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Integrating fall-planted cereal rye cover crop with herbicides for reducing Palmer amaranth seed production in soybean under planting green conditions

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Abstract

Cover crops are usually terminated prior to planting the cash crop; however, "planting green" is an alternative approach that allows growers to plant cash crop into an actively growing, green cover crop, which is then terminated after the establishment of the cash crop. The objectives of this study were (1) to determine whether planting soybean (*Glycine max* L. Merr.) into a standing cereal rye (*Secale cereale* L.) cover crop provides superior weed suppression compared to terminating cereal rye 2 weeks before soybean planting and (2) to evaluate an integrated effect of herbicide programs and cereal rye termination timing on Palmer amaranth (*Amaranthus palmeri* S. Watson) control, biomass, seed production, soybean grain yield, and benefit/cost ratio. Field experiments were conducted in southcentral Nebraska from 2020 to 2022. Preemergence (PRE) herbicide with 2 weeks after planting (WAP) termination of cereal rye provided >95% Palmer amaranth control in 2021 and varied from 88% to 98% in 2022 at 28 days after PRE. A PRE herbicide followed by (fb) late-postemergence (LPOST) herbicide with 2 WAP termination of cereal rye controlled *Palmer amaranth* 85%–92% in 2021 compared with 97%–99% control 28 days after LPOST herbicide application in 2022. Palmer amaranth density was higher with 2 WBP cereal rye termination compared with 2 WAP termination regardless of the herbicide program. PRE fb LPOST herbicide programs integrated with 2 WAP termination of cereal rye reduced Palmer amaranth seed production to less than 9100 seeds plant^{-1} in 2021 and no seed production in 2022. In 2021, terminating cereal rye 2 WAP played an integral role in controlling and reducing the density of Palmer amaranth; however, it had noticeable impact on soybean yield compared to terminating 2 WBP. In 2022, hail and windstorm had a confounding effect on soybean stand and yield.

Abbreviations: DAPRE, days after pre-emergence; DAT, days after treatment; EPOST, early post-emergence; POST, post-emergence; PRE, pre-emergence; WAP, weeks after planting; WBP, weeks before planting.

1 | INTRODUCTION

Soybean (*Glycine max* L. Merr.) is the second most grown crop in Nebraska, with an estimated 2.2 million ha planted in 2021 (USDA-ERS, 2021). Soybean production in Nebraska ranked fifth in the United States, with production of ∼9.5 billion kg in 2021 (USDA-ERS, 2021) and an average soybean yield of 4237 kg ha^{-1} (USDA-NASS, 2021). One of the major obstacles to optimum soybean yield is competition with weeds (Vivian et al., 2013). Early-season weed control in soybean is required to achieve optimum grain yields (Hock et al., 2005). If weeds are not controlled in soybean from soybean emergence up to the beginning of seed formation (R5) stage, yield reductions in the range of 8%–55% have been reported (Van Acker et al., 1993).

To combat weed control issues, multiple herbicide-resistant soybean has been developed and rapidly adopted by growers (de Sanctis, Knezevic, et al., 2021; McDonald et al., 2021). This technology began with glyphosate-resistant soybean to allow glyphosate applications during the growing season; however, the evolution of glyphosate-resistant weeds has created a challenge for growers (Striegel & Jhala, 2022). For example, six broadleaf weeds have evolved resistance to glyphosate in Nebraska as of 2023, including common ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), horseweed (*Erigeron canadensis* L.), kochia [*Bassia scoparia* (L.) A.J. Scoot)], Palmer amaranth (*Amaranthus palmeri* S. Watson), and waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Saueer] (Heap, 2024). Several producers control weeds in soybean in the early growing season by applying PRE herbicides (Sarangi & Jhala, 2018): for example, a statewide survey in 2015 indicated that 59% of soybean producers use soil-applied residual herbicides to control glyphosate-resistant weeds in Nebraska (Sarangi & Jhala, 2018). Weed competition with crops can reduce crop growth and yield (Teasdale & Mohler, 2000), and if weeds are controlled during the early season, the crops can close their canopy and compete with late-emerging weeds (Rajcan & Swanton, 2001). One specific weed control method does not often provide complete control of weeds (Datta & Knezevic, 2013), and a multidisciplinary approach (defined as integrated weed management) is imperative for reducing herbicide selection pressure (Bunchek et al., 2020) and weed seed bank addition (Striegel & Jhala, 2022).

The use of cover crops can be dated back over millennia; however, the adoption of cover crops has greatly increased in the last two decades (Blanco-Canqui et al., 2022). The conventional practice of cover crop establishment occurs during the fallow period in the winter in the Midwestern United States. Cover crops have been known to suppress weeds through both competition (Mirsky et al., 2013) and allelopathic effects (Hutchinson & McGiffen, 2000); therefore, cover crops can play an integral role in integrated weed management strategies (Rueda-Ayala et al., 2015). The integration of cover crops in Midwestern crop rotations has increased in the past decade, and Nebraska has a cover crop adoption rate of 2.5% per year, ranked fifth among states in the United States (USDA-ERS, 2021). The integration of cover crops in row crop production can provide many benefits, such as weed suppression, soil erosion reduction, nutrient cycling, and improvement in water quality and soil health (Snapp et al., 2005). However, short-term economic return from cover crops is lacking and has led to slow adoption. Immediate economic return in weed management cost could lead to more adoption of cover crops (Nicholas et al., 2020), and reducing herbicide selection pressure is a potential benefit that should be considered when assessing the long-term net returns of integrating cover crops in corn–soybean cropping systems in the Midwest (Bunchek et al., 2020; Grint, Arneson, Arriaga, et al., 2022).

Core Ideas

- Planting green is to plant a cash crop into an actively growing, green cover crop.
- Herbicide programs and cereal rye termination timings were evaluated for weed control in soybean.
- Terminating cereal rye 2 weeks after planting was an integral part of Palmer amaranth suppression.
- Soybean yield was reduced when terminating cereal rye 2 weeks after soybean planting.

In recent years, growers have started to plant cash crops such as soybean directly into actively growing cover crops (known as “planting green”), then terminate the cover crop at the time of planting (Grint, Arneson, Oliveira, et al., 2022) or a few days after planting (Reed et al., 2019). Planting green is in contrast to the dominant practice of terminating cover crops at least 2 weeks prior to planting (Oliveira et al., 2019). This practice could provide much-needed early-season weed suppression if cover crops produce abundant biomass (Grint, Arneson, Arriaga, et al., 2022). According to a survey conducted in 2017, the most commonly grown cover crop in Nebraska is cereal rye (*Secale cereale* L.) (Butts & Werle, 2017), which is due to its winter hardiness, high biomass production, and high germination rate (Curran, 2010). The recommended seeding rate of cereal rye is 67 kg ha^{-1} (Lesoing, 2019); however, growers usually drill cereal rye at 33–45 kg ha^{-1} to reduce the cost of seeds (Grubinger, 2021). The emergence and growth of summer annual weeds such as Palmer amaranth and waterhemp [*A. tuberculatus* (Moq.) J.D. Sauer] can be suppressed if cover crop is actively growing at the time of planting and terminated later (Bezuidenhout et al., 2012). Cover crop residues can also create a competitive environment and conserve soil moisture (Mirsky et al., 2013; Teasdale & Mohler, 1993). An adequate amount of cover crop biomass (around 4600 kg ha^{-1}) can sufficiently suppress weeds (Finney et al., 2016). However, the effect of planting green on crop yield has been variable: some studies reported that planting green can reduce corn yield (Grint, Arneson, Arriaga, et al., 2022) but not soybean yield (Montgomery et al., 2018; Reed et al., 2019), and Osipitan et al. (2018) reported no effect when planting green was used for weed suppression.

It is recommended not to rely solely on cover crops for season-long weed control in agronomic crops (Wiggins et al., 2015), and the integration of herbicides and planting green needs to be researched alongside an analysis of benefit/cost ratio and soybean yield. The assessment of the interactions between soil-applied PRE herbicides and cereal rye is vital to the integration of planting green. Additionally, the application of PRE and POST herbicides along with planting green needs to be assessed to further understand the level of weed control provided by their integration. Producer hesitancy to adopt cover crop varies and can be due to the policy-based barrier that crop insurance prevents the use of cover crops (Connor et al., 2021), that cover crops have limited or no effect on weed control (Vincent-Caboud et al., 2017), that cover crops cause soil moisture depletion (Reed et al., 2019; Williams et al., 2000), the cost of new equipment and labor expenses (Lee & McCann, 2019), and the lack of immediate return on investment (Nicholas et al., 2020). Further research could create confidence among producers who may wish to adopt cover crops or more specifically adopt the practice of planting green.

The use of PRE residual herbicide with multiple sites of action applied at planting is one of the foremost recommendations for the control of glyphosate-resistant weeds such as Palmer amaranth and waterhemp in soybean (de Sanctis, Barnes, et al., 2021). Applying PRE herbicides on standing cereal rye may affect the performance of the residual herbicides because cover crop residue may intercept some of the herbicide. Whalen et al. (2020) reported that the fate of some soil-applied residual herbicides may be affected by cover crop stand and biomass amount. Therefore, more research is needed to determine the performance of residual herbicides for the control and seed production of Palmer amaranth when applied on standing cereal rye compared with cereal rye terminated 2 weeks before planting soybean. The objectives of this research were (1) to assess whether planting soybean into a standing cereal rye cover crop provides superior weed suppression compared to terminating cereal rye 2 weeks before soybean planting and (2) to evaluate the integrated effect of herbicide programs and cereal rye termination timing on Palmer amaranth control, density, seed production, soybean grain yield, and cost/benefit ratio in a no-till production system.

2 | MATERIALS AND METHODS

2.1 | Study location and cereal rye/soybean planting

This study was conducted at the University of Nebraska–Lincoln's South-Central Agricultural Lab near Harvard, NE (40.52˚N, 98.05˚W), during 2020–2022. The soil at the experimental site was silt loam (58% silt, 17% sand, and 25% clay), with a soil organic matter content of 3.4% and pH 6.8. The site was under a lateral irrigation system. The experiment was established after corn harvest in 2020 and after soybean harvest in 2021. The study was conducted in a no-till cropping system with crop residue left on the surface post-harvest through the following growing season. The most common weed at the research site was Palmer amaranth. Cereal rye (Elbon cereal rye, GreenCover Seed) was drilled after corn harvest in the fall of 2020 and soybean harvest in the fall of 2021 with 20.32-cm row spacing, 3.2-cm seeding depth, and a seeding rate of 95.32 kg ha^{-1}. Glyphosate-/dicamba-resistant soybean (NK S30-M9X) with a 2.7 maturity group at a rate of 330,000 seeds ha^{-1} at a depth of 3.0 cm and 76.2 cm width between rows was planted on May 12, 2021, and May 18, 2022. Field experiments were conducted under linear irrigation; however, irrigation was not applied for cereal rye emergence in early spring. The irrigation was started in June in both years.

2.2 | Experimental design and treatments

The experimental design was a factorial randomized complete block design with four replications. The three factors were cereal rye termination timing, herbicide application timing, and herbicide. Factor 1: Termination of cereal rye occurred 2 weeks before planting (WBP) or 2 weeks after planting (WAP). Factor 2: Herbicide application timings consisted of pre-emergence (PRE), early POST (EPOST), and PRE followed by (fb) late POST (LPOST). Factor 3: PRE herbicides (Authority Supreme, Fierce MTZ, and Zidua PRO), early-POST herbicides (XtendiMax + Roundup PowerMax, Prefix, and XtendiMax + Warrant), and a PRE (Authority Supreme, Fierce MTZ, or Zidua PRO) followed by a late-POST herbicide (XtendiMax) (Table 1). In addition, a non-treated control (cereal rye present), a weed-free control, and weed and cereal rye present/absent treatments were included for comparison (Table 1). The non-treated control had cereal rye present due to a missed termination in the fall of both years, but the presence of cereal rye throughout the growing season allows it to be closely compared to a true non-treated control with weeds present during the entire growing season.

TABLE 1 Herbicide programs, application timings, and rates used for weed control in dicamba-/glyphosate-resistant soybean in field experiments conducted near Harvard, NE, in 2021 and 2022.

Herbicide program	Timing	Rate (g a.i./ae ha^{-1})	Trade name	Manufacturer[a]	Adjuvants[b]
Nontreated control					
Weed-free control: chlorimuron ethyl/sulfentrazone Dicamba + acetochlor	PRE EPOST	245 560 + 840	Authority XL XtendiMax + Warrant	FMC Bayer	DRA + WC
Weed- and cereal rye-free control: chlorimuron ethyl/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	Fall PRE EPOST	245 + 1260 fb 1260 + 556 fb 560	Authority XL + Roundup PowerMax fb Roundup PowerMax + Fierce MTZ fb XtendiMax	FMC + Bayer + Valent + Bayer	COC + AMS + DRA + WC
Pyroxasulfone/sulfentrazone	PRE	292	Authority Supreme	FMC	–
Flumioxazin/pyroxasulfone/metribuzin	PRE	475	Fierce MTZ	Valent	–
Imazethapyr/saflufenacil/pyroxasulfone	PRE	215	Zidua PRO	BASF	–
Dicamba + glyphosate	EPOST	560 + 1260	XtendiMax+ Roundup PowerMax	Bayer	DRA + WC
Fomesafen/*S*-metolachlor	EPOST	1480	Prefix	Syngenta	NIS
Dicamba + acetochlor	EPOST	560 + 840	XtendiMax+ Warrant	Bayer	DRA + WC
Pyroxasulfone/sulfentrazone fb dicamba	PRE fb LPOST	292 + 560	Authority Supreme fb XtendiMax	FMC, Bayer	DRA + WC
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	PRE fb LPOST	556 + 560	Fierce MTZ fb XtendiMax	Valent, Bayer	DRA + WC
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	PRE fb LPOST	215 + 560	Zidua PRO fb XtendiMax	BASF, Bayer	DRA + WC

Abbreviations: ae, acid equivalent; AMS, ammonium sulfate (N-Pak AMS Liquid, Winfield United, LLC.); ai, active ingredient; COC, crop oil concentrate; DRA, drift reducing agent (Intact, Precision Laboratories); EPOST, early postemergence; fb, followed by; LPOST, late postemergence; NIS, non-ionic surfactant (Induce, Helena Chemical); WC, water conditioner (Class Act Ridion, Winfield United, Arden Hills, MN).

[a]Bayer CropScience; BASF Corporation; FMC Corporation; Syngenta Crop Protection, LLC.; Valent USA Corporation.

[b]AMS at 3% vol/vol, DRA at 0.5% vol/vol, NIS at 0.25%, and WC at 1% vol/vol were mixed with herbicide treatments based on label recommendations.

The individual plot was 3 m wide and 9 m long with four soybean rows spaced 0.76 m apart. Cereal rye termination was accomplished using glyphosate at 1260 g acid equivalent (ae) ha^{-1} + crop oil concentrate 1% v/v + ammonium sulfate 3% v/v at 2 WBP and 2 WAP soybean. Soybean plants had not emerged when cereal rye was terminated 2 WBP. In 2021, soybean plants were at the V1 growth stage when cereal rye terminated 2 WAP and were at the VC growth stage in 2022. Herbicides were applied using a handheld CO_2-pressurized backpack sprayer equipped with AIXR 110015 flat-fan nozzles (TeeJet Technologies, Spraying Systems Co.) spaced 51 cm apart and calibrated to deliver 140 L ha^{-1} at 276 kPa at a constant speed of 4.8 km h^{-1}. Dicamba-containing treatments were applied with TTI 11005 flat-fan nozzles (TeeJet Technologies). PRE herbicides were applied 2 days after soybean planting, early POST herbicides were applied 31 days after pre-emergence (DAPRE), and late POST herbicides were applied 40 DAPRE herbicide application. The growth stage of cereal rye was determined using the Zadoks scale (Zadoks et al., 1974).

2.3 | Data collection

Weed control was estimated through visual observations of injury and growth suppression at 14, 28, and 42 days after treatment (DAT), except for 42 days after PRE fb LPOST, on a scale of 0%–100%, where 0% refers to no weed control and 100% refers to complete weed control. The density of observed weed species was recorded from two randomly placed 0.5-m^2 quadrats $plot^{-1}$ between the two middle soybean rows at the time of weed control data collection. Similarly, weed biomass (0.5 m^2) was collected from all species on the day of early POST (EPOST) application and 21 days after early POST (DAEPOST) by clipping plants to the soil surface, drying them at 64°C for 10 days until they reached a constant mass, then weighing each sample.

Cereal rye biomass was collected at each termination timing from two randomly placed 0.5-m^2 quadrats per plot. Planting occurred during the same week in 2021 and 2022; therefore, biomass collection at each termination timing was taken within the same week in both years. The growth stage of cereal rye was determined using the Zadoks scale (Zadoks et al., 1974). Cereal rye was at the 21–32 growth stage when terminated 2 WBP compared with the 49–59 growth stage in the 2 WAP termination. Palmer amaranth estimated seed production was collected by sampling inflorescence of five female plants (when available) from the middle two rows. Seeds were separated and cleaned from the inflorescence (Kaur et al., 2024). To record estimated seed production, 1000 seeds were counted from each sample and mass weighed, after which the entire sample mass was taken, and estimations were made from the 1000 seed weight. Soybean was harvested from the middle two rows with a plot combine, and yields were adjusted to 13% moisture content and converted into kg ha^{-1}.

2.4 | Economic analysis

Economic analysis was used to assess weed management programs for profitability, and gross profitability was calculated for each program using the following equation (Sarangi & Jhala, 2019):

$$\text{Gross Profit (US\$)} = (R - W), \tag{1}$$

where R is the gross revenue calculated by multiplying the soybean yield for each treatment by the average price of soybean in Nebraska in 2021 and 2022 and W is the weed management program cost, including the cost of herbicide, adjuvants, and application. Benefit/cost ratio for each program was calculated using the following equation (Sarangi & Jhala, 2019):

$$\text{Benefit/Cost Ratio (US\$/US\$)} = \frac{(R_T - R_C)}{W}, \tag{2}$$

where R_T is the gross revenue, R_C is the gross revenue for the non-treated control, and W is the cost of the weed management program, including the cost of herbicide, adjuvant, and application (Sarangi & Jhala, 2019). The gross revenue was calculated by multiplying soybean grain yield for each treatment by an average price ($0.51 kg ha^{-1}) received for soybean in the spring 2022 and October 2022. Herbicide and custom application prices were sourced from three independent commercial sources in Nebraska (Central Valley Ag Cooperative, Frontier Cooperative, and Nutrien Ag Solutions) and averaged out as follows: PRE herbicide at US$17.30 ha^{-1}, non-dicamba-containing POST herbicide at US $18.94 ha^{-1}, and dicamba-containing POST herbicide at US $31.71 ha^{-1}.

2.5 | Statistical analysis

Statistical analysis was performed using PROC GLIMMIX procedure in SAS statistical software 9.4. The interaction of year × treatment was significant for all experimental variables; thus, years were not combined for all variables. In the single-year models, herbicide type and timing and termination timing were considered a fixed effect that was nested within year. The replication nested within year was considered a random effect. Discrete variables (e.g., soybean yield, Palmer amaranth seed production, cereal rye biomass, weed biomass, and weed density) were fit into a mixed linear model with gaussian (link = "density") error distributions. Continuous variables (e.g., weed control) were fit to a linear mixed effect model with gaussian (link = "density") error distributions (Striegel & Jhala, 2022). Multiple iterations were performed for each model of each variable, and there was assumed to be a normal distribution on all variables, except for weed biomass, which was log transformed and then back transformed for mean comparison. For both types of variables, the final model was selected based on Akaike information criterion values, square root, log(x+1), and logit transformations with gaussian error distributions.

Before conducting ANOVA, normality was tested by PROC UNIVARIATE, and then ANOVA was performed using Type III tests. When differences were indicated for treatment effects, multiple comparisons were made using Tukey–Kramer's LSD test with a 95% confidence interval, and least significant (LS) means were compared. To determine the significance of cereal rye termination timings, contrast analyses were performed comparing the termination timing of 2 WBP to 2 WAP. Likewise, to determine herbicide type differences and significances, contrast analyses were performed to compare herbicide timing of PRE-only to EPOST-only and PRE fb LPOST. Herbicide types were subjected to contrast analyses to determine significance by comparing each herbicide within each herbicide timing and termination timing.

3 | RESULTS AND DISCUSSION

Year-by-treatment interaction for Palmer amaranth (p = 0.0002) control estimates were significant; therefore, data are presented by year. Cereal rye termination timing was significant (p = 0.0007), resulting in the separation of termination timings when analyzing control and density of Palmer amaranth ($p < 0.0001$). Herbicide ($p < 0.0001$) and herbicide application timings ($p < 0.0001$) were significant for Palmer amaranth ($p < 0.0001$) control. Year-by-treatment interaction for soybean yield was significant ($p < 0.0001$); therefore, data are presented by year. Hail and windstorms in June 2022 reduced soybean stand up to 70% in plots where cereal rye was terminated 2 WBP compared with up to 15% soybean stand reduction in plots where cereal rye was terminated 2 WAP (data not shown).

TABLE 2 Monthly mean air temperature and total precipitation during the 2021 and 2022 soybean growing seasons (May–September) and cereal rye growing seasons (November–March) along with the 30-year average at the research site near Harvard, NE.

Mean air temperature, ˚C				Cumulative precipitation, mm		
Month	2021	2022	30-year average	2021	2022	30-year average
May	15.7	16.2	16.4	102.1	105.2	135.6
June	23.1	22.8	22.6	145.3	160.8	241.7
July	23.3	24.0	24.7	194.1	261.1	347.1
August	23.5	22.7	23.4	252.0	277.6	444.9
September	21.1	21.6	18.9	287.8	308.6	502.1

Mean air temperature, ˚C					Monthly precipitation, mm			
Month	2020	2021	2022	30-year average	2020	2021	2022	30-year average
November	7.3	6.6		4.3	41.7	10.4		34.8
December	0	2.3		−4.1	15.7	6.4		24.6
January		−0.9	−3.7	−3.4		33.5	8.4	14.7
February		−9.6	−2.6	−7.1		15.5	0	20.8
March		7.2	4.2	4.6		162.56	35.8	33.5

Note: Data were obtained from National Oceanic and Atmospheric Administration (NOAA, 2022).

3.1 | Temperature and precipitation

Growing conditions differed between the 2021 and 2022 growing seasons. A drier May than average was recorded in both years, but rainfall events in 2022 pushed planting a week later than 2021. In both years, soybean planting occurred within the normal planting dates for the study region in Nebraska. During 2022, the irrigation system was not available until July 1 due to the installation of a new linear irrigation system at the site; therefore, soybean establishment in 2022 relied on precipitation (Table 2). The cumulative precipitation was 287 mm in 2021 and 309 mm in 2022, which is below the 30-year average. In 2021 and 2022, the average temperature was 21˚C throughout the growing season, which is equivalent to the 30-year average for the research site. A hail and windstorm event occurred on June 7, 2022, when soybean was at the V1–V2 growth stage, impacting soybean plant stand, growth, and development. In fall 2020 and winter 2021, there was adequate rain and snowfall that resulted in adequate stand of cereal rye; however, average rain and snow accumulation in fall 2021 and below-average snow in winter 2022 hindered the optimum emergence of cereal rye in fall 2021 and winter 2022, and a viable stand was not successful until spring 2022.

3.2 | Cereal rye biomass production

Cereal rye biomass was affected by termination timing. In 2021, cereal rye produced 1950 kg ha^{-1} biomass at 2 WBP termination compared with greater than six times biomass of 12,775 kg ha^{-1} at 2 WAP termination (Figure 1). Similarly, in 2022, cereal rye biomass was 2750 kg ha^{-1} at 2 WBP termination compared with 11,290 kg ha^{-1} at 2 WAP termination. Grint, Arneson, Arriaga, et al. (2022) reported that cereal rye biomass increased greater than six times when terminated 2 weeks after planting soybean compared to cereal rye terminated at soybean planting in field studies conducted in Wisconsin. Similar results of cereal rye biomass accumulation at different termination timings have been reported (Keene et al., 2017; Ruis et al., 2017). Some studies revealed that a mixture of cover crop species leads to better weed suppression (Döring et al., 2012; Linares et al., 2008); however, studies in last 10 years conclude that cover crop biomass production is essential for weed suppression rather than a cover crop mixture (Finney et al., 2016; MacLaren et al., 2019; Smith et al., 2014).

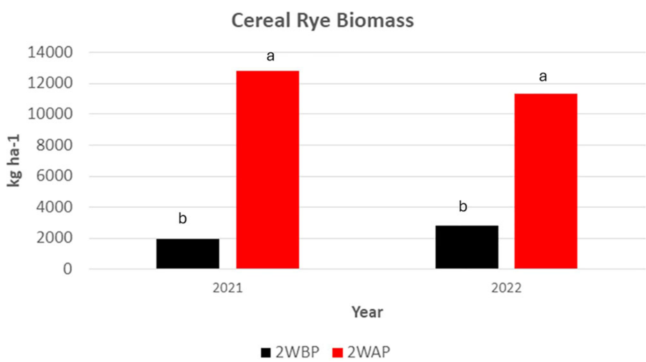

FIGURE 1 Effect of termination timing of cereal rye on cumulative biomass in 2021 and 2022 in a study conducted near Harvard, NE. Cereal rye termination timings: 2 weeks before planting (WBP), 2 weeks after planting (WAP), and no termination timing (NA). Means presented for each bar with no common letter(s) are significantly different according to Tukey–Kramer's LSD test at $p \leq 0.05$.

TABLE 3 Effect of cereal rye termination timing and preemergence (PRE) herbicides on Palmer amaranth control in dicamba-/glyphosate-resistant soybean at 14, 28, and 42 DAPRE, days after preemergence herbicide application (DAPRE) in field experiments conducted near Harvard, NE, in 2021 and 2022.

Herbicide program	Cereal rye termination	Application timing	Rate (g ae or a.i. ha^{-1})	Palmer amaranth control[a] (%)					
				14 DAPRE		28 DAPRE		42 DAPRE	
				2021	2022	2021	2022	2021	2022
Nontreated (cereal rye present)	NA	NA		85 a	99 a	65 b	50 c	67 b	70 b
Weed-free control: dicamba + acetochlor	NA	EPOST	560 + 840	99 a	99 a	96 a	98 a	96 a	92 a
Weed and cereal rye free control: pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	NA	Fall, PRE fb EPOST	245 + 1260 fb 1260 + 556 fb 560	99 a	97 a	97 a	93 a	99 a	90 a
Pyroxasulfone/sulfentrazone	2 WBP	PRE	292	85 a	99 a	79 a	56 c	98 a	59 bc
Pyroxasulfone/sulfentrazone	2 WAP	PRE	292	98 a	99 a	99 a	88 ab	99 a	53 bc
Flumioxazin/pyroxasulfone/metribuzin	2 WBP	PRE	475	99 a	97 a	98 a	80 ab	99 a	73 b
Flumioxazin/pyroxasulfone/metribuzin	2 WAP	PRE	475	99 a	99 a	95 a	98 a	99 a	60 bc
Imazethapyr/saflufenacil/pyroxasulfone	2 WBP	PRE	215	95 a	89 a	83 a	69 bcbc	91 a	46 c
Imazethapyr/saflufenacil/pyroxasulfone	2 WAP	PRE	215	99 a	97 a	99 a	89 ab	99 a	73 b

Note: Means presented within each column with no common letter(s) are significantly different according to Tukey–Kramer's LSD test at $p \leq 0.05$.

Abbreviations: fb, followed by; NA, not applicable; WAP, weeks after planting; WBP, weeks before planting.

[c]Year-by-treatment interaction for Palmer amaranth control at 14, 28, and 42 DAPRE was significant; therefore, data were separated for both years.

3.3 | Soybean stand count

Soybean stand counts were made 2 weeks after emergence in both years and were not different between years ($p = 0.07821$). The three different terminations of cereal rye cover crop were compared when evaluating stand counts: no cover crop (cereal rye free), 2 WBP termination, and 2 WAP. The no cover crop treatment had a mean count of 322,916 soybean plants ha^{-1}, and the 2 WBP and 2 WAP terminations had 320,333 and 310,000 plants ha^{-1}, respectively, without difference among them (data not shown). This indicates that soybean emergence and plant stand were not affected due to cereal rye biomass even when terminated 2 WAP.

3.4 | Palmer amaranth control

PRE herbicides evaluated in this study controlled Palmer amaranth 85%–99% 14 DAPRE (Table 3). Although statistically similar with 2 WBP cereal rye termination, 2 WAP termination combined with PRE herbicide controlled Palmer amaranth 97%–99% 14 DAPRE. The greater amount of biomass from cereal rye due to 2 WAP termination contributed to greater Palmer amaranth control 14 DAPRE, which has been observed in other studies (Bunchek et al., 2020; Montgomery et al., 2018; Schramski et al., 2021; Wiggins et al., 2017). Palmer amaranth control varied by year and cereal rye termination timing at 28 DAPRE. The termination of cereal rye 2 WBP paired with PRE herbicides provided 79%–98% control of Palmer amaranth in 2021, whereas 2 WAP termination of cereal rye with PRE herbicides controlled Palmer amaranth 95%–99%. Similar results have been reported where Palmer amaranth is suppressed by soil-applied residual herbicides and late terminated cover crop (Perkins et al., 2021). In 2022, there was a consistent decline in Palmer amaranth control, except for the flumioxazin/pyroxasulfone/metribuzin with 2 WAP termination of cereal rye (95%–98% control). PRE herbicides provided 80%–99% control of Palmer amaranth 42 DAPRE in 2021. Although not statistically different, 2 WBP termination of cereal rye controlled Palmer amaranth 80%–99% compared to consistent control of 98%–99% with 2 WAP termination. In 2022, a consistent trend of decreased control compared with 2021 was observed. Herbicides-applied PRE with 2 WBP termination of cereal rye provided 46%–73% control of Palmer amaranth. Montgomery et al. (2018) reported that at least one POST herbicide application was needed to obtain the highest weed control and soybean yield.

Palmer amaranth control was variable in EPOST herbicide programs compared with the PRE-only herbicide program. Palmer amaranth control was 11%–50% when EPOST herbicides were paired with 2 WBP termination of cereal rye 14 DAEPOST in 2021 (Table 4). In contrast, EPOST herbicides with 2 WAP termination of cereal rye provided 79%–98% control of Palmer amaranth. At 28 DAEPOST, EPOST herbicides and 2 WBP termination timing controlled Palmer amaranth

TABLE 4 Effect of cereal rye termination timing and early postemergence (EPOST) herbicide programs on Palmer amaranth control at 14, 28, and 42 days after early postemergence herbicide application (DAEPOST) in dicamba-/glyphosate-resistant soybean near Harvard, NE, in 2021 and 2022.

Herbicide program	Cereal rye termination	Application timing	Rate (g ae or a.i. ha^{-1})	Palmer amaranth control[a] (%)					
				14 DAEPOST		28 DAEPOST		42 DAEPOST	
				2021	2022	2021	2022	2021	2022
Nontreated control (cereal rye present)	NA	NA	NA	48 b	77 b	45 c	63 b	59 c	55 b
Weed-free control: dicamba + acetochlor	NA	EPOST	560 + 840	96 a	92 a	96 a	98 a	63 c	87 a
Weed- and rye-free control: pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	NA	Fall, PRE fb EPOST	245 + 1260 fb 1260 + 556 fb 560	99 a	90 ab	97 a	67 b	99 a	72 ab
Dicamba + glyphosate	2 WBP	EPOST	560 + 1260	50 b	86 a	68 c	66 b	80 abc	63 b
Dicamba + glyphosate	2 WAP	EPOST	560 + 1260	93 a	97 a	93 ab	93 a	71 b	99 a
Fomesafen/*S*-metolachlor	2 WBP	EPOST	1480	11 c	96 a	14 d	94 a	23 d	94 a
Fomesafen/*S*-metolachlor	2 WAP	EPOST	1480	79 ab	84 b	73 bc	96 a	69 bc	95 a
Dicamba + acetochlor	2 WBP	EPOST	560 + 840	50 b	99 a	60 c	99 a	86 ab	99 a
Dicamba + acetochlor	2 WAP	EPOST	560 + 840	98 a	99 a	95 a	99 a	97 a	99 a

Note: Means presented within each column with no common letter(s) are significantly different according to Tukey–Kramer's LSD test at $P \leq 0.05$.
Abbreviations: fb, followed by; NA, not applicable; PRE, preemergence; WAP, weeks after planting; WBP, weeks before planting.
[a]Year-by-treatment interaction for Palmer amaranth control 14, 28, and 42 DAPRE was significant; therefore, data were separated for both years.

14%–68% in 2021 and 66%–99% in 2022. Palmer amaranth control 42 DAEPOST varied between years. EPOST herbicides and 2 WAP termination of cereal rye provided 69%–97% control of Palmer amaranth in 2021 at 42 DAEPOST and 95%–99% control in 2022.

Palmer amaranth control varied between years in PRE fb LPOST herbicide programs regardless of cereal rye termination timing (Table 5). PRE fb LPOST herbicide programs with 2 WBP termination of cereal rye controlled Palmer amaranth 60%–97% at 14 DALPOST. PRE fb LPOST herbicide programs with 2 WAP termination of cereal rye provided 63%–99% control of Palmer amaranth at 14 DALPOST and 85%–99% control at DALPOST in both years. The PRE fb LPOST herbicide program with cereal rye termination 2 WAP provided better control of Palmer amaranth in this study compared to the same herbicide program with cereal rye terminated 2 WBP. This might be due to the additional biomass from the 2 WAP cereal rye termination that suppressed weeds earlier in the season, which is critical for soybean. The results of this study are similar to literature reporting the termination of the cover crop after crop planting provides better weed suppression (Grint, Arneson, Oliveira, et al., 2022; Rosa et al., 2021). Reduced control of Palmer amaranth in PRE fb LPOST herbicides with 2 WBP termination of cereal rye in 2022 can be attributed to the hail and windstorm events in that year, which reduced soybean stand and leaf count. This led to a later canopy or absence of a canopy, resulting in reduced competition against weeds for light, water, and other resources (Nordby et al., 2007).

3.5 | Palmer amaranth density

Palmer amaranth density and control were highly correlated (−0.8607678) (data not shown). Year-by-herbicide treatment ($p < 0.0001$) and herbicide treatment by cereal rye termination timings were significant ($p < 0.0002$). The treatment-by-herbicide and herbicide timing were significant ($p < 0.0001$) for both factors. The termination of cereal rye 2 WAP with herbicide programs reduced the density of Palmer amaranth. PRE herbicides with cereal rye termination 2 WAP reduced Palmer amaranth density to 0 and 3 plants m^{-2} in 2021 and 2022, respectively. The most effective program for reducing Palmer amaranth density was a PRE fb LPOST herbicide program (1 plant m^{-2}) for both years. A PRE-only herbicide combined with either termination timing of cereal rye was not effective for season-long weed control, especially in the case of Palmer amaranth, which has multiple emergence patterns and can emerge until the end of August in southcentral Nebraska (Chahal et al., 2021). Palmer amaranth density was relatively higher in each herbicide program with 2 WBP cereal rye termination compared with 2 WAP termination. A study in Wisconsin reported that cereal rye cover crop terminated at crop planting reduced weed density by 31% and reduced weed biomass by 61% compared with no cover crop (Grint, Arneson, Oliveira, et al., 2022). An observation of reduced density in the 2 WAP termination in combination with herbicides alludes to less variability when attempting to reduce Palmer amaranth density. Such reduction in Palmer amaranth density has been observed in other studies (Montgomery et al., 2018; Wiggins et al., 2015, 2016, 2017).

TABLE 5 Effect of cereal rye termination timing and preemergence (PRE) followed by (fb) late-postemergence (LPOST) herbicide programs on Palmer amaranth control at 14, 28, and 42 days after preemergence herbicide application (DAPRE) and 14 and 28 days after late postemergence herbicide application (DALPOST) in dicamba-/glyphosate-resistant soybean near Harvard, NE, in 2021 and 2022.

				Palmer amaranth control[a] (%)									
				14 DAPRE		28 DAPRE		42 DAPRE		14 DALPOST		28 DALPOST	
Herbicide program	Cereal rye termination	Application timing	Rate (g ae or a.i. ha^{-1})	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Nontreated control (cereal rye present)	NA	NA	NA	84 a	80 b	70 b	60 b	72 b	65 b	40 c	45 c	59 b	45 b
Weed-free control: dicamba + acetochlor	NA	EPOST	560 + 840	85 a	99 a	96 a	98 a	96 a	92 a	63 b	98 a	63 b	87 a
Weed- and rye-free control: pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	NA	Fall, PRE fb EPOST	245 + 1260 fb 1260 + 556 fb 560	99 a	97 a	97 a	67 b	99 a	90 a	99 a	98 a	99 a	72 a
Pyroxasulfone/sulfentrazone fb dicamba	2 WBP	PRE fb LPOST	292 + 560	96 a	90 a	71 b	90 a	98 a	67 b	60 b	71 b	90 a	71 abc
Pyroxasulfone/sulfentrazone fb dicamba	2 WAP	PRE fb LPOST	292 + 560	99 a	99 a	95 a	87 a	99 a	93 a	92 a	99 a	92 a	99 a
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WBP	PRE fb LPOST	556 + 560	99 a	99 a	99 a	94 a	99 a	98 a	91 a	97 a	91 a	97 a
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WAP	PRE fb LPOST	556 +560	98 a	99 a	99 a	91 a	99 a	97 a	92 a	97 a	92 a	97 a
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WBP	PRE fb LPOST	215 + 560	89 a	99 a	84 ab	65 b	94 a	69 b	85 a	75 ab	97 a	75 a
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WAP	PRE fb LPOST	215 + 560	99 a	99 a	99 a	92 a	99 a	98 a	63 ab	84 ab	85 a	99 a

Note: Means presented within each column with no common letter(s) are significantly different according to Tukey–Kramer's LSD test at $p \leq 0.05$.

Abbreviations: NA, not applicable; WAP, weeks after planting; WBP, weeks before planting.

[a]Year-by-treatment interaction for Palmer amaranth control 14, 28, and 42 DAPRE and 14, 28 LPOST was significant; therefore, data were separated for both years.

TABLE 6 Effect of herbicide programs and cereal rye termination timing on Palmer amaranth seed production plant^{-1} in glyphosate-/dicamba-resistant soybean near Harvard, NE, in 2021 and 2022.

Herbicide program	Cereal rye termination	Application timing	Rate (g ae or a.i. ha^{-1})	Estimated Palmer amaranth seed count[a] (Seeds plant^{-1})	
				2021	2022
Nontreated control (rye present)	NA	NA	NA	13,142 bcde	10,500 b
Weed-free control: dicamba + acetechlor	NA	EPOST	420 + 820	17,942 de	0 a
Weed- and rye-free control: Pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	NA	Fall, PRE fb EPOST	245 + 1260 fb 1260 + 556 fb 560	0 a	7860 a
Pyroxasulfone/sulfentrazone	2 WBP	PRE	292	18,037 de	7423 ab
Pyroxasulfone/sulfentrazone	2 WAP	PRE	292	16,109 abcd	7026 ab
Flumioxazin/pyroxasulfone/metribruzin	2 WBP	PRE	475	16,770 cde	9055 ab
Flumioxazin/pyroxasulfone/metribruzin	2 WAP	PRE	475	15,326 abcde	7103 b
Imazethapyr/saflufenacil/pyroxasulfone	2 WBP	PRE	215	21,1137 cde	9543 b
Imazethapyr/saflufenacil/pyroxasulfone	2 WAP	PRE	215	16,822 abc	5685 ab
Dicamba + glyphosate	2 WBP	EPOST	560 + 1260	17,642 abcd	8171 ab
Dicamba + glyphosate	2 WAP	EPOST	560 + 1260	14,216 abcd	0 a
Fomesafen/*S*-metolachlor	2 WBP	EPOST	1480	15,908 e	0 a
Fomesafen/*S*-metolachlor	2 WAP	EPOST	1480	14,790 bcde	0 a
Dicamba + acetochlor	2 WBP	EPOST	560 + 840	14,832 abcd	0 a
Dicamba + acetochlor	2 WAP	EPOST	560 +840	0 a	0 a
Pyroxasulfone/sulfentrazone fb dicamba	2 WBP	PRE fb LPOST	292 + 560	7196 ab	23,632
Pyroxasulfone/sulfentrazone fb dicamba	2 WAP	PRE fb LPOST	292 + 560	9078 ab	0 a
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WBP	PRE fb LPOST	556 + 560	6473 ab	0 a
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WAP	PRE fb LPOST	556 +560	6561 ab	0 a
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WBP	PRE fb LPOST	215 + 560	8505 ab	4943 a
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WAP	PRE fb LPOST	215 + 560	7130 ab	0 a

Note: Means presented within each column with no common letter(s) are significantly different according to Tukey–Kramer's LSD test at $p \leq 0.05$.

Abbreviations: EPOST, early postemergence; fb, followed by; LPOST, late postemergence; NA, not applicable; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

[a]Year-by-treatment interaction for estimated Palmer amaranth seed plant^{-1} was significant; therefore, data were separated by year.

3.6 | Palmer amaranth seed production

Palmer amaranth seed production was reduced the most by a PRE fb LPOST herbicide program in both years, with 6473–9078 seeds female plant^{-1} in 2021 (Table 6). Other herbicide programs ranged from 14,000 to 21,000 seeds plant^{-1} in 2021. In 2022, EPOST and PRE fb LPOST herbicide programs showed great reduction in Palmer amaranth seed production, with many of the treatments having no seed production. PRE fb LPOST herbicide programs with 2 WAP termination of cereal rye limited seed production to 0 seeds plant^{-1} in 2022. Across both years, the least effective treatment to reduce Palmer amaranth seed production was a PRE-only herbicide combined with 2 WBP cereal rye termination. In most cases, 2 WAP termination of cereal rye reduced Palmer amaranth seed production compared with the same herbicide program with the 2 WBP termination, indicating the importance of planting green to reduce the Palmer amaranth seedbank. Palmer amaranth seed production can vary depending on the crop competition and control methods adopted in the field; for example, de Sanctis, Knezevic, et al. (2021) reported that non-treated plots with crop competition (soybean) produced 25,800–34,000 seeds female plant^{-1} in a 2-year study conducted in Nebraska. Webster and Grey (2015) have reported up to 832,000 seeds per female plant without crop competition, while Sosnoskie et al. (2014) indicated that Palmer amaranth can produce up to 1.6 million seeds in cotton (*Gossypium hirsutum* L.) field.

3.7 | Soybean yield

Year-by-treatment interaction of cereal rye termination and herbicide programs for soybean grain yield was significant

TABLE 7 Effect of herbicide programs and cereal rye termination timing on soybean yield in dicamba-/glyphosate-resistant soybean in field experiments conducted near Harvard, NE, in 2021 and 2022.

Herbicide program	Cereal rye termination	Application timing	Rate (g ae or a.i. ha^{-1})	Soybean yield[a] (kg ha^{-1})	
				2021	2022
Nontreated control (cereal rye present)	NA	NA	NA	226 d	235 e
Weed-free control: dicamba + acetochlor	NA	EPOST	560 + 840	2174 c	1941 abcde
Weed- and rye-free control: pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	NA	Fall, PRE fb EPOST	245 + 1260 fb 1260 + 556 fb 560	4875 a	2104 abcde
Pyroxasulfone/sulfentrazone	2 WBP	PRE	292	2480 bc	515 de
Pyroxasulfone/sulfentrazone	2 WAP	PRE	292	3500 abc	1934 abcde
Flumioxazin/pyroxasulfone/metribuzin	2 WBP	PRE	475	3614 abc	391 de
Flumioxazin/pyroxasulfone/metribuzin	2 WAP	PRE	475	4891 a	2182 abcde
Imazethapyr/saflufenacil/pyroxasulfone	2 WBP	PRE	215	3486 abc	821 dce
Imazethapyr/saflufenacil/pyroxasulfone	2 WAP	PRE	215	3424 abc	2099 abcde
Dicamba + glyphosate	2 WBP	EPOST	560 + 1260	4830 a	2393 abcde
Dicamba + glyphosate	2 WAP	EPOST	560 + 1260	3713 abc	3838 a
Fomesafen/*S*-metolachlor	2 WBP	EPOST	1480	2652 bc	400 de
Fomesafen/*S*-metolachlor	2 WAP	EPOST	1480	3694 abc	2934 abc
Dicamba + acetochlor	2 WBP	EPOST	560 + 840	4631 ab	240 e
Dicamba + acetochlor	2 WAP	EPOST	560 +840	4331 ab	2791 abc
Pyroxasulfone/sulfentrazone fb dicamba	2 WBP	PRE fb LPOST	292 + 560	4613 ab	1075 dce
Pyroxasulfone/sulfentrazone fb dicamba	2 WAP	PRE fb LPOST	292 + 560	3350 abc	2526 abcd
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WBP	PRE fb LPOST	556 + 560	4499 ab	461 de
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WAP	PRE fb LPOST	556 +560	3324 abc	2875 abc
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WBP	PRE fb LPOST	215 + 560	4316 ab	1602 bcde
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WAP	PRE fb LPOST	215 + 560	3741 abc	3582 ab

Note: Means presented within each column with no common letter(s) are significantly different according to Tukey–Kramer's LSD test at $p \leq 0.05$.
Abbreviations: DAPRE, days after preemergence herbicide application; fb, followed by; NA, not applicable; WAP, weeks after planting; WBP, weeks before planting.
[a]Year-by-treatment interaction of soybean yield was significant; therefore, data were separated for both years.

($p = 0.0015$); therefore, data are presented separately for both years. Soybean yield in 2021 was higher compared to 2022 due to the hail and windstorm that occurred in June 2022. Dicamba plus glyphosate applied EPOST with 2 WAP cereal rye termination was the only treatment that increased yield from 3713 to 3838 kg ha^{-1} from 2021 to 2022 (Table 7). In 2021, yields varied between termination timings and herbicide application timings. Several herbicide programs with the 2 WBP termination timing produced similar yields (3486–4830 kg ha^{-1}), and programs with the 2 WAP termination timing produced similar yields in the range of 3324 –4891 kg ha^{-1}. Cereal rye terminated 2 WBP usually yielded higher than the 2 WAP termination in 2021, and visual differences of yellowing and stunting were observed in the 2 WAP termination. A recent study in Pennsylvania reported a reduction in corn yield when cereal rye was terminated 5 days after planting corn compared with terminating 2 weeks before planting corn (Gall et al., 2022). Grint, Arneson, Arriaga, et al. (2022) reported that corn yield was lower at the southcentral Wisconsin study site when cereal rye was terminated 2 weeks after planting corn. However, in contrast, multi-year/location field studies in Pennsylvania reported no effect of planting green on soybean grain yield (Reed et al., 2019), though the cover crop species and termination timings were variable in this study. In 2022, herbicide programs with 2 WAP termination of cereal rye produced higher yield than 2 WBP termination paired with herbicide programs, apart from dicamba plus glyphosate, which had a soybean yield of 2393 kg ha^{-1}. The difference in yield was expected due to the hail and windstorm events in 2022. As stated above, the biomass from the later termination timing seemed to protect the soybean plants, and yields correlated.

3.8 | Economic analysis

Gross profit was lower in 2022 because of the reduction in soybean grain yield due to the hail and windstorm compared

TABLE 8 Effect of herbicide programs and cereal rye termination timing on gross profit margin and benefit/cost ratio in dicamba-/glyphosate-resistant soybean in field experiments conducted near Harvard, NE, in 2021 and 2022.

Herbicide program + termination timing	Weed management program cost[a] ($ ha^{-1})						Gross profit margin ($ ha^{-1})		Benefit/cost ratio ($ ha^{-1})	
	PRE	EPOST	LPOST	AC[b]	Rye[b]	Total	2021	2022	2021	2022
PRE										
Nontreated control (cereal rye present)	–	–	–	–	99	99	115	120	–	–
Weed-free control	–	56	–	32	99	187	934	1001	1.56	0.74
Weed/rye-free control	141	45	–	68	99	431	2116	1207	3.42	0.80
Pyroxasulfone/sulfentrazone + 2 WBP	92	–	–	17	99	208	1080	276	2.10	−2.82
Pyroxasulfone/sulfentrazone + 2 WAP	92	–	–	17	99	208	1518	1000	4.21	0.66
Flumioxazin/pyroxasulfone/metribruzin + 2 WBP	125	–	–	17	99	241	1401	207	3.15	−2.72
Flumioxazin/pyroxasulfone/metribruzin + 2 WBP	125	–	–	17	99	241	2131	1104	6.18	1.00
Imazethapyr/saflufenacil/pyroxasulfone + 2 WBP	70	–	–	17	99	186	1518	414	4.70	−2.41
Imazethapyr/saflufenacil/pyroxasulfone + 2 WAP	70	–	–	17	99	186	1488	1069	4.55	1.11
EPOST										
Dicamba + glyphosate + 2 WBP	–	45	–	32	99	176	2101	1242	8.29	2.16
Dicamba + glyphosate + 2 WAP	–	45	–	32	99	176	1605	1966	5.47	6.28
Fomesafen/*S*-metolachlor + 2 WBP	–	40	–	19	99	157	1138	207	3.15	−4.16
Fomesafen/*S*-metolachlor + 2 WAP	–	40	–	19	99	157	1171	1518	3.36	4.16
Dicamba + acetochlor + 2 WBP	–	56	–	32	99	187	2014	138	7.34	−3.87
Dicamba + acetochlor + 2 WAP	–	56	–	32	99	187	1868	1449	6.56	3.14
PRE fb LPOST										
Pyroxasulfone/sulfentrazone fb Dicamba + 2 WBP	92	–	29	49	99	268	2014	552	5.11	−1.16
Pyroxasulfone/sulfentrazone fb Dicamba + 2 WAP	92	–	29	49	99	268	1459	1311	3.04	1.67
Flumioxazin/pyroxasulfone/metribruzin fb dicamba + 2 WBP	125	–	29	49	99	301	1955	241	4.36	−2.06
Flumioxazin/pyroxasulfone/metribruzin fb dicamba + 2 WBP	125	–	29	49	99	301	1430	1484	2.62	2.06
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba + 2 WBP	70	–	29	49	99	246	1868	828	4.97	−0.14
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba + 2 WAP	70	–	29	49	99	246	1634	1828	4.03	3.92

Abbreviations: AC, application cost; EPOST, early postemergence; fb, followed by; LPOST, late postemergence; PRE, preemergence; WAP, weeks after planting; WBP, weeks before planting.

[a]Weed management program costs were averaged from three sources in Nebraska in 2021: PRE ($17.30 ha^{-1}), non-dicamba-containing POST herbicide application ($18.94 ha^{-1}), and dicamba-containing POST application ($31.71 ha^{-1}).

[b]Cereal rye seed price + termination cost.

with soybean grain yield in 2021. Gross profit ranged from US $642 to $2116 ha^{-1} in 2021 and $207 to $1966 ha^{-1} in 2022 (Table 8). The total cost of PRE-only and PRE fb LPOST herbicide programs with the cereal rye cover crop was higher than that of an EPOST herbicide program. EPOST programs ranged from $157 to $187 ha^{-1}, whereas PRE herbicide programs ranged from $186 to $241 ha^{-1}. However, PRE fb LPOST herbicide programs were the most expensive, ranging from $246 to $301 ha^{-1}.

Benefit/cost ratios varied between years, herbicide programs, and termination timings. The reduction in soybean grain yield in 2022 due to the hail and windstorm in June resulted in a lower benefit/cost ratio compared with 2021. Across herbicide programs, EPOST herbicide programs had the highest average benefit/cost ratio in 2021 (5.7) and 2022 (1.29) due to better performance of dicamba fb glyphosate with both 2 WBP and 2 WAP termination timing in 2021 (8.29 and 5.47, respectively) and 2022 (2.16 and 6.28, respectively). Dicamba plus acetochlor added to the higher average benefit/cost ratio across EPOST herbicide programs with both termination timings in 2021 but struggled to add value in 2022 when paired with the 2 WBP termination of cereal rye. The benefit/cost ratio for PRE herbicides with either termination ranged between 2.1 and 6.18 in 2021 and between −2.82 and 1.10 in 2022. The PRE fb LPOST herbicide programs with either termination timing of cereal rye ranged between 2.62 and 5.11 in 2021 and −2.06 and 3.92 in 2022. Dicamba plus glyphosate consistently added value both years with cereal rye terminated 2 WAP (5.47 in 2021 and 6.28 in 2022). This can be attributed to the relatively lower cost of POST herbicides and the consistent soybean yield produced in both years. EPOST herbicide programs with 2 WBP termination of cereal rye provided the highest benefit/cost ratio in 2021, while in 2022, EPOST herbicide programs with 2 WAP cereal rye termination resulted in the highest benefit/cost ratio. EPOST herbicide programs used under normal irrigated conditions and stress-induced situations provide the highest benefit/cost ratio and should therefore be considered as a weed management program in dicamba/glyphosate-resistant soybean.

3.9 | Practical implications

The results of this study indicated that the practice of planting green (cereal rye terminated 2 weeks after soybean planting in this study) integrated with a PRE fb LPOST herbicide program provided the greatest control of Palmer amaranth in soybean. Palmer amaranth density showed similar results, and this study indicates that a PRE fb LPOST herbicide program with 2 WAP cereal rye termination would reduce Palmer amaranth density compared with other herbicide programs. The accumulation of cereal rye biomass-terminated 2 WAP soybean helped reduce Palmer amaranth density and seed production. A PRE fb LPOST herbicide program with 2 WAP termination of cereal rye had lower yields compared with 2 WBP termination in 2021. Additional research is needed to determine the critical time of cereal rye termination after planting soybean to avoid grain yield reduction. When planting green was combined with a single herbicide program such as a PRE-only or POST-only program, soybean grain yields were variable in 2021, though in 2022, due to the wind and hailstorm, the treatments where cereal rye was terminated 2 WAP yielded higher than those that had cereal rye terminated 2 WBP. The accumulation of biomass on top of soybean plants protected them from hail and windstorm injury; therefore, yields in 2022 should be considered but not compared with 2021. Further research is needed to evaluate whether herbicide or biomass accumulation of cereal rye or other cover crop species influences the fate of residual herbicides.

Due to increasing number of herbicide-resistant weeds and their widespread occurrence, interest in cover crops is growing across the Midwestern United States, particularly to understand the economics. The results of this study indicated that soybean grain yields from a POST-only herbicide program with cereal rye terminated 2 WAP provided the highest benefit and the best return on investment. Cover crops should not be used alone and should be aided by additional weed control options such as herbicides as observed in this study due to the ability of Palmer amaranth to emerge, produce seeds, and reduce soybean yield after terminating cereal rye, if not controlled. Planting green could be integrated into soybean production as observed in this study specifically to reduce the seed production of Palmer amaranth; however, soil moisture, disease and insect pressure, and the effect on grain yield should be carefully considered when implementing planting green in commercial soybean production fields.

AUTHOR CONTRIBUTIONS

Trey Stephens: Data curation; formal analysis; methodology; validation; writing—original draft. **Humberto Blanco-Canqui**: Resources; validation; writing—review and editing. **Stevan Z. Knezevic**: Writing—review and editing. **Jenny Rees**: Methodology; resources; writing—review and editing. **Katja Kohler-Cole**: Methodology; writing—review and editing. **Amit J. Jhala**: Conceptualization; funding acquisition; investigation; methodology; project administration; 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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