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Responses of waterhemp and horseweed to cereal rye cover crop termination timing in soybean

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Abstract

Field experiments were conducted in soybeans (*Glycine max* L.) to determine the effects of a cereal rye (*Secale cereale* L.) cover crop (CC), two CC termination timings (TTs), and four herbicide programs (HP) on the emergence, biomass, and seed production of waterhemp (*Amaranthus tuberculatus* [Moq.] J.D. Sauer) and horseweed (*Erigeron canadensis* L.). The early cereal rye CC termination occurred seven days (d) before soybean planting, and the late termination occurred 12 days after soybean planting. The presence of a cereal rye CC, regardless of the TT, reduced waterhemp emergence by 39% and 44% compared to no CC at 5 and 10 weeks after planting (WAP), respectively. The late termination of the CC reduced waterhemp population density and biomass by 49% and 44%, respectively, compared to no CC 10 WAP. The presence of a cereal rye CC reduced horseweed population density and biomass at 5 WAP by 90% and 80%, respectively, compared with no CC. Horseweed seed production was 89% lower with a CC compared to no cover crop and was reduced to 0 seeds plant^{-1} at the late TT. Delayed cereal rye CC termination reduced soybean plant width but not yield. This research highlights the utility of multi-tactic strategies for controlling waterhemp and horseweed in soybeans.

Plain Language Summary

The research demonstrates the potential for cover crops to improve the management of two important weeds in soybean.

1 | INTRODUCTION

Waterhemp (*Amaranthus tuberculatus* [Moq.] J.D. Sauer) and horseweed (*Erigeron canadensis* L.) rank among the most common and troublesome weeds in US soybean production (Van Wychen, 2022). Waterhemp is a dioecious summer annual species native to the Midwest US and possesses several weedy traits that allow it to persist in soybeans, including extended germination periodicity, rapid growth rate, and high fecundity (Buhler & Hartzler, 2001; Costea et al., 2005; Hartzler et al., 2004; Sauer, 1957). Season-long waterhemp interference in soybeans can reduce yields by 56% (Bensch et al., 2003). The dioecious reproduction of waterhemp increases genetic diversity and supports the rapid adaptation to management tactics (Tranel, 2020). Waterhemp

Abbreviations: CC, cover crop; HP, herbicide program; NCC, no cover crop; SOA, site of action; TT, termination timing; WAP, weeks after planting.

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populations are resistant to seven herbicide sites of action (SOAs) (Heap, 2023). Recently published studies reported waterhemp populations that are multiple herbicide resistant to three, four, five, and six herbicide SOAs (Faleco et al., 2022; Hamberg et al., 2023; Shergill et al., 2018).

Horseweed is a facultative winter annual species germinating primarily in the fall; however, some cohorts emerge in spring (Buhler & Owen, 1997). It thrives in environments that lack annual soil disturbance and is common in no-till crop systems across the Midwest US (Bruce & Kells, 1990). The high fecundity (~200,000 seeds plant^{-1}) and wind-dispersal of horseweed seeds has resulted in seeds that traveled 500 km from the source plant, allowing for rapid invasion of agricultural fields (Bhowmik & Bekech, 1993; Shields et al., 2006). Season-long horseweed interference can reduce soybean yield by 96% (Bruce & Kells, 1990). Herbicides are the primary management option for horseweed in no-till soybean production, resulting in the widespread evolution of herbicide-resistant horseweed biotypes (Davis et al., 2008; Heap, 2023; Kruger et al., 2009).

Given the propensity of waterhemp and horseweed to evolve herbicide resistance, the addition of non-chemical management tactics is warranted to mitigate resistance evolution. Including a cereal rye (*Secale cereale* L.) cover crop (CC) has suppressed waterhemp and horseweed interference in soybeans (Bish et al., 2021; Fisher & Sprague, 2022). Cereal rye CC can suppress weeds through a variety of mechanisms, including competition, physical barriers, nutrient and light quality competition, allelopathy, and soil temperature reductions (Camargo Silva & Bagavathiannan, 2023). Liebl et al. (1992) and Moore et al. (1994) reported that a cereal rye CC reduced the biomass and population density of multiple weed species in soybeans. Werle et al. (2017) reported that cereal rye CC reduced weed population density by 91% and weed biomass by 91%–95% compared to fallow. Similarly, Hayden et al. (2012) indicated that winter annual weed population densities were reduced by >90% in the presence of a cereal rye CC. The capability of cereal rye for weed suppression is well documented but depends on several factors and considerations of how to best optimize the CC in soybean production.

CC termination timing (TT) is one consideration to improve weed management with CC. Teasdale and Mohler (1993) reported that cereal rye must produce 5000–8000 kg ha^{-1} of biomass to suppress weed emergence. Cereal rye biomass production levels depend on planting date and TT, which will vary depending on the previous and future crops in the rotation (Mirsky et al., 2011). Biomass accumulation of cereal rye preceding a soybean crop will vary by region but has been reported to range between 4000 and 6000 kg ha^{-1} in the eastern United States but can produce between 10,000 and 12,000 kg ha^{-1} with proper management and when grown to maturity (Mirsky et al., 2013). Delaying CC TT relative to soybean emergence increases cereal rye biomass and may enhance weed suppression (Fisher & Sprague, 2022; Mirsky et al., 2011). Studies conducted by Duiker and Curran (2005) and Teasdale et al. (2004) reported weed suppression by a cereal rye CC varied depending on the fall planting and spring termination dates. However, little research has investigated how cereal rye TTs and herbicide programs (HP) with multiple SOAs influence waterhemp and horseweed emergence, growth, and control. Therefore, this research examined the effect of two cereal rye TTs and four HP on the emergence, growth, and seed production of waterhemp and horseweed.

Core Ideas

- Waterhemp population density and biomass were reduced by a cereal rye cover crop early in the growing season.
- Cereal rye significantly reduced horseweed population density, growth, and fecundity.
- Cereal rye suppression of horseweed fecundity increased when the cover crop termination was delayed.
- Soybean morphology was influenced by cover crop and termination timing, but yield was not reduced.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental setup

Field experiments were conducted from fall 2020 through fall 2021 at the Iowa State University Curtiss Research and Demonstration Farm in Ames, IA (42°00′08″ N, 93°39′32″ W), and the Iowa State University Bruner Research Farm near Boone, Iowa (42°00′31.4″ N, 93°43′52.1″ W). The soil at the Ames site was a Canisteo silt clay loam with a 7.4 pH and 4.4% organic matter. The soil at the Bruner location included a Nicollet clay loam and a Canisteo silt clay loam with a 6.9 pH and 4% organic matter. The experiment sites had infestations of glyphosate-resistant waterhemp and horseweed. The monthly mean air temperatures and rainfall for the 2020 and 2021 growing seasons were similar to the 30-year average within the region (data not shown). The experiment was arranged in a split-split-plot design with four replications. The main plots (24 m wide by 9 m long) were a cereal rye CC or no CC. The sub-plots (12 m wide by 9 m long) had CC TTs 7 days (d) before and 12 days after soybean planting. Sub-sub-plots (3 m wide by 9 m long) were four soybean HP. Cereal rye (variety Elbon) was drill-seeded at 67 kg ha^{-1} on September 29, 2020 at the Ames location and October 6, 2020, at the Boone location into soybean

TABLE 1 Herbicides used in 2021 field experiments conducted in soybean at two Iowa State University research farms near Ames and Boone, IA.

Herbicide program	Common name(s)	Rate (g ai or ae ha^{-1})	Timing	Trade name(s)	Manufacturer
HP 1	Glyphosate	1261	PRE	Roundup PowerMax	Bayer
HP 2	Glyphosate fb glufosinate	1261 fb 656	PRE fb POST	Roundup PowerMax fb Liberty	Bayer and BASF
HP 3	Glyphosate + S-Metolachlor + Fomesafen fb Glufosinate	1261 + 261 + 266 fb 656	PRE fb POST	Roundup PowerMax + Prefix fb Liberty	Bayer, Syngenta, and BASF
HP 4	Glyphosate fb S-Metolachlor + Fomesafen + Glufosinate	1261 fb 261 + 266 + 656	PRE fb POST	Roundup PowerMax fb Prefix + Liberty	Bayer, Syngenta, and BASF

Abbreviations: fb, followed by; HP, herbicide program; POST, postemergence; PRE, preemergence.

stubble using a no-till drill (Marliss Industries, Jonesboro, AR 72401), with rows spaced 19 cm apart and seeds placed 2.5 cm deep. On May 13, 2021, experiments were planted with glyphosate- and glufosinate-tolerant soybean variety S28 E3 (varitey 79150907) at 380,000 seeds ha^{-1} placed 3 cm deep with rows spaced 76 cm apart. The optimum soybean planting window in Iowa falls between April 25 and May 20 (Licht & Clemens, 2021). The general recommendation is to terminate cereal rye 7–14 days prior to soybean planting; however, planting into a living CC (planting green) and delaying termination can maximize biomass production and may increase weed suppression (Fisher & Sprague, 2022; Grint et al., 2022). The cereal rye was terminated 7 days before soybean planting (general recommendation) and 12 days after soybean planting (planting green) to determine if increased CC biomass influenced weed population density, biomass, and seed production. The cereal rye CC for both timings was terminated with 2.24 kg of ha^{-1} glyphosate applied alone or with preemergence (PRE) residual herbicides (Table 1). The residual herbicide treatments of s-metolachlor (261 g ai ha^{-1}) and fomesafen (266 g ai or ae ha^{-1}) were selected based on their use in the region, effectiveness on the species of interest, and labeling for early POST in soybean. The POST herbicide treatments were applied 5 weeks after planting (WAP). All herbicide applications were applied using a CO2-pressurized backpack sprayer with a 6-nozzle boom (TT11015 nozzles) calibrated to deliver 187 L ha^{-1}.

2.2 | Data collection

Cereal rye biomass was collected by sampling 1 m of a single row arbitrarily selected within each experimental unit (adapted from Yadav et al., 2023). Samples were clipped at ground level and put in brown paper bags. The CC dry weight was recorded after samples were oven-dried for 96 h at 60°C. Waterhemp and horseweed population density counts were collected weekly from two fixed 0.5 m^2 quadrats arbitrarily established in each split-split plot, starting 10 days before soybean planting until 10 WAP. Weed biomass was collected 5 and 10 WAP from a single arbitrarily established 1 m^2 quadrat within each experimental unit. Weed biomass was oven-dried at 60°C for 4 days and weighed. When waterhemp and horseweed started to senesce, and seeds were mature, seed production was determined by collecting inflorescences from all mature plants inside a single 1 m^2 quadrat established arbitrarily at the time of sampling. Seeds were cleaned using a combination of hand threshing, sieves, and an air column seed separator (Seedburo Equipment Company). Horseweed seed samples were not processed with the air column seed separator due to the pappus and seed size, and all cleaning/threshing was done using a series of hand sieves. Waterhemp seed production was calculated using the following equation (adapted from Jones et al., 2019):

$$T = (W/S) \times 1000 \quad (1)$$

where W equals the total seed mass (g) 1 m^{-2} quadrat, S equals the mass of the 1000-seed sub-samples, and T equals the calculated number of seeds produced 1 m^{-2} quadrat. Horseweed seed production was calculated using the following equation (adapted from Hamberg et al., 2023):

$$T = (S \times 10) \times W \quad (2)$$

where W is the total seed mass 1 m^{-2} quadrat, S is the seed number of the 0.1 g sub-samples, and T is the total number of seeds produced 1 m^{-2} quadrat.

TABLE 2 Fixed effects of cereal rye cover crop, cover crop termination timing, and herbicide program on horseweed and waterhemp population density, abovegrosund biomass, and seed production in 2021 soybean experiments combined across two Iowa State University research farms near Ames and Boone, IA.

	Population density		Aboveground biomass		Seed production
Fixed effects	**5 WAP**	**10 WAP**	**5 WAP**	**10 WAP**	**At soybean harvest**
	p-values[a]				
	Horseweed				
CC[b]	**0.001**	**0.001**	**0.012**	**0.001**	**0.001**
TT[c]	0.815	0.549	0.355	0.200	**0.001**
HP[d]	0.280	0.268	0.838	0.793	0.759
CC × TT	0.388	0.231	0.530	**0.001**	**0.001**
CC × HP	0.527	0.576	0.722	0.755	0.055
TT × HP	0.472	0.448	0.873	0.478	0.978
CC × TT × HP	0.995	0.981	0.967	0.663	0.849
	Waterhemp				
CC	**0.001**	**0.001**	–	**0.001**	**0.001**
TT	**0.002**	0.539	–	**0.023**	0.300
HP	0.061	**0.001**	–	0.051	**0.046**
CC × TT	**0.015**	0.680	–	0.995	0.765
CC × HP	0.321	0.341	–	0.325	0.800
TT × HP	0.077	0.876	–	0.337	0.642
CC × TT × HP	0.624	0.596	–	**0.004**	0.957

Abbreviations: CC, cover crop; HP, herbicide program; NCC, no cover crop; TT, termination timing; WAP, weeks after planting.

[a]Effects were declared significant at the 0.05 probability level and are noted in bold.

[b]Cereal rye cover crop versus no cereal rye cover crop.

[c]Cereal rye cover crop termination timing, early (7 days before soybean planting) and late (12 days after soybean planting).

[d]Herbicide program: HP 1: glyphosate applied preemergence (PRE), HP 2: glyphosate applied PRE followed by (fb) glufosinate postemergence (POST), HP 3: glyphosate + s-metolachlor + fomesafen applied PRE fb glufosinate POST, HP 4: glyphosate applied PRE fb glufosinate + s-metolachlor + fomesafen POST.

The effects of cereal rye CC and TT on soybean growth, development, and yield were also quantified. Soybean stand counts were taken at the V2 growth stage (28 days after planting from an arbitrarily selected single 1-m row section from the center two rows in each plot. Soybean height and plant width measurements were collected at 14 days intervals from June 10 to July 1. The heights of 10 arbitrarily selected soybean plants were taken from the soil surface to the tallest part of the plant. Soybean plant width was determined by measuring the distance between the two widest points in the plant span of 10 arbitrarily selected plants. Soybean yield was collected by a plot-sized machine harvester on October 12, 2021, at the Curtiss Research and Demonstration Farm and October 8, 2021, at the Bruner Research Farm. Soybean grain yields were adjusted to 13% moisture.

2.3 | Statistical analysis

All data were analyzed with R statistical software v. 4.3.2 (R Core Team, 2024). Above-ground weed biomass and soybean height, diameter, and yield response variables were analyzed using the *lm4* package as mixed-effects models (Bates et al., 2015). Prior to analysis, data were inspected to ensure assumptions of normality and homogeneity of variance were satisfied using the *shapiro.test* and *bartlett.test* functions, respectively. Biomass data were log-transformed before analysis to satisfy the normality assumption. However, means from the non-transformed data are presented for easier interpretation. Waterhemp and horseweed population density and seed production were analyzed with a generalized linear mixed model following a negative binomial distribution using the *GLMMTMB* package (Brooks et al., 2017). CC, TT, location, HPs, and all interactions were considered fixed effects, whereas replications nested in location and replications nested within CC were considered random effects for all models. Location-by-treatment interactions were not significant; thus, data from the experiments were pooled for analysis. When significant differences among main effects or interactions were observed, post hoc analyses were conducted using Tukey's honestly significant difference test at $\alpha = 0.05$.

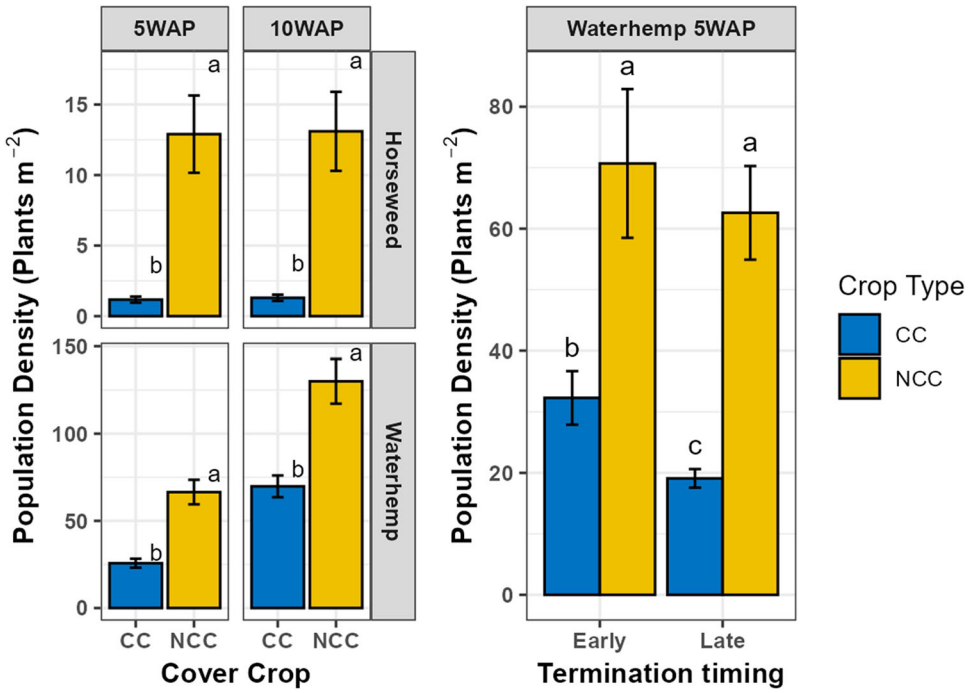


FIGURE 1 Influence of a cereal rye cover crop (CC) and no cover crop (NCC) on horseweed and waterhemp population density in soybean (Left). The influence of CC termination timing (early: 7 days before soybean planting and late; 12 days after planting) on waterhemp population density 5 weeks after planting (WAP; Right). Treatment means not sharing any letter(s) are significantly different (Tukey test $\alpha = 0.05$).

3 | RESULTS AND DISCUSSION

3.1 | Waterhemp population density, biomass, and fecundity

The effects of CC and TT and their interaction were significant ($p < 0.05$) on waterhemp population density 5 WAP (Table 2). The CC reduced waterhemp population density by ~2.5-fold when averaged across all treatments 5 WAP (Figure 1). Waterhemp population density in the no cover crop (NCC) treatments averaged 67 plants m^{-2} 5 WAP compared to 26 plants m^{-2} in the CC treatments. Moreover, delayed termination significantly reduced waterhemp population density from 32 plants m^{-2} in the early-terminated CC treatments to 19 plants m^{-2} in the late-terminated CC treatments 5 WAP (Figure 1). Nunes et al. (2024) reported that 5200 kg ha^{-1} of cereal rye CC reduced waterhemp population density by 50%, and population density decreased as biomass increased. In the present study, biomass accumulation was similar between locations, and the early and late CC TTs produced averages of 5100 and 11,800 kg ha^{-1} of cereal rye biomass, respectively. The differences between early and late TT in our study corroborate the findings of Nunes et al. (2024).

CC and HP had significant ($p < 0.01$) effects on waterhemp population density 10 WAP (Table 2). The waterhemp population density was reduced from 130 plants m^{-2} in the NCC treatments to 70 plants m^{-2} in the CC (Figure 1). In contrast to the 5 WAP observation, cereal rye TT did not influence waterhemp population density 10 WAP (Table 2). The extended waterhemp emergence periodicity led to continued emergence throughout the season, even after the CC residue was reduced due to decay (personal observation), which may explain why no differences were detected between early and late TT 10 WAP. The HPs with the lowest waterhemp population densities were those that included a residual herbicide (s-metolachlor + fomesafen) applied either PRE or POST (HP 3 and 4), which significantly reduced waterhemp population density by 1.7-fold when compared to those with POST-only activity (HP 1 and 2; Figure 2). However, no differences were detected between HP 3 and HP 4 10 WAP (Figure 2).

Our results revealed that including cereal rye CC in soybean can significantly reduce waterhemp population densities (Figure 1). Mirsky et al. (2011) and Essman et al. (2023) found that delayed cereal rye termination reduced weed population density in soybean. Results of our present study support this, finding that the delayed termination of a cereal rye CC can reduce waterhemp population density early (5 WAP) in the season. However, the suppressive benefit of delayed termination was diminished later (10 WAP) in the growing season (Table 2). Additionally, our results support the widely established principle that the combination of PRE-residual and POST herbicides will lead to lower weed population densities compared to POST only HP (Renton et al., 2024). However, the interaction between CC and HP was not significant, revealing that the combination of HP and CC did not significantly reduce waterhemp population densities.

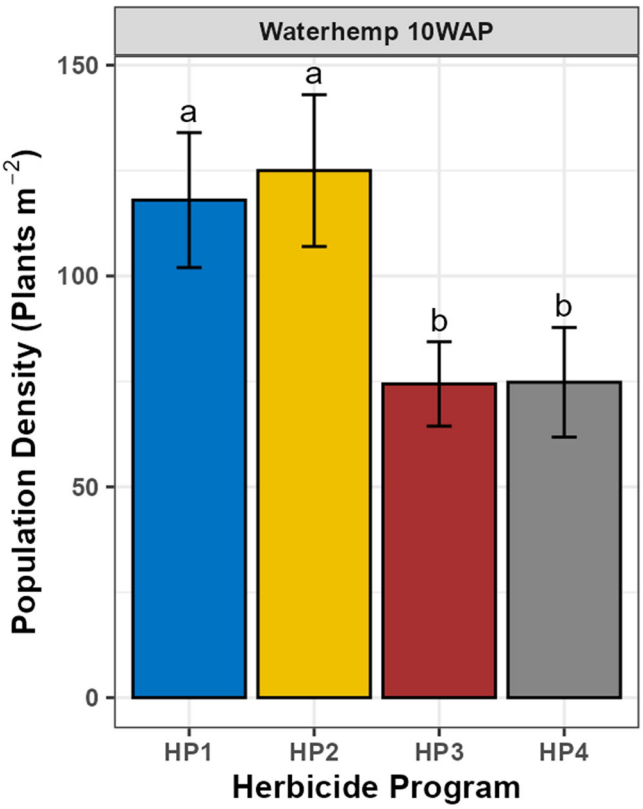


FIGURE 2 Influence of herbicide programs (HP) on waterhemp population density in soybean. Herbicide program: HP 1: glyphosate applied preemergence (PRE), HP 2: glyphosate applied PRE followed by (fb) glufosinate postemergence (POST), HP 3: glyphosate + s-metolachlor + fomesafen applied PRE fb glufosinate POST, HP 4: glyphosate applied PRE fb glufosinate + s-metolachlor + fomesafen POST. Treatment means not sharing any letter(s) are significantly different (Tukey test $\alpha = 0.05$).

The effects of CC, TT, and the interaction of CC, TT, and HP were significant ($p < 0.001$) on waterhemp biomass (Table 2). The influence of CC and TT on waterhemp biomass varied across HP (data not shown). Despite some treatments having significantly lower waterhemp population densities 10 WAP, biomass differences were not significant. This may be attributable to decreased intraspecific competition, allowing for accelerated biomass accumulation of waterhemp plants. Thus, lower population densities of larger plants had similar cumulative biomass as high population densities of smaller plants (Begna et al., 2001). The treatments with the highest waterhemp biomass were the NCC with POST-only herbicides (data not shown). CC TT was significant for some treatments, most notably, the early-terminated CC and NCC HP 1 treatments (data not shown). The early-terminated CC and NCC HP 1 treatments had over 100 g m^{-2} of waterhemp biomass, compared to 60 g m^{-2} in late-terminated CC HP 1 treatments. The HPs with residual herbicides (HP 3 and 4) were not significantly different from HP 1 in the late-terminated CC. This provides further evidence of the suppressive ability of cereal rye CC in leu of residual herbicides. The results of our study are corroborated by Nunes et al. (2024), who reported 50% reductions in waterhemp biomass from as little as 1760 kg ha^{-1} of cereal rye biomass.

CC and HP were significant ($p < 0.05$) on waterhemp seed production (Table 2). The treatments with the highest seed production were the NCC (Figure 3). HPs with only glyphosate and glufosinate (HP 1 and 2) had significantly higher seed production than HP 4, which combined a glyphosate burndown with POST applications of glufosinate and residual herbicides (Figure 3). It should be noted that even when combining PRE residual and POST-only herbicides, waterhemp seed production was still >5000 m^{-2}. Waterhemp can replenish soil seedbanks rapidly due to high individual plant fecundity, and a previous study suggested that populations can persist with less than 150 seeds plant^{-1} (Uscanga-Mortera et al., 2007). When waterhemp escapes are prevalent, growers should consider including additional management tactics such as harvest weed seed control to minimize seed bank additions (Bennett et al., 2023).

These results support the inclusion of a cereal rye CC to suppress waterhemp. However, sole reliance on CC alone for early-season weed management is not advisable. Growers should consider combining multiple tactics to maximize weed suppression potential and minimize the risk of weed adaptation to any one management tactic.

3.2 | Horseweed population density, biomass, and seed production

The effect of CC was significant ($p < 0.001$) on the horseweed population density 5 WAP (Table 2). Treatments with a cereal rye CC had eightfold less horseweed population density than without a CC 5 WAP (Figure 1). Fisher and Sprague (2022) reported a 67%–80% decrease in horseweed population density in the presence of a cereal rye CC in soybean 4–6 WAP. A similar study in Ohio reported that cereal rye reduced horseweed population density threefold 4 weeks after soybean planting (Essman et al., 2020). No differences in TT were detected in the CC treatments 5 WAP (Table 2). These data support findings by Fisher and Sprague (2022), who reported no differences between early and late cereal rye CC termination in horseweed population density 4–6 WAP in soybean. The horseweed population density did not change between 5 and 10 WAP, presumably because it was beyond the emergence period (Buhler & Owen, 1997). The majority of horseweed emergence in Iowa occurs in the fall, with <30% of cumulative emergence occurring in spring from late April to mid-May (Buhler & Owen, 1997).

CC was the only significant ($p < 0.01$) factor that influenced horseweed biomass 5 WAP (Table 2). The horseweed biomass followed a similar trend as population density 5 WAP

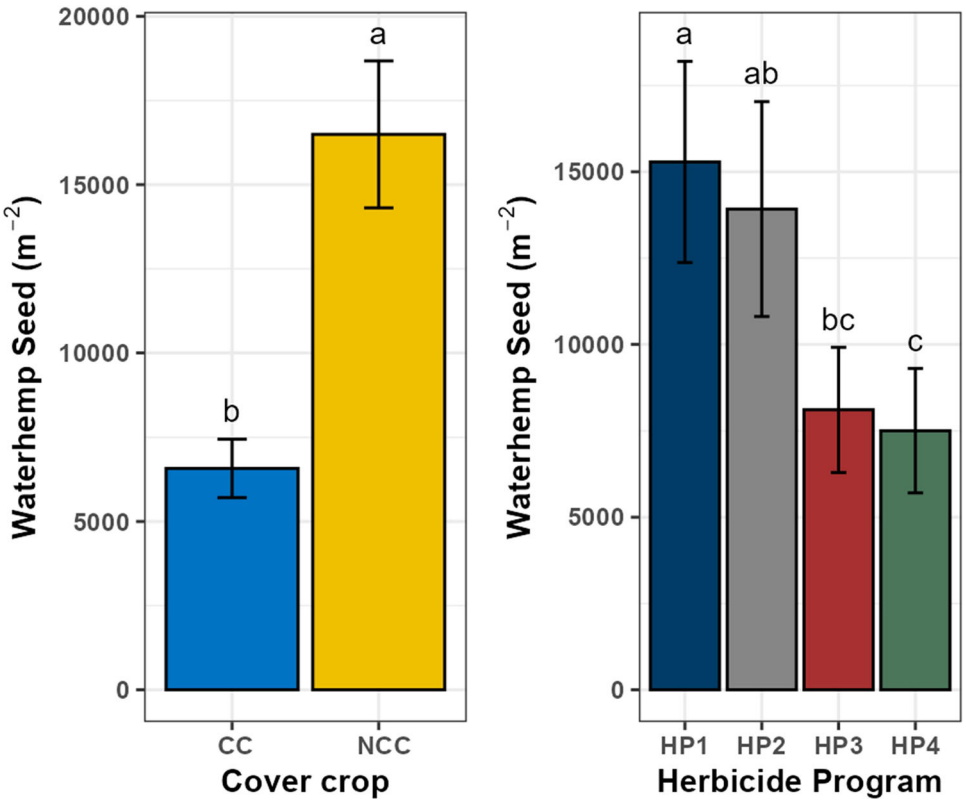


FIGURE 3 Influence of a cereal rye cover crop (CC), no cover crop (NCC) (left), and herbicide programs (HP; right) on the seed production of waterhemp in soybean. Herbicide program: HP 1: glyphosate applied preemergence (PRE), HP 2: glyphosate applied PRE followed by (fb) glufosinate postemergence (POST), HP 3: glyphosate + s-metolachlor + fomesafen applied PRE fb glufosinate POST, HP 4: glyphosate applied PRE fb glufosinate + s-metolachlor + fomesafen POST. Treatment means not sharing any letter(s) are significantly different (Tukey test $\alpha = 0.05$).

(Figure 4). Horseweed biomass averaged only 10 g m^{-2} in the CC treatments as compared to 50 g m^{-2} without a CC 5 WAP. Delayed termination of the CC did not affect horseweed biomass 5 WAP (Table 2). These data contrast results by Fisher and Sprague (2022) and Schramski et al. (2021), who found that a delayed cereal rye CC termination significantly reduced horseweed biomass 4–6 WAP in soybean. It should be noted that these Michigan studies had lower cereal rye biomass accumulation (<2000 kg ha^{-1}) at the early TT and ≤5000 kg ha^{-1} at the late TT, compared to 5100 and 11,800 kg ha^{-1}, early and late TT, respectively, in our Iowa study. The late CC TT in the Michigan studies had biomass accumulation similar to our early TT. The results of our present study suggest that ~5000 kg ha^{-1} of cereal rye CC biomass is highly suppressive on horseweed biomass.

The effect of CC and the interaction of CC and TT were significant on horseweed biomass 10 WAP (Table 2). Horseweed biomass was 80% lower in the late CC TT treatments than in the early CC TT treatments (Figure 4). These results are due, in part, to higher CC biomass accumulation, which allows for longer persistence of the CC residue. Mirsky et al. (2011) reported prolonged weed suppression with high biomass-producing cereal rye varieties and delayed termination. Moreover, Fisher and Sprague (2022) reported that delayed termination of a cereal rye CC decreased horseweed biomass by 36% when compared to early CC termination. While weed size was not measured in the present study, Fisher and Sprague (2022) found horseweed was significantly shorter in the presence of a CC when measured at soybean harvest.

The effects of CC and the interaction of CC and TT were significant on horseweed seed production (Table 2). The presence of a CC significantly reduced horseweed seed production regardless of TT (Figure 5). However, when CC termination was delayed, horseweed seed production was reduced to 0 m^{-2} across all HP treatments compared to ~ 60,000 seeds m^{-2} when the CC was terminated early. The extra CC biomass accumulation in the late TT prolonged the mulch effect of the CC, which reduced resource availability for the horseweed. Little research has evaluated what factors influence horseweed fecundity, but our results suggested that horseweed seed production is highly influenced by cereal rye CC. One study reported that horseweed grown under a vine canopy was far less fecund than those grown in full sun (Alcorta et al., 2011). Thus, shading may significantly reduce horseweed fecundity, but more research is warranted.

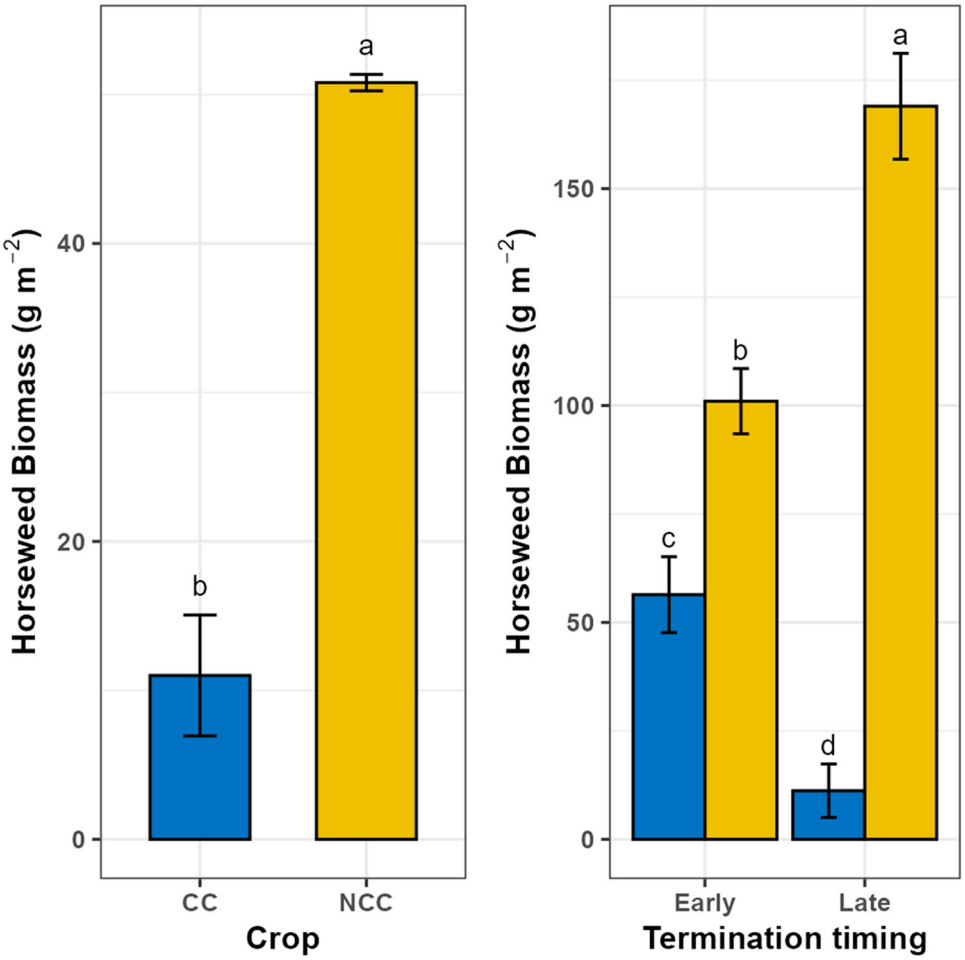


FIGURE 4 Influence of a cereal rye cover crop (CC), no cover crop (NCC) (left), and termination timing (early; 7 days before planting and late; 12 days after planting) (right) on horseweed aboveground biomass in soybean. Treatment means not sharing any letter(s) are significantly different (Tukey test $\alpha = 0.05$).

3.3 | Soybean height, plant width, and yield

No differences in soybean emergence were detected across CC treatments (data not shown). Soybean stands varied from 28 to 30 plants linear m^{-1} row. The only significant factor on soybean plant height 4 WAP was the presence of CC (Table 3). Soybean plants in no CC treatments were 28% taller than those in CC treatments (Table 3). This height difference was measurable until 7 WAP, at which point the CC treatments had no significant height differences on soybeans (Table 3). These results contrast Reddy (2001), who found that soybean plants were 20 cm shorter on average in the presence of cereal rye CC 12 WAP.

The interaction between CC and TT was significant on soybean plant width 4 WAP (Table 3). Soybean plant widths were least in the late-terminated CC treatments (Table 3). The effects of CC and TT and interactions were significant on soybean plant width 7 WAP (Table 3). At the 7 WAP observations, soybean plant widths were significantly different, and 1.3- and 1.5-fold lower in the late-terminated CC treatments when compared with the early-terminated CC and no CC treatments, respectively (Table 3). The reduction in soybean plant width may be attributed to several factors, including reductions in light quantity due to increased biomass in the late-terminated CC timing. Additionally, the delayed termination of the CC caused the soybean seedlings to emerge under the still green CC canopy, which likely reduced the light quality (red to far-red ratio) triggering a "shade avoidance" response during their development. Shade avoidance responses, leading to stem elongation and lower branch number, have been demonstrated in soybeans when grown under low red/far-red light environments (Green-Tracewicz et al., 2011). Soybean plants in the late-terminated CC plots were one growth stage behind those in the no CC treatments (personal observation). Delayed soybean development by late CC termination was also observed by Nunes et al. (2023a) in a similar experiment. Despite reductions in soybean plant widths 7 WAP, soybean yield was not influenced by CC or TT (Table 3). Similar studies have reported that delayed cereal rye CC termination did not influence soybean yield

TABLE 3 Effects of cereal rye cover crop, cover crop termination timing, and herbicide programs on soybean plant height, plant width, and 2021 grain yield combined across two Iowa State University research farms near Ames and Boone, IA.

Cover crop	Termination timing	Height (cm)		Diameter (cm)		Yield (kg ha^{-1})
		4 WAP	7 WAP	4 WAP	7 WAP	
CC[a]	Early	11.2 (0.4)c	30.8 (0.7)a	12.7 (0.6)ab	31.0 (1.0)b	3026
CC	Late	12.3 (0.3)c	27.4 (0.9)b	10.0 (0.2)c	24.0 (0.8)c	2858
NCC	Early	17.2 (0.4)a	29.8 (1.3)ab	11.5 (0.5)b	35.4 (0.7)a	2639
NCC	Late	15.6 (0.6)b	32.3 (0.7)a	13.4 (0.5)a	36.3 (0.8)a	3144
Fixed effects		*p*-values[b]				
CC		**0.006**	0.392	**0.026**	**0.006**	0.754
TT[c]		0.630	0.553	0.379	**0.001**	0.513
HP[d]		0.961	0.855	0.923	0.487	0.260
CC × TT		**0.002**	**0.001**	**0.001**	**0.001**	0.058
CC × HP		0.967	0.947	0.998	0.265	0.845
TT × HP		0.963	0.880	0.993	0.572	0.910
CC × TT × HP		0.975	0.644	0.953	0.468	0.630

Abbreviations: CC, cover crop; HP, herbicide program; NCC, no cover crop; TT, termination timing; WAP, weeks after planting.

[a]Cereal rye cover crop versus no cereal rye cover crop.

[b]Effects were declared significant at the 0.05 probability level and are noted in bold. Post hoc test used Tukey's honestly significant difference ($\alpha = 0.05$).

[c]Cereal rye cover crop termination timing, early (7 days before soybean planting) and late (12 days after soybean planting).

[d]Herbicide program: HP 1: glyphosate applied preemergence (PRE), HP 2: glyphosate applied PRE followed by (fb) glufosinate postemergence (POST), HP 3: glyphosate + s-metolachlor + fomesafen applied PRE fb glufosinate POST, HP 4: glyphosate applied PRE fb glufosinate + s-metolachlor + fomesafen POST.

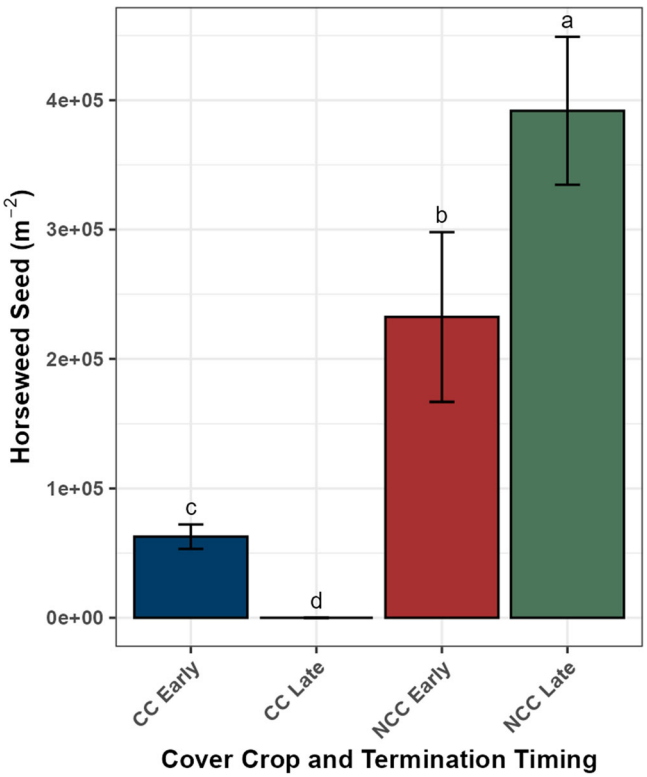


FIGURE 5 Influence of a cereal rye cover crop (CC) and no cover crop (NCC) and termination timing (early; 7 days before planting and late; 12 days after planting) on the seed production of horseweed in soybean. Treatment means not sharing any letter(s) are significantly different (Tukey test $\alpha = 0.05$).

(Fisher & Sprague, 2022). Nunes et al. (2023), Reed et al. (2019), and Schramski et al. (2021) reported that when cereal rye was terminated with glyphosate, only 1 year of 3 years had reduced soybean yields, which they attributed to lower-than-average precipitation. In the present study, rainfall during the 2021 growing season was near the 30-year average, which likely contributed to the yield similarities across treatments (data not shown).

The inclusion of cereal rye CC suppressed waterhemp and horseweed by reducing their respective population densities. Horseweed population density was more influenced by CC, likely due to its winter annual lifecycle. Delayed CC termination was more suppressive on horseweed than waterhemp across all measurements. The delayed termination led to higher CC biomass accumulation, which prolonged the horseweed suppression. It should be noted that in the present study, biomass accumulation at the early TT exceeded 500 kg ha^{-1} and 11,000 kg ha^{-1}, which is higher than the expected value across much of the Midwest US (Nichols et al., 2020). A meta-analysis found that within the typical corn–soybean rotation, only 2% counties in Midwest US states would achieve ≥5000 kg ha^{-1} of cereal rye biomass based on models using 30-year historical climate data (Nichols et al., 2020). Although CC and TT influenced the height and width of soybeans, yield was not impacted. The results of the present study revealed that cereal rye CC is an effective method of weed suppression. However, it is recommended that chemical and non-chemical tactics be combined to reduce over-reliance on any individual tactic (Yadav et al., 2023). The benefits of

including multiple effective herbicide sites of action, which include residual herbicides, are well documented (Evans et al., 2016).

AUTHOR CONTRIBUTIONS

Ryan C. Hamberg: Formal analysis; writing—review and editing. **Edward S. Dearden**: Conceptualization; formal analysis; investigation; methodology; writing—original draft. **Ramawatar Yadav**: Conceptualization; formal analysis; writing—review and editing. **Micheal D. K. Owen**: Project administration; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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