitive cards were placed on the right-hand side of each plot to avoid disturbance from the tractor tracks during application.

### Environmental Conditions

Daily precipitation (mm) and minimum, maximum, and average air temperature (C) from fall 2019 through the end of 2022 (Table 3) were obtained from the Enviro-weather Michigan State University system using the Arlington (43.30°N, 89.38°W) station ID "alt," which is located approximately 3 km from the study area. The 30-yr (1989 to 2019) historical monthly precipitation and air temperature (Table 3) were obtained from the daily Daymet weather data using R statistical software version 4.1.0 (R Core Team 2022) and the package DAYMETR (Correndo et al. 2021; Thornton et al. 2022). Moreover, temperature data were used to calculate total monthly growing degree days (GDD [temperature base 4.4 C]) for cereal rye development and biomass accumulation using the following equation (Mirsky et al. 2011):

$$\mathrm{GDD} = \frac{T_{\max} + T_{\min}}{2} - T_{\mathrm{base}} \qquad [1]$$

where $T_{\max}$ and $T_{\min}$ are the maximum and minimum daily temperatures, respectively, and $T_{\mathrm{base}}$ is the base temperature where physiological activity and growth occur set at 4.4 C. Thus, for days on which the mean temperature was lower than $T_{\mathrm{base}}$, GDD accumulation was assumed to be zero.

### Statistical Analyses

All statistical analyses were performed in R statistical software (R Core Team, 2022). Generalized linear mixed models (GLMMTMB package; Brooks et al. 2017) with a Poisson and Beta (link = "logit") distributions were fit to the density of droplets and spray coverage data, respectively. The remaining variables (concentration of herbicides in the soil and crop yield) were analyzed with linear mixed effect models (LME4 package; Bates et al. 2015). For all models, treatment and experimental year were treated as fixed effects and block nested within year as a random effect. Model assumptions of normality and homogeneity of variance were assessed by visual inspection of residuals. When a significant interaction or main effect was observed ($P \leq 0.05$), means were separated using Fisher's least significant difference test (EMMEANS package; Lenth 2022). Pearson's correlation was also calculated using the *cor* function in R (STATS package; R Core Team 2022) to understand the relationship between crop residue (no-till residue and cereal rye biomass) with the dependent variables that included density of droplets, spray coverage, metolachlor and sulfentrazone concentration in the soil, and soybean yield.

## Results and Discussion

### Cereal Rye Biomass Accumulation

Cereal rye biomass accumulation varied across years, with 2020 (5.2 Mg $\mathrm{ha}^{-1}$) having the lowest biomass level compared to 2021 (12.2 Mg $\mathrm{ha}^{-1}$) and 2022 (9.3 Mg $\mathrm{ha}^{-1}$) (Table 1). The higher GDD accumulation between cereal rye planting and termination in 2021 (GDD 672) and 2022 (GDD 745) was likely responsible for the higher biomass accumulation compared to 2020 (GDD 414; Table 3). GDD accumulation is one of the main drivers for cereal rye biomass production, and practices like earlier planting and later termination dates can greatly impact heat accumulation and cereal rye growth (Mirsky et al. 2011; Schramski et al. 2021). The difference in cereal rye biomass accumulation across the three experimental years affected the study's results by creating a contrast between low (2020) and high (2021 and 2022) cereal rye biomass accumulation scenarios. Therefore, whenever a significant interaction between treatment and year was observed, the results were presented to evaluate the treatment effects within each experimental year.

### Spray Deposition

There was a significant interaction between treatment and year ($P < 0.001$) for both spray deposition variables evaluated in this study (density of droplets and spray coverage). Soybean stubble in the no-till treatment and cereal rye biomass intercepted a significant amount of spray solution during the PRE application, reducing the density of droplets and spray coverage reaching the soil surface compared to tillage (Table 4). The magnitude of interception varied across years and was positively correlated (density of droplets [$r = 0.8$, $P < 0.001$] and spray coverage [$r = 0.9$, $P < 0.001$]) with the increase in soybean stubble and cereal rye biomass present at the time of study establishment (Figure 2). The soil coverage provided by crop residue has been shown to intercept the spray solution and reduce droplet deposition during herbicide application (Khalil et al. 2019; Kim et al. 2011).

**Table 3.** Monthly precipitation, air temperature, and growing degree days ($T_{base}$ 4.4 C) at the Arlington Agricultural Research Station, WI: 30-yr history (1989 to 2019) and 2020, 2021, and 2022.[a,b]

| | Precipitation | | | | Air temperature | | | | GDD, $T_{base}$ 4.4 C | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 30 yr | 2020 | 2021 | 2022 | 30 yr | 2020 | 2021 | 2022 | 2020 | 2021 | 2022 |
| | mm | | | | C | | | | heat units | | |
| Month | | | | | | | | | | | |
| Jan | 37 | 21 | 15 | 0 | −7.7 | −4.9 | −7.2 | −11.8 | 2.2 | 0.0 | 0.5 |
| Feb | 40 | 12 | 5 | 6 | −5.9 | −7.4 | −12.4 | −7.7 | 2.0 | 3.8 | 4.5 |
| Mar | 59 | 102 | 39 | 109 | 0.5 | 2.2 | 3.0 | 0.1 | 39.5 | 76.1 | 49.2 |
| Apr | 104 | 37 | 39 | 94 | 7.4 | 6.0 | 8.5 | 5.2 | 117.5 | 144.3 | 90.8 |
| May | 113 | 122 | 66 | 58 | 14.0 | 12.9 | 13.6 | 15.4 | 184.7 | 209.9 | 216.0 |
| Jun | 142 | 110 | 115 | 149 | 19.5 | 20.1 | 21.4 | 19.2 | 273.4 | 279.9 | 251.2 |
| Jul | 108 | 142 | 18 | 74 | 21.5 | 22.3 | 20.7 | 20.7 | 302.8 | 286.5 | 286.8 |
| Aug | 112 | 96 | 90 | 163 | 20.4 | 19.7 | 21.0 | 19.8 | 280.2 | 299.8 | 267.0 |
| Sep | 88 | 76 | 2 | 150 | 16.2 | 14.3 | 16.4 | 15.6 | 184.6 | 240.8 | 207.3 |
| Oct | 76 | 111 | 78 | 27 | 9.3 | 6.2 | 12.4 | 8.7 | 114.3 | 174.2 | 168.0 |
| Nov | 61 | 74 | 10 | 73 | 1.8 | 4.7 | 1.1 | 2.2 | 91.4 | 57.8 | 71.2 |
| Dec | 45 | 0.0 | 36 | 40 | −4.9 | −4.4 | −2.2 | −6.1 | 11.0 | 22.5 | 6.7 |
| Total/average[c] | 985 | 903 | 513 | 943 | 7.7 | 7.6 | 8.0 | 6.8 | 1,603.7 | 1,795.7 | 1,619.7 |
| Cereal rye[d] | — | 394 | 350 | 457 | — | 1.1 | 1.9 | 2.6 | 414.4 | 671.9 | 744.7 |
| Soybean[e] | — | 523 | 322 | 497 | — | 16.4 | 18.1 | 16.9 | — | — | — |

[a] Abbreviation: GDD, growing degree day.

[b] Year 2019 cumulated precipitation in November, 60 mm, and in December, 34 mm. Year 2019 average air temperature in November. −1.9 C, and in December, −2.5 C. Year 2019 cumulated GDD in November, 11.2, and in December, 19.7.

[c] Yearly cumulated precipitation and GDD and monthly average air temperature.

[d] Cumulated precipitation and GDD and average monthly air temperature during cereal rye cover crop growth.

[e] Cumulated precipitation and average air temperature during the soybean growing season.

**Table 4.** Density of droplets and spray coverage at preemergence application in 2020, 2021, and 2022.[a,b]

| | Density of droplets | | | Spray coverage | | |
|---|---|---|---|---|---|---|
| | 2020 | 2021 | 2022 | 2020 | 2021 | 2022 |
| | droplets cm$^{-2}$ | | | % | | |
| Treatment | | | | | | |
| Tillage | 35.2 (2.3) a | 21.8 (0.9) a | 33.0 (0.8) a | 27.8 (0.4) a | 20.1 (0.6) a | 21.5 (0.3) a |
| No-till | 22.5 (1.0) bc | 15.2 (0.3) b | 28.8 (2.1) a | 20.9 (1.8) b | 11.7 (0.1) b | 21.4 (1.0) a |
| Glyphosate | 26.5 (1.3) b | 5.5 (0.6) c | 19.5 (0.6) b | 11.5 (0.7) c | 2.2 (0.6) c | 9.1 (0.2) b |
| Roller | 19.5 (3.0) c | 3.0 (0.4) c | 17.8 (2.8) b | 9.1 (1.2) d | 1.7 (0.1) c | 8.5 (1.3) b |
| P-values | | | | | | |
| Treatment (T) | | <0.001 | | | <0.001 | |
| Year (Y) | | <0.001 | | | <0.001 | |
| T × Y | | <0.001 | | | <0.001 | |

[a] Values between parentheses indicate the standard error of means.

[b] Treatments followed by the same letter within the column of each year are not significantly different according to Fisher's least significant difference test (α = 0.05).

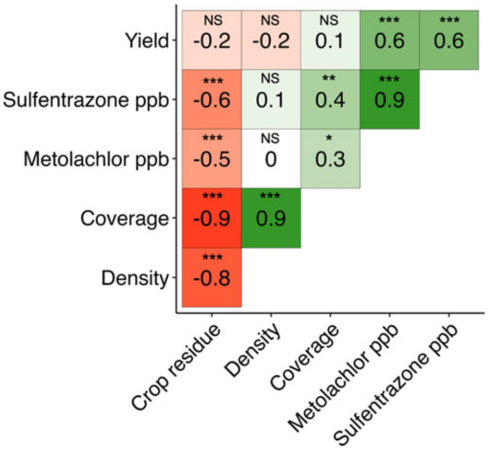

**Figure 2.** Pearson's correlation for crop residue (no-till soybean residue and cereal rye biomass [$n = 48$]), droplet density ($n = 48$), spray coverage ($n = 48$), metolachlor ($n = 48$), and sulfentrazone ($n = 48$) concentration in the soil, and soybean yield ($n = 48$). NS, not significant. *P < 0.05. **P < 0.01. ***P < 0.001.

The higher levels of cereal rye biomass observed in 2021 and 2022 also diminished the difference between spraying PRE herbicides over standing (glyphosate) versus rolled (roller) cereal rye because no differences were observed between glyphosate and roller for either spray deposition variables in those years. Yet, in 2020, the chemical termination with glyphosate resulted in a higher density of droplets and spray coverage than the roller, which is likely because, under lower biomass accumulation, standing cereal rye allowed the spray droplets to travel between rows and reach the soil, whereas the rolled rye intercepted a higher amount of spray solution owing to its flattened pattern (Table 4). A similar effect was observed by Haramoto et al. (2020), who evaluated the spray deposition of 2,4-D applied in the spring targeting horseweed (*Erigeron canadensis* L.) control and did not observe significant differences between cereal rye and non–cereal rye treatments in percentage of spray coverage when water-sensitive cards were placed between cereal rye rows. However, cereal rye resulted in up to 44% reduction in coverage when cards were placed adjacent to cereal rye rows. Despite allowing the spray droplets to travel

**Table 5.** Sulfentrazone and metolachlor concentration in the soil (0 to 7.6 cm) at 25 DAT in 2020, 2021, and 2022.[a,b]

| | Sulfentrazone | | | Metolachlor | | |
|---|---|---|---|---|---|---|
| | 2020 | 2021 | 2022 | 2020 | 2021 | 2022 |
| | ng $g^{-1}$ soil | | | | | |
| Treatment | | | | | | |
| Tillage | 161.2 (16.9) a | 343.2 (12.5) a | 129.8 (16.8) a | 522.8 (63.9) a | 3,340.0 (236.0) a | 575.0 (104.4) a |
| No-till | 150.2 (11.7) a | 242.5 (36.4) b | 126.5 (5.9) a | 485.5 (89.2) ab | 1,527.5 (160.5) b | 347.8 (21.5) ab |
| Glyphosate | 93.9 (5.4) b | 102.5 (18.1) c | 67.8 (13.7) b | 195.0 (13.1) c | 336.8 (60.9) c | 66.8 (14.8) b |
| Roller | 103.4 (7.2) b | 95.0 (16.2) c | 80.2 (7.4) b | 222.0 (50.5) bc | 258.0 (24.3) c | 114.2 (33.5) b |
| P-values | | | | | | |
| Treatment (T) | | <0.001 | | | <0.001 | |
| Year (Y) | | <0.001 | | | <0.001 | |
| T × Y | | <0.001 | | | <0.001 | |

[a] Values between parentheses indicate the standard error of means.

[b] Treatments followed by the same letter within the column of each year are not significantly different according to Fisher's least significant difference test ($\alpha = 0.05$).

between rows, spraying PRE herbicides over standing cereal rye requires the sprayer boom to operate at a higher height than over rolled cereal rye because of its canopy height, which can also affect spray deposition (Simão et al. 2020). When comparing the experimental years, it is likely that the higher cereal rye height at PRE application in 2021 (148 cm) and 2022 (132 cm) compared to 2020 (78 cm) also impacted the spray deposition by requiring an elevated boom height during PRE application, thus justifying the nonsignificant difference observed between roller and glyphosate on the density of droplets and spray coverage in 2021 and 2022 (Table 4). We hypothesize that under lower cereal rye biomass and plant height, like in 2020, terminating cereal rye with glyphosate can favor spray deposition by allowing the spray droplets to travel within the cereal rye rows and reach the soil surface. Conversely, higher cereal rye biomass and plant height yield a denser canopy that challenges spray droplets from reaching the soil and requires a higher boom height during application, which diminishes the effect of having standing cereal rye when terminating with glyphosate.

## *Herbicide Concentration in the Soil*

There was a significant interaction ($P < 0.001$) between treatment and year for the concentration of sulfentrazone and metolachlor in the soil 25 DAT (Table 5). It is important to point out that the process adopted to quantify the concentration of the herbicides in the soil does not allow for differentiation between the *R* and *S* isomers of metolachlor. Thus *metolachlor* will be the nomenclature used herein, except when referring to the physicochemical properties of *S*-metolachlor. For more information about *R*- and *S*-metolachlor isomers, refer to Shaner et al. (2006). Despite the much higher concentration observed in 2021, the herbicides presented similar responses to treatments in all years, with tillage being the treatment with the highest herbicide concentration in the soil. The spray solution intercepted by the cereal rye during PRE application reflected significant reductions in the concentration of both herbicides in the soil 25 DAT compared to tillage in all years (Table 5). The degree of reduction in herbicide concentration in the soil by the cereal rye treatments followed a similar trend to what was observed with spray deposition and was also negatively correlated (sulfentrazone [$r$: 0.6, p-value <0.001] and metolachlor [$r = 0.5$, $P < 0.001$]) with the increase in soybean stubble and cereal rye biomass at the time of study establishment (Figure 2). Nevertheless, no significant differences between roller and glyphosate were observed despite year and cereal rye biomass levels. As for the no-till treatment, it affected the fate of the PRE herbicides to a smaller extent and reduced the concentration of the herbicides in the soil only in 2021 compared to tillage (Table 5). In 2021, the average of soybean stubble was also the highest in the three years (Table 1). Thus, similar to cereal rye biomass, higher soybean residue likely had a larger impact on the concentrations of both herbicides in the soil.

As previously discussed, the reduction in herbicide concentration in the soil by the cereal rye treatments was negatively correlated with the increase in soybean stubble and cereal rye biomass across years (Figure 2). In a similar study evaluating the impact of cereal rye termination before soybean planting (7 or 21 d before planting), Whalen et al. (2020) observed that the increase in cereal rye biomass accumulation due to the delay in its termination increased sulfentrazone retention by the cereal rye residue and lowered the herbicide concentration in the soil as the biomass accumulation increased. Moreover, Banks and Robinson (1982) reported that the increase in wheat straw reduced the concentration of metribuzin in the soil immediately after application, and 9,000 kg $ha^{-1}$ of stubble intercepted nearly 100% of the applied herbicide. In another study working with acetanilide herbicides (acetochlor, alachlor, and metolachlor), Banks and Robinson (1986) also observed that the increase in wheat straw reduced the concentration of the herbicides in the soil and that less than 10% of the herbicides reached the soil at the application when the straw exceeded 4,480 kg $ha^{-1}$. Previous research conducted with dead crop residue (cereal rye biomass or wheat straw) corroborates the current findings that the increase in crop residue results in higher herbicide interception and lower concentration in the soil.

Once intercepted by the cover crop biomass or crop stubble, the movement or wash-off of herbicides to the soil is correlated with the time and amount of the first precipitation after application, and the first rainfall event is crucial for herbicide wash-off (Ghadiri et al. 1984; Carbonari et al. 2016). Carbonari et al. reported that 20 mm of precipitation applied 1 d after herbicide application was enough to achieve the highest sulfentrazone release from dry sugarcane residue, regardless of residue level (5 to 20 Mg $ha^{-1}$). Similarly, Ghadiri et al. (1984) observed that increasing precipitation from 12.5 to 25 mm significantly increased atrazine wash-off from dry wheat straw (6.5 Mg $ha^{-1}$), but no difference was observed when the precipitation increased from 25 to 50 mm. Moreover, both studies reported that only part of the intercepted herbicide was released from the crop residue. Therefore, once intercepted, a degree of herbicide loss is expected owing to environmental factors that affect herbicide degradation. In the

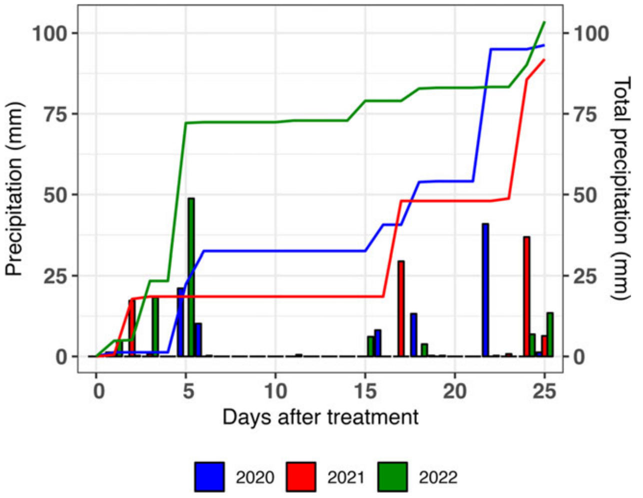

**Figure 3.** Daily (bars) and cumulative (lines) precipitation (mm) from preemergence application to soil sampling for herbicide concentration in the soil at 25 DAT in 2020 (96 mm total), 2021 (92 mm total), and 2022 (104 mm total).

present study, the cumulated precipitation and precipitation patterns between PRE application and soil sampling were similar in all three years (between 96 and 104 mm total; Figure 3). Thus it is assumed that most differences in the concentration of both herbicides in the soil can be attributed to the cereal rye biomass at the application that intercepted the spray solution. Future research investigating water and herbicide movement in the soil under different cropping and cover crop management practices can better elucidate the impacts of such management approaches on herbicide leaching and potential water contamination.

When comparing the degree of reduction of each herbicide in the soil in the cereal rye treatments (average of glyphosate and roller) compared to tillage, metolachlor (60.1%, 91.0%, and 84.2% in 2020, 2021, and 2022, respectively) presented a higher reduction than sulfentrazone (38.8%, 71.2%, and 42.9 % in 2020, 2021, and 2022, respectively) in all years. One of the factors that can affect herbicide wash-off from the cereal rye biomass to the soil is water solubility. Owing to its weak-acid behavior, sulfentrazone solubility varies based on the pH of the environment (e.g., spray solution and soil), ranging from 110 mg $L^{-1}$ (pH 6) to 1,600 mg $L^{-1}$ (pH 7.5). As for *S*-metolachlor, its water solubility is 488 mg $L^{-1}$ and does not change with pH (Shaner 2014). However, comparing the behavior of the herbicides based on water solubility is difficult because sulfentrazone solubility changes with pH, and the only pH measured in the study was the soil pH. Yet, in this case, the pH effect of the spray solution and of the cereal rye biomass likely had a larger influence on sulfentrazone solubility and wash-off. Another factor that better explains the higher reduction of metolachlor when intercepted by the cereal rye biomass is the vapor pressure of both herbicides. Sulfentrazone has a much lower vapor pressure ($1.07 \times 10^{-7}$ Pa [25 C]) than *S*-metolachlor ($3.73 \times 10^{-3}$ Pa [25 C]), which can lead to lower losses due to volatility (Shaner 2014; Zimdahl 2018). Also, when comparing the *Kow* and *Koc* of both herbicides, which indicates the herbicide sorption to soil and organic carbon, respectively, *S*-metolachlor has much higher values (795 and 200 mL $g^{-1}$ *Kow* and *Koc*, respectively) compared to sulfentrazone (9.8 and 43 mL $g^{-1}$ *Kow* and *Koc*, respectively) (Alletto et al. 2013; Shaner 2014; Zimdahl 2018). Moreover, sulfentrazone is reported as not susceptible to photodegradation, whereas for *S*-metolachlor, photodegradation is a major contributor to degradation in the field (Shaner 2014). Thus, given the study conditions where the herbicides were intercepted by the cereal rye biomass and remained exposed to sunlight until the first rainfall, metolachlor was likely more adsorbed by the cereal rye biomass and further affected by photodegradation than sulfentrazone.

Despite following the same treatment trends, the concentration of both herbicides was higher in 2021 compared to 2020 and 2022 (Table 5). Variability in the herbicide concentration in the soil across years can be expected due to small differences in soil characteristics and environmental conditions during herbicide application until soil sampling that can affect the overall fate of the herbicides. The soil analysis revealed that the soil characteristics (organic matter, texture, and pH) were similar across years (Table 1). Nevertheless, it does not contain any information about soil microbiology, which is known to be the main source of herbicide degradation and dissipation in the soil (Szmigielski et al. 2014). From an environmental perspective, in 2021, the average daily temperature from the second to the fifth days after treatment was below 10 C, with a minimum average of 1.8 C (Supplementary Figure S1). Lower temperatures have been shown to decrease herbicide degradation rate in the soil (Walker et al. 1992), which could have contributed to the final higher concentration of sulfentrazone and metolachlor in 2021.

## *Soybean Yield*

A significant interaction between treatment and year was also observed for soybean yield ($P = 0.006$). Across years, the tillage and no-till treatments resulted in the highest yield levels, and no differences were observed between these two systems. However, glyphosate in 2021 and roller in all experimental years reduced soybean yield compared to tillage and no-till treatments (Table 6). Because a yield reduction by the roller was observed in 2020, the yield component data (soybean stand, number of pods and beans per plant, and seed weight) were collected in 2021 and 2022 to understand what was driving differences in yield. No differences were observed in soybean stand ($P = 0.545$) or in the number of pods ($P = 0.648$) or beans per plant ($P = 0.380$) across treatments (data not shown). Yet, a significant treatment effect ($P < 0.001$) revealed that both cereal rye treatments (glyphosate and roller) reduced seed weight compared to tillage and no-till (Table 6). Thus, despite not affecting soybean establishment or the number of pods per plant, the cereal rye negatively affected seed filling, which was likely the factor driving the yield reductions observed in 2020 and 2022 (roller only) and 2021 (glyphosate and roller) by the cereal rye treatments.

It was observed under field conditions that both cereal rye treatments (glyphosate and roller) delayed soybean growth stages during the growing season compared to tillage and no-till to a varied extent in all years (JJN, personal observation). During the vegetative phases, soybean planted in cereal rye treatments were usually one to two stages behind and took between 1 and 2 wk longer to reach maturity compared to tillage and no-till. The most extreme differences in maturity were observed in 2021 (Supplementary Figure S3). A similar trend was observed by Reed et al. (2019), who reported a delay in emergence and lag to reach maturity when soybean was planted green compared to planting in early-terminated cereal rye. As a consequence of the delay or lag in soybean growth stages during the vegetative phases by the cereal rye treatments, its cycle was also shifted, and the reproductive phases occurred later in the growing season than in

**Table 6.** Soybean yield in 2020, 2021, and 2022 and 100-seed weight average of 2021 and 2022.[a,b]

| | Soybean yield | | | |
|---|---|---|---|---|
| | 2020 | 2021 | 2022 | 100-seed weight |
| | kg ha$^{-1}$ | | | g$^{-1}$ |
| Treatment | | | | |
| Tillage | 3,851 (58) a | 4,659 (122) a | 3,424 (254) a | 19.05 (0.09) a |
| No-till | 4,022 (24) a | 4,608 (62) a | 3,373 (211) a | 18.95 (0.11) a |
| Glyphosate | 3,844 (45) a | 3,928 (57) b | 3,239 (308) a | 18.36 (0.14) b |
| Roller | 3,173 (54) b | 4,135 (151) b | 2,879 (310) b | 18.09 (0.17) b |
| P-values | | | | |
| Treatment (T) | | <0.001 | | <0.001 |
| Year (Y) | | 0.008 | | 0.863 |
| T × Y | | 0.006 | | 0.079 |

[a] Values between parentheses indicate the standard error of means.

[b] Treatments followed by the same letter within the column of each year for yield and within the column for seed weight are not significantly different according to Fisher's least significant difference test ($\alpha = 0.05$).

the tillage and no-till treatments. Thus we hypothesized that soybean seed weight was negatively affected by the shift in growth stages observed in the cereal rye treatments owing to reduced time for seed filling (Andrade 1995; Hu and Wiatrak 2012; Weaver et al. 1991). Moreover, because soybean planting dates for all experimental years were relatively later than recommended for Wisconsin owing to the need for cereal rye to reach the anthesis growth stage for the mechanical termination (Mirsky et al. 2009), lower seed filling was most likely due to the shift in typical growth stage accumulation during the season (Gaspar and Conley 2015).

Unlike spray deposition and herbicide concentration in the soil, there was no significant correlation between soybean yield ($r = 0.2$, $P > 0.05$) and soybean stubble and cereal rye biomass (Figure 2), which corroborates the findings of Smith et al. (2011), who also reported no direct effect of cereal rye biomass on soybean yield. Yet, it is unclear why the roller treatment reduced soybean yield compared to tillage and no-till in all experimental years and glyphosate only in 2021 (Table 6). In 2020, only the roller was used to terminate the cereal rye, and poor termination was observed, which likely favored yield reduction because of early-season competition between cereal rye and soybean. However, in 2021 and 2022, glyphosate was also sprayed after the mechanical termination. Thus the effectiveness of the cereal rye termination was the same in both systems (JJN, personal observation). One factor that possibly favored yield reduction in both cereal rye termination methods was the dry growing season recorded in 2021 (precipitation from planting to harvest 322 mm) compared to 2020 (precipitation from planting to harvest 523 mm) and 2022 (precipitation from planting to harvest 497 mm) (Table 3). Reed and Karsten (2022) reported that cereal rye can reduce soil water content close to the termination date, and Rosa et al. (2021) observed that the reduction in soil moisture by cereal rye negatively affected corn yield. Therefore, given that 2021 had the lowest precipitation during the first 2 wk following soybean planting (Supplementary Figure S2), it might have contributed to the yield reduction observed in the glyphosate and roller treatments. Nevertheless, more studies recording soil moisture during the growing season and measuring yield component data are needed to understand in which instances cereal rye can negatively affect soybean yield.

Previous research evaluating the effect of early-terminated cereal rye or cereal rye planted green shows that cereal rye can either have no negative effect (Bish et al. 2021; Reed et al. 2019; Grint et al. 2022; Schramski et al. 2021; Smith et al. 2011; Reed and Karsten 2022) or reduce soybean yield (Hodgskiss et al. 2022; Liebl et al. 1992; Moore et al. 1994). Out of the studies that reported soybean yield reduction by cereal rye, Liebl et al. (1992) observed a stand reduction when soybean was established under the planting-green system compared to early termination and no-till without cereal rye. Moore et al. (1994) reported that the likely cause of yield reduction in soybeans was a lower 100-seed weight when the cereal rye was terminated 3 to 10 d before soybean planting. Thus, based on the present study and previous research, soybean yield is often not affected by the cereal rye terminated with glyphosate before or at soybean planting. In instances when yield reduction is observed, collecting yield component data is important to support findings and elucidate the source of yield differences.

## Practical Implications

The interception of the herbicide spray solution and the reduction in the concentration of PRE herbicides in the soil by cereal rye biomass seem to be inevitable outcomes when adopting these two practices together. Our findings indicate that the increase in cereal rye biomass accumulation can lead to higher herbicide interception and that metolachlor was more affected than sulfentrazone, but no major differences were observed between termination methods (glyphosate and roller). Farmers should be aware that cereal rye can lower the concentration of PRE herbicides reaching the soil and intensify the need for field scouting to ensure that weed control is not being negatively affected. This brings the need for more research to test the hypothesis that the weed suppression provided by cereal rye can compensate for the lower herbicide concentration in the soil, thus not negatively affecting preemergence weed control. More research is also needed to investigate which herbicides are less affected by cereal rye biomass based on their physicochemical properties, which can provide additional options for farmers planting green for effective preemergence weed control. Moreover, studies investigating application technology parameters, such as different nozzles, varying carrier rates, and the use of adjuvants to enhance spray deposition in heavy planting-green cereal rye biomass, can provide valuable information for farmers adopting this system. The mechanical termination with a roller reduced soybean yield in all experimental years compared to tillage and no-till and to glyphosate in 2020 and 2022. Despite not being clear why the mechanical termination had a negative impact on yield in all years, this should be taken into consideration by farmers evaluating methods for effective cereal rye termination without yield penalties.

**Supplementary material.** To view supplementary material for this article, please visit https://doi.org/10.1017/wet.2023.41

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## References

Alletto L, Benoit P, Bolognési B, Couffignal M, Bergheaud V, Dumény V, Longueval C, Barriuso E (2013) Sorption and mineralisation of S-metolachlor in soils from fields cultivated with different conservation tillage systems. Soil Tillage Res 128:97–103

Andrade FH (1995) Analysis of growth and yield of maize, sunflower and soybean grown at Balcarce, Argentina. Field Crop Res 41:1–12

Appelgate SR, Lenssen AW, Wiedenhoeft MH, Kaspar TC (2017) Cover crop options and mixes for Upper Midwest corn–soybean systems. Agron J 109:968–984

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

Bates D, Maechler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. J Stat Soft 67:1–48

Bish M, Dintelmann B, Oseland E, Vaughn J, Bradley K (2021) Effects of cereal rye seeding rate on waterhemp (*Amaranthus tuberculatus*) emergence and soybean growth and yield. Weed Technol 35:838–844

Blanco-Canqui H, Shaver TM, Lindquist JL, Shapiro CA, Elmore RW, Francis CA, Hergert GW (2015) Cover crops and ecosystem services: insights from studies in temperate soils. Agron J 107:2449–2474

Bowman M, Poley K, McFarland E (2022) Farmers employ diverse cover crop management strategies to meet soil health goals. Agric Environ Lett 7:e20070.

Brooks ME, Kristensen K, van Benthem KJ, Magnusson A, Berg CW, Nielsen A, Skaug HJ, Maechler M, Bolker BM (2017) glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. R J 9:378–400

Carbonari C, Gomes G, Trindade M, Silva J, Velini E (2016) Dynamics of sulfentrazone applied to sugarcane crop residues. Weed Sci 64:201–206

Chaim A, Camargo Neto J, Pessoa MCPY (2006) Uso do programa computacional Gotas para avaliação da deposição da pulverização aérea sob diferentes condições climáticas. Jaguariuna, Brazil: Embrapa Meio Ambiente. 18 p

Cornelius CD, Bradley KW (2017) Influence of various cover crop species on winter and summer annual weed emergence in soybean. Weed Technol 31:503–513

Correndo AA, Moro Rosso LH, Ciampitti IA (2021) Agrometeorological data using R-software. Harvard Dataverse V5

Gaspar AP, Conley SP (2015) Responses of canopy reflectance, light interception, and soybean seed yield to replanting suboptimal stands. Crop Sci 55:377–385

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

Grint KR, Arneson NJ, Arriaga F, DeWerff R, Oliveira M, Smith DH, Stoltenberg DE, Werle R (2022) Cover crops and preemergence herbicides: an integrated approach for weed management in corn–soybean systems in the US Midwest. Front Agron 4:888349

Haramoto ER, Sherman AD, Green JD (2020) 2,4-D deposition is reduced and more variable immediately adjacent to cereal rye cover crop rows. Weed Technol 34:147–152

Hayden ZD, Brainard DC, Henshaw B, Ngouajio M (2012) Winter annual weed suppression in rye-vetch cover crop mixtures. Weed Technol 26:818–825

Heap I (2023) The international survey of herbicide resistant weeds. http://www.weedscience.org/. Accessed: February 16, 2023

Hodgskiss CL, Young BG, Armstrong SD, Johnson WG (2022) Utilizing cover crops for weed suppression within buffer areas of 2,4-D-resistant soybean. Weed Technol 36:118–129

Hu M, Wiatrak P (2012) Effect of planting date on soybean growth, yield, and grain quality: review. Agron J 104:785–790

Kaspar TC, Jaynes DB, Parkin TB, Moorman TB, Singer JW (2012) Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. Agric Water Manag 110:25–33

Kaspar TC, Singer JW (2011) The use of cover crops to manage soil. Pages 321–337 *in* Hatfield JL, Sauer TJ, eds. Soil Management: Building a Stable Base for Agriculture. Madison, WI: SSSA

Keene CL, Curran WS, Wallace JM, Ryan MR, Mirsky SB, VanGessel MJ, Barbercheck ME (2017) Cover crop termination timing is critical in organic rotational no-till systems. Agron J 109:272–282

Khalil Y, Ken Flower K, Siddique KHM, Ward P (2019) Rainfall affects leaching of pre-emergent herbicide from wheat residue into the soil. PLoS ONE 14(2): e0210219

Kim DS, Marshall EJP, Brain P, Caseley JC (2011) Effects of crop canopy structure on herbicide deposition and performance. Weed Res 51:310–320

Knezevic SZ, Pavlovic P, Osipitan OA, Barnes ER, Beiermann C, Oliveira MC, Lawrence N, Scott JE, Jhala A (2019) Critical time for weed removal in glyphosate-resistant soybean as influenced by preemergence herbicides. Weed Technol 33:393–399

Lenth R (2022) emmeans: estimated marginal means, aka least-squares means. R package version 1.8.2. https://CRAN.R-project.org/package=emmeans. Accessed: June 29, 2023

Liebl R, Simmons FW, Wax LM, Stoller EW (1992) Effect of rye (*Secale cereale*) mulch on weed control and soil moisture in soybean (*Glycine max*). Weed Technol 6:838–846

Lopes-Ovejero RF, Soares DJ, Oliveira WS, Fonseca LB, Berger GU, Soteres JK, Christoffoleti PJ (2013) Residual herbicides in weed management for glyphosate-resistant soybean in Brazil. Planta Daninha 31:947–959

Mirsky S, Curran W, Mortensen D, Ryan M, Shumway D (2009) Control of cereal rye with a roller/crimper as influenced by cover crop phenology. Agron J 101:1589–1596

Mirsky S, Curran W, Mortenseny D, Ryany M, Shumway D (2011) Timing of cover-crop management effects on weed suppression in no-till planted soybean using a roller-crimper. Weed Sci 59:380–389

Moore M, Gillespie TJ, Swanton CJ (1994) Effect of cover crop mulches on weed emergence, weed biomass, and soybean (*Glycine max*) development. Weed Technol 8:512–518

Norsworthy J, Ward S, Shaw D, Llewellyn R, Nichols R, Webster T, Bradley K, Frisvold G, Powles S, Burgos N, Witt W, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60(SP1):31–62

Palhano MG, Norsworthy JK, Barber T (2018) Cover crops suppression of Palmer amaranth (*Amaranthus palmeri*) in cotton. Weed Technol 32:60–65

Perkins CM, Gage KL, Norsworthy JK, Young BG, Bradley KW, Bish MD, Hager A, Steckel LE (2021) Efficacy of residual herbicides influenced by cover-crop residue for control of *Amaranthus palmeri* and *A. tuberculatus* in soybean. Weed Technol 35:77–81

Price A, Balkcom K, Duzy L, Kelton J (2012). Herbicide and cover crop residue integration for amaranthus control in conservation agriculture cotton and implications for resistance management. Weed Technol 26:490–498

R Core Team (2022) R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing

Reddy KN (2003) Impact of rye cover crop and herbicides on weeds, yield, and net return in narrow-row transgenic and conventional soybean (*Glycine max*). Weed Technol 17:28–35

Reed HK, Karsten HD (2022) Does winter cereal rye seeding rate, termination time, and N rate impact no-till soybean? Agron J 114:1311–1323

Reed HK, Karsten HD, Curran WS, Tooker JF, Duiker SW (2019) Planting green effects on corn and soybean production. Agron J 111:2314–2325

Rosa AT, Creech CF, Elmore RW, Rudnick DR, Lindquist JL, Fudolig M, Butts L, Werle R (2021) Implications of cover crop planting and termination timing on rainfed maize production in semi-arid cropping systems. Field Crops Res 271:108251

Schramski JA, Sprague CL, Renner KA (2021) Effects of fall-planted cereal cover-crop termination time on glyphosate-resistant horseweed (*Conyza canadensis*) suppression. Weed Technol 35:223–233

Selim HM, Zhou L, Zhu H (2003) Herbicide retention in soil as affected by sugarcane mulch residue. J Environ Qual 32:1445–54

Shaner DL, ed (2014) Herbicide Handbook. 10th ed. Lawrence, KS: Weed Science Society of America. 513 p

Shaner DL, Brunk G, Belles D, Westra P, Nissen S (2006) Soil dissipation and biological activity of metolachlor and *S*-metolachlor in five soils. Pest Manag Sci 62:617–623

Simão LM, Easterly AC, Kruger GR, Creech CF (2020) Herbicide spray deposition in wheat stubble as affected by nozzle type and application direction. Agron J 10:1507

Smith AN, Reberg-Horton SC, Place GT, Meijer AD, Arellano C, Mueller JP (2011) Rolled rye mulch for weed suppression in organic no-tillage soybeans. Weed Sci 59:224–231

Szmigielski AM, Johnson EN, Schoenau JJ (2014) A bioassay evaluation of pyroxasulfone behavior in prairie soils. J Pestic Sci 39:22–28

Thornton MM, Shrestha R, Wei Y, Thornton PE, Kao SC, Wilson BE (2022) Daymet: daily surface weather data on a 1-km grid for North America. Version 4 R1. Oak Ridge, TN: ORNL DAAC

Walker A, Moon Y-H, Welch SJ (1992) Influence of temperature, soil moisture and soil characteristics on the persistence of alachlor. Pestic Sci 35:109–116

Weaver DB, Akridge RL, Thomas CA (1991) Growth habit, planting date, and row-spacing effects on late-planted soybean. Crop Sci 31: 805–810

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

Zadoks JC, Chang TT, Konzak CF (1974) A decimal code for the growth stages of cereals. Weed Res 14:415–421

Zimdahl RL (2018) Herbicides and soil. Pages 445–464 *in* Zimdahl RL, ed. Fundamentals of Weed Science. London, UK: Academic Press