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DOI: 10.1017/wsc.2025.10059

Short title: Residual herbicide fate

Influence of Cover Crop Termination Strategies on Weed Suppression, Concentration of Residual Herbicides in the Soil, and Soybean Yield

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Cover crops and soil residual herbicides are considered essential tools within integrated weed management practices. However, interception of soil-applied herbicides by cover crop residue can reduce weed control and crop yield. Field trials were conducted in 2022 and 2023, in Indiana, to investigate the effect of cereal rye (*Secale cereale* L.) termination strategies on the concentration of sulfentrazone, *S*-metolachlor, and cloransulam-methyl in soil, weed control, and soybean [*Glycine max* (L.) Merr.] yield. Soybean were planted at cereal rye anthesis. Termination strategies included roller crimped cereal rye, standing cereal rye, and a fallow control. The average cereal rye biomass in 2022 and 2023 was 4,061 and 14,211 kg ha^{-1}, respectively. Soybean stands were unaffected in 2022 but were reduced by 24 and 69% in the presence of roller crimped and standing cereal rye, respectively, in 2023. On average, 75 and 84% of the soil residual herbicides applied were intercepted by the roller crimped cereal rye residue in 2022 and 2023, respectively. The use of cereal rye did not improve overall weed control relative to fallow at 18 WAP, in 2022 and 2023. In 2022, roller crimped cereal rye reduced soybean yields by up to 13% in comparison to the presence of to the fallow. In 2023, regardless of management strategy, the use of cereal rye as cover crop reduced soybean yields by an average 44% in comparison to the fallow. Results from this research suggest that the adoption of the planting green system can significantly reduce soybean yield primarily due to stand losses if proper planting equipment is not used. Furthermore, the high levels of cereal rye biomass achieved in both years of the study did not provide additional season-long weed suppression relative to the non-cover crop control.

Keywords: Cover crop termination, roller crimper, soil residual herbicides, soybean planting green, soybean yield, weed suppression.

Introduction

Resource competition between weeds and soybean [*Glycine max* (L.) Merr.] has caused significant yield losses in the United States. Annually, potential soybean yield losses were estimated up to 52% in the absence of weed control measures (Soltani et al. 2017). Considering the U.S. soybean production from 2023 (112 million tons; NASS 2023), these losses due to weed interference would be equivalent to approximately 58 million tons of soybean or $28 billion ($473.99 t^{-1} or $12.9 bu^{-1} of soybean; USDA-ERS 2023). Yield losses can be significantly reduced when chemical weed control measures are adopted. However, the overreliance on herbicides to control weeds led to the development of more than 600 cases of herbicide resistance in the U.S. since 1957 (Heap 2024). In this regard, integrated weed management (IWM) strategies that include cultural and mechanical methods to control weeds have become more popular to potentially delay the development of herbicide resistance.

Cover crops are one of the IWM tools often used to suppress weed growth (Swanton and Murphy 1996). In addition, cover crops are known for improving the soil physical, chemical and biological properties, as well as reducing soil erosion and nutrient leaching (Kladivko et al. 2014; Rorick and Kladivko 2017; Ruffatti et al. 2019; Villamil et al. 2006). Cereal rye (*Secale cereale* L.) is the most commonly used cover crop species and has the highest potential to suppress weeds through the competition for resources (light, water, and nutrients), allelopathy, and the physical barrier created by the residue after termination (Clark 2007; Fernando and Shrestha 2023; Teasdale 1996). Previous studies have indicated that biomass accumulation is the limiting factor for weed suppression, and was directly proportional with weed suppression (Hodgskiss et al. 2020; Teasdale and Mohler 1993; Wallace et al. 2019). In the presence of 3,910 kg ha^{-1} of cereal rye biomass, Wallace et al. (2019) observed horseweed [*Conyza canadensis* (L.) Cronquist; syn. *Erigeron canadensis* L.] densities reduced up to 95% at the time of spring cover crop termination, compared to no cover crop.

The soybean planting green method consists of planting soybean into a live stand of cereal rye. Cereal rye is terminated at the anthesis growth stage, when the plants are close to their maximum biomass accumulation. The goals are to delay the termination of the cover crop so there is enough biomass to provide weed suppression, conserve soil moisture, reduce soil temperature fluctuations, and maximize carbon inputs to the soil (Balkcom et al. 2015; Basche et al. 2016; Reed and Karsten 2022). However, high-residue systems are challenging not only

https://doi.org/10.1017/wsc.2025.10059 Published online by Cambridge University Press

during planting but throughout the growing season. Reduced efficiency of closing the seed furrow while planting the cash crop, or reduced soil-to-seed contact in the seed furrow are some of the problems faced during planting (Kornecki et al. 2009; Reed et al. 2019). Early in the season, the cover crop residue mat also retains soil moisture, thus providing near optimal environment for the growth of seedling pathogens (Acharya et al. 2022). The term “green bridge” is related to planting green systems, where insects migrate from the decaying cover crop and start feeding on newly emerged soybean plants sometimes causing yield losses due to stand reductions early in the season (Dean et al. 2022; Dunbar et al. 2016; Obermeyer 2020). Furthermore, the presence of high amounts of biomass can result in nutrient immobilization and therefore, reduce nutrient availability to the soybean (Wells et al. 2013). Nitrogen (N) and sulfur are two examples of nutrients that can become unavailable if the cover crop residue has C:N and C:S ratios above 25:1 and 400:1, respectively (Tabatabai and Chae 1991; White et al. 2016).

The impact of planting green on soybean yield is highly variable. For instance, several studies have reported soybean yield reductions varying from 14 to 45% when cover crop termination was delayed (Nunes et al. 2023; Hodgskiss et al. 2022; Liebl et al. 1992). Conversely, Reed et al. (2019) did not observe soybean yield reductions due to the adoption of the planting green method.

Cereal rye can be terminated chemically with herbicides or mechanically with roller crimper, mower, or tillage. Roller crimper use has gained popularity among growers that are adopting the soybean planting green method as an alternative to lay the residue flat above the soil surface and potentially increase the ground cover (Mirsky et al. 2011). Effective termination of cereal rye with a roller crimper is only possible if the plants have reached the reproductive stage and is more effective as the plants mature (Parr et al. 2014; Wells et al. 2014). The use of a roller crimper, however, does not eliminate the need for herbicides even when high amounts of biomass are present (Davis 2010; Dorn et al. 2013). The season-long effects of high-residue accumulation such as moisture conservation and reduced temperature fluctuations can favor the germination and emergence of weeds later in the season (Teasdale and Mohler 1993). Previous studies have reported inadequate weed control when cover crops were used as the sole weed management strategy (Teasdale et al. 2005). Conversely, adequate weed control was achieved when cover crops were used in combination with comprehensive weed management programs including pre- and post-emergence herbicides (Cornelius and Bradley 2017; Whalen et al. 2020; Wiggins et al. 2016).

The use of soil residual herbicides at cover crop termination has been suggested to extend the weed control through the critical weed-free period (Nunes et al. 2023a; Whalen et al. 2020). However, when used at cover crop termination, only some of the herbicide applied reaches the soil while the rest is intercepted by the cover crop biomass, hence reducing initial herbicide concentrations in the soil that would be biologically available to germinating weed seeds (Banks and Robinson 1982, 1984; Ghadiri et al. 1984; Nunes et al. 2023a; Whalen et al. 2020). The extent of herbicide interception has been correlated with biomass accumulation, with high-residue systems intercepting more herbicide than cover cropping systems with early terminations (less biomass) (Nunes et al. 2023a; Whalen et al. 2020). Research conducted by Whalen et al. (2020) suggested that when cover crop termination was delayed from 21 to 7 days prior to planting, sulfentrazone concentration in the soil at the time of application was reduced by approximately 57% due to cover crop biomass.

Once intercepted, the herbicides can only move to the soil with rainfall or irrigation, with greater water volumes washing off more herbicide from the biomass to the soil (Khalil et al. 2019). Previous studies have reported differences in metribuzin concentration in the soil varying from 1 to 15% relative to what was applied, after 20 mm of rainfall (Banks and Robinson 1982). Similarly, Ghadiri et al. (1984) demonstrated that after 50 mm of rain, atrazine concentration in the soil increased more than 2-fold, while the amount retained in the wheat straw was reduced by 90%. Furthermore, ground cover, age of cover crop residue, and herbicide solubility are other factors that will influence how much and how fast the herbicide will move from the cover crop biomass to the soil. Generally, greater ground cover, older residue (Dao 1991), and lower herbicide solubility (Khalil et al. 2019) tend to limit the amount of residual herbicides reaching the soil at application and after rainfall or irrigation. Khalil et al. (2019) reported that with 5 mm of rainfall, more pyroxasulfone (3.49 mg L^{-1} water solubility) leached from the residue to the soil than trifluralin (0.3 mg L^{-1} water solubility) largely due to differences in water solubility between these two compounds. Reduced herbicide concentrations in the soil due to interference from cover crop residue may contribute to the selection of non-target site herbicide resistance (Busi et al. 2013; Neve and Powles 2005). For instance, a multiple-resistant rigid ryegrass (*Lolium rigidum* Gaudin) population that was subjected for three generations to low doses of pyroxasulfone had more than 30% survival rate after the application of 240 g ai ha^{-1} (2.4-fold the label rate) (Busi et al. 2012).

Research regarding the fate of residual herbicides in high-residue cover cropping systems and its impact on weed control is still limited. The objectives of this research were (1) to determine if the practice of roller crimping cereal rye increases ground cover and reduces the density of giant ragweed (*Ambrosia trifida* L.) and grasses relative to standing cereal rye, (2) determine the concentration of sulfentrazone, *s*-metolachlor, and cloransulam-methyl in soil at seven sample timings, and (3) determine if roller crimping cereal rye increases soybean yield relative to standing cereal rye.

Materials and Methods

Field experiments were established in the fall of 2021 and 2022 at the Throckmorton Purdue Agricultural Center (TPAC; 40.29°N, 86.90°W). Trial locations varied from one year to another respecting the corn (*Zea mays* L.)-soybean rotation at TPAC (adjacent fields; same soil type). Soil was Toronto-Millbrook silty clay loam with 20% sand, 53% silt, 26% clay, with organic matter and pH ranging from 2.9 to 4.2% and 6.0 to 6.5, respectively, between 2022 and 2023. The fields were previously managed under a corn-soybean rotation for more than 10 years and were in corn during the 2021 and 2022 growing seasons. Prior to cereal rye planting in fall of 2021, corn crop was mowed, and residue incorporated into the top 10 cm of soil using a rotary tiller. Conversely, in the fall of 2022, the previous corn crop was also mowed but the field was disked and cultivated to eliminate crop residue and weeds, which resulted in a deeper incorporation of the corn residue compared to the management practice adopted in 2021. The target seeding rate for this experiment was 50 kg ha^{-1} of cereal rye (Elbon variety, Cisco Company, Indianapolis, IN). However, due to excessive soil moisture in October of 2021, the use of a box drill seeder was not possible. Thus, 20 kg ha^{-1} of extra seed were added to account for losses post planting (e.g., lack of seed incorporation, animal feeding, rotting) and, on October 23^{rd}, 2021, cereal rye was spread at 70 kg ha^{-1} on the soil surface using a chest-mounted spreader (421-S, Solo, Newport News, VA). Conversely, soil conditions were adequate in 2022 and cereal rye was planted at 50 kg ha^{-1} on September 16^{th}, 2022, using a John Deere 1590 box drill. Soil samples were taken in March of 2022 and 2023, at 0-10 cm depth to determine the physicochemical properties of the soil (Table 1).

The experiment was laid out under randomized complete block design (RCBD) with a 3x2 factorial arrangement having four replications for a total of 24 experimental units that measured 9.1 by 4.6 m in size. Treatments included two cereal rye termination management strategies (roller crimped and standing cereal rye) as well as a fallow control, and two residual herbicide programs for a total of 6 treatments. The herbicide programs consisted of 1) with residual – glyphosate at 1,750 g ae ha^{-1}, glufosinate at 737 1,750 g ai ha^{-1}, sulfentrazone at 280 g ai ha^{-1}, s-metolachlor at 1,790 g ai ha^{-1}, and cloransulam-methyl at 44 g ai ha^{-1}, and 2) no residual – glyphosate at 1,750 g ae ha^{-1} plus glufosinate at 737 g ai ha^{-1}. All herbicides within each program were applied in tank mix and at cover crop termination, immediately after the use of the roller crimper. Herbicides were applied using a CO_2-pressurized spray boom equipped with eight AIXR 11002 nozzles (TeeJet Spraying Systems Co., Wheaton, IL). Nozzles were spaced 38 cm apart and calibrated to deliver 140 L ha^{-1} while traveling at 4.8 km h^{-1} and operating at 165 kPa. Nonionic surfactant (Class Act Ridion, Winfield Solutions LLC, St. Paul, MN) at 0.5 % v/v and ammonium sulfate (34%, Amsol, Winfield Solutions LLC, St. Paul, MN) at 5% v/v were added to all herbicide applications.

Glyphosate (Roundup PowerMax, Bayer Crop Science, Saint Louis, MO) was applied in March of 2022 and 2023 at 1540 g ae ha^{-1} to eliminate cereal rye plants from the fallow control plots. At that point, plants were up to 10 cm in height with little biomass accumulation. The residue had, therefore, approximately 2 months to decay and did not provide interception of residual herbicides at the time of treatment application.

Soybeans (AG30XF2; Asgrow, Bayer Crop Science, St. Louis, MO) were planted at 350,000 seeds ha^{-1}, in 76-cm row spacing, when cereal rye plants reached anthesis [i.e., Zadoks 60 (Zadoks et al. 1974)]. Immediately after planting, plots assigned to the roller crimper treatment were rolled using a tractor-mounted 2.4 m wide roller-crimper filled with water to increase weight. Following the use of the roller crimper, all plots were sprayed with their specific herbicide treatments on May 20th of 2022 and May 18th of 2023. One POST application of glyphosate plus glufosinate at 1740 g ae ha^{-1} and 737 g ai ha^{-1}, respectively, was made four weeks after soybean planting (WAP).

Precipitation data (mm) was recorded by an automatic weather station (WatchDog Weather Station 2700, Spectrum Technologies, Aurora, IL) placed within 10 m of the edge of the trial, at one-hour intervals, and averaged daily (Figure 1).

https://doi.org/10.1017/wsc.2025.10059 Published online by Cambridge University Press

In 2022 and 2023, the cereal rye stand was uniform across the trial area. Thus, average cereal rye biomass was measured for the whole trial and not per plot. Ten 0.25 m^2 quadrats were randomly placed within the trial area and all aboveground plant material was harvested by cutting the plants at the base (1 cm above soil surface). Samples were placed in a forced-air oven at 80 C for 48 h. The average cereal rye biomass was 4,061 and 14,211 kg ha^{-1} in 2022 and 2023, respectively.

Density of *A. trifida* and grasses was determined prior to the postemergence application (4 WAP) and at 18 WAP (Table 2). Two 0.25 m^2 quadrats were randomly placed in each plot (one in the first half of the plot area and one in the second half). The number of plants was recorded, averaged for each plot, and converted to plants m^{-2}.

Soybean stands were determined at 18 WAP by counting the number of soybean plants m^{-1} of row, in the two center rows of each plot (Table 3). The first count was done in the front half of the plot and second count was done in the back half of the plot. The number of plants m^{-1} of row was then converted to plants ha^{-1}. Soybean yield, in kg ha^{-1}, was determined by harvesting all six soybean rows from each plot with a plot combine.

The concentration of residual herbicides in the soil throughout the growing season was determined by collecting soil samples immediately after herbicide application and at 10, 14, 28, 56, 84 and 112 d after application (Figure 2). Fifteen soil cores (2 cm in diameter by 5 cm in depth) were collected using a gator probe (AMS, Inc. American Falls, ID), placed in a plastic bag (composite sample), and stored in a cooler at 4 C. Soil probe was cleaned with a 50% acetone solution to prevent sample contamination from one plot to another. No later than one day after sampling, soil cores from each plot were sieved (2 mm) to remove debris and homogenize the sample and then stored in a -20 C freezer until further processing.

The concentration of sulfentrazone, *S*-metolachlor, and cloransulam-methyl in soil samples was determined using the QuEChERS (Quick-Easy-Cheap-Effective-Rugged-Safe) method as previously described by (Olaya-Arenas and Kaplan 2019) with modifications. All samples were analyzed within four months of collection in an Agilent 1290 Infinity II ultra-high performance liquid chromatography (UHPLC) with a 6470 triple quadrupole mass spectrometry and an EclipsePlus C18 RRHD 1.8µm, 2.1x50mm column (Agilent Technologies, Santa Clara, CA) at the Bindley Bioscience Center at Purdue University. Recoveries from fortified untreated

https://doi.org/10.1017/wsc.2025.10059 Published online by Cambridge University Press

soil samples indicated that recovery was 112, 80, and 74% for sulfentrazone, *s*-metolachlor, and cloransulam-methyl, respectively.

Soil samples were thawed, and a 3 g (± 0.01) subsample of wet soil was transferred from each composite sample into 50-ml tubes (Falcon 50-mL centrifuge tubes, Thermo Fisher Scientific, Waltham, Massachusetts, USA). The exact weight of each sample was recorded and later used to calculate the dry weight based on the moisture content from each composite sample. The moisture content from each sample was determined from a 5 g subsample of wet soil that was placed in a forced-air oven at 105 C for 24 h. Next, 15 ml of double deionized water, 15 ml of acetonitrile enriched with 1% formic acid (all reagents MS grade, Thermo Fisher Scientific, Waltham, Massachusetts, USA), and 10 µl of an isotopically labeled internal standard containing sulfentrazone, *S*-metolachlor, and cloransulam-methyl (PESTANAL® standard 98.8%, Sigma-Aldrich, MO, USA) were added to the 50-ml tube containing the 3 g soil sample. The tube was agitated for 30 seconds with a Mini vortex mixer (VWR, Radnor, PA). Once agitation was complete, anhydrous salts of magnesium sulfate (6 g) and sodium acetate (1.5 g) (Thermo Fisher Scientific, Waltham, Massachusetts, USA) were added to the tubes, followed by another agitation of 30 s. Tubes were then transferred to the Geno/Grinder 2010 (SPEX sample prep, Metuchen, NJ) and shaken for three minutes at 1100 rpm and then centrifuged at 2500 rpm for 10 min. Twelve ml of the supernatant were transferred into 15 ml dispersive solid-phase extraction tubes (part no: 5982-5158; Agilent Technologies, Santa Clara, CA) that were shaken for 3 min at 1100 rpm in the Geno/Grinder 2010 and then centrifuged at 4,000 rpm for 5 min. The supernatant was transferred into 15-ml tubes (Falcon 15-mL centrifuge tubes, Thermo Fisher Scientific, Waltham, Massachusetts, USA) and dried overnight in a speed vacuum (SC250EXP; ThermoFisher Scientific, Waltham, MA). The dried pellet was re-suspended with 150 µl of a 50% acetonitrile solution and the tube was agitated with a Mini vortex mixer until the pellet was dissolved. The 15-ml tubes were then centrifuged at 4,000 rpm for 5 min and 130 µl of the supernatant was transferred to 96-well microplates (Nunc™ low-binding polypropylene, ThermoFisher Scientific, Waltham, MA) prior to the analysis in the UHPLC.

All data were subjected to an Analysis of Variance (ANOVA) using the PROC GLIMMIX procedure in SAS 9.4 (Tables S1-S3). There was a significant treatment by year interaction for the weed density, soybean stand and yield, and herbicide concentration in the soil. Therefore, results were presented separately by year. The interaction between cereal rye management and herbicide treatments for weed density and soybean stand and yield were non-significant, therefore, data were combined over herbicide treatments within each year. One exception was in 2022, for the grasses density at 4 WAP, when a significant interaction between cereal rye management and herbicide treatments was observed. In this case, the results were discussed separately by herbicide treatment. Assumptions of normality and homogeneity of variance were evaluated by visual assessment of residual plots. Data were log or square-root transformed when needed. However, original mean values are presented. Treatment means were separated using Fisher's protected LSD ($P \leq 0.05$). Non-linear regression analysis of herbicide concentration over time (0 to 112 days after application) was performed to determine the first-order-dissipation rate constants for each herbicide within each year and each cereal rye management strategy (Table 4).

Results and Discussion

Cereal rye biomass. The amount of cereal rye biomass produced in the spring of 2022 (4,061 kg ha^{-1}) was 18% above the average biomass produced in eastern half of the U.S. (3,428 kg ha^{-1}; n = 5,695) (Huddell et al. 2024). In 2023, however, the biomass accumulated (14,211 kg ha^{-1}) was 4-fold greater than the same average, which can be considered excessive and not common for most growers utilizing cover crops in the U.S. We attribute this difference in biomass accumulation mainly to the difference in planting dates. Due to not ideal conditions for planting, cereal rye was broadcasted in October 23rd of 2021. However, in the fall of 2022, cereal rye was drilled in in September 16th. Therefore, the 37 extra days allowed the plants to grow more in the fall of 2022 and resulted in bigger plants in the spring of the following year when growth resumed. Similar results were reported in previous studies that showed a 21% increase in biomass accumulation when triticale (*xTriticosecale* Wittmack) was planted in mid-September in comparison to a late-October planting date (Lyons et al. 2017). In addition to planting date, planting method was also another contributing factor to the difference in biomass between 2022 and 2023. With drilling of cereal rye resulting in greater stands due to increased soil-to-seed contact in comparison to broadcasting (Fisher et al. 2011).

Interception of residual herbicides by cereal rye biomass. Although herbicide concentration in the cereal rye biomass was not measured on this study, we postulate that nearly all the herbicide applied should reach the soil in the absence of biomass, with only a negligible amount being lost through drift, volatility, and/or photodecomposition. Similarly, in the presence of biomass, part of the herbicide applied should be intercepted by the biomass and the remaining part reaches the soil. This concept aligns with previous research showing that the reduction in the concentration of residual herbicide in the soil at the time of application is positively correlated with cereal rye biomass accumulation (Nunes et al. 2023b). Therefore, herbicide interception was calculated as the percent reduction from the concentration of the residual herbicide in the soil of plots with cereal rye relative to plots without cereal rye, at 0 DAT. In 2022, the presence of 4,061 kg ha^{-1} of roller crimped cereal rye biomass resulted in about 75% interception of the residual herbicides (Figure 2; Table S4). As cereal rye biomass increased from 2022 to 2023 (3.5-fold), herbicide interception also increased. Up to 94 and 95% of the applied sulfentrazone and cloransulam-methyl, respectively, were intercepted by roller crimped cereal rye biomass in 2023. These results corroborate those reported by previous studies (Banks and Robinson 1984 and 1986; Crutchfield et al. 1986; Khalil et al. 2018; and Nunes et al. 2023b). Investigating the effect of increasing amounts of wheat straw, going from 2,240 and up to 6,720 kg ha^{-1}, Banks and Robinson (1986) observed between 67 to 97% interception of acetochlor. Previous research has also reported a 12-fold reduction in spray coverage underneath 12,200 kg ha^{-1} of cereal rye biomass in comparison to a no cover crop control (Nunes et al. 2023b).

Concentration of residual herbicide in soil during the growing season. The application of residual herbicides in 2022 and 2023 was followed by 37 and 15 mm of rainfall, respectively, within 7 days (Figure 2). In 2022, the concentration of all residual herbicides tested were similar for all cereal rye and fallow treatments in nearly all sample timings except at cereal rye termination and at 84 DAT (sulfentrazone and *s*-metolachlor only) (Figure 2; Table S4). In 2023, with 14,211 kg ha^{-1} of cereal rye biomass, the concentrations of sulfentrazone and *s*-metolachlor in the soil with roller crimped cereal rye were lower than the concentrations measured in the soil of fallow plots during most of the growing season (at least 4 out of 7 sample timings). With roller crimped cereal rye biomass ranging from 5,200 to 12,200 kg ha^{-1}, Nunes et al. (2023b) observed, on average, 49 and 77% reductions in the concentrations of sulfentrazone and metolachlor in the soil, respectively, when compared to the concentrations measured in the tilled soil, at 25 d after herbicide application.

Giant ragweed and grasses density at four and eighteen weeks after soybean planting. No cereal rye management strategy by year interactions were observed for weed density. Therefore, data was pooled over years (Table 2). The primary weed species present in the field trial areas in

2022 and 2023 were: *A. trifida*, giant foxtail (*Setaria faberi* Herrm.), yellow foxtail [Setaria pumila (Poir.) Roem. & Schult.; syn. *Setaria glauca* (L.) P. Beauv.], barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.), and fall panicum (*Panicum dichotomiflorum* Michx.).

Ambrosia trifida density in 2022 was similar for all treatments at the two evaluation timings (Table 2). However, in 2023, there were 15 *A. trifida* plants m^{-2} at four WAP, whereas in plots with cereal rye there were no *A. trifida* plants. Other researchers have reported *A. trifida* densities being reduced by 56% with the use of cereal rye relative to the fallow treatment, at the time of termination (DeSimini et al. 2020). There was a significant interaction between cereal rye management strategy and herbicide treatments in 2022, at four WAP, for grasses density. Therefore, results are discussed separately by herbicide treatment. In that year, the inclusion of residual herbicides at termination and to the tank mixture applied to the fallow plots provided 95 and 50% control of grasses at four WAP, respectively, in comparison to the application of glyphosate plus glufosinate. These results were corroborated by those from Essman et al. (2023) that observed 85 to 90% lower *S. faberi* densities in plots with cereal rye and that were sprayed with a residual herbicide, relative to the densities from plots without cereal rye or residual herbicide.

The 3.5-fold increase in cereal rye biomass from 2022 to 2023 contributed to the complete control of *A. trifida* at four WAP (Table 2). At that same evaluation timing, the average giant ragweed density in fallow plots was 15 plants m^{-2}. Investigating the effect of cereal rye termination timing in weed control, Essman et al. (2023) reported reductions in *A. trifida* density going from 60 to 90% when cereal rye termination was delayed from 7 to 21 days after soybean planting, in comparison to the densities observed at preplant termination timing (7 days before planting). Other recent studies also suggest that increased amounts of cereal rye biomass (achieved with delayed termination) can result in greater suppression of *C. canadensis* (Schramski et al. 2021) and waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] (Hodgskiss et al. 2022). The use of roller crimper resulted in a grass control that was similar to the fallow treatment in both years and evaluation timings. In 2023, the standing cereal rye treatment resulted in an average of 8 grasses m^{-2}, while there were no grasses in plots with roller crimped cereal rye or fallow, at 18 WAP.

Soybean stand and yield. No cereal rye management strategy by herbicide interactions were observed for soybean stand and yield, while the main effect of cereal rye management strategy was significant. Therefore, data was pooled over herbicide treatments within each year (Table 3). No differences were observed in soybean stand in 2022 (Table 3). In 2023, when the biomass increased to 14,211 kg ha^{-1} (3.5-fold increase relative to 2022), standing cereal rye reduced soybean stands by an average of 69% in comparison to the fallow. The use of roller crimper that year increased soybean stands relative to the standing cereal rye by 58% but was still 29% lower than the soybean stands from fallow plots. Our findings are consistent with the range of 20 to 60% reductions in soybean stand reported for the use of cereal rye as cover crop (Westgate et al. 2005; Reddy 2001; Williams et al. 2000). We attribute the soybean stand reductions observed in this research mostly to poor seed slot closure that led to reduced soil-to-seed contact. Furthermore, the use of roller crimper likely increased the soil-to-seed contact resulting in greater soybean stands than standing cereal rye. During planting, the presence of large amounts of cereal rye biomass in combination with higher soil moisture (in comparison to the soil moisture from fallow plots; data not shown) resulted in hair pinning, when the front coulters were pushing the residue into the furrow, and required more down force than what the planter was capable to provide to the closing wheels. Similar issues during soybean planting were also reported in previous studies (Eckert 1988; Hovermale et al. 1979; Liebl et al. 1992; Wagner-Riddle et al. 1994; Williams et al. 2000). Currently, there is a wide range of planter adaptations that can be made and that would minimize or prevent the issues observed in our field trial. Successful soybean establishment in high levels of green cereal rye biomass is possible with the use of planters capable of providing a much greater down force to the row-cleaners, coulters, closing wheels, and gauge wheels than planters that are used to plant into conventional tilled ground (Lal et al. 2007; Triplett et al. 1963; Triplett and Dick 2008). In addition to the down force, these planters also have seed firmers to enhance soil-to-seed contact and capacity to inject insecticide in-furrow. Insect feeding was another cause of soybean stand reduction. The cover crop biomass accumulated in 2023 created the optimal environment for true armyworms [*Mythimna* (*Psuedaletia*) *unipuncta* Haworth] to start feeding on newly emerged soybean seedlings . In the last few years, Iowa State University extensionists have reported several occurrences of heavy infestations of this insect species in cover crop systems (Dean et al. 2022; Dean and Hodgson 2023).

In 2022, soybean yields from plots with standing cereal rye were similar to the fallow control (Table 3). The use of roller crimper in that year resulted in 13% lower soybean yield in comparison to the fallow treatment. Also in 2022, no significant effects of cereal management strategy or fallow treatments were observed for the *A. trifida* densities at 4 and 18 WAP. In that year, the densities of grasses were similar between treatments at 18 WAP. This result suggests that the yield reduction was not a result of competition for resources between the soybean and weeds. It does suggest that there may have been a substantial nutrient immobilization during the degradation of the roller crimped cereal rye residue, consequently reducing the availability of essential nutrients for soybean growth. Many previous studies have demonstrated that cereal rye residue decomposition can immobilize N thus reducing the pool of N available in the soil for plant uptake (Krueger et al. 2011; Nevins et al. 2020; Preza-Fontes et al. 2022; Tollenaar et al. 1993; Wells et al. 2013). Although soybean plants are able to fix N from the atmosphere, 40 to 50% of its total N demand comes from mineral sources from the soil (Salvagiotti et al. 2008). In addition to nutrient immobilization, some studies have also suggested that cereal rye residue decomposition may release allelochemicals into the soil (Burgos et al. 1999; Raimbault et al. 1990; Rice et al. 2005). To date, there are no reports of yield reductions in soybean following cereal rye cover crop due to allelopathy. However, considering that most research in this area is relatively recent and that there are few researchers studying allelopathy from cereal rye (Brooks et al. 2012; Burgos et al. 1999; Reberg-Horton et al. 2005), there could be an allelopathic compound yet to be studied that could be affecting soybean growth (Koehler-Cole et al. 2020).

In this study, we suggested that weed interference was not a contributing factor to soybean yield losses. In 2022, when the density of grasses reached an average of 31 plants m^{-2} in plots with standing cereal rye at four WAP and two plants m^{-2} at 18 WAP, soybean yields were similar to the fallow and reached an average of 5,201 kg ha^{-1}. However, in 2023, when the density of grasses varied from zero plants m^{-2} at four WAP to an average of 8 plants m^{-2} at 18 WAP in plots with standing cereal rye, soybean yield was reduced by 55%. In 2023, soybean yields from fallow plots were, on average, 61% higher than soybean yields from plots with cereal rye. These results are partially corroborated by those reported by Nord et al. (2011) that observed reduced weed biomass and soybean yield with increasing amounts of cereal rye biomass.

In 2023, soybean yields were reduced by up to 55% with the use of cereal rye (Table 3). When the roller crimper was used at cereal rye termination, yield losses were reduced to an average of 33% in comparison to the fallow. Different than 2022, when soybean stands were similar for all treatments and we suggested that the yield losses may have been due to nutrient immobilization, in 2023, lower soybean stands in plots with cereal rye were the main cause for yield reductions. Soybean yield reductions due to stand losses in cover cropping systems were also reported in previous studies (Eckert 1988; Moore et al. 1994; Reddy 2001). In 2023, the use of roller crimper resulted in a residue layer with 12 to 15 cm in thickness, imposing a significant barrier for the early development of the soybean plants that end up growing taller than plants from the fallow plots (Figure 3). However, once the plants had grown enough to surpass the residue layer, they had full access to sun light. Conversely, soybean plants growing under standing cereal rye did not have full access to sun light for several weeks after planting, which may have contributed to the slow growth and delayed maturity in 2023. Overall, in 2022, we observed that soybean plants growing in plots with cereal rye were always one growing stage behind plants growing in the fallow plots. In 2023, this difference increased to an average of three growing stages throughout the growing season (Figure 4).

In conclusion, the results of this research showed that the planting green method imposes significant challenges to the successful establishment of a soybean crop. We have demonstrated that the excessive biomass accumulation inherent from this method resulted primarily in soybean stand losses that led to substantial yield losses. In addition, roller crimped cereal rye residue consistently reduced the concentration of residual herbicides in the soil immediately after application. On average, 75 and 83% of the soil residual herbicides applied were intercepted by the roller crimped cereal rye residue in 2022 and 2023, respectively. Despite the significant interception, the application of soil residual herbicides at cereal rye termination reduced the density of grassy weed species in 2022, at four WAP, relative to termination without residual herbicides. The rainfall events following the herbicide applications likely washed some of the herbicide off of the residue onto the soil. For all other evaluation timings in 2022 and 2023, the effect of herbicide treatments was non-significant for grasses densities. Moreover, the use of residual herbicides did not reduce the density of *A. trifida* at any of the evaluation timings during the two years of the study. The utilization of proper planting equipment with the correct adjustments is critical for the successful establishment of a soybean crop in high-residue cover cropping systems and is one alternative to prevent the issues encountered in our field trials. In addition, our observations (consistent within the two years of field trials) suggest that the planting green systems may require a more comprehensive nutrient management program in order to overcome the potential nutrient immobilization. More work is needed to understand the correct cereal rye seeding rate and application timing for residual herbicides in planting green systems. Perhaps, a substantial reduction (e.g., 50%) in the seeding rate normally used for early terminated cereal rye would be adequate to prevent the accumulation of excessive amounts of biomass like we observed in 2023. Although, the options of residual herbicide for after planting are limited in soybean, the delay in the application of residual herbicide to an early POST timing may reduce the interception relative to the application onto green biomass. Lastly, recent studies have shown promising results with the adoption of the precision planting of cover crops (Kurtz et al. 2021, Sadeghpour et al. 2021), which consists on planting the cover crop only in the space between the cash crop rows, thus reducing the interference of the cover crop residue with the cash crop.

Acknowledgments

The authors would like to thank Pete Illingworth for technical assistance with field work.

Funding: This research was partially funded by Indiana Corn Marketing Council.

Competing interests: The author(s) declare none.

https://doi.org/10.1017/wsc.2025.10059 Published online by Cambridge University Press

Table 1. Chemical and physical properties of the soil from experiments conducted in 2022 and 2023, at 0 to 10 cm depth.

Year[1]	pH	OM	CEC	Sand	Silt	Clay	Bulk density	Classification
		%	meq 100 g^{-1}	——— % ———			g cm^{-3}	
2022	6.5	4.2[2]	13.9	21	52	27	1.25	Toronto-Millbrook silty clay loam
2023	6.0	2.9	11.4	20	55	25	1.21	

Abbreviations: OM, organic matter; CEC, cation exchange capacity

[1] Trials were conducted in adjacent fields between 2022 and 2023.

[2] Difference in OM content is due to management practices adopted prior to cereal rye planting in the fall of 2021 and 2022.

https://doi.org/10.1017/wsc.2025.10059 Published online by Cambridge University Press

Table 2. Giant ragweed and grasses density in each cereal rye management strategy at 4 and 18 weeks after soybean planting.

WAP	Cereal rye management	2022 Giant ragweed	2022 Grasses	2023 Giant ragweed	2023 Grasses
		— Plants m^{-2} —		— Plants m^{-2} —	
4 WAP[1]	Standing	13	31[3]	0 b[4]	0
	Roller crimped	15	5	0 b	0
	Fallow	14	22	15 a	0
18 WAP[2]	Standing	1	2	0 b	8 a
	Roller crimped	1	2	1 ab	1 b
	Fallow	1	0	1 a	0 b

Abbreviations: WAP, weeks after planting; NR, no residual herbicide; WR, with residual herbicides.

[1] Giant ragweed and grasses density data at 4 WAP were log transformed. However, original mean values are presented.

[2] Giant ragweed and grasses density data at 18 WAP were square root transformed. However, original mean values are presented.

[4] Data is presented as pooled over herbicide treatments. However, there was a significant interaction between cover crop and herbicide treatments for grasses density in 2022, at 4 WAP. The interactions are discussed in the text.

[3] Numbers followed by the same letter or no letters within year, WAP, and weed species are not significantly different according to Fisher's protected LSD ($P \leq 0.05$).

Table 3. Soybean final stand and yield from each cereal rye management strategy from experiments conducted in 2022 and 2023

Year	Cereal rye management	Final stand		Yield	
		Plants ha^{-1}		kg ha^{-1}	
2022	Standing	349,409	a[1]	5,201	ab
	Roller crimped	278,871	a	4,822	b
	Fallow	306,758	a	5,552	a
2023	Standing	76,280	c	2,905	c
	Roller crimped	212,434	b	4,288	b
	Fallow	281,332	a	6,395	a

[1] Numbers followed by the same letter within year are not significantly different according to Fisher's protected LSD ($P \leq 0.05$).

https://doi.org/10.1017/wsc.2025.10059 Published online by Cambridge University Press

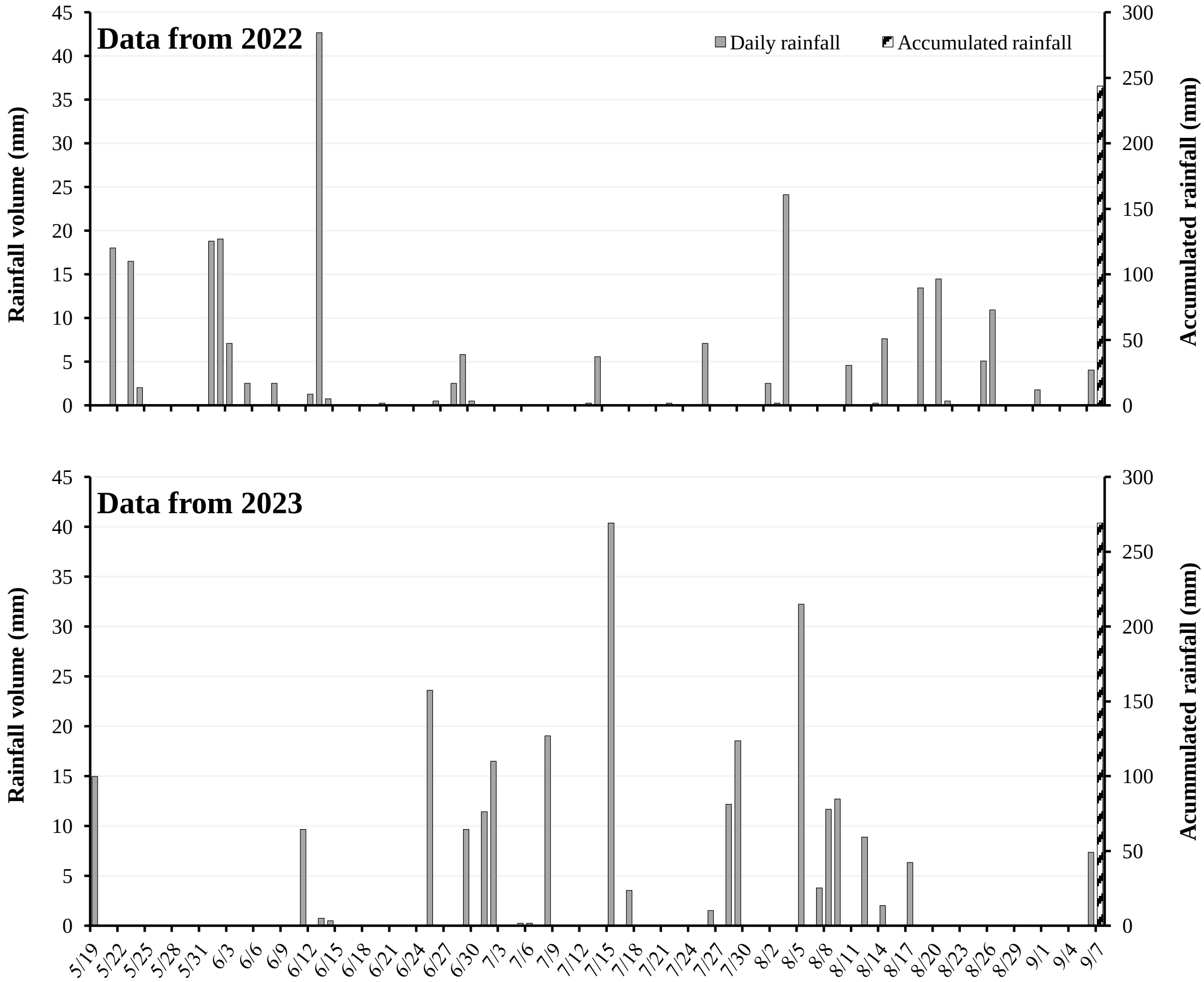

Figure 1. Daily precipitation during the 2022 and 2023 growing seasons. Herbicide treatments were applied on 05/23/2022 and 05/19/2023. Data was collected from a weather station placed in the trial area.

https://doi.org/10.1017/wsc.2025.10059 Published online by Cambridge University Press

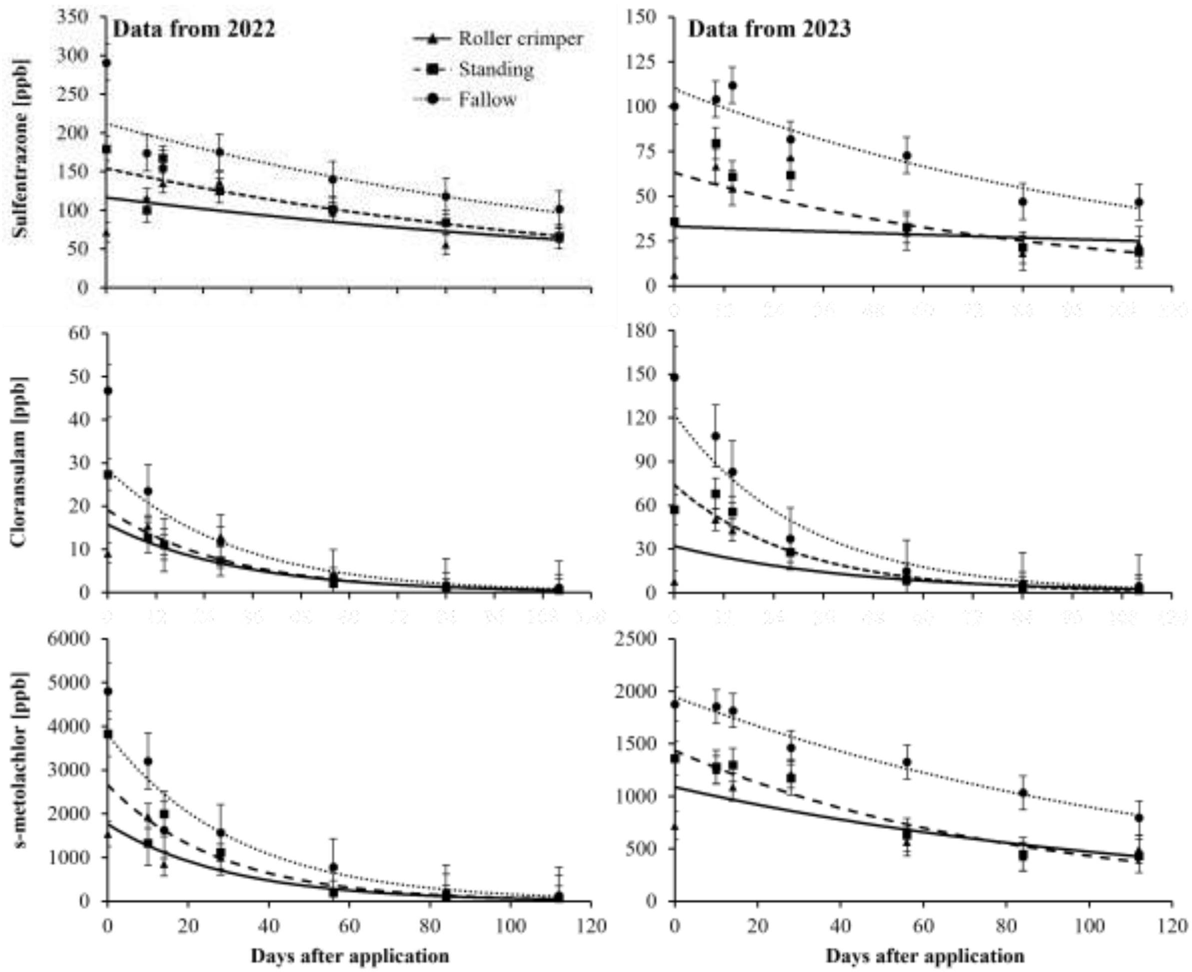

Figure 2. Dissipation of sulfentrazone, cloransulam, and s-metolachlor from 0 to 112 days after herbicide application and under three cereal rye management strategies, in 2022 and 2023. Data points represent mean ± standard error of four replications. Lines represent the first-order regression equations for each cereal rye management strategy. Parameter estimates for each regression line are detailed in table 4.

https://doi.org/10.1017/wsc.2025.10059 Published online by Cambridge University Press

Table 4. Parameter estimates for sulfentrazone, cloransulam, and s-metolachlor from each cereal rye management strategy in 2022 and 2023.

Year	Herbicide	Cereal rye management	Kinetic equation[1]	R^2
2022	sulfentrazone	roller crimper	$y = 116.42\, e^{-0.006x}$	0.34
		standing	$y = 154.16\, e^{-0.007x}$	0.70
		fallow	$y = 212.25\, e^{-0.007x}$	0.66
	cloransulam	roller crimper	$y = 15.76\, e^{-0.030x}$	0.60
		standing	$y = 19.10\, e^{-0.033x}$	0.92
		fallow	$y = 28.48\, e^{-0.032x}$	0.84
	s-metolachlor	roller crimper	$y = 1764.3\, e^{-0.033x}$	0.80
		standing	$y = 2661.7\, e^{-0.036x}$	0.89
		fallow	$y = 3821.9\, e^{-0.032x}$	0.91
2023	sulfentrazone	roller crimper	$y = 33.19\, e^{-0.003x}$	0.14
		standing	$y = 63.20\, e^{-0.011x}$	0.51
		fallow	$y = 109.76\, e^{-0.008x}$	0.90
	cloransulam	roller crimper	$y = 32.12\, e^{-0.023x}$	0.33
		standing	$y = 74.12\, e^{-0.034x}$	0.87
		fallow	$y = 122.41\, e^{-0.032x}$	0.97
	s-metolachlor	roller crimper	$y = 1087.70\, e^{-0.008x}$	0.51
		standing	$y = 1434.80\, e^{-0.012x}$	0.95
		fallow	$y = 1948.20\, e^{-0.008x}$	0.97

[1] First-order regression equation: non-linear regression of herbicide concentration over time (0 to 112 days after application).

https://doi.org/10.1017/wsc.2025.10059 Published online by Cambridge University Press

Figure 3. Physical barrier created by roller crimped cereal rye residue in 2023. Soybean plants showing spindly growth.

https://doi.org/10.1017/wsc.2025.10059 Published online by Cambridge University Press

Figure 4. Difference in soybean growth between fallow (left) and roller crimped cereal rye treatments (right). Pictures taken eight weeks after soybean planting, in 2023.

https://doi.org/10.1017/wsc.2025.10059 Published online by Cambridge University Press

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