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Integrating early spring-planted barley or oat for Palmer amaranth management in soybean

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Abstract

Fall-planted cover crops (CCs) are widely used for weed suppression, but CC establishment challenges after fall harvest in temperate regions necessitate alternative approaches. The objectives of this study were to evaluate the integrated effect of spring-planted barley or oat CC and herbicide programs for CC biomass production, Palmer amaranth (*Amaranthus palmeri* S. Watson) suppression, and soybean [*Glycine max* (L.) Merr] yield. Field experiments were conducted during 2023–2024 in an irrigated no-till soybean in south central Nebraska. A split-plot design with early spring planted (i) barley (*Hordeum vulgare* L.) CC, (ii) oat (*Avena sativa* L.) CC, and (iii) no cover crop (NCC) as main factors and sub-factors included five herbicide programs: (i) nontreated, (ii) pre-emergence (PRE) only (PRE-only), (iii) post-emergence (POST) only (POST-only) (iv) PRE followed by POST herbicide (PP), (v) PRE followed by POST plus residual herbicide (PPR). Barley or oats were drill-planted a month before soybean planting. Oat produced 42% more biomass than barley in 2023 (1.44 Mg ha^{-1}) and 102% more biomass in 2024 (3.47 Mg ha^{-1}). In 2023, CCs had no effect on Palmer amaranth at CC termination. In 2024, oat and barley without PRE herbicide reduced Palmer amaranth density by 89% and 83% and biomass by 90% and 92%, respectively, compared to NCC without PRE herbicide. At 4 weeks after POST herbicide application, oat-nontreated treatment reduced Palmer amaranth density by 80% and biomass by 64%, while barley-nontreated had similar results compared to NCC-nontreated. Soybean yields were not affected by CCs but improved by integrating with herbicide program, with PPR treatment (4.12 Mg ha^{-1}) yielding 225% higher than the nontreated control. It is concluded that spring-planted oat CC integrated with herbicides can be included in Palmer amaranth management program in soybean.

Abbreviations: CC, cover crop; GDD, growing degree day; HSD, honestly signficant difference; NCC, no cover crop; POST, post-emergence; PRE, pre-emergence.

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Plain Language Summary

Palmer amaranth is a tough weed that reduces soybean yield, and farmers often plant cover crops in the fall to help control it. However, in cooler regions, fall planting is difficult after harvest. This study tested whether planting barley or oat cover crops in early spring—combined with herbicide use—can help control Palmer amaranth and maintain soybean yield. Field trials in Nebraska during 2023 and 2024 showed that spring-planted oat produced more growth than barley and suppressed more Palmer amaranth, especially without early-season herbicides. In 2024, oat alone reduced weed density by 80%. Soybean yield was not harmed by cover crops and was highest when herbicide programs were used with or without cover crops. The most effective program increased soybean yield by 225% compared to no treatment. These results suggest that spring-planted oat, when combined with herbicides, is a practical tool to manage Palmer amaranth in soybean fields.

1 | INTRODUCTION

Soybean [*Glycine max* (L.) Merr] is a vital crop for US agriculture, annually grown over approximately 35 million ha (Vaiknoras, 2023), with a production of approximately 108 million Mg (USDA-NASS, 2024). Over a 5-year period (2017–2022), on average, soybean production had a direct economic impact of about $45 billion annually on the US economy (LMC International, 2023). However, soybean production faces numerous challenges, including competition from weeds, pests, and adverse weather conditions (Landau et al., 2022; Oerke, 2006). Among them, weeds are one of the most significant yield-limiting factors, competing for essential resources such as moisture, nutrients, and light. If left uncontrolled, weeds can reduce soybean yields as much as 52% (Soltani et al., 2017), translating into potential annual economic losses exceeding US$20 billion in the US.

Palmer amaranth (*Amaranthus palmeri* S. Watson) is one of the most persistent weed species in soybean fields across the United States (Van Wychen, 2022). It adapts and thrives in various cropping systems due to its season-long emergence window, rapid growth rate, high photosynthetic efficiency, phenotypic flexibility, and prolific seed production (Chahal et al., 2021; Sellers et al., 2003; Ward et al., 2013). Studies found that uncontrolled Palmer amaranth infestations reduced soybean yields by 68% in Arkansas (10 plants m^{-2}; Klingaman & Oliver, 1994) and 79% in Kansas (8 plants m^{-2}; Bensch et al., 2003). Herbicides remain the primary tool for Palmer amaranth control, with approximately 99% of soybean fields receiving one or more herbicide applications (USDA-NASS, 2021). However, over-reliance on herbicides has led to the selection for herbicide-resistant Palmer amaranth biotypes (Bagavathiannan & Norsworthy, 2016; Ward et al., 2013).

Across the US soybean fields, Palmer amaranth has evolved resistance to multiple herbicide groups, including acetolactate synthase inhibitor (Group 2), microtubule assembly inhibitor (Group 3), synthetic auxin (Group 4), photosystem II inhibitor (Group 5), 5-enolpyruvyl shikimate-3-phosphate synthase inhibitor (Group 9), glutamine synthetase inhibitor (Group 10), protoporphyrinogen oxidase inhibitor (Group 14), very long-chain fatty acid synthesis inhibitor (Group 15), and 4-hydroxyphenyl pyruvate dioxygenase inhibitor (Group 27) (Foster & Steckel, 2022; Heap, 2024; Priess et al., 2022). Additionally, multiple herbicide-resistant biotypes of Palmer amaranth are becoming widespread (Aulakh et al., 2021; Bagavathiannan & Norsworthy, 2016; Shyam et al., 2021). To mitigate the selection pressure for resistance, alternative strategies for herbicide use are needed for effective Palmer amaranth management.

Cover crops (CCs) are increasingly recognized as an integral part of integrated weed management strategies (Dhanda et al., 2024; Kumar, Singh, Flessner, et al., 2025; Kumari et al., 2024a; Norsworthy et al., 2011). CC residues suppress weeds by acting as a physical barrier (Stephens et al., 2024; Teasdale, 1996) and through allelopathic effects (Sturm et al., 2018). Additionally, CCs can also alter the quality and quantity of sunlight reaching the soil surface, modifying the ratio of red:far-red light, which can inhibit weed seed germination (Teasdale & Mohler, 1993). For instance, cereal rye (*Secale cereale* L.) CC reduced Palmer amaranth emergence by 56%–75% in soybean in Arkansas (DeVore et al., 2013), while winter wheat (*Triticum aestivum* L.) reduced Palmer amaranth density by 49% and biomass by 24% in soybean in Kansas. Moreover, CCs may shorten the critical period for weed control in soybean (Kumari et al., 2023).

In soybean-based cropping systems in temperate regions, CCs are typically planted in the fall after the harvest of the cash crop and terminated in the spring before or after planting the cash crop (Ruis et al., 2019). However, fall planting presents challenges, such as labor shortages, limited

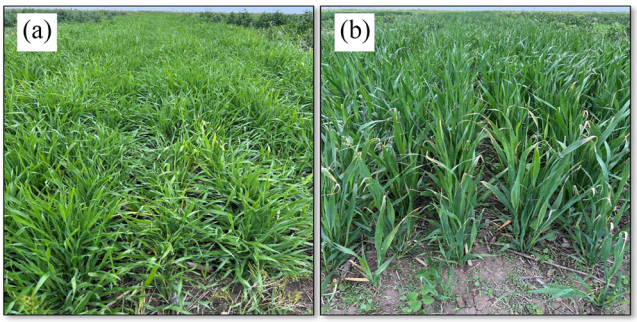


FIGURE 1 Spring-planted (a) barley and (b) oat cover crops for Palmer amaranth suppression in soybean in a field study conducted at University of Nebraska-Lincoln's South-Central Agricultural Lab, near Clay Center, NE. The photos were taken a day before cover crop termination in 2024.

Core Ideas

- Oat produced 0.43 Mg ha^{-1} more biomass than barley in 2023 and 1.75 Mg ha^{-1} more biomass in 2024.
- Oat reduced Palmer amaranth density by 80% and biomass by 64% compared to no cover crop.
- Soybean yield was not affected by cover crops but increased by integrating with herbicide programs.
- Spring-planted cover crops must be integrated with herbicides for effective Palmer amaranth control in soybean.

equipment availability (Oliveira et al., 2019), and time constraints during the harvest season (Roesch-McNally et al., 2018). Moreover, harsh winter conditions (Koehler-Cole et al., 2021) and the residual activity of in-season herbicides (Palhano et al., 2018) can restrict the choice of suitable CC species and hinder their successful establishment (Cornelius & Bradley, 2017; Petrosino et al., 2015).

Spring-planted CCs may mitigate the challenges with fall-planted CCs. However, shorter growing window for spring-planted CCs might result in lower biomass production compared to fall-planted CCs (Koehler-Cole et al., 2021; Ruis et al., 2019). For example, fall-planted CCs in Kansas produced an average biomass of 3.44 Mg ha^{-1} compared to 1.86 Mg ha^{-1} for spring-planted CCs (Petrosino et al., 2015). Biomass accumulation is a key factor in weed suppression, and lower biomass from spring-planted CCs may reduce the effectiveness of Palmer amaranth suppression (Ficks et al., 2022; Nunes, Arneson, Wallace, et al., 2023). Delaying spring-planted CC termination until after soybean planting could help increase biomass accumulation and enhance weed control. For instance, Stephens et al. (2024) reported that greater cereal rye biomass produced a thicker and more uniform residue mulch following CC termination, which enhances suppression of Palmer amaranth compared with lower biomass in a study conducted in Nebraska.

Considerable research has focused on the effects of fall-planted CCs on biomass accumulation, Palmer amaranth suppression, and soybean yield. However, fewer studies have evaluated spring-planted CCs terminated after soybean planting. CCs may not provide season-long weed control, necessitating their integration with herbicide programs (Bhaskar et al., 2020; Brainard & Bellinder, 2004; Kumari et al., 2024b). The objectives of this study were to evaluate the effects of spring-planted barley (*Hordeum vulgare* L.) and oat (*Avena sativa* L.) CCs (Figure 1), terminated 3 weeks after soybean planting, in combination with different herbicide programs on CC biomass accumulation, Palmer amaranth density and biomass, and soybean yield.

2 | MATERIALS AND METHODS

2.1 | Site description

A 2-year field study was conducted from spring 2023 to fall 2024 at the University of Nebraska-Lincoln's South-Central Agricultural Lab, near Clay Center, NE (40.52°N, 98.05°W). The soil series at the experimental site was Hastings silty clay loam (fine, smectitic, mesic Udic Argiustolls) with an organic matter content of 37 g kg^{-1} and pH 6.8. The experimental site was under sprinkler irrigated corn–soybean rotation before the establishment of experiment and then managed under no-till soybean during the duration of the experiment. The experimental site had a natural population of glyphosate-resistant Palmer amaranth, ensuring uniform weed pressure across treatments.

2.2 | Experimental design and study setup

The experiment was a split-plot design with four replications. The main plot factor was spring-planted CC species: (i) barley, (ii) oat, and (iii) no cover crop (NCC). The subplot factor consisted of herbicide programs: (i) nontreated, (ii) pre-emergence (PRE) only (PRE-only), (iii) post-emergence (POST) only (POST-only), and (iv) PRE followed by POST herbicide (PP), and (v) PRE followed by POST plus residual herbicide (PPR). The individual main-plot size was 3.05 × 38.1 m, and subplot was 3.05 × 7.62 m. Table 1 lists the type, rate, and application timings of the herbicides used.

Barley variety P-919 (Husker Genetics, University of Nebraska-Lincoln) was drill seeded at 100 kg ha^{-1}, and

TABLE 1 Herbicides, manufacturers, active ingredients, rate, and application timing used in a study to integrate spring-planted barley and oat cover crops for Palmer amaranth suppression in field studies conducted at University of Nebraska-Lincoln's South-Central Agricultural Lab, near Clay Center, NE.

Herbicide	Manufacturer	Active ingredient[a,b]	Rate[a] (g ai ha^{-1})	Application timing
Sharpen	BASF Ag Products, Research Triangle Park, NC	Saflufenacil	50	Pre-emergence
Metribuzin 75	Loveland Products, Greeley, CO	Metribuzin	472	Pre-emergence
Liberty	BASF Ag Products, Research Triangle Park, NC	Glufosinate	655	Post-emergence
Select max	Valent USA, San Ramon, CA	Clethodim	136	Post-emergence
Warrant	Bayer CropScience, St. Louis, MO	Acetochlor	1257	Residual[c]

Note: Ammonium sulfate (25 mL L^{-1}) + crop oil concentrate (10 mL L^{-1}) was mixed with post-emergence herbicide.

[a]Saflufenacil was applied pre-emergence in soybean at 50 g ai ha^{-1}; however, this rate has a minimum plant-back interval of 30 days. According to the product label, the recommended rate for pre-plant or pre-emergence application in soybean on fine-textured soils is 25 g ai ha^{-1}, with no restriction on the plant-back interval. No soybean injury was observed. This deviation is acknowledged, and the results should be interpreted considering the elevated saflufenacil rate.

[b]Clethodim was applied to control grass weed species, including giant foxtail (*Setaria faberi* Herrm) and large crabgrass (*Digitaria sanguinalis* L.), which were present at low densities at the research site.

[c]Residual herbicide was tank-mixed with post-emergence herbicides.

TABLE 2 Information of the field operations in 2023 and 2024 in a study to integrate spring-planted barley and oat cover crops for Palmer amaranth suppression in field studies conducted at University of Nebraska-Lincoln's South-Central Agricultural Lab, near Clay Center, NE.

Year		
2023	2024	Operation
April 3	April 10	Planting barley and oat cover crop
May 2	May 10	Soybean planting and pre-emergence herbicide application
May 21	May 28	Barley and oat termination
May 23	July 16	First irrigation of the season
June 6	June 10	Post-emergence and post-emergence + residual herbicide application
October15	November 18	Soybean harvesting

oat variety Jerry (Husker Genetics, University of Nebraska-Lincoln) was drill seeded at 78.4 kg ha^{-1}. Both CCs were drilled at 2.54-cm depth with 19.05-cm row spacing. Soybean variety NK31-J9XF (NK Soybean, Syngenta) was seeded at 330,000 seeds ha^{-1} at 4.4-cm depth with 76.2-cm row spacing. The CCs were terminated about 3 weeks after soybean planting using glyphosate (1343 g ae ha^{-1}; Roundup PowerMAX, Bayer CropScience LP) + crop oil concentrate (10 mL L^{-1}) + ammonium sufhate (25 mL L^{-1}).

Herbicides were applied using CO_2-pressurized backpack sprayer fitted with an XR 11002 nozzle boom delivering 140 L ha^{-1} spray mix at 276 kPa. Details on planting dates for CCs and soybean, along with other agronomic practices for both years, are listed in Table 2. The field was irrigated 10 times with a total of 288-mm water in 2023 and six times with a total of 183 mm water in 2024. The first irrigation was applied on May 23 in 2023 and July 16 in 2024.

2.3 | Data collection

Soybean stand counts were recorded at V1 and V5 growth stages. The counts were taken from two center rows of each four-row plot. For each observation, a 1-m row length was marked in each of the two center rows, and the number of plants within this length was counted manually. The same meter-length was used at both growth stages to assess any changes in stand count after CC termination. Aboveground biomass of barley and oat CC was collected from each plot using a randomly placed 0.5 m^2 quadrat at the time of their termination. Barley and oat CC accumulated growing degree day (GDD) was calculated from the date of planting to date of termination, using a base temperature of 0°C (Koehler-Cole et al., 2021). Gravimetric soil moisture was measured at spring-planted CC termination. A 2.5-cm-diameter soil probe was used to collect six samples from the 0- to 5-cm depth in each plot, which were thoroughly mixed to form a composite sample. A 30-g subsample was removed from the composite sample and oven-dried at 105°C for 48 h. Gravimetric soil moisture was calculated as the percentage of water mass relative to the dry soil mass.

Palmer amaranth density and biomass were collected at three time points: CC termination, POST herbicide application, and 4 weeks after POST herbicide application, from a randomly placed 0.5 m^2 quadrat. Biomass of CC and Palmer amaranth was determined by cutting the plants from 0.5 m^2

quadrat in each plot and drying the biomass to constant weight in an oven at 60°C. At maturity, soybean was harvested using a plot combine from the middle two rows of the four-row plot, and the yields were reported at 13.5% moisture content.

2.4 | Data analysis

Data were analyzed using the PROC MIXED model in SAS version 9.4 (SAS Institute). Analysis of variance was used to assess the effects of CCs and herbicide programs on CC biomass, soybean stand counts, Palmer amaranth density and biomass, and soybean yield. Normality of data were evaluated using Shapiro–Wilk test and quantile-quantile plots. When data did not follow a normal distribution, transformations were applied. Palmer amaranth density and biomass data from both years were log-transformed [$\log(x + 1)$], followed by back-transformation to present original means.

Palmer amaranth density and biomass were measured at CC termination and before POST herbicide application to assess the impact of PRE herbicides and CC species. Since only PRE herbicides were applied at these data collection points, sub-plot treatments were categorized within each main plot as follows: (i) with PRE herbicide applied (PRE-only, PP, and PPR), and (ii) without PRE herbicide applied (nontreated and POST-only). A contrast analysis was then conducted to compare plots with PRE herbicide to those without it. For data collected after POST herbicide application, split-plot analysis was performed without grouping the sub-plot treatments. Year-wise analyses were performed for variables where the effect of the year was significant; otherwise, data from both years were pooled. In the model, CCs and herbicide programs were treated as fixed effects, while replication was considered as a random effect. Means were separated using the Tukey's honestly significant difference (HSD) test at $\alpha < 0.05$.

3 | RESULTS AND DISCUSSION

3.1 | CC biomass production

There was a significant effect of year on the aboveground biomass of barley and oat CCs. Therefore, year-wise analysis was performed. On average, the biomass in 2024 was 111% (1.36 Mg ha^{-1}) higher than 2023. This difference is likely due to more favorable growing conditions in 2024, including higher rainfall and greater GDD accumulation (Figure 2).

The experimental field was under a linear-move pivot irrigation, but the field was not irrigated until the termination of CCs. From planting to termination, total rainfall in 2024 was 129 mm, nearly five times the rainfall received in 2023 (27 mm) (Figure 2). Additionally, the total rainfall in April and May (the months when CCs were growing in the field) at the experimental site in 2023 was 77% lower than the 30-year average of 201 mm. In 2024, GDD accumulation from planting to termination reached 700 units, which was 78 units higher than 2023 (Figure 2). The required $120^{-1}30$ GDD for barley and oat CC emergence (Miller et al., 2001) accumulated 3 days earlier in 2024 than in 2023. Koehler-Cole et al. (2021) reported higher biomass in spring-planted barley and oat CCs during a year with higher total rainfall (153 mm) and GDD accumulation (719 units) compared to a year with lower rainfall (43 mm) and GDD accumulation (625 units) in Nebraska.

Oat biomass was 1.44 Mg ha^{-1} in 2023 and 3.47 Mg ha^{-1} in 2024. Oat biomass was 42% higher than barley in 2023 and 102% higher in 2024 (Figure 3). The difference in biomass production between barley and oat CCs may be attributed to their genetic variation and efficiency in CC biomass accumulation. Bailey-Elkin et al. (2021) found 50% higher oat biomass than barley at their physiological maturity in a study conducted in Manitoba, Canada. Carr et al. (2000) also reported 35% higher biomass production in oat compared to barley in North Dakota. Barley and oat CC biomass observed in this study was comparable to other studies conducted in Nebraska (Koehler-Cole et al., 2021; Pflueger et al., 2020).

Koehler-Cole et al. (2021) reported barley CC biomass ranging from 0.35 to 3.38 Mg ha^{-1}, depending on the year and experiment duration (52–70 days), and oat CC biomass ranging from 0.32 to 3.81 Mg ha^{-1} in a study conducted near Mead, Nebraska. In this study, oat CC biomass in 2024 was similar to the 4.00 Mg ha^{-1} biomass reported by Pflueger et al. (2020) for oats planted in early April and terminated in mid-June in Lincoln, NE. In 2024, total rainfall in April and May (150 mm) was 25% lower than 30-year average, suggesting that even higher CC biomass accumulation could be expected under average rainfall conditions. Moreover, supplemental irrigation can be considered to improve CC biomass production during low rainfall years. There was no significant effect of herbicide application on CC biomass production in either year, indicating that saflufenacil + metribuzin applied PRE after soybean planting at the rates used in this study did not negatively affect barley or CC biomass.

3.2 | Soybean stand count

The soybean stand count at the V1 growth stage varied across years. Thus, a year-wise analysis was conducted. In 2023, soybean stand counts were 20% lower in barley and 35% lower in oat compared to the NCC treatment, which had 22.1 plants m^{-1} (Table 3). This reduction is likely attributed to limited rainfall and moisture stress conditions. Total rainfall during the week before and after soybean planting was 8.9 mm in 2023 (Figure 2). Additionally, gravimetric soil moisture

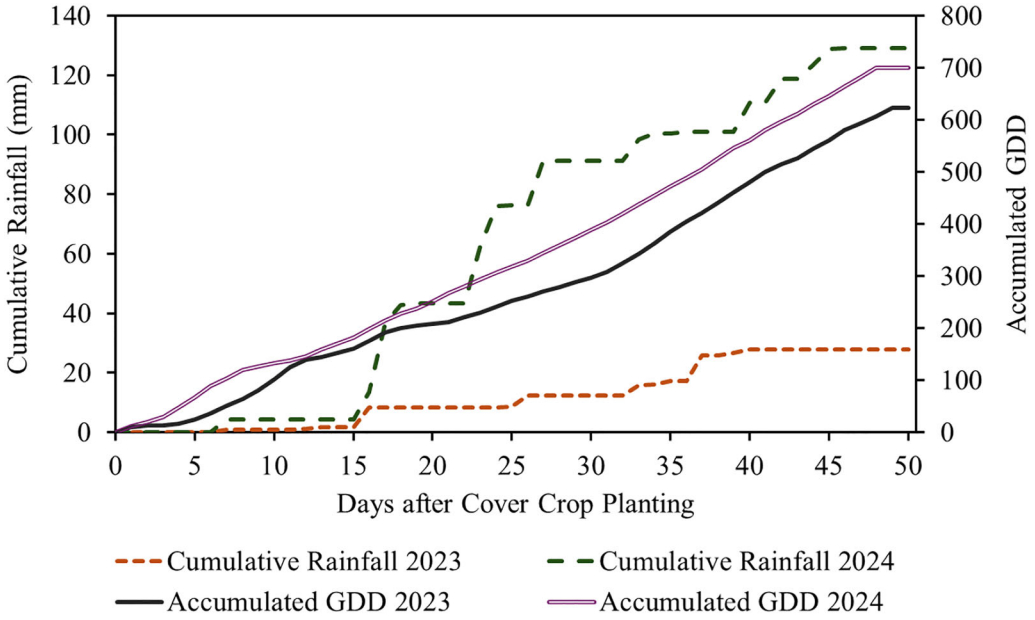


FIGURE 2 Cumulative rainfall (mm) and accumulated GDD (growing degree days) with base temperature 0°C from cover crop planting to termination in a study to integrate spring-planted barley and oat cover crops for Palmer amaranth suppression in field studies conducted at University of Nebraska-Lincoln's South-Central Agricultural Lab, near Clay Center, NE in 2023 and 2024.

TABLE 3 Soybean stand count at V1 and V5 growth stages in a study to integrate spring-planted barley and oat cover crops for Palmer amaranth suppression in field studies conducted at University of Nebraska-Lincoln's South-Central Agricultural Lab, near Clay Center, NE.

Year	Cover crop	Soybean stand count at V1[a] (plants m^{-1})	Soybean stand count at V5[a] (plants m^{-1})
2023	Barley	17.7c	22.6a
	Oat	14.4b	24.0a
	No cover crop	22.1a	22.5a
2024	Barley	22.8a	23.2a
	Oat	22.6a	23.2a
	No cover crop	22.4a	23.3a

[a]Soybean stand count mean at particular growth stage followed by the same letter within a year are not significantly different using the Tukey's honestly signficant difference (HSD) test at $\alpha < 0.05$.

content at 0^{-1}0-cm soil depth at CC termination was 101 g kg^{-1} in barley, 94 g kg^{-1} in oat, and 176 g kg^{-1} in NCC plots.

Similar reductions in soybean emergence due to moisture stress have been documented in other studies (Helms et al., 1996, 1997; Kaur et al., 2023). For instance, in a study conducted without CCs in Fargo, ND, reducing gravimetric soil moisture content from 130 to 90 g kg^{-1} led to a 10% decrease in soybean emergence (Helms et al., 1996). Some researchers have reported a reduction in soybean stand in CC plots due to inadequate soil-to-seed contact when the planter fails to properly close the seed furrows (Gross et al., 2022; Mirsky et al., 2013). This issue is more prevalent when soybean is planted into a high biomass CC residue mulch (Gross et al., 2022; Mischler et al., 2010). However, in this experiment, soybean was planted into growing CC. Additionally, the CC biomass at the time of soybean planting, particularly in 2023, was relatively low (<0.4 Mg ha^{-1}) in this study. The reduction in soybean stand in 2023 was more pronounced where soybeans were planted over or very close to the CC rows (personal observation). Modifying CC planting in such a way that skipping one row after every three rows of CCs (each spaced 19.05 cm) and then planting soybean in the skipped row (for soybean planted with 76.2 cm row spacing) could mitigate the impact of moisture stress due to competition with CC on soybean emergence. The limitation of this approach is it might reduce weed suppression within the intra-row space of soybean.

CC treatment had no significant effect on soybean stand count at the V5 growth stage in 2023 (Table 3). This may be attributed to the 21 mm of irrigation applied the day after CC termination in 2023, which alleviated moisture stress and encouraged the germination of previously non-germinated soybean seeds in barley and oat CC plots. The late-emerging soybean plants contributed to the improved stand count in barley and oat by the V5 growth stage.

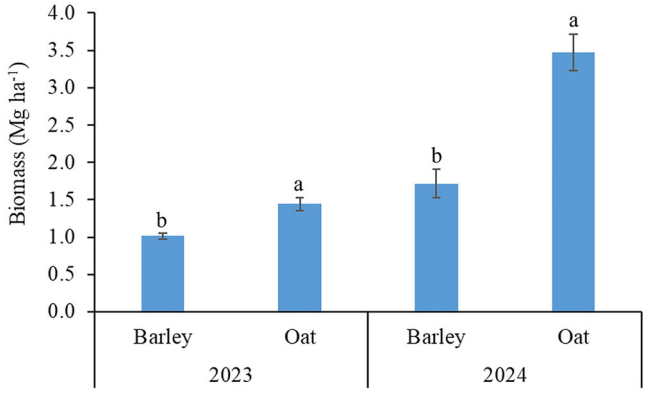


FIGURE 3 Barley and oat cover crop biomass (Mg ha^{-1}) at termination in a study to integrate spring-planted barley and oat cover crops for Palmer amaranth suppression in field studies conducted at University of Nebraska-Lincoln's South-Central Agricultural Lab, near Clay Center, NE in 2023 and 2024. Cover crop biomass means followed by the different letters within a year are significantly different using the Tukey's honestly signficant difference (HSD) test at $\alpha < 0.05$. Error bars represent the standard deviation.

Soybean stand count at V1 and V5 stages did not differ across CC treatments in 2024, likely due to sufficient rainfall (Table 3). Total rainfall within a week before and after soybean planting was 38.9 mm in 2024 (Figure 2), promoting optimal soybean emergence. There was no effect of herbicide programs on soybean stand count at any growth stage in either year. Results suggest that under adequate rainfall, spring-planted barley and oat CCs do not negatively impact soybean stand establishment. However, in years with low rainfall, supplemental irrigation following soybean planting may be beneficial to improve germination and emergence.

3.3 | Palmer amaranth density and biomass at CC termination and before POST herbicide application

Palmer amaranth density and biomass at CC termination, as well as Palmer amaranth biomass at the time of POST herbicide application, exhibited significant variation between the 2 years. Consequently, the data for each year were analyzed separately. Palmer amaranth density and biomass at the time of termination of barley and oat CCs were lower in 2023 compared to 2024. The reduced density and biomass in 2023 are likely due to lower rainfall leading up to CC termination compared to 2024 (Figure 2). Palmer amaranth germination is particularly sensitive to environmental conditions, with poor germination occurring under low rainfall and soil moisture conditions (Chahal et al., 2018; Franca, 2015; Jha & Norsworthy, 2009). Similar yearly variations in Palmer amaranth emergence patterns with varying rainfall have been documented by Jha and Norsworthy (2009) in Arkansas and by Franca (2015) in Illinois.

Small-grain CCs did not affect Palmer amaranth density and biomass at termination in 2023. Additionally, there was no significant impact of CCs on Palmer amaranth biomass at the time of POST herbicide application. This lack of effect may be due to the overall low biomass of barley and oat CCs in 2023, as weed suppression by living CCs is positively correlated with CC biomass accumulation (Holmes et al., 2017; Koehler-Cole et al., 2021). The lower Palmer amaranth density and biomass observed across all plots in 2023 can further confound the potential impact of CCs. In a multi-state study conducted across Illinois, Kansas, Pennsylvania, and Wisconsin, Nunes, Arneson, Wallace, et al. (2023) found that the effect of cereal rye CC was confounded under low densities of Palmer amaranth and waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer].

The effect of herbicide program was significant for Palmer amaranth density and biomass at CC termination in 2023. Palmer amaranth density (0.12 plants m^{-2}) was 94% lower, and biomass (0.001 g m^{-2}) was 98% lower in treatments where PRE herbicide was applied (PRE-only, PP, and PPR) compared to without PRE herbicide (nontreated and POST-only). Similar trends were noted for Palmer amaranth biomass at the time of POST herbicide application in 2023, with PRE herbicide applied plots (0.23 g m^{-2}) showing lower biomass than without PRE herbicide applied plots (9.86 g m^{-2}). A mixture of metribuzin and saflufenacil was used as a PRE herbicide; metribuzin is a photosystem II inhibitor, while saflufenacil is a protoporphyrinogen oxidase inhibitor, both effectively controlling Palmer amaranth (Legleiter & Johnson, 2013; Shyam et al., 2020).

In 2024, interaction between CCs and herbicide programs was significant for Palmer amaranth density and biomass at CC termination. The NCC—without PRE herbicide applied treatments—recorded the highest Palmer amaranth density (204.2 plants m^{-2}) and biomass (14.58 g m^{-2}) (Table 4). Palmer amaranth density and biomass at CC termination in 2024 were comparable between barley and oat plots without PRE herbicide (Table 4).

Palmer amaranth density at POST herbicide application did not vary across years; thus, data from both years were pooled. The interaction between CCs and herbicide program for Palmer amaranth density at POST herbicide application was significant. Palmer amaranth density at POST herbicide application in barley and oat CC treatments without PRE was 46% and 47% lower than NCC without PRE herbicide plots (415.1 plants m^{-2}), respectively (Table 4). Similarly, CCs interacted with herbicide programs for Palmer amaranth biomass at POST herbicide application in 2024. The highest Palmer amaranth biomass at POST herbicide application in 2024 was recorded in NCC—without PRE herbicide (245.5 g m^{-2}), followed by barley—without PRE herbicide treatments

TABLE 4 Palmer amaranth density and biomass at cover crop termination and biomass at post-emergence herbicide application in 2024, and density at post-emergence herbicide application averaged across 2023 and 2024 in a study to integrate spring-planted barley and oat cover crops for Palmer amaranth suppression in field studies conducted at University of Nebraska-Lincoln's South-Central Agricultural Lab, near Clay Center, NE.

Cover crop species	Herbicide program[a,b]	At cover crop termination		At post-emergence herbicide application	
		Density[c] (plants m^{-2})	Biomass[c] (g m^{-2})	Density[c] plants m^{-2}	Biomass[c] (g m^{-2})
Barley	Without pre-emergence	33.90b	1.12bc	225.2b	29.5b
	With pre-emergence	0.17c	0.002c	2.9c	0.05c
Oat	Without pre-emergence	22.20bc	1.40b	221.7b	25.2b
	With pre-emergence	0.08c	0.004c	4.6c	0.07c
No cover crop	Without pre-emergence	204.20a	14.58a	415.1a	239.31a
	With pre-emergence	1.70c	0.11c	8.9c	2.50c

[a]With pre-emergence included treatment which received pre-emergence herbicide: pre-emergence only, pre-emergence followed by post-emergence herbicide, and pre-emergence followed by post-emergence plus residual herbicide. Without pre-emergence included treatment which did not receive pre-emergence herbicide: nontreated, and post-emergence only.

[b]Mixture of metribuzin (472 g ai ha^{-1}) + saflufenacil (50 g ai ha^{-1}) was used as pre-emergence herbicide.

[c]Palmer amaranth density, and biomass mean followed by the same letter within a column are not significantly different using the Tukey's honestly signficant difference (HSD) test at $\alpha < 0.05$.

(29.5 g m^{-2}), and oat—without PRE herbicide (25.2 g m^{-2}) (Table 4).

Before termination, CCs actively compete with weeds, including Palmer amaranth, for resources such as nutrients (Haramoto, 2019; Sherman et al., 2020), soil moisture (Snapp et al., 2005), space, and sunlight (Wayman et al., 2015; Webster et al., 2016), thereby reducing weed emergence and growth. The ratio of red:far-red light also affects Palmer amaranth germination, with higher red:far-red light ratio promoting germination (Silva & Bagavathiannan, 2023). Chlorophyll in living CC plants absorbs red light, while far-red light can either be reflected or penetrate the canopy (Brodersen & Vogelmann, 2010; Roig-Villanova & Martínez-García, 2016). This results in a lower red:far-red light ratio reaching the soil surface, which negatively impacts Palmer amaranth germination (Silva & Bagavathiannan, 2023).

In 2024, inclusion of PRE herbicide with respective CC treatment further reduced Palmer amaranth density and biomass at CC termination and biomass at POST application compared to without PRE herbicide plots (Table 4). These results indicate that, while CCs were effective in reducing Palmer amaranth density and biomass, combining CCs with PRE herbicide resulted in an even greater reduction in both parameters. Improved Palmer amaranth control with combination of CC and PRE herbicide compared to sole CC has been observed across several states in the US (Nunes, Arneson, Wallace, et al., 2023; Nunes et al., 2024).

Palmer amaranth density and biomass at CC termination and at POST herbicide application were similar across PRE herbicide-treated plots, regardless of the CC treatment (Table 4). The lack of additional reduction in Palmer amaranth by CCs may be due to the strong efficacy of the PRE herbicides, which controlled the species effectively in all PRE herbicide-treated plots. A study by Hand et al. (2021) in Georgia found similar Palmer amaranth density in CC and NCC plots when PRE herbicide was used. Similar findings were reported by Burgos and Talbert (1996) in Arkansas, where CCs reduced redroot pigweed (*Amaranthus retroflexus* L.) density compared to NCC in nontreated plots but had similar densities in PRE herbicide-treated plots. While herbicide use resulted in similar Palmer amaranth density and biomass across CC and NCC treatments, CCs still play a valuable role in broader weed management goals. By reducing Palmer amaranth germination, CCs can decrease the number of germinating seeds and emerging seedlings exposed to PRE herbicides, thereby reducing the selection pressure for the evolution of herbicide resistance (Bunchek et al., 2020; Hand et al., 2021).

3.4 | Palmer amaranth density and biomass at 4 weeks after POST herbicide application

Palmer amaranth density and biomass at 4 weeks after POST herbicide application did not vary across the years, so data from both years were pooled for further analysis. CCs interacted with herbicide programs for Palmer amaranth density and biomass. NCC—nontreated treatment had the highest Palmer amaranth density (514.7 plants m^{-2}) and biomass (1224.4 g m^{-2}) at 4 weeks after POST herbicide application (Table 5). Palmer amaranth density and biomass in barley—nontreated treatment were similar to the NCC—nontreated plots (Table 5). Although oat-nontreated treatment had 80% lower density and 64% lower biomass than the NCC-nontreated plots. These findings indicate that oat CC was superior to barley CC for Palmer amaranth suppression, likely due to higher CC biomass production. Greater CC biomass amounts create a thicker, more consistent residue

TABLE 5 Palmer amaranth density and biomass at 4 weeks after post-emergence herbicide application averaged across 2023, and 2024 in a study to integrate spring-planted barley and oat cover crops for palmer amaranth suppression in field studies conducted at University of Nebraska-Lincoln's South-Central Agricultural Lab, near Clay Center, NE.

	Four weeks after post-emergence herbicide application		
Cover crop species	**Herbicide program[a]**	**Density[b] (plants m^{-2})**	**Biomass[b] (g m^{-2})**
Barley	Nontreated	408.5ab	1188.6ab
	PRE-only	75.5cde	36.9cd
	POST-only	232bc	152.3c
	PP	75.5cde	17.2cd
	PPR	51.5de	22.3cd
Oat	Nontreated	103.5cd	444.5b
	PRE-only	37.5de	62.8cd
	POST-only	116.5cd	51.9cd
	PP	40de	24.1cd
	PPR	17.5de	8.8d
No cover crop	Nontreated	514.7a	1224.4a
	PRE-only	35.2de	45.6cd
	POST-only	70de	72.9cd
	PP	62.8de	10.3d
	PPR	1.6e	0.99d

Abbreviations: POST-only, post-emergence only; PP, pre-emergence followed by post-emergence; PPR, pre-emergence followed by post-emergence + residual herbicide; PRE-only, pre-emergence only.

[a]Mixture of metribuzin (472 g ai ha^{-1}) + saflufenacil (50 g ai ha^{-1}) was used as pre-emergence herbicide, mixture of glufosinate (655 g ai ha^{-1}) + clethodim (136 g ai ha^{-1}) as post-emergence herbicide, and acetochlor (1257 g ai ha^{-1}) as residual herbicide.

[b]Palmer amaranth density and biomass mean followed by the same letter within a column are not significantly different using the Tukey's honestly signficant difference (HSD) test at $\alpha < 0.05$.

mulch after CC termination, effectively suppressing Palmer amaranth compared to lower CC biomass input (Dhanda et al., 2024; Nunes, Arneson, Wallace, et al., 2023; Nunes et al., 2024; Stephens et al., 2024).

In a meta-analysis, Kumar, Singh, Thapa, et al. (2025) reported that achieving a 50% reduction in *Amaranthus* spp. weed density and biomass requires CC biomass of 4.08 and 5.35 Mg ha^{-1}, respectively. Although oat CC biomass in this study was below those thresholds, the oat-nontreated treatment resulted in more than a 50% reduction in Palmer amaranth density and biomass compared to the NCC-nontreated treatment. This may be attributed to the extreme Palmer amaranth interference observed in the NCC—nontreated treatment. Similarly, Hand et al. (2021) reported a 75% reduction in Palmer amaranth density with 3388 kg ha^{-1} of cereal rye CC biomass without herbicide treatment under high infestation levels in Georgia compared to without CC and herbicide (196 plants m^{-2}).

Palmer amaranth density in barley-POST-only plots (232 plants m^{-2}) was almost three times higher than in the NCC-POST-only plots (70 plants m^{-2}) (Table 5). Similarly, oat-POST-only treatment also had numerically higher Palmer amaranth density than NCC-POST-only. This may be attributed to glufosinate applied POST which, as a contact herbicide, requires thorough spray coverage for optimal efficacy (Creech et al., 2016; Takano & Dayan, 2020). Residue from barley and oats likely hindered effective herbicide coverage over Palmer amaranth plants growing in/under CC residues, reducing glufosinate performance. Previous studies have shown that CC residues can intercept spray droplets, leading to reduced herbicide deposition and concentration in the soil (Nunes, Arneson, DeWerff, et al., 2023; Nunes, Arneson, Wallace, et al., 2023; Whalen et al., 2020).

3.5 | Soybean yield

Soybean yield did not vary across years. Thus, yield data were pooled for both years. Soybean yield did not differ among barley (2.74 Mg ha^{-1}), oat (2.92 Mg ha^{-1}), and NCC (2.79 Mg ha^{-1}); however, the effect of herbicide program was significant. Soybean yield for PPR herbicide program was 225% higher than nontreated (1.27 Mg ha^{-1}), 85% higher than POST-only (2.57 Mg ha^{-1}), and 60% higher than PRE-only (2.23 Mg ha^{-1}) herbicide program (Figure 4). The absence of a significant yield difference among CC treatments suggests that spring-planted barley and oat CCs did not negatively impact soybean grain yield. This aligns with previous findings

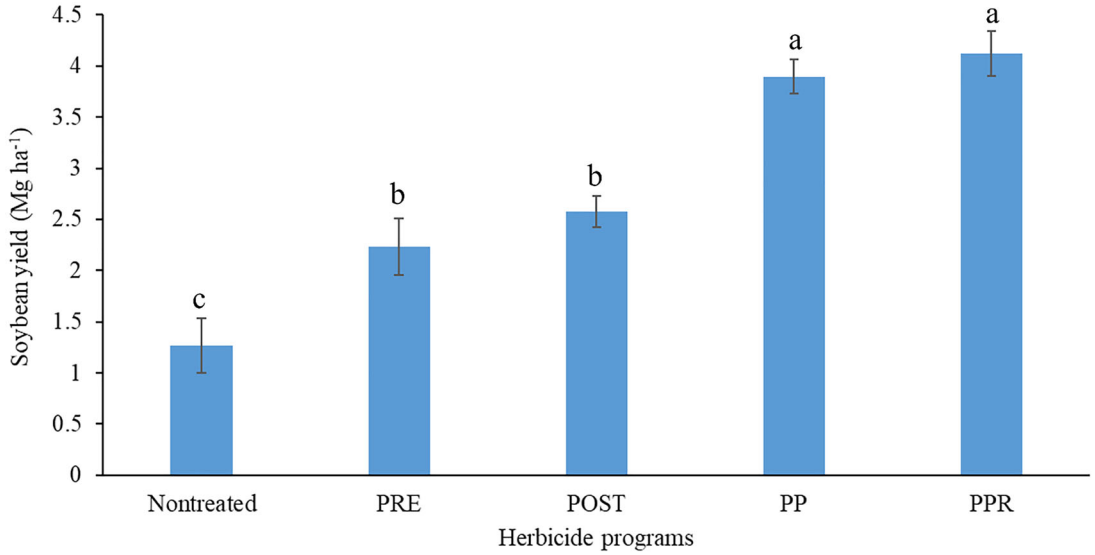


FIGURE 4 Soybean yield (kg ha^{-1}) averaged across 2023 and 2024 for different herbicide programs in a study to integrate spring-planted barley and oat cover crops for Palmer amaranth suppression in field studies conducted at University of Nebraska-Lincoln's South-Central Agricultural Lab, near Clay Center, NE. PRE, pre-emergence; POST, post-emergence; PP, pre-emergence followed by post-emergence; PPR, pre-emergence followed by post-emergence + residual. A mixture of metribuzin (472 g ai ha^{-1}) + saflufenacil (50 g ai ha^{-1}) was used as pre-emergence herbicide, mixture of glufosinate (655 g ai ha^{-1}) + clethodim (136 g ai ha^{-1}) as post-emergence herbicide, and acetochlor (1,257 g ai ha^{-1}) as residual herbicide.

that CCs, when properly managed, can be integrated into soybean cropping systems without reducing grain yield (Mischler et al., 2010; Nunes et al., 2024) and can even increase soybean yield in some cases (Kirkpatrick et al., 2023; Kumari et al., 2024a). However, the effectiveness of CC in improving soybean productivity may depend on factors such as CC species, soil moisture availability, and termination timing (Essman et al., 2023; Kumari et al., 2024a; Overmyer et al., 2023). In contrast, herbicide programs had a significant impact on soybean yield, underscoring the importance of effective weed control in maximizing soybean productivity. The higher yields observed in the PPR and PP programs compared to the PRE-only and POST-only treatments indicate that a season-long weed management strategy—integrating both PRE and POST herbicides—is essential for minimizing soybean yield loss.

Soybean yield mean followed by the same letter are not significantly different using the Tukey's HSD test at $\alpha < 0.05$. Error bars represent the standard deviation.

4 | CONCLUSION

The results of this study showed that spring-planted oat CC outperformed barley in terms of biomass production, which is crucial as higher biomass is associated with greater weed suppression. Oat produced 42% higher biomass in 2023 and 102% higher biomass in 2024 compared to barley. Biomass production by CCs was likely affected by precipitation and accumulated GDD. In the absence of herbicides, CCs substantially reduced Palmer amaranth density and biomass relative to NCC, highlighting the potential of spring-planted barley and oat CCs to reduce the number of Palmer amaranth plants exposed to herbicides, thereby decreasing selection pressure for herbicide resistance. Furthermore, Palmer amaranth density and biomass were lower when herbicides were integrated with CCs compared to CCs without herbicide. Therefore, integrating CCs with herbicide programs is recommended to enhance Palmer amaranth control and reduce the risk of the evolution of herbicide resistance.

The similar soybean yields among barley, oat, and NCC treatments indicate that spring-planted CCs before a month of planting soybean can be integrated into production systems without negatively affecting grain yield while suppressing Palmer amaranth. This is particularly important for farmers interested in cover cropping for soil health, erosion control, and weed suppression benefits. The significant impact of herbicide programs on soybean yield highlights the importance of season-long Palmer amaranth control that can reduce seedbank addition. The highest yields in the PPR and PP herbicide programs suggest that combining PRE and POST herbicides, with a residual component, is essential for minimizing yield losses due to Palmer amaranth competition.

Further research is warranted to quantify the influence of CC residues on the interception and retention dynamics of POST herbicides and to compare the relative efficacy of contact and systemic herbicides in residue-rich environments. Additionally, future investigations should focus on

optimizing herbicide application technologies and formulations to enhance residue penetration and maximize weed control efficacy in high-biomass CC systems.

AUTHOR CONTRIBUTIONS

Vipin Kumar: Data curation; formal analysis; investigation; methodology; validation; visualization; writing—original draft; writing—review and editing. **Annu Kumari**: Data curation; formal analysis. **Humberto Blanco-Canqui**: Writing—review and editing. **Samuel E. Wortman**: Writing—review and editing. **Saleh Taghvaeian**: Writing—review and editing. **Amit J. Jhala**: Conceptualization; project administration; resources; software; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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