Weed Technology

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Research Article

Cite this article: de Sanctis JHS and Jhala AJ (2025) Evaluating glyphosate alternative acetyl-CoA carboxylase–inhibiting herbicides and application timings to terminate cereal rye in soybean. Weed Technol. **39**(e42), 1–10. doi: 10.1017/wet.2025.17

Received: 10 March 2024
Revised: 3 January 2025
Accepted: 15 February 2025

Associate Editor:
Rafael Pedroso, University of São Paulo (ESALQ/USP)

Nomenclature:
Clethodim; fenoxaprop-P-ethyl; fluazifop-P-butyl; glyphosate; quizalofop-P-ethyl; giant foxtail; *Setaria faberi* Herrm.; Palmer amaranth; *Amaranthus palmeri* S. Watson.; yellow foxtail; *Setaria pumila* (Poir.) Roem. & Schult.; cereal rye; *Secale cereale* L.; soybean; *Glycine max* (L.) Merr.

Keywords:
Biomass; cover crop; density; integrated weed management; termination timing

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Evaluating glyphosate alternative acetyl-CoA carboxylase–inhibiting herbicides and application timings to terminate cereal rye in soybean

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Abstract

Fall-planted cover crops are becoming popular among growers in the Midwest for various reasons, including their ability to suppress weeds. Cereal rye is the cover crop most often planted in Nebraska. Glyphosate availability was limited in 2022, so growers sought information about glyphosate alternatives for terminating cover crops such as cereal rye. The objectives of this study were to evaluate glyphosate alternative acetyl-CoA carboxylase (ACCase)-inhibiting herbicides for terminating cereal rye 15 d before soybean planting (DBSP), at soybean planting day (SPD), and 15 d after soybean planting (DASP) and their effect on weed control, density, biomass, soybean plant stand, and soybean grain yield. Field experiments were conducted from 2018 to 2020 at South Central Ag Lab near Clay Center, Nebraska. Cereal rye biomass collected 15 d after termination was 394, 1,697, and 3,700 kg ha^{-1} in 2019 and 330, 1,304, and 4,550 kg ha^{-1} in 2020, respectively, at the 15 DBSP at SPD and 15 DASP termination timings. Clethodim provided 77% control of cereal rye 15 DBSP compared with greater than 94% control with applications of fluazifop-P-butyl, fluazifop-P-butyl/fenoxaprop-P-ethyl, quizalofop-P-ethyl, and glyphosate. Similarly, at the SPD and 15 DASP termination timings, 66% and 31% control of cereal rye, respectively, were recorded after clethodim was used compared with greater than 92% control after other ACCase-inhibitors and glyphosate were used. Palmer amaranth control at the R5 soybean growth stage was 70%, 88%, and 96%, respectively, at 15 DBSP, SPD, and 15 DASP. Soybean yield was reduced to 2,184 kg ha^{-1} when cereal rye was terminated at 15 DASP compared with 4,566 kg ha^{-1} when it was terminated at SPD, and 4,460 kg ha^{-1} at 15 DBSP.

Introduction

Glyphosate-resistant (GR) soybean became commercially available in the United States in 1996, and by 2014, more than 90% of corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean in the nation had been planted with GR cultivars (Duke 2018). The wide adoption of GR crops led to simplified weed control programs that relied mostly on glyphosate for postemergence weed control (Shaner 2014) and significantly reduced use of residual herbicides (Jhala et al. 2023). Consequently, the overreliance on a single herbicide coupled with the lack of alternative control methods resulted in the evolution of GR weeds. As of December 2024, 60 weed species around the world have evolved resistance to glyphosate, including 18 in the United States (Heap 2024). In Nebraska, six broadleaf weeds have evolved resistance to glyphosate including horseweed (*Erigeron canadensis* L.), giant ragweed (*Ambrosia trifida* L.), common ragweed (*Ambrosia artemisiifolia* L.), kochia [*Bassia scoparia* (L.) A. J. Scott], waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer], and Palmer amaranth (Chahal et al. 2017; Ganie and Jhala 2017; Rana and Jhala 2016; Sandell et al. 2011; Sarangi et al. 2015).

The rapid evolution of multiple herbicide–resistant weed biotypes threatens the long-term sustainability of agricultural systems (Evans et al. 2016; Jhala et al. 2024). Thus, alternative control tactics must be implemented to mitigate the evolution and spread of herbicide-resistant weeds (Norsworthy et al. 2012). Integrated weed management is the combination of biological, chemical, cultural, and/or physical weed control practices to provide the crop with an advantage over weeds (Harker and O'Donovan 2013). Cover crops are considered a cultural weed control tactic that can physically suppress weeds (Teasdale and Moehler 2000) and may have allelopathic effects (Barnes and Putnam 1986; Burgos et al. 1999).

Cover crops are usually planted in the fall after the cash crop harvest and terminated in the spring, more commonly before the next cash crop is planted (Werle et al. 2017). Previous studies have shown that the amount of weed suppression is correlated with the amount of biomass produced by the cover crops (Bish et al. 2021; Kumar et al. 2025; Stephens et al. 2024; Wiggins et al. 2016). It has been estimated that to provide satisfactory weed suppression, cover crop biomass should be at least 5,000 kg ha^{-1} (Nichols et al. 2020). While investigating the impact of cover crop management systems on weed suppression, Mirsky et al. (2011) observed greater weed suppression at later termination timings, and differences were attributed to greater biomass production.

The 2017 Census of Agriculture demonstrated that the area in the United States planted with a cover crop increased from 4.17 million ha in 2012 to 6.3 million ha in 2017, a 50% increase (USDA-NASS 2019). In Nebraska, cover crops were planted on 144,641 ha in 2012, and that acreage increased to 302,795 ha in 2017, more than a 2-fold increase in 5 yr (USDA-NASS 2019). Among different cover crop species, cereal rye is the cover crop most commonly adopted by Nebraska growers, which is mostly planted alone or sometimes in a seeding mix (Drewnoski et al. 2015; Oliveira et al. 2019). Previous studies have demonstrated the potential of cereal rye to suppress weed emergence early in the season (Bish et al. 2021; Hand et al. 2019). Furthermore, Schramski et al. (2020) observed that planting the cash crop within actively growing cereal rye and winter wheat (*Triticum aestivum* L.), a practice known as planting green, to reduce horseweed emergence and biomass, was effective compared with terminating the cover crop before planting the cash crop.

Despite their benefits, cover crops can compete with cash crops for resources (Holman et al. 2018; Nielsen et al. 2016); therefore, it is imperative to determine the timing of cover crop termination to obtain the highest amount of biomass that does not lead to a reduction in grain yield (Stephens et al. 2024). Cover crop termination may vary from a few weeks before the cash crop is planted to about 2 wk after planting (Blanco-Canqui and Jhala, 2024; Werle et al. 2017), and it is usually executed by mechanical or chemical methods (Kumar et al. 2025). A survey of farmers in Nebraska demonstrated that 95% of respondents used a chemical termination, and within that group, 100% of respondents used glyphosate (Oliveira et al. 2019). Shortages of glyphosate and glufosinate in 2022 could limit glyphosate availability again, and result in higher prices (Johnson et al. 2021; Morgan 2021). Furthermore, the repeated use of glyphosate in the same field for terminating cover crops in the spring can result in the evolution of GR winter annual weed biotypes. Growers may need to seek other options for terminating cover crops; hence, it is important to evaluate glyphosate alternatives for terminating cover crops in case glyphosate supply is disrupted again in the future, and to reduce the evolution of GR winter annual weeds.

Herbicides that inhibit acetyl-CoA carboxylase (ACCase) are considered graminicides due to specific herbicidal binding sites that do not occur in dicot plants (Herbert et al. 1997). However, little is known about ACCase-inhibiting herbicides for terminating cereal rye and their efficacy at various termination timings in soybean. Thus the objectives of this study were to investigate the use of ACCase-inhibiting herbicides (clethodim, fluazifop-P-butyl, fluazifop-P-butyl/fenoxaprop-P-ethyl, and quizalofop-P-ethyl) for terminating cereal rye, to evaluate their efficacy at different termination timings (15 d before soybean planting [DBSP], at soybean planting day [SPD], and 15 d after soybean planting [DASP]), and to assess their effect on weed suppression and soybean grain yield.

Materials and Methods

Site Description

Field experiments were conducted at the University of Nebraska–Lincoln's South Central Agricultural Laboratory, near Clay Center, NE (40.5752°N, 98.1428°W) from 2018 to 2020. The soil type was Hastings silt loam (montmorillonitic, mesic, Pachic Argiustolls; 17% sand, 58% silt, and 25% clay) with 3.0% organic matter, pH 6.5. The dominant weed species at the site were Palmer amaranth and a mix of foxtail species that included giant foxtail and yellow foxtail, that collectively will be addressed as *Setaria* species throughout the paper. Palmer amaranth is resistant to herbicides from Groups 2 and 9 (as categorized by the Weed Science Society of America), and no herbicide resistance has been observed in *Setaria* species.

Cereal rye was drill-planted on October 29, 2018, and October 24, 2019, at 92 kg ha^{-1} with 19-cm row spacing. Dicamba/glyphosate-resistant soybean (S29 K3X; Syngenta, Greensboro, NC) was planted on May 13, 2019, and May 15, 2020, at 345,000 seeds ha^{-1} in 76-cm row spacing.

Experimental Design and Treatments

The experiment was arranged in a split-plot design with four replications over 2 yr, with cereal rye termination timings as the main plot and the termination herbicides as the subplot factor (Table 1). Additionally, a conventional treatment without cereal rye cover crop and cereal rye without termination were included for comparison. Termination timings included DBSP, SPD, and DASP; cereal rye growth stages were 22, 31, and 50 according to the Zadoks scale (Zadoks et al. 1974) or 18, 44, and 92 cm tall on average at the time of termination, respectively. The termination herbicides consisted of clethodim, fluazifop, fluazifop/fenoxaprop, glyphosate, and quizalofop (Table 1). A preemergence herbicide followed by a postemergence herbicide was applied to the entire area, with a premix of chlorimuron/flumioxazin/pyroxasulfone (230 g ai ha^{-1}, Fierce XLT; Valent USA, Walnut Creek, CA) applied preemergence at soybean planting day, and dicamba (560 g ae ha^{-1}, XtendiMax with VaporGrip; Bayer Crop Science, St. Louis, MO) applied postemergence at the V4 soybean growth stage. Labeled adjuvants were included. Herbicides were applied using a handheld CO_2-pressurized backpack sprayer equipped with five AIXR 110015 flat-fan nozzles (TeeJet Technologies, Glendale Heights, IL) 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 was applied with TeeJet TTI 11005 flat-fan nozzles.

Data Collection

Cover crop data collection consisted of visual estimates of cereal rye control and aboveground biomass 28 d after treatment (DAT). Cereal rye aboveground biomass was obtained within a 1-m^2 quadrant randomly placed between the middle two soybean rows within the corresponding plot. Control estimates were visibly assessed using a scale of 0% to 100%, with 0% representing no control and 100% representing complete control. Cereal rye biomass samples were placed in paper bags and placed in an oven at 65 C for 10 d until constant mass, samples were then weighted. Cereal rye dry weights were converted to percent biomass reduction from nontreated plants using the following equation (Polli et al. 2022):

$$BR = 100 \times (1 - P/C) \tag{1}$$

where BR is the cereal rye biomass reduction relative to the nontreated control, P is the treatment plot dry cereal rye weight, and C is the cereal rye dry weight from cereal rye without herbicide plots.

https://doi.org/10.1017/wet.2025.17

Table 1. Herbicide products, rates, manufacturers, and adjuvants used to evaluate glyphosate alternatives for cereal rye termination in soybean.[a,b,c]

Termination herbicide	Rate	Trade name	Manufacturer[d]	Adjuvants
	g ae/ai ha^{-1}			
Clethodim	136	Select Max®	Valent Agricultural Products	COC 1.0 L 100 L^{-1} + NIS 250 ml 100 L^{-1}
Fluazifop-P-butyl	420	Fusilade® DX	Syngenta Crop Protection LLC	COC 1.0 L 100 L^{-1} + NIS 250 ml 100 L^{-1}
Fluazifop-P-butyl/ fenoxaprop-P-ethyl	314	Fusion®	Syngenta Crop Protection LLC	COC 1.0 L 100 L^{-1} + NIS 250 ml 100 L^{-1}
Glyphosate	1,260	Roundup PowerMax®	Bayer Crop Science	AMS 3.0 L 100 L^{-1} + NIS 250 ml 100 L^{-1}
Quizalofop-P-ethyl	92	Assure® II	AMVAC Chemical Corporation	COC 1.0 L 100 L^{-1} + NIS 250 ml 100 L^{-1}

[a]Abbreviations: AMS ammonium sulfate (DSM Chemicals North America Inc., Augusta, GA); COC, crop oil concentrate; NIS, nonionic surfactant (Induce Helena Chemical Co, Collierville, TN).
[b]Cereal rye cover crops were terminated 15 d before soybean planting, at soybean planting day, and 15 d after soybean planting.
[c]Field studies were conducted at the South Central Agricultural Laboratory, near Clay Center, NE, in 2019 and 2020.
[d]Manufacturer locations: AMVAC Chemical Corporation, Newport Beach, CA; Bayer Crop Science, St. Louis, MO; Syngenta Crop Protection LLC, Greensboro, NC; Valent Agricultural Products, Walnut Creek, CA.

Late-season weed control data were collected at the R5 soybean growth stage, and it consisted of visual estimates of weed control, aboveground fresh biomass, and density. Density and aboveground biomass were obtained within a 1-m^2 quadrant, and weed biomass was oven-dried to constant mass, as described for the cereal rye sampling methods.

Soybean stand was obtained at the R1 growth stage, and soybean grain yield was harvested using a research plot combine from the center two rows and corrected to 13% moisture content. A severe hailstorm in 2019 at the R6 soybean growth stage resulted in significant soybean injury and pod loss, with yield losses of up to 60% (data not shown); therefore, plots were not harvested. Temperature and rainfall data for the 2019 and 2020 growing seasons were obtained from the nearest High Plains Regional Climate Center near Clay Center, Nebraska.

Statistical Analysis

Data were subjected to ANOVA using R base package (R Core Team 2019) and Agricolae package (Mendiburu, 2019). Replications were treated as a random effect, and year, termination time, and termination herbicide as fixed effects. Soybean yield data were subjected to ANOVA; however, the year effect was not included because of the availability of only 1-yr data due to a hailstorm in 2019. Fisher's protected least significant difference was used to separate means at $\alpha = 0.05$.

Results and Discussion

Cereal Rye Control and Biomass Reduction

The termination time by termination herbicide interaction was significant ($P < 0.001$) for cereal rye control at 28 DAT (Table 2). Therefore, data were pooled over the years. For cereal rye biomass reduction, due to the year-by-termination time by termination herbicide interaction being significant ($P < 0.001$), data were analyzed separately for the 2019 and 2020 seasons. Different weather conditions, when 2020 was dryer with warmer early season temperatures, may have affected the different levels of cereal rye biomass production (Figure 1).

The average of cereal rye biomass after each termination timing (15 DBSP, SPD, and 15 DASP) was, respectively, 394, 1,697, and 3,700 kg ha^{-1} in 2019; and 330, 1,304, and 4,550 kg ha^{-1} in 2020 (Figure 2). Cereal rye was controlled by ≥98% after glyphosate was used regardless of the termination timing (Table 3). Glyphosate efficacy on cereal rye has been extensively documented in the literature. For example, Palhano et al (2018b) reported that cereal rye that was 134 to 154 cm tall was controlled by 100% when glyphosate was used, while Noorenberghe et al. (2023), in a multilocation study, reported ≥99% cereal rye control at the Zadoks 31 stage (10–43 cm tall). Similarly, Cornelius and Bradley (2017) reported 98% and 87% cereal rye control in early April and early May, respectively, when the cover crop was terminated with glyphosate. At 15 DBSP, 77% control of cereal rye was recorded after clethodim was used compared with ≥94% control when fluazifop-P, fluazifop-P plus fenoxaprop, quizalofop, and glyphosate were applied (Figure 3). Young et al. (2016) reported 60% control of feral cereal rye (*Secale cereale* L.) with clethodim at 105 g ai ha^{-1} 42 d after spring application compared with 93% control when glyphosate at 866 g ae ha^{-1} was applied, and 99% control when quizalofop was applied at 62 g ai ha^{-1}. Similar trends were observed when cereal rye was terminated at SPD and 15 DASP, when 66% and 31% control, respectively, was recorded after clethodim was used, whereas >92% control was recorded when other ACCase inhibitors were used (Figure 4). Similarly, Bushong et al. (2011) in a multilocation study investigated control options for feral cereal rye in winter canola and reported that winter application of clethodim (88 g ai ha^{-1}) resulted in 15.3% feral cereal rye seed content of harvested canola compared with 0.1% and 0.2% content after applications of glyphosate (770 g ae ha^{-1}) and quizalofop (62 g ai ha^{-1}), respectively.

Cereal rye biomass reduction occurring from applications of fluazifop-P, fluazifop-P plus fenoxaprop, and quizalofop was mostly comparable to the reduction that occurred after glyphosate was used, and clethodim was the least effective herbicide at all termination timings (Table 3). For instance, at 15 DBSP, cereal rye biomass was reduced by 67% and 75% in 2019 and 2020, respectively, when glyphosate was applied. These percentages are comparable to those of other ACCase-inhibiting herbicides, except clethodim, for which reductions of 53% and 66% occurred in 2019 and 2020, respectively (Table 3). Furthermore, at 15 DASP, differences in biomass reduction between treatments were more subtle, which can be attributed to higher cereal rye biomass at later growth stages, and plants were no longer developing vegetatively, but were developing reproductive structures instead. Clethodim was the least effective herbicide, when its application resulted in a 27% and 15% biomass reduction in 2019 and 2020, respectively; however, the reduction was comparable to that when fluazifop (36%) and fluazifop plus fenoxaprop (38%) were applied in 2019, and to that of fluazifop (23%) in 2020 (Table 3). Few studies have investigated using ACCase-inhibiting herbicides for cereal rye termination as an alternative to glyphosate. Kumar et al. (2023), while investigating chemical and mechanical cereal rye termination methods, reported that an application of clethodim resulted in 7% biomass reduction, which is comparable to that of quizalofop at 13%. In contrast, Felsman et al. (2023) reported that when terminating cereal rye on the day when soybean is planted,

https://doi.org/10.1017/wet.2025.17

Table 2. ANOVA results (significance of *F*-values) for the fixed effects of year, termination time, and termination herbicide on response variables.[a,b]

	Ceral rye control at 28 DAT	Cereal rye biomass reduction	Palmer amaranth control	Palmer amaranth density	Palmer amaranth biomass	*Setaria* ssp. control	*Setaria* ssp. density	*Setaria* ssp. biomass	Soybean stand	Soybean yield
	P-value									
Year (*Y*)	NS	NS	NS	NS	NS	NS	NS	NS	NS	–
Termination time (*T*)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	NS	0.004	0.002
Y * *T*	NS	0.009	NS	NS	NS	NS	NS	NS	NS	–
Termination herbicide (*H*)	<0.001	0.048	NS	NS	NS	NS	NS	NS	NS	NS
H * *Y*	NS	<0.001	NS	NS	NS	NS	NS	NS	NS	–
T * *H*	<0.001	<0.001	NS	NS	NS	NS	NS	NS	NS	NS
T * *H* * *Y*	NS	<0.001	NS	NS	NS	NS	NS	NS	NS	–

[a]Abbreviations: DAT, days after treatment; *H*, herbicide NS, nonsignificant, P-value > 0.05; *T*, termination time; *Y*, year.
[b]This experiment was conducted as a split-plot design, with cereal rye termination time as the whole plot and cereal rye termination herbicide as the subplot, during the 2019 and 2020 growing seasons at the South Central Agricultural Laboratory, near Clay Center, NE.

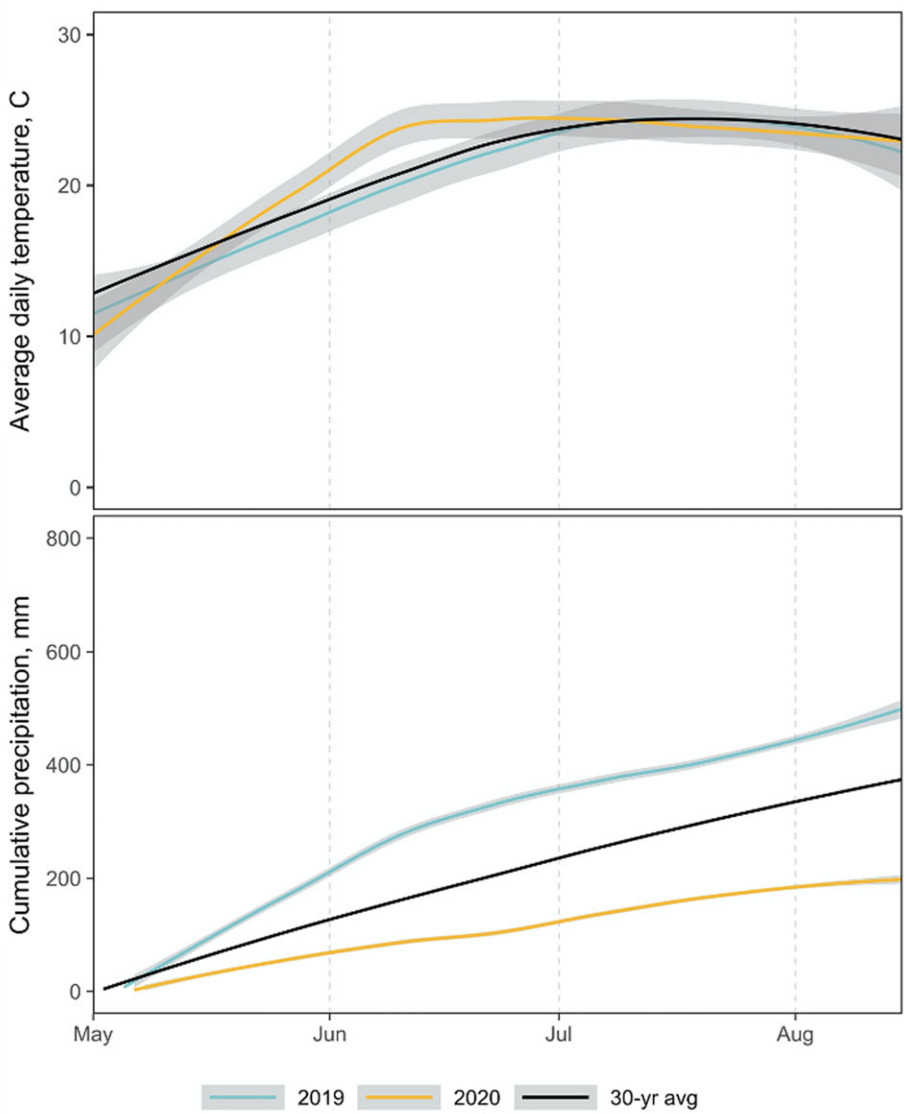

Figure 1. Average daily air temperature and total precipitation during the 2019 and 2020 growing seasons compared with the 30-yr average at the South Central Agricultural Laboratory near Clay Center, NE.

https://doi.org/10.1017/wet.2025.17

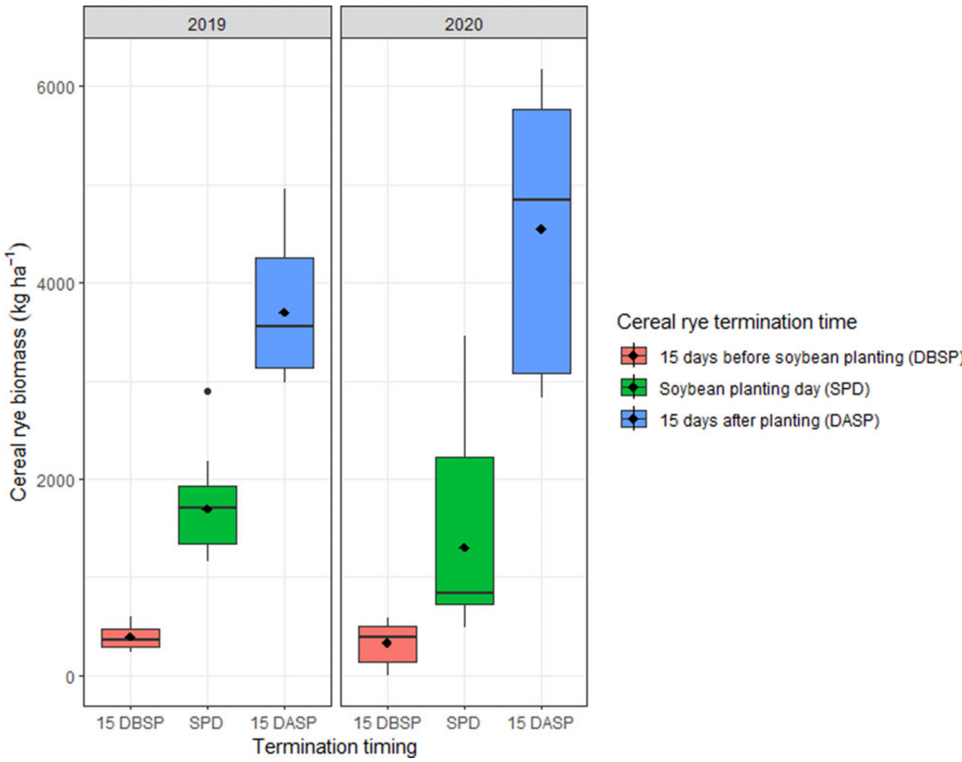

Figure 2. Cereal rye biomass harvested 15 d after each termination timing (15 d before soybean planting [DBSP], soybean planting day [SPD], and 15 d after soybean planting [DASP]) averaged over termination herbicides during the 2019 and 2020 growing seasons in field experiments conducted at the South Central Agricultural Laboratory near Clay Center, NE.

glyphosate (≥98%) was more effective than quizalofop and clethodim (<57%). However, those authors reported that cereal rye yielded 9,019 and 15,819 kg ha^{-1} of biomass in 2020 and 2021, respectively. Therefore, more research is needed to investigate whether reduced efficacy of ACCase inhibitors against cereal rye is affected by cover crop biomass.

Palmer amaranth and Setaria species Control, Biomass, and Density

The main effect of termination time was significant for Palmer amaranth control, biomass, and density, and *Setaria* species control and density; therefore, means were pooled over termination time (Table 2). No differences were observed among the cover crop termination herbicides in their ability to control late-season Palmer amaranth and *Setaria* species, biomass, or density, which is expected because the entire study was treated with the same preemergence/postemergence herbicide program and none of the cereal rye termination herbicides have any soil residual activity. For instance, Palmer amaranth and *Setaria* species control ranged from 82% to 92% at the R5 soybean growth stage regardless of the herbicide that was used for cereal rye termination (Table 4).

Late-season Palmer amaranth control increased with delayed cereal rye termination timings, with 70%, 88%, and 96% control at 15 DBSP, at SPD, and 15 DASP, respectively. Additionally, Palmer amaranth control without cereal rye cover crop was 65%, which is comparable to 70% control observed at 15 DBSP (Table 4). This might be partially due to a premix of chlorimuron/flumioxazin/pyroxasulfone (Fierce XLT) applied preemergence that might have contributed to the residual control of Palmer amaranth. Webster et al. (2016) reported that Palmer amaranth biomass and density were inversely correlated to winter rye cover crop biomass, for which 5,200 kg ha^{-1} of winter rye biomass resulted in a 50% reduction in Palmer amaranth emergence. This further highlights the importance of integrating cereal rye cover crop with herbicides for management of troublesome weeds.

In accordance with Palmer amaranth control ratings, reduced weed biomass and density were observed at later cereal rye termination timings; in addition, at 15 DBSP, Palmer amaranth biomass and density were similar to the conventional treatment without cover crops (Table 4). For example, Palmer amaranth density within cereal rye plantings was 1 and 2 plants m^{-2} at 15 DASP and SPD, respectively, compared with 8 and 9 plants m^{-2} when cereal rye was terminated at 15 DBSP and with conventional treatment, respectively. Vollmer et al. (2020a) observed a similar result, in which the presence of cereal rye cover crop resulted in a reduced density of *Amaranthus* species. More specifically, those authors reported that terminating cereal rye at 3 and 5 wk after watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai] is transplanted resulted in a reduced density of *Amaranthus* species by 45 and 8 plants m^{-2}, respectively, whereas 193 plants m^{-2} was observed when cereal rye was not planted as a cover crop.

The response of *Setaria* species to cereal rye termination timings was similar to that of Palmer amaranth. For instance, greater control of *Setaria* species in the late season was observed at SPD and 15 DASP termination timings, with 92% and 96% control, respectively, and control shifted to 82% when cereal rye was terminated 15 DBSP and to 71% when a conventional treatment without cereal rye was implemented. Vollmer et al. (2020a) reported similar results when cereal rye was terminated 10 d before watermelon planting resulted in 81% large crabgrass [*Digitaria sanguinalis* L. (Scop.)] control

Table 3. Cereal rye control and biomass reduction at 28 d after termination.[a–e]

Termination time	Terminating herbicide[f]	Cereal rye control	Cereal rye biomass reduction	
			2019	2020
		%		
15 d before soybean planting	Clethodim	77 c	53 b	66 c
	Fluazifop-P-butyl	94 b	71 a	75 b
	Fluazifop-P-butyl + fenoxaprop-P-ethyl	98 ab	71 a	83 a
	Glyphosate	99 a	67 a	75 b
	Quizalofop-P-ethyl	96 ab	68 a	78 ab
		***	*	***
At soybean planting	Clethodim	66 B	18 B	49 B
	Fluazifop-P-butyl	98 A	32 A	64 A
	Fluazifop-P-butyl + fenoxaprop-P-ethyl	96 A	37 A	60 A
	Glyphosate	98 A	43 A	61 A
	Quizalofop-P-ethyl	94 A	38 A	61 A
		***	**	*
15 d after soybean planting	Clethodim	31 *c*	27 *b*	15 *c*
	Fluazifop-P-butyl	94 *ab*	36 *ab*	23 *bc*
	Fluazifop-P-butyl + fenoxaprop-P-ethyl	92 *b*	38 *ab*	26 *ab*
	Glyphosate	98 *ab*	50 *a*	32 *a*
	Quizalofop-P-ethyl	96 *ab*	44 *a*	30 *ab*
		***	*	**

[a]Field experiments were conducted at the South Central Agricultural Laboratory, near Clay Center, NE, in 2019 and 2020.
[b]Year by treatment interaction was significant for biomass reduction; therefore, data were analyzed separately. Herbicides were applied at various timings mentioned in column 1 and data were collected 28 d after treatment; therefore, comparisons were made separately for treatments applied and evaluated at the same time.
[c]Means presented within the same column and with no common letter(s) are significantly different according to Fisher's Protected Least Significant Difference test.
[d]Significance levels: NS, nonsignificant at $\alpha = 0.05$; *P ≤ 0.05; **P ≤ 0.01; ***P ≤ 0.001.
[e]Different letters (A, a, *a*) indicate a separated analysis because herbicides were applied at different timings and data were collected 28 d after treatment.
[f]Herbicides were applied in the following amounts: clethodim, 136 g ai ha^{-1}; fluazifop-P-butyl, 420 g ai ha^{-1}; fluazifop-P-butyl + fenoxaprop-P-ethyl, 314 g ai ha^{-1}; glyphosate, 1,260 g ae ha^{-1}; and quizalofop-P-ethyl, 92 g ai ha^{-1}.

compared with 72% control when cereal rye was terminated 20 d before watermelon was planted.

Although no differences in *Setaria* species biomass were observed (less than 2 g m^{-2} for all treatments), density was reduced at SDP and 15 DASP (2 and 1 plants m^{-2}, respectively) compared with density at 15 DBSP (5 plants m^{-2}). Mirsky et al. (2011) reported that densities of multiple weed species were reduced when cover crop termination was delayed; for instance, *Setaria* species density when cover crops were terminated early (May 1) was 9 plants m^{-2} compared with 2 plants m^{-2} when termination occurred late (May 30). Essman et al. (2023) observed a lower density of late-season giant foxtail when cereal rye termination was delayed, and when cereal rye was terminated 7 DBSP, 7 DASP, and 21 DASP it resulted in 63, 46, and 9 plants m^{-2}, respectively.

Results from this study highlight the importance of an integrated weed management approach in which the greatest level of weed control was achieved when cereal rye termination was delayed to SPD or 15 DASP. Previous research has shown that the presence of a cereal rye cover crop typically reduces Palmer amaranth density; for instance, Palhano et al. (2018a) reported that when cereal rye was terminated 3 wk before cotton planting, Palmer amaranth density 8 wk after cotton planting was 3.8 plants m^{-2} compared with 22.4 plants m^{-2} when cereal rye was not used as a cover crop. Furthermore, in accordance with what we observed in this study, Hodgskiss et al. (2021) concluded that because of greater cereal rye biomass production from delayed termination timings, waterhemp density in plots where cereal rye was terminated on the day when soybean was planted (352 plants m^{-2}) and after soybean planting (287 plants m^{-2}) were reduced compared with 915 plants m^{-2} before the soybean planting termination timing. In addition, the negative impact of cereal rye cover crop on weed density has been reported for other broadleaf weeds. Vollmer et al. (2020a) reported that common lambsquarters (*Chenopodium album* L.) density was 18 plants m^{-2} in a treatment without cereal rye and it shifted to 6 and 0 plants m^{-2} at 3 and 5 wk, respectively, after watermelon transplant termination timings. Furthermore, Schramski et al. (2020), in a multilocation study, reported that horseweed density was minimized in plots where cereal rye and winter wheat were terminated 7 DASP (198 plants m^{-2}) compared to 7 DBSP (582 plants m^{-2}). Although weed suppression from cereal rye cover crop has been largely documented, it is not a stand-alone weed control tactic, and its ability to suppress weeds might vary by season and environment. For instance, Bish et al. (2021), while investigating the effects of cereal rye seeding rates on waterhemp emergence, reported that in 2020 waterhemp cumulative emergence at 28 DASP ranged from 49 to 63 plants m^{-2} regardless of the cereal rye seeding rate compared to 385 plants m^{-2} in a treatment without cereal rye; however, in the 2019 season, all treatments had comparable waterhemp emergence, ranging from 927 to 1,412 plants m^{-2}.

Soybean Stand and Grain Yield

Soybean stand count was reduced to 17 plants m^{-1} row when cereal rye was terminated 15 DASP compared with the 19 plants m^{-1} row observed in other termination timings and the conventional treatment (Table 5). There were no differences in soybean stand observed among termination herbicides, ranging from 18 to 19 plants m^{-1} row. Furthermore, soybean grain yields were greater when cereal rye was terminated at 15 DBSP, SDP, and conventional treatment with 4,460, 4,566, and 3,977 kg ha^{-1}, respectively, compared to 2,184 kg ha^{-1} at 15 DASP. In addition, no differences in soybean yield were observed among the termination herbicides tested, suggesting that the reduced efficacy of clethodim in cereal rye did not impact cash crop performance.

https://doi.org/10.1017/wet.2025.17

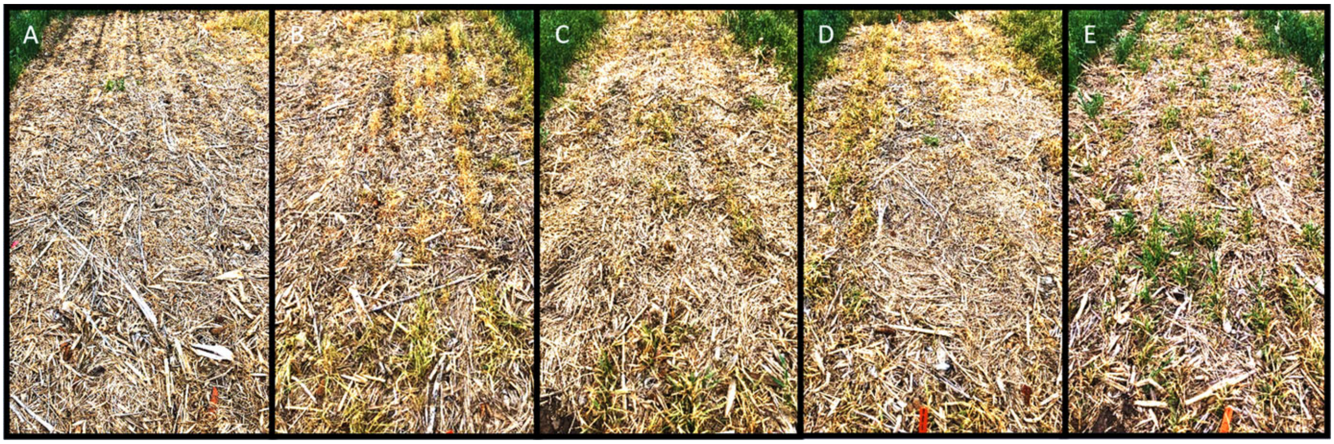

Figure 3. Cereal rye terminated 15 d before soybean planting using herbicides (A) glyphosate at 1,260 g ae ha^{-1}, (B) fluazifop-P-butyl at 420 g ai ha^{-1}, (C) quizalofop at 92 g ai ha^{-1}, (D) fluazifop-P-butyl/fenoxaprop-P-ethyl at 314 g ai ha^{-1}, and (E) clethodim at 136 g ai ha^{-1} in field experiments conducted at the South Central Agricultural Laboratory near Clay Center, NE. Photographs were taken at the soybean planting day, 15 d after herbicides were applied.

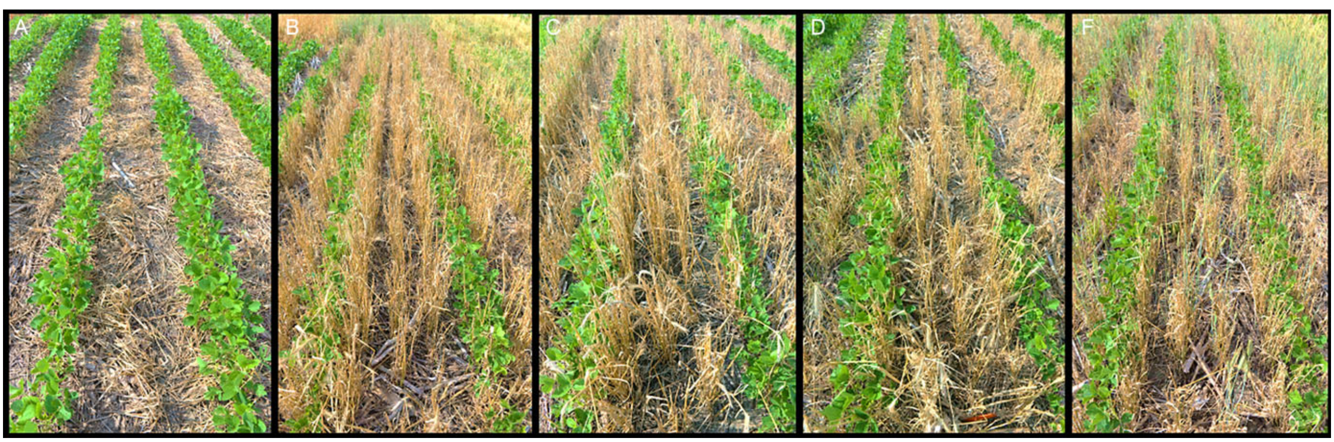

Figure 4. Cereal rye terminated 15 d after soybean planting with (A) glyphosate at 1,260 g ae ha^{-1}, (B) fluazifop-P-butyl at 420 g ai ha^{-1}, (C) quizalofop at 92 g ai ha^{-1}, (D) fluazifop-P-butyl/fenoxaprop-P-ethyl at 314 g ai ha^{-1}, and (E) clethodim at 136 g ai ha^{-1} in field experiments conducted at the South Central Agricultural Laboratory near Clay Center, NE. Photographs were taken 28 d after herbicides were applied.

Results from this study suggest that, although delaying cover crop termination resulted in greater weed suppression, it may also negatively impact soybean stand and yield. Similarly, Hodgskiss et al. (2022) reported up to 28% soybean yield loss when cereal rye was terminated 9 to 14 DASP compared to termination before soybean planting. Nunes et al. (2023) reported that planting soybean into actively growing green cereal rye cover crop alters preemergence herbicide dynamics and can reduce yield. However, other studies reported no soybean yield penalties in delayed cereal rye termination timings (Grint et al. 2022; Mischler et al. 2010; Reed and Karsten 2022; Vollmer et al. 2020b). Silva et al. (2024) in a comprehensive study investigating the impacts of delayed cereal rye termination on soybean yield across multiple locations in the Midwest, reported that delayed termination did not reduce soybean yield in 25 of 28 location-years. The outcome of integrating cover crops into a cropping system depends on multiple variables, such as rainfall, irrigation, temperature, planting conditions, soil nitrogen, etc. (Garba et al. 2022). Consequently, more research is needed to make accurate predictions of the potential impact of cover crops on cash crop yields and potential long-term benefits within the various agronomic systems.

Practical Implications

Results of this study showed that, except for clethodim, ACCase-inhibiting herbicides evaluated were as effective as glyphosate for terminating cereal rye in soybean regardless of the termination timing. Thus, growers can consider using ACCase-inhibiting herbicides such as fluazifop-P-butyl (Fusilade DX), fluazifop-P-butyl/fenoxaprop-P-ethyl (Fusion), or quizalofop-P-ethyl (Assure II) as glyphosate alternative for effectively terminating cereal rye in soybean, reducing reliance on glyphosate and selection pressure on winter annual weeds present at the time of application. Moreover, delaying cover crop termination to soybean planting day or 15 DASP resulted in increased cereal rye biomass production and greater Palmer amaranth and *Setaria* species suppression compared to 15 DBSP termination timing and conventional treatment without cereal rye cover crop. Previous studies have reported that weed biomass is negatively correlated with cover crop biomass (MacLaren et al. 2019; Hodgskiss et al. 2021); hence, with greater cover crop biomass, more weed suppression is expected (Kumar et al. 2025). However, it is important to note that there might be a yield penalty associated with delayed cereal rye termination. In this study, cereal rye terminated at 15 DASP

https://doi.org/10.1017/wet.2025.17

Table 4. Effect of cereal rye termination timing and termination herbicides along with preemergence and postemergence herbicides on weed control and weed biomass at the R5 soybean growth stage.[a,b]

	Palmer amaranth[d,e]			*Setaria* species[d,e]		
Termination time[c]	Control	Biomass	Density	Control	Biomass	Density
	%	g m^{-2}	plants m^{-2}	%	g m^{-2}	plants m^{-2}
No cereal rye cover crop	65 c	9 a	9 a	71 c	1	3 ab
15 d before planting	70 c	7 a	8 a	82 b	2	5 a
At planting	88 b	1 b	2 b	92 a	1	2 b
15 d after planting	96 a	1 b	1 b	96 a	1	1 b
	***	**	***	**	NS	**
Termination herbicide[c]						
Clethodim (136 g ai ha^{-1})	86	4	3	92	1	1
Fluazifop-P-butyl (420 g ai ha^{-1})	84	6	3	90	1	3
Fluazifop-P-butyl + Fenoxaprop-P-ethyl (314 g ai ha^{-1})	86	2	5	88	2	2
Glyphosate (1,260 g ae ha^{-1})	82	4	3	88	1	2
Quizalofop-P-ethyl (92 g ai ha^{-1})	87	3	4	90	1	3
	NS	NS	NS	NS	NS	NS

[a]Field experiments were conducted at the South Central Agricultural Laboratory, near Clay Center, NE, in 2019 and 2020.
[b]The main effect of termination time was significant for Palmer amaranth control, biomass, and density, and *Setaria* species control and density; therefore, treatment means were averaged over within each main effect.
[c]All the treatments received a premix of chlorimuron/flumioxazin/pyroxasulfone applied preemergence (Fierce® XLT; Valent USA LLC, Walnut Creek, CA) at 230 g ai ha^{-1} and dicamba (XtendiMax®; Bayer Crop Science, St. Louis, MO) applied postemergence at 560 g ae ha^{-1}.
[d]Means presented within the same column and with no common letters are significantly different according to Fisher's protected least significant difference test.
[e]Significance levels: NS, nonsignificant at $\alpha = 0.05$; *$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$.

Table 5. Effect of cereal rye termination timing and termination herbicides on soybean stand and yield.[a,b]

Termination time[b]	Soybean stand[c,d,e]	Soybean yield[c,d,e]
	Number of plants m row^{-1}	kg ha^{-1}
No cereal rye cover crop	19 a	3,977 a
15 days before soybean planting	19 a	4,460 a
At soybean planting day	19 a	4,566 a
15 days after soybean planting	17 b	2,184 b
	*	***
Termination herbicide		
Clethodim (136 g ai ha^{-1})	19	3,803
Fluazifop-P-butyl (420 g ai ha^{-1})	18	3,850
Fluazifop-P-butyl + fenoxaprop-P-ethyl (314 g ai ha^{-1})	19	3,839
Glyphosate (1,260 g ae ha^{-1})	19	3,559
Quizalofop-P-ethyl (92 g ai ha^{-1})	18	3,901
	NS	NS

[a]Field experiments were conducted at the South Central Agriculture Laboratory near Clay Center, NE. Soybean stand was obtained from the 2019 and 2020 seasons; however, due to a hailstorm in 2019, only 2020 soybean yield data are reported.
[b]All the treatments received a premix of chlorimuron/flumioxazin/pyroxasulfone applied preemergence (Fierce® XLT; Valent USA LLC, Walnut Creek, CA) at 230 g ai ha^{-1} and dicamba (XtendiMax®; Bayer Crop Science, St. Louis, MO) applied postemergence at 560 g ae ha^{-1} + labeled adjuvants.
[c]The main effect of termination timing was significant for soybean stand and yield; therefore, treatment means were averaged over within each main effect.
[d]Means presented within the same column and with no common letters are significantly different according to Fisher's protected least significant difference test.
[e]Significance levels: NS, nonsignificant at $\alpha = 0.05$; *$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$.

reduced soybean stand and resulted in up to 52% soybean yield loss. However, no soybean yield differences were observed between conventional treatment without cereal rye cover crop, and cereal rye termination at SPD and 15 DBSP. Moreover, despite the reduced efficacy of clethodim on cereal rye, termination herbicide did not impact weed suppression and soybean yield. Further investigation is needed to better understand potential cash crop impacts when cereal rye termination efficacy is reduced, and farmers should take this into consideration when choosing how to terminate their cover crops.

In conclusion, cereal rye termination timing relative to soybean planting should be carefully considered to achieve greater weed suppression without compromising cash crop yields. In this research, cereal rye terminated at soybean planting day resulted in greater late season weed control and similar yields compared to conventional treatment without cereal rye and cereal rye terminated at 15 days before soybean plating. Cover crops have the potential to suppress troublesome weeds and growers must leverage added input costs and potential yield penalties against the long-term benefits of this practice.

Acknowledgements. We thank graduate students and technicians of the Jhala Lab for their help with this project.

Funding. This research received no specific grant from any funding agency, commercial or not-for-profit sectors.

Competing interests. The authors declare that they have no competing interests.

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