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The effects of cereal rye cover crop seeding rate, termination timing, and herbicide inputs on weed control and soybean yield

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Research Article

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Abstract

Growers have been experimenting with cover crop termination timings to maximize weed suppression and potentially reduce herbicide inputs in soybean [*Glycine max* (L.) Merr.]. A field study was replicated three times from 2018 through 2021 in South Charleston, OH, to evaluate different management strategies involving a cereal rye (*Secale cereale* L.) cover crop. The objectives were to determine the effects of cereal rye seeding rate (0, 50, and 100 kg ha^{-1}), management program (preplant, postplant, and delayed), and soybean residual herbicide (flumioxazin + chlorimuron ethyl and no herbicide) on cover crop, weed, and soybean parameters. The preplant program consisted of cereal rye terminated 7 d before planting (DBP) + a postemergence application. The postplant program consisted of cereal rye terminated 7 d after planting (DAP) + a postemergence application. In the delayed program, saflufenacil was applied in April and cereal rye was terminated 21 DAP, and there was no postemergence application. Giant foxtail (*Setaria faberi* Herrm.) density was reduced by the presence of cereal rye, averaged over other factors, regardless of seeding rate. Cereal rye seeding rate did not affect giant ragweed (*Ambrosia trifida* L.) density. The delayed management program was generally associated with the lowest weed density, but weed density was often similar in the postplant program. *Setaria faberi* density was lower in treatments that included a residual herbicide. Residual soybean herbicide use did not affect density of *A. trifida*. Terminating cereal rye after soybean planting resulted in increased soybean yield in 2019 and reduced yield in 2020, compared with preplant rye termination. These data suggest that adjusting the cereal rye management program may have a greater effect on weed suppression than adjustments to seeding rate. Delaying termination of cereal rye can aid in the suppression of weeds, but a comprehensive herbicide program was necessary to provide adequate (>85%) weed control.

Introduction

Since the introduction of herbicide-resistant (HR) soybean [*Glycine max* (L.) Merr.] varieties, the primary management tool for troublesome weed species has been trait programs that allow for in-season applications of highly effective herbicides that were once limited to burndown or preemergence applications. Adoption of HR soybean varieties was rapid due to limited weed control options for postemergence applications (USDA-ERS 2020). The introduction and use of these varieties led to greatly simplified weed control programs, economic savings, and yield increases for soybean production (Duke 2015). The use of genetically engineered HR crops and a lack of diversity in herbicide programs annually increased selection pressure on weed populations, which led to an increase in resistance issues among weed species (Norsworthy et al. 2012; Vencill et al. 2012).

Herbicide resistance in weeds has been an increasing area of concern for producers (Ervin et al. 2019). Since 1981, there have been 19 reports of herbicide resistance in 12 weed species in Ohio. Giant foxtail (*Setaria faberi* Herrm.) has exhibited resistance to WSSA Group 1, 2, and 5 herbicides in several states in the Midwest, and giant ragweed (*Ambrosia trifida* L.) has reported single and multiple resistance to WSSA Groups 2 and 9 in Ohio (Heap 2023). *Setaria faberi* interference can cause as much as 82% to 93% yield loss in soybean, with losses of approximately 0.8% of soybean yield per foxtail plant in a 9-m row (Conley et al. 2003; Harrison et al. 1985). Fewer than two *A. trifida* plants within 9 m of row can reduce soybean yields by up to 50%, and densities of 360,000 plants ha^{-1} can result in nearly total crop loss (Baysinger and Sims 1991).

HR weeds threaten the longevity of herbicide-based weed control tactics. Data show that in recent years, herbicides have been applied in greater quantities, less crop has been produced per herbicide input, and costs of dealing with HR weeds have been increasing (Davis and Frisvold

2017). As a result, growers are increasingly interested in implementing integrated pest management strategies to provide additional weed suppression. Cover crops have been suggested as a potential tool to facilitate a reduction in herbicide inputs and reduce selection pressure, and therefore proactively manage the development of herbicide resistance (Bunchek et al. 2020). The weed suppressive benefits of fall-planted cover crops have been well documented (Clark 2012; Dabney et al. 2001; Osipitan et al. 2018, 2019; SARE 2020; Teasdale 1996, 1998; Teasdale et al. 2007). Weed suppression is consistently reported as one of the top reasons growers adopted cover cropping as a practice, second only to improving soil structure and health in a national cover crop survey (SARE 2020). In 2017, 6.2 million ha of cover crops were reported in the United States, a 50% increase from 2012, when 4.2 million ha were planted (USDA-ERS 2021). There are several mechanisms by which cover crops suppress weeds, including altering quantity and quality of light, influencing temperature and moisture of the soil near the seed surface, niche disruption, and the formation of a physical barrier that can hinder weed growth (Creamer et al. 1996; Dabney et al. 2001; Teasdale 1998; Teasdale and Mohler 2000).

Biomass production and ground cover are the two main drivers of weed suppression by cover crops (Hodgskiss et al. 2021; Mohler and Teasdale 1993; Teasdale and Mohler 2000; Wallace et al. 2019). Grass cover crops in general are effective at reducing the biomass of weeds (Nichols et al. 2020). Cereals such as cereal rye (*Secale cereale* L.), henceforth referred to as "rye," can be planted later in the fall than other species, following corn (*Zea mays* L.) or soybean harvest, relative to more frost-sensitive species (Clark 2012). The minimum temperature required for germination and growth of rye (3 C) makes it well adapted for late planting in the Midwest following harvest (Clark 2012). For these reasons, rye is the most highly utilized species nationwide, and especially in the eastern Corn Belt, followed by radish (*Raphanus sativus* L.) and oats (*Avena sativa* L.) (SARE 2020). Previously, it was recommended that a rye cover crop be terminated 1 to 2 wk before planting the soybean crop, especially for growers new to cover cropping (Kaspar and Licht 2019). Interest in the practice of terminating a cover crop after planting the cash crop, also known as "planting green," has increased in recent years (Reed et al. 2019). Planting into living vegetation can be more efficient than planting into dead residue (Kaspar and Licht 2019; SARE 2020). In the eastern Corn Belt, spring weather is increasingly unpredictable. Trends show an increase in heavy rainfall events and climate extremes that are projected to increase in the next 30 to 80 yr (Wilson et al. 2022). Ohio growers have been increasingly interested in planting green to ease the burden of spring preplant fieldwork, given the variability in weather patterns, and to maximize weed suppression by the cover crop.

Termination timing is one of the most important management factors that affects the weed suppressive potential of a cover crop and generally has a greater influence on cover crop biomass production than planting date for grass cover crops and species mixes that include grasses (Lawson et al. 2015; Mirsky et al. 2013; Nord et al. 2012). Delaying termination can increase biomass production and improve weed suppression (Mirsky et al. 2011; Osipitan et al. 2019; Rosario-Lebron et al. 2019; Wallace et al. 2017), but the effect on weed control is not consistent (Mischler et al. 2010; Nord et al. 2012). Delaying termination can increase the interval of time in which weeds remain at a manageable height and potentially lengthen the window of control (Montgomery et al. 2018). Cash crop yield can be compromised by late termination if the cover crop competes with the cash crop, if stand establishment is influenced, or if seed production results in the cover crop becoming a weedy concern (Wallace et al. 2017). This research evaluates an integrated approach to weed management, specifically the use of varying herbicide inputs with planting green. The objectives of this study were to determine the effects of rye seeding rate, rye termination timings, and herbicide inputs on cover crop biomass, weed density, and soybean density and yield. The hypothesis was that a high seeding rate of rye combined with delayed rye termination could supplement or replace weed suppression typically provided by spring-applied residual herbicides or a second postemergence application.

Materials and Methods

A field study was conducted during three growing seasons from 2018 through 2021 at the Ohio Agricultural Research and Development Center (OARDC) Western Agricultural Research Station in South Charleston, OH (39.861642°N, 83.667583°W). The fields used for each year of the study were previously in corn production, and naturally occurring weed populations within trial sites were used to evaluate treatment effects. Trials were conducted on new areas each year. The soil type was a Crosby loam (fine, mixed, active, mesic Aeric Epiaqualfs; 2.4% organic matter) in 2018 to 2019 and a Kokomo silty clay loam in 2019 to 2020 and 2020 to 2021 (fine, mixed, superactive, mesic Typic Argiaquolls; 3.1% and 2.2% organic matter, respectively). Treatments were arranged in a randomized complete block design with a split-plot randomization restriction with four replications. Rye seeding rate was the main plot factor, and rye management program and residual herbicide were independently randomized subplot factors. Individual experimental units were 3-m wide by 9-m deep.

Rye seeding rates were 0, 50, and 100 kg of seed ha^{-1}. The 100 kg ha^{-1} rate represents a typical recommendation for forage production of rye and is on the higher end of what Ohio growers use for a cover crop (Sulc et al. 2017). The 50 kg ha^{-1} rate is a representative rate of what many growers in Ohio use as a seeding rate for rye as a cover crop, typically in the range of 39 to 56 kg ha^{-1} (MCCC 2019), and the 0 kg ha^{-1} served as a control. Rye (2018 and 2019: variety not stated, Cisco Company, Indianapolis, IN; 2020: 'Hazlet', Heartland Seed, West Jefferson, OH) was planted with an end wheel no-till drill (Great Plains 10 NT; Salina, KS) shortly after corn harvest at a depth of 2.6 cm and row spacing of 19 cm. Planting dates were mid-October through early November, typical for cover crop planting following corn harvest in Ohio (Table 1).

The management programs consisted of three termination timings with varying herbicide inputs (Table 2). In the first management program, "preplant," rye was terminated approximately 7 d before soybean planting (DBP) and postemergence herbicides were applied in late June. In the second management program, "postplant," rye was terminated approximately 7 d after soybean planting (DAP), followed by a postemergence application in late June. In the third management program, "delayed termination," rye was terminated 21 DAP. The delayed management program was modeled after a method used by growers in the surrounding region in which saflufenacil is applied in early April and the rye termination herbicide application serves as the only postemergence application during the growing season (Table 2). For each of the management programs, treatments with no rye still received the same herbicide applications at the designated treatment time. Saflufenacil (0.025 kg ai ha^{-1}; Sharpen®, BASF, Ludwigshafen, Germany) was applied in the delayed management programs in early April.

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Table 1. Dates of field activities and treatments in planting green study, evaluating the effects of rye seeding rate, management program and herbicide inputs on weed suppression in no-till soybean at South Charleston, OH, from 2018 to 2021.

Field activity	2018–2019	2019–2020	2020–2021
Rye cover crop planted	October 10	October 11	November 4
Delayed program saflufenacil application	April 2	April 2	April 6
Preplant program rye biomass collection	April 23	May 1	April 26
Preplant program rye termination	April 23	May 1	April 27
Early-season weed density counts	April 23	May 1	April 26
Spring residual application	April 23	May 1	April 27
Soybeans planted	May 16	May 7	May 14
Postplant program rye biomass collection	May 22	May 13	May 21
Postplant program rye termination	May 22	May 13	May 21
Visual estimation of weed control	May 20	May 13	May 18
Midseason weed density counts	June 6	May 27	June 4
Delayed program biomass collection	June 6	May 27	June 4
Delayed program rye termination	June 6	May 27	June 6
Soybean population density	June 6	May 27	June 11
Late-season weed density counts	June 24	June 24	June 24
Postemergence application in preplant and postplant programs	June 27	June 29	June 24
Visual estimation of weed control	—	July 29	July 21
Soybean harvest	October 4	October 8	October 1

The two levels of spring-applied residual herbicide were flumioxazin (0.09 kg ai ha^{-1}; Valor®, Valent, San Ramon, CA) + chlorimuron-ethyl (0.03 kg ai ha^{-1}; Classic®, Corteva Agriscience, Indianapolis, IN) and no herbicide. Rye was terminated with glyphosate at the various termination timings, and the residual herbicide was applied at the time of the preplant termination applications (Tables 1 and 2). A soybean variety resistant to dicamba and glyphosate (33A24X RR2X, Pioneer®, DuPont, Wilmington, DE) was planted in May of 2019 and 2020. Dicamba (XtendiMax®, Bayer Crop Science, Leverkusen, Germany) was applied with glyphosate (Roundup PowerMAX®, Bayer Crop Science) in the termination applications. Soybean resistant to 2,4-D (SC7320E, Seed Consultants, Washington Court House, OH) was planted in the 2020 to 2021 trial year, and 2,4-D was applied with the glyphosate for rye termination (Table 1). The seeding rate for soybean was 358,000, 432,000, and 383,000 seeds ha^{-1}, in 2019, 2020, and 2021, respectively, and seeds were planted in 38-cm row spacing at a depth of 3.8 cm. A postemergence application of glyphosate + dicamba was made in the preplant and postplant rye management programs in late June in 2019 and 2020 (Table 1). In 2021, 2,4-D (Enlist One®, Corteva Agriscience) was used in the postemergence treatments instead of dicamba. Herbicides and rates used each year are reported in Table 2. Herbicide treatments were applied in an application volume of 140 L ha^{-1} using AIXR nozzles (AIXR, 11002, TeeJet® Technologies, Springfield, IL) in early April applications, and TTI nozzles (TTI 110015, TeeJet® Technologies) in the rye termination and postemergence applications.

Measurements included aboveground rye biomass, weed and soybean density, visual evaluations of weed control, and soybean seed yield. Biomass at the time of termination was determined by clipping rye at the soil surface from a 0.25-m^2 quadrat placed in the middle of the plot, after which samples were dried at 55 C for 3 to 5 d and weighed. Weed density was measured early, mid- and late season at the time of the preplant rye termination, the delayed rye termination, and the postemergence application, respectively (Table 1). Two 0.25-m^2 quadrats were placed approximately 2 m from the front and back of each plot, and the total number of weeds within the quadrat were counted by species. Weed control was visually estimated throughout plots using a scale of 0 to 100, where 0 and 100 represented no control and complete control, respectively. Control was assessed approximately 1 mo after the postemergence herbicide application (except in 2019). Soybean density was measured at 21 to 28 DAP by counting number of plants per 2.6 m of row in each plot, which was converted to number of plants per hectare. Soybean seeds were mechanically harvested with a Massey Ferguson plot combine (Kinkaid Equipment Manufacturing, Haven, KS) in early October, and data presented were adjusted to a moisture content of 13%.

Statistics

Data were analyzed separately for each year as a three by three by two factorial in a split-plot randomized complete block using PROC GLIMMIX in SAS v. 9.4 (SAS Institute, Cary, NC). Fixed factors were rye seeding rate, rye management program, residual herbicide, and their respective interactions. Random factors were replication and rye seeding rate by replication. Normality and variance were evaluated for each model by a visual assessment of the residual plots. To improve normality of the data and improve the fit of the model, transformations were performed when needed using a square-root transformation. The global *F*-test was used to evaluate significance, and treatment means were separated using Fisher's protected LSD with an alpha value of 0.05. The back-transformed means are presented herein, and back-transformed data are presented without LSD values.

Results and Discussion

Seasonal Weed Pressure and Weather

In each year, naturally occurring populations of *A. trifida* and *S. faberi* were the predominant weeds throughout the study sites. Other weeds present included horseweed [*Conyza canadensis* (L.) Cronquist], lambsquarters (*Chenopodium album* L.), barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], redroot pigweed (*Amaranthus retroflexus* L.), and ivyleaf morningglory (*Ipomoea hederacea* Jacq.). These species were not consistent enough throughout the study sites or years to be included in analysis. *Setaria faberi* emergence occurred later than *A. trifida* emergence and was not included in the early ratings in any year or in the midseason rating in 2020. There was a greater natural density of *A. trifida* in 2020 and 2021 than in 2019, which may have been caused by the greater level of precipitation in spring of 2019. The population of *A. trifida* that was present late season in 2019 was smaller, which could have been a result of increased precipitation negatively affecting germination and growth. As such, visual evaluations of weed control were not conducted in late July in 2019 as was done in 2020 and 2021.

Weather patterns varied greatly among years, which led to differences in dates of field operations and weed emergence patterns (Table 3). In the 2019 growing season, high levels of spring precipitation resulted in later planting dates than what is typical for Ohio soybean production. The differences in field operation dates

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Table 2. Treatment structure for the three rye management programs consisting of various termination timings and herbicide inputs.

Field operation	Preplant	Postplant	Delayed
	——— kg ai or ae ha^{-1} ———		
April saflufenacil application	None	None	Saflufenacil 0.025
Rye termination[a]	7 DBP	7 DAP	21 DAP
2019 and 2020	1.26 glyphosate + 0.69 dicamba	1.26 glyphosate + 0.69 dicamba	1.26 glyphosate + 0.69 dicamba
2021	1.26 glyphosate + 0.65 2,4-D	1.26 glyphosate + 0.65 2,4-D	1.26 glyphosate + 0.65 2,4-D
Late June postemergence application			
2019 and 2020	1.26 glyphosate + 0.69 dicamba	1.26 glyphosate + 0.69 dicamba	None
2021	1.26 glyphosate + 0.65 2,4-D	1.26 glyphosate + 0.65 2,4-D	None

[a]DBP, days before soybean planting; DAP, days after soybean planting.

due to inclement weather likely influenced cover crop and soybean responses and weed emergence patterns. Rye in the preplant program plots was terminated April 23, 2019, with the intention of planting soybean approximately 1wk after, but soybean planting did not occur until more than 3 wk later (Table 1). The first termination of rye occurred 23, 6, and 17 DBP in 2019, 2020, and 2021, respectively, because of precipitation patterns. The second and third rye termination applications were closer to the desired timings of 7 and 21 DAP each year. This discrepancy in desired versus actual timing of rye termination illustrates the reality of managing cropping systems as spring weather conditions become increasingly unpredictable, and especially in more intensive programs that include cover crops. As such, results have been presented by year to most accurately illustrate the influence of environmental differences and the resulting effect on management.

Cover Crop Parameters

The biomass of rye was affected by management program and residual herbicides all 3 yr, with an interaction between management program and residual herbicide in 2019 and 2021 (Table 4). Rye biomass was not affected by seeding rate except in 2019, when it was 910 kg ha^{-1} greater at the 100 versus 50 kg ha^{-1} seeding rate, averaged over other factors (data not shown). This finding is consistent with other studies that found marginal effects of rye seeding rate on biomass or weed suppression beyond a certain threshold. For example, Bish et al. (2021) found little difference in cereal rye biomass or waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] suppression between rye seeding rates of 56 and 123 kg ha^{-1}. The management program by residual herbicide interaction reflected more biomass in the absence of residual herbicide in the postplant and delayed programs in 2019 and 2021 (Table 5). Residual herbicide, which was applied at the time of the preplant termination application, reduced rye biomass at the two later termination timings by 34% and 38% in 2019 and 2021, respectively (data not shown). Flumioxazin as a preemergent herbicide has been shown to reduce the biomass of rye (Cornelius and Bradley 2017), and both flumioxazin and chlorimuron-ethyl can influence plant growth when applied to foliage. Differences in biomass were likely influenced by differences in the length of time between termination applications, as previously discussed, with the postplant rye termination taking place 12 d after the preplant termination in 2020, and nearly a month after the preplant termination in 2019 and 2021.

Effects of Rye Seeding Rate, Rye Management Program, and Herbicide Inputs on Weed Density

Rye seeding rate did not affect the density of *A. trifida*, and the density of *S. faberi* was generally less in treatments with rye compared with the absence of rye. *Setaria faberi* at the time of the early-season measurements had not emerged and could not be evaluated. At the midseason rating, treatments that included rye had 90 to 130 m^{-2} fewer *S. faberi* plants in 2019, compared with treatments with no rye (data not shown). The 50 kg ha^{-1} rate was similar to the 0 kg ha^{-1} and 100 kg ha^{-1} rates midseason in 2021. This effect was also seen in the 2020 late-season evaluations, in which treatments with rye had 35 to 39 m^{-2} fewer *S. faberi* plants than treatments without rye (data not shown).

Rye management program had the most consistent effect on the density and control of *A. trifida* and *S. faberi*. The delayed management program generally decreased the density of weeds but was not always different from postplant management treatments. The postplant and delayed programs had 60% and 90% lower *A. trifida* densities, respectively, than the preplant program at the early-season evaluation in 2020 (Table 6). In 2021, the density of *A. trifida* was 88% less in the delayed management program relative to the preplant or postplant programs. The density of *A. trifida* at the midseason rating in 2019 was less in the postplant program than in the preplant program, and neither was different from the delayed program (Table 6). Midseason in 2020 and 2021, the density of *A. trifida* was greater in the preplant management program than in the postplant or delayed programs. Late-season, *A. trifida* density was greatest in the preplant program, except for 2020, when it was similar to density in the postplant program (Table 6). At the time of the delayed termination in 2020, there was a seeding rate by management program interaction on the density of *A. trifida*. The lowest densities occurred where rye was present in the delayed and post programs and at the high seeding rate in the preplant program relative to other combinations of seeding rate and management program (data not shown).

The postplant program had 110 to 130 m^{-2} fewer *S. faberi* plants at the midseason rating relative to the preplant and delayed programs in 2019, respectively. The postplant and delayed programs had 98% and 97% fewer *S. faberi* plants than the preplant program in 2021, respectively. In 2019 and 2020, the densities of *A. trifida* and *S. faberi* were generally lower in the delayed program but were not always different from densities in the postplant program (Table 6). In 2021, there was an interaction between rye seeding rate and residual herbicide use on the midseason rating for *S. faberi*. Treatments with rye that included a residual herbicide had 85% to 90% lower *S. faberi* densities than treatments with an absence of rye or lack of a residual herbicide (data not shown). The reduction in weed density from the various management programs was likely the combined effect of increased rye biomass at later termination timings and the herbicide applied at termination, which resulted in control of weeds present at that time. Findings were consistent with other recent studies conducted in the Midwest on the effect of termination timing on weed populations. Schramski et al. (2020) found that in Michigan, delaying rye and wheat (*Triticum aestivum* L.) termination until

Table 3. Weather conditions at the Western Agricultural Research Station in South Charleston, OH, during the trial period from 2018 to 2021.[a]

	Precipitation					Average air temperature					Average soil temperature (5-cm depth)					GDD[b]				
	2018	2019	2020	2021	30 yr avg.	2018	2019	2020	2021	30-yr avg.	2018	2019	2020	2021	30-yr avg.	2018	2019	2020	2021	30-yr avg.
	mm					C					C									
Jan	39	50	55	4	58	−4.3	−3.4	1.8	−0.5	−2.3	2.2	2.4	3.6	1.6	1.7	2	0	8	0	5
Feb	124	122	0	19	49	2.7	0.2	4.9	−3.8	−0.9	4.5	1.9	3.9	1.2	2	27	0	11.2	0.8	5
Mar	87	94	83	46	78	2.1	2.4	7.9	7.3	4.5	5.2	4.6	8.8	7.6	5.5	2	11.7	43	57	38
Apr	120	92	108	60	96	7.2	11.6	9.4	11.1	11	9.3	11.3	11.3	12.2	11.7	60	140	79	150	142
May	71	136	116	71	99	21	17.6	15.2	15.7	17.1	19	18.1	16.7	17.2	18	614	427	324	340	399
Jun	115	128	34	78	100	22.4	20.9	22.3	22.6	21.7	22.8	21.7	22.8	22.7	23.4	667	588	663	678	633
Jul	94	65	69	141	114	22.8	24.3	24.9	22.9	23.1	24.3	25.7	25.6	25.2	25.5	711	798	830	719	727
Aug	93	29	70	87	67	22.7	22.1	22	23.4	22.2	23.9	23.6	23.9	25.1	24.9	685	671	665	748	674
Sep	157	27	44	69	75	20.7	21.6	18.2	19.5	18.4	21.7	22.2	20.6	20.9	20.9	577	626	440	511	454
Oct	36	60	98	66	70	12.8	13.8	11.7	15.7	12.2	14.7	15.2	13.1	17	14.2	226	210	150	328	177
Nov	143	30	44	16	65	2.3	2.6	7.9	4.6	5.3	6.4	5.9	8.4	7.3	7.3	4.4	0	62	15.3	33
Dec	109	47	21	42	71	1.4	2.4	0.9	4.8	0.4	3.6	4	3.2	5.7	3.2	2.4	5.7	0.7	11.2	6

[a]Weather data from 1991 to 2021 at the OARDC Western Agricultural Research Station in South Charleston, OH.
[b]GDD, growing degree days, base 10 C.

1 wk after soybean planting increased cover crop biomass 200% relative to termination 1 wk before planting and improved consistency of *C. canadensis* suppression. Hodgskiss et al. (2021) found that in Indiana, terminating rye or rye and crimson clover (*Trifolium incarnatum* L.) at or after soybean planting led to a 40% increase in biomass and increased suppression of *A. tuberculatus* and *C. canadensis*. Thus, cover crops could be considered one of the many hammers in an integrated approach to weed management.

Control of *A. trifida* and *S. faberi* was less in the delayed program, in which no second postemergence herbicide was applied in July 2020 and 2021 (Table 7). These results indicate that delayed rye termination can reduce the density of weeds present at the time of herbicide applications. A second application of a postemergence herbicide, in addition to the termination treatment, was still necessary for acceptable control of *A. trifida* and *S. faberi* throughout the season. Delaying termination until 21 DAP can reduce weed pressure relative to 7 DAP in some instances. However, due to the lengthy germination patterns and competitive nature of these weed species, the reduction in density was not sufficient to replace chemical control methods. Postemergence herbicide applications in late June were still necessary to ensure adequate late-season weed control, regardless of rye management program or biomass production.

The use of a residual herbicide had no effect on the density of *A. trifida* in 2019 or 2020 but reduced *A. trifida* density by 83% in May 2021 (data not shown). The density of *S. faberi* at mid- and late-season evaluations was lower in treatments that included a residual herbicide (Table 8). These results suggest that the reduction in weed density provided by a rye cover crop was not sufficient to replace the early-season control provided by a spring residual herbicide, even at later rye termination timings. Other studies have also illustrated that late termination of rye was not sufficient to replace preemergence residual herbicides in terms of weed suppression and that multiple tactics are necessary as part of an integrated approach (Dearden 2022).

Soybean Density and Yield

There was no treatment effect on soybean density in 2019. In 2020, there was a seeding rate by rye management program interaction. Where rye was present, soybean densities were generally higher with later rye termination at either rye seeding rate (data not shown). In 2021, soybean densities were lower where rye was present at either seeding rate relative to treatments without rye (data not shown). There was extensive soybean predation by voles (*Microtus* spp.) in 2021 in the experimental units with high levels of rye residue. While not significant ($P = 0.14$), soybean densities decreased with each delay in termination timing. The reduction of soybean plants in these plots likely influenced late-season weed pressure and yield data are not presented for 2021.

In 2019, soybean yield was influenced by the main effects of rye seeding rate, rye management program, and residual herbicide, and the interaction between management program and residual herbicide. Yield was greater where rye was present relative to treatments with no rye and in treatments where rye was terminated at either date after soybean planting (Table 9). Yield was lowest in the treatments managed with the preplant program that did not include a residual herbicide relative to other combinations of management program and residual levels (data not shown). All treatments in 2019 yielded above the state average for the year, except the treatment in which there was no rye in the preplant program with no residual (data not shown; Turner and

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Table 4. Results of ANOVA (significance of *F*-values) for fixed effects on spring rye cover crop biomass and weed density at the early-, mid-, and late-season evaluations.[a]

		– *Ambrosia trifida* –			– *Setaria faberi* –	
Effects	Rye biomass	Early	Mid	Late	Mid	Late
			2019			
Seeding rate (SR)	**0.01**	0.08	0.59	0.94	**0.01**	0.46
Management program (MP)	**<0.0001**	0.79	0.02	**<0.0001**	**0.02**	**<0.0001**
SR × MP	0.39	0.69	0.35	0.98	0.44	0.31
Residual herbicide (RH)	**<0.0001**	0.49	0.90	0.41	**0.003**	**0.001**
SR × RH	0.45	0.23	0.92	0.69	0.91	0.94
MP × RH	**0.0001**	0.31	0.99	0.67	0.08	0.69
SR × MP × RH	0.51	0.47	0.86	0.19	0.73	0.60
			2020			
SR	0.09	0.28	0.87	0.58	—	**0.01**
MP	**0.0004**	**0.002**	**0.0009**	**<0.0001**	—	**0.01**
SR × MP	0.31	**0.01**	**0.02**	**0.001**	—	0.99
RH	0.63	0.37	0.06	0.95	—	**0.04**
SR × RH	0.39	0.34	0.60	0.85	—	0.32
MP × RH	0.14	0.83	0.50	0.15	—	0.18
SR × MP × RH	0.83	0.86	0.34	0.46	—	0.98
2021						
SR	0.42	0.16	0.08	0.37	0.04	0.58
MP	**<0.0001**	**0.04**	**0.0007**	**0.0008**	**<0.0001**	0.26
SR × MP	0.70	0.91	**0.009**	0.29	0.98	0.37
RH	**0.0001**	0.10	0.73	0.41	0.09	**0.008**
SR × RH	0.63	0.39	0.22	0.38	**0.03**	0.35
MP × RH	**0.01**	0.63	0.99	0.62	0.61	0.56
SR × MP × RH	0.18	0.14	0.77	0.72	0.56	0.34
SR × MP × RH	0.83	0.86	0.34	0.46	—	0.98

[a]Bold values are significant at α = 0.05.

Table 5. Effect of the management program and residual herbicide interaction on rye biomass, averaged over rye seeding rate.[a]

Management program	Residual herbicide[b]	2019	2020	2021
		——— kg ha^{-1} ———		
Preplant	Flumioxazin + chlorimuron-ethyl	1,360 d	4,100	1,150 d
	Nontreated	1,470 d	5,000	1,560 d
Postplant	Flumioxazin + chlorimuron-ethyl	2,410 c	5,400	4,540 c
	Nontreated	3,330 b	4,600	6,430 b
Delayed	Flumioxazin + chlorimuron-ethyl	3,170 b	6,200	4,650 c
	Nontreated	5,750 a	6,600	8,690 a
LSD		735	NS	1,643

[a]Means within a column followed by a different letter are significantly different at α ≤ 0.05.
[b]Flumioxazin was applied at 0.09 kg ai ha^{-1} and chlorimuron-ethyl at 0.03 kg ai ha^{-1}.

Table 6. Effect of management program on weed density, averaged over rye seeding rate and residual herbicide use.[a]

	Evaluation timing[b]				
	— *Ambrosia trifida* m^{-2} —			*Setaria faberi* m^{-2}	
Management program	Early	Mid	Late	Mid	Late
			2019		
Preplant	0.05	0.6 a	0.9 a	170 a	63 a
Postplant	0.1	0.01 b	0.04 b	60 b	46 a
Delayed	0.05	0.3 ab	0 b	190 a	9 b
			2020		
Preplant	2 a	6 a	14 a	—	32 a
Postplant	0.8 b	3 b	11 a	—	6 b
Delayed	0.2 b	1 b	2 b	—	4 b
			2021		
Preplant	4 a	13 a	8 a	9 a	8
Postplant	4 a	2 b	3 b	0.2 b	4
Delayed	0.5 b	3 b	0.9 b	0.3 b	3

[a]Means within a column followed by a different letter are significantly different at α ≤ 0.05.
[b]Early-season ratings (Early) took place at the time of the preplant termination application or just before, midseason ratings (Mid) occurred at the time of the delayed termination application or just before, and late-season ratings (Late) occurred at the time of the postemergence application or just before.

Morris 2020). In 2020, soybean yield was 400 and 450 kg ha^{-1} less in the delayed management program than in the preplant or postplant programs, respectively (Table 9).

Beyond treatment effects, differences in soybean density and yield between study years were likely influenced by differences in weather patterns and animal predation. In the wet spring of 2019, early soybean growth and vigor could have benefited from the presence of rye, especially where soybeans were planted into actively growing rye versus dead residue. Planting green can lead to drier soils at the time of soybean planting relative to planting into killed residue (Reed et al. 2019). Studies suggest that terminating after soybean planting could increase soybean yields in some years, reduce soybean yields in other years, or have no effect (Dearden 2022; Ficks et al. 2022; Fisher and Sprague 2022; Liebl et al. 1992; Reed et al. 2019; Schramski et al. 2020). In years with less problematic weather patterns, such as 2020, terminating the rye at 21 DAP would be a less practical option compared with 7 DBP or 7 DAP. Soybean yields were above the 5-yr state average of 3,457 kg ha^{-1} for each rye management program each year, other than 2021, when vole predation reduced soybean density and yield within the delayed rye management treatments.

The results of this study indicate that a rye cover crop can reduce weed density in soybean production and that rye management program and residual herbicide influence the biomass production and weed suppressive potential of a rye cover crop. The inclusion of rye may be more important than the

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Table 7. Effect of rye management program on visible weed control in July, averaged over rye seeding rate and residual herbicide use.[a]

Management program	*Ambrosia trifida*	*Setaria faberi*
	——— % control ———	
	2020	
Preplant	95 a	98 a
Postplant	95 a	98 a
Delayed	70 b	86 b
LSD	8	5
	2021	
Preplant	89 a	95 a
Postplant	94 a	97 a
Delayed	78 b	83 b
LSD	8	4

[a]Means within a column followed by a different letter are significantly different at $\alpha \leq 0.05$.

Table 8. Effect of residual herbicide on *Setaria faberi* density, averaged over rye seeding rate and management program midseason at the time of the delayed rye termination application and late-season at the time of the postemergence application in the preplant and postplant programs.[a]

	Evaluation timing	
Residual herbicide	Mid	Late
	—— plants m^{-2} ——	
	2019	
Flumioxazin + chlorimuron-ethyl	75 b	26 b
Nontreated	208 a	46 a
	2020	
Flumioxazin + chlorimuron-ethyl	—	5 b
Nontreated	—	20 a
	2021	
Flumioxazin + chlorimuron-ethyl	0.9	2 b
Nontreated	3	9 a

[a]Means within a column followed by a different letter are significantly different at $\alpha \leq 0.05$.

Table 9. Main effects of rye seeding rate on soybean yield, averaged over rye management program and residual herbicide, and rye management program on soybean yield, averaged over rye seeding rate and residual herbicide use.[a]

Seeding rate	2019	2020
kg ha^{-1}	—— soybean yield kg ha^{-1} ——	
100	4,290 a	5,230
50	4,340 a	5,140
0	4,000 b	5,060
LSD	255	NS
Management program	2019	2020
	—— soybean yield kg ha^{-1} ——	
Preplant	3,820 b	5,260 a
Postplant	4,470 a	5,310 a
Delayed	4,340 a	4,860 b
LSD	364	293

[a]Means within a column followed by a different letter are significantly different at $\alpha \leq 0.05$.

selection of a seeding rate of 50 kg ha^{-1} or more. There was a lack of seeding rate effect on rye biomass beyond the first year of the study or on weed density, aside from *S. faberi* at one evaluation. Rye management program influenced the density of *A. trifida* and *S. faberi*, and the delayed program generally increased rye biomass and reduced weed density. Terminating rye after soybean planting generally improved weed suppression, and weed density was not always different between the postplant and delayed programs. However, the reduction in weed density provided by delayed termination of rye was not sufficient to replace a final postemergence herbicide application in this study. The inclusion of a residual herbicide at the time of the preplant termination application reduced rye biomass in 2 out of 3 yr in this study. A delay in rye termination combined with the absence of a residual herbicide increased rye biomass in 2 out of 3 yr, but residual herbicides were still necessary for *S. faberi* suppression through July.

The presence or absence of a rye cover crop and the effect of a management program on soybean yield varied based on weather patterns. In springs with a high amount of precipitation, planting into growing rye may lead to improved soybean performance. In springs with more timely rain events, delaying rye termination may reduce soybean yield potential. Additionally, the presence of a rye cover crop with high residue may increase predation from pests. Overall, these results confirm the findings of other studies that suggest a rye cover crop can reduce weed pressure but should not be relied upon as the sole method of control. Management of the cover crop should be planned on a field-by-field and year-by-year basis, and the integration of cover crops with herbicide tactics is recommended for acceptable weed control. Future research should evaluate the long-term implications of cover cropping on the weed seedbank, including the effects of planting green versus terminating early.

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