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Planting soybean green: how cereal rye biomass and preemergence herbicides impact *Amaranthus* spp. management and soybean yield

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Abstract

Cereal rye (*Secale cereale* L.) cover crop and preemergence herbicides are important components of an integrated weed management program for waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] and Palmer amaranth (*Amaranthus palmeri* S. Watson) management in soybean [*Glycine max* (L.) Merr.]. Accumulating adequate cereal rye biomass for effective suppression of *Amaranthus* spp. can be challenging in the upper Midwest due to the short window for cereal rye growth in a corn–soybean rotation. Farmers are adopting the planting green system to optimize cereal rye biomass production and weed suppression. This study aimed to evaluate the feasibility of planting soybean green when integrated with preemergence herbicides for the control of *Amaranthus* spp. under two soybean planting time frames. The study was conducted across 19 site-years in the United States over the 2021 and 2022 growing seasons. Factors included cover crop management practices ("no-till," "cereal rye early-term," and "cereal rye plant-green"), soybean planting times ("early" and "late"), and use of preemergence herbicides ("NO PRE" and "YES PRE"). Planting soybean green increased cereal rye biomass production by 33% compared with early termination. Greater cereal rye biomass production when planting green provided a 44% reduction in *Amaranthus* spp. density compared with no-till. The use of preemergence herbicides also resulted in a 68% reduction in *Amaranthus* spp. density compared with NO PRE. Greater cereal rye biomass produced when planting green reduced soybean stand, which directly reduced soybean yield in some site-years. Planting soybean green is a feasible management practice to optimize cereal rye biomass production, which, combined with preemergence herbicides, provided effective *Amaranthus* spp. management. Soybean stand was a key factor in maintaining soybean yields compared with no-till when planting green. Farmers should follow best management recommendations for proper planter and equipment setup to ensure effective soybean establishment under high levels of cereal rye biomass when planting green.

Introduction

Weeds challenge crop production due to their ability to reduce crop yield, increase production costs, cause financial losses, and depreciate land value (Bensch et al. 2003; Oerke 2006; Soltani et al. 2017). Waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] and Palmer amaranth (*Amaranthus palmeri* S. Watson), hereafter referred to as *Amaranthus* spp., stand out as the two most troublesome weed species in soybean [*Glycine max* (L.) Merr.] production systems across multiple regions of the United States (Steckel 2007; Van Wychen 2022). *Amaranthus* spp. are highly competitive weed species due to their rapid and vigorous growth and prolific seed production (Bensch et al. 2003; Heneghan and Johnson 2017; Schwartz et al. 2016; Sellers et al. 2003; Steckel 2007). Currently, herbicides are utilized as the primary method to control *Amaranthus* spp. in U.S. corn (*Zea mays* L.), soybean, and cotton (*Gossypium hirsutum* L.) production systems (Steckel 2007). The overreliance on herbicides has favored the selection of *Amaranthus* spp. populations resistant to effective postemergence herbicide active ingredients and groups (i.e., glyphosate [WSSA Group 9], imazethapyr [WSSA Group 2], lactofen [WSSA Group 14], and 2,4-D [WSSA Group 4]) adopted for management of *Amaranthus* spp. in soybean production systems (Faleco et al. 2022; Heap 2023; Legleiter and Bradley 2008; Norsworthy et al. 2008; Shyam et al. 2022). With the rapid increase in herbicide-resistant *Amaranthus* spp. populations, nonchemical weed control methods such as cover cropping have gained interest and popularity among soybean producers as an alternative weed management strategy (Essman et al. 2023; Nichols and MacKenzie 2023; SARE 2023).

Cereal rye (*Secale cereale* L.) is the most common cover crop species adopted by North American farmers for weed suppression and for rendering other ecosystem services, such as reducing soil erosion, increasing soil organic matter, and improving biological soil health (Bowman et al. 2022; Palhano et al. 2018; SARE 2023). Cereal rye is a widely adopted winter cover crop due to its winter hardiness and potential high biomass production in the spring (Bowman et al. 2022; Nichols et al. 2020; Nunes et al. 2023; Palhano et al. 2018). Biomass production is the primary driver for effective weed suppression by cover crops (Hodgskiss et al. 2022; Mirsky et al. 2011; Nichols et al. 2020; Nunes et al. 2024). The increase in biomass augments the mulching effect of the cover crop by intercepting sunlight and lowering mean soil temperatures and temperature fluctuations (Nunes et al. 2024; Teasdale and Mohler 1993), which are key triggers of *Amaranthus* spp. germination (Leon and Knapp 2004; Steckel et al. 2004). Nevertheless, heat accumulation in the upper Midwest is a limiting factor for cereal rye growth in the short window that exists between its planting after corn harvest and before soybean planting the following spring in a standard corn–soybean rotation (Grint et al. 2022; Nichols et al. 2020). If cereal rye is terminated before achieving desired levels of biomass, it is unlikely that it will provide effective weed suppression (Nichols et al. 2020; Nunes et al. 2024; Schramski et al. 2021). Hence, management practices that postpone cereal rye termination and increase biomass production are of paramount importance for the success of this practice.

In order to postpone cereal rye termination, researchers have been investigating the feasibility of the planting green system (Ficks et al. 2023; Grint et al. 2022; Nunes et al. 2023). Planting green is a practice wherein the cash crop is planted into a living cover crop to maximize ecosystem services provided by cover crops (Fisher and Sprague 2022; Reed and Karsten 2022; Reed et al. 2019). It allows extra time for cereal rye growth and biomass production compared with the standard recommendation of terminating the cover crop 1 to 2 wk before cash crop planting (Grint et al. 2022). This practice has triggered the interest of farmers as a viable option to optimize cereal rye biomass production and weed suppression without interfering with soybean planting dates (SARE 2023). Reed and Karsten (2022) studied the adoption of the planting green system in no-till soybean production and observed that terminating cereal rye at planting nearly doubled biomass production (5.5 Mg ha^{-1}) when compared with terminating the cover crop on average 13 d prior (2.9 Mg ha^{-1}). Schramski et al. (2021) also observed an average increase of 2.5 Mg ha^{-1} in cereal rye biomass production by planting green (3.8 Mg ha^{-1}) compared with early termination 2 wk prior (1.3 Mg ha^{-1}). Postponing cereal rye termination in the planting green system also increased the cover crop C:N ratio, which improved residue persistence and horseweed [*Conyza canadensis* (L.) Cronquist; syn.: *Erigeron canadensis* L.) suppression (Schramski et al. 2021). Hodgskiss et al. (2022) also reported that postponing cereal rye termination until soybean planting increased biomass production compared with the early termination on average 3 wk prior (4.5 Mg ha^{-1} vs 2.1 Mg ha^{-1}). This increase in cereal rye biomass also improved *A. tuberculatus* suppression (Hodgskiss et al. 2022). It is evident that the planting green system can effectively optimize cereal rye biomass production and improve weed suppression. Nonetheless, soybean response to cover crop termination at planting is variable, with some studies reporting no effect on yield (Reed and Karsten 2022; Schramski et al. 2021) and some studies reporting yield reduction by the planting green system (Hodgskiss et al. 2022; Nunes et al. 2023).

Despite providing effective weed suppression when properly managed to accumulate adequate levels of biomass, cereal rye biomass alone is unlikely to consistently provide season-long weed control (Loux et al. 2017). Thus, combining cereal rye cover crop with additional weed management strategies, such as preemergence herbicides, is a sound approach for effective *Amaranthus* spp. control (Yadav et al. 2023). Previous research has reported that combining these two practices can reduce early-season *Amaranthus* spp. density and delay the number of days needed for plants to reach the recommended height (10 cm) for postemergence herbicide applications (Perkins et al. 2021). A lower weed density can reduce the selection pressure imposed by postemergence herbicides, and more time to reach the recommended height for postemergence control can give farmers flexibility to plan and execute postemergence herbicide applications (Knezevic et al. 2019; Lopes-Ovejero et al. 2013; Perkins et al. 2021). Integrating preemergence herbicides as part of *Amaranthus* spp. herbicide programs can also introduce different herbicide sites of action used during a growing season, and the cereal rye might be considered an additional layer of control due to its physical effect on *Amaranthus* spp. emergence (Nunes et al. 2024; Price et al. 2012; Teasdale and Mohler 1993). Thus, when properly managed and executed, the combination of these two practices can serve as valuable approaches to mitigate *Amaranthus* spp. herbicide resistance evolution and crop yield loss due to competition.

In a survey of cover crop adoption, Bowman et al. (2022) revealed that 40% of farmers terminate cover crops 2 wk before cash crop establishment and 27% adopt the planting green system. Potential yield loss due to competition between cover and cash crops was cited as a common concern preventing farmers from postponing cereal rye termination (Bowman et al. 2022). Research covering a wide range of conditions in different soybean-growing regions across the United States can help elucidate which factors drive effective *Amaranthus* spp. suppression and potential yield penalties by this system. Therefore, this multilocation study was conducted to evaluate the feasibility of planting soybean green when integrated with preemergence herbicides on *Amaranthus* spp. control and soybean yield under two soybean planting times. We hypothesized that (1) delaying cereal rye termination by planting green can increase cereal rye biomass production, (2)

Table 1. Geographic coordinates and soil properties of each site-year

Site	Geographic coordinates	Year	Soil properties					Soil texture
			OM[a]	Sand	Silt	Clay	pH	
			%					
Illinois, IL	37.70°N, 89.24°W	2021	2.5	8.0	77.0	15.0	6.5	Silt loam
		2022	1.9	3.0	78.0	19.0	6.1	Silt loam
Indiana, IN	40.51°N, 86.87°W	2021	2.4	27.0	52.0	21.0	7.1	Silt loam
		2022	2.4	27.0	52.0	21.0	7.1	Silt loam
Iowa, IA	42.41°N, 93.62°W	2021	2.9	54.0	23.0	23.0	7.1	Sandy clay loam
		2022	2.9	54.0	23.0	23.0	7.1	Sandy clay loam
Kansas East, KS-E	39.12°N, 95.92°W	2021	1.2	76.0	16.0	8.0	6.4	Sandy loam
		2022	1.7	40.0	50.0	10.0	5.5	Silt loam
Kentucky, KY	37.92°N, 87.86°W	2021	2.5	10.8	74.3	15.0	6.1	Silt loam
		2022	1.9	10.8	74.3	15.0	6.2	Silt loam
North Dakota, ND	46.93°N, 96.82°W	2021	4.5	2.3	41.0	56.7	7.3	Silty clay
		2022	5.0	2.3	41.0	56.7	7.3	Silty clay
Pennsylvania, PA	40.72°N, 77.94°W	2021	2.0	9.2	56.7	34.1	7.0	Silty clay loam
		2022	2.0	23.2	44.5	32.3	7.0	Clay loam
Wisconsin, WI	42.87°N, 89.39°W	2021	1.7	40.0	42.0	18.0	7.0	Loam
		2022	1.6	48.0	37.0	15.0	7.1	Loam
Arkansas, AR	36.51°N, 94.45°W	2022	1.8	22.2	59.0	18.8	6.4	Silt loam
Kansas Central, KS-C	38.61°N, 98.89°W	2021	1.1	79.0	14.0	7.0	4.9	Loamy sand
Missouri, MO	38.72°N, 92.51°W	2022	1.9	12.5	67.5	20.0	6.8	Silt loam

[a]OM, organic matter.

greater cereal rye biomass production in conjunction with preemergence herbicides can effectively control *Amaranthus* spp., and (3) planting soybean green will not lead to yield penalties.

Materials and Methods

Study Design

A field study was conducted across 19 site-years in 10 different states during the 2021 and 2022 growing seasons (Table 1). The study was conducted as a two by three by two factorial. Factor A comprised two soybean planting times ("early" and "late"); in the early planting, soybean was planted at the earliest possible date given the planting window and environmental conditions of each site-year, and in the late planting, soybean was planted on average 17 d after the early planting. Factor B comprised three cover crop management practices ("no-till," "cereal rye early-term," and "cereal rye plant-green"); no-till consisted of undisturbed soil with corn stubble from the previous growing season without cereal rye (except in ND, where the study was established after wheat [*Triticum aestivum* L.]), cereal rye early-term consisted of no-till cereal rye planted over corn stubble and terminated on average 13 d before each soybean planting time (early termination), and cereal rye plant-green consisted of no-till cereal rye planted over corn stubble and terminated at each soybean planting time (planting green). Factor C comprised the use of a preemergence herbicide program applied at the cereal rye plant-green termination ("NO PRE" and "YES PRE"). A diagram illustrating the timing of herbicide applications in the study is available in Supplementary Figure S1. The experimental design adopted was a randomized complete block design with a treatment arrangement adapted from a split-plot design (Supplementary Figure S2). Experimental units consisted of 3 by 9.1 m plots replicated four times. The main plots were a combination of soybean planting time and cover crop management applied as strips (two 37.6 by 3 m strips of each soybean planting time and cereal rye management combination) in the experimental area. The split plot was the use of the preemergence herbicide program that was randomly applied to one of the two plots of each soybean planting time and cover crop management combination within each block. Soybean planting time and cover crop management were applied as strips to facilitate soybean and cereal rye establishment. Instead of soybean planting time and cover crop management being attributed to adjacent strips, they were randomized within the experimental area to improve the distribution of treatments across the experimental field, which was the reason for this design being adapted from a split-plot treatment arrangement (e.g., instead of having the two split plots side by side within each block, they were randomized within the block). Unlike a split-plot arrangement, where the split plot is nested within the main plot, it was not assumed that the preemergence herbicide (NO PRE and YES PRE) plots (split plot) had any degree of dependence within each soybean planting time and cover crop management combination (main plot).

Study Establishment and Herbicide Applications

The study was initiated in the fall before each experimental year by no-till drilling cereal rye after corn harvest at a seeding rate of 67 kg ha^{-1} (except KY 2022, which was planted at 90 kg ha^{-1}), 19-cm row spacing, and an average seeding depth of 3.0 cm. The cover crop was chemically terminated the following spring with glyphosate (Roundup PowerMax®, 1,262 g ae ha^{-1}, Bayer CropScience, St Louis, MO) and ammonium sulfate at 2,200 g ha^{-1} applied at each termination time (Table 2). Glyphosate was tank mixed with glufosinate (Liberty®, 655 g ai ha^{-1}, BASF, Research Triangle Park, NC) as part of a standard burndown applied to all treatments (no-till, cereal rye early-term, and cereal rye plant-green) at the cereal rye plant-green termination date to eliminate potential glyphosate-resistant weeds established at soybean planting. For the YES PRE treatments, flumioxazin plus pyroxasulfone (Fierce EZ®, 70.4 g ai ha^{-1} plus 89.3 g ai ha^{-1}, Valent U.S.A., Walnut Creek, CA) were included in the spray mix containing glyphosate and glufosinate and sprayed at the cereal rye plant-green termination time (Table 2). Soybean was planted using a no-till planter adjusted to place seeds at an average depth of 2.5 cm on 76-cm row spacing, except for KY in both years, which used 38-cm row spacing, and

Table 2. Cereal rye planting, cereal rye termination, and soybean planting dates of each site-year

			Cereal rye termination				Soybean planting	
			Early soybean		Late soybean			
Site	Year	Cereal rye planting	Early termination	Planting green	Early termination	Planting green	Early	Late
Illinois, IL	2021	2-Oct-2020	26-Apr	7-May	7-May	17-May	7-May	17-May
	2022	7-Oct-2021	15-Apr	28-Apr	28-Apr	12-May	28-Apr	13-May
Indiana, IN	2021	12-Oct-2020	2-May	16-May	16-May	1-Jun	16-May	1-Jun
	2022	8-Nov-2021	16-Apr	29-Apr	11-May	24-May	29-Apr	24-May
Iowa, IA	2021	6-Nov-2020	7-May	14-May	14-May	21-May	14-May	21-May
	2022	1-Nov-2021	18-May	2-Jun	2-Jun	20-Jun	2-Jun	20-Jun
Kansas East, KS-E	2021	24-Sep-2020	24-Apr	4-May	20-May	25-May	4-May	25-May
	2022	18-Oct-2021	21-Apr	10-May	10-May	20-May	10-May	20-May
Kentucky, KY	2021	1-Oct-2020	15-Apr	28-Apr	14-May	25-May	24-Apr	25-May
	2022	11-Oct-2021	27-Apr	10-May	4-May	16-May	10-May	16-May
North Dakota, ND	2021	16-Sep-2020	10-May	19-May	19-May	1-Jun	19-May	1-Jun
	2022	15-Sep-2021	23-May	3-Jun	3-Jun	17-Jun	3-Jun	16-Jun
Pennsylvania, PA	2021	1-Oct-2020	13-Apr	4-May	4-May	19-May	3-May	18-May
	2022	20-Oct-2021	30-Apr	12-May	12-May	25-May	11-May	24-May
Wisconsin, WI	2021	25-Sep-2020	28-Apr	7-May	7-May	18-May	7-May	18-May
	2022	23-Sep-2021	29-Apr	12-May	12-May	24-May	11-May	24-May
Arkansas, AR	2022	5-Nov-2021	9-Apr	18-Apr	6-May	16-May	22-Apr	20-May
Kansas Central, KS-C	2021	17-Sep-2020	27-Apr	7-May	7-May	27-May	7-May	27-May
Missouri, MO	2022	7-Nov-2021	4-Apr	15-Apr	11-May	1-Jun	12-Apr	31-May

AR 2022, which used 91-cm row spacing (Table 2). Planters were equipped with mounted floating row cleaners and no-till coulters to prepare the seedbed. The soybean variety and seeding rate varied across site-years and were selected based on local recommendations (Supplementary Table S1).

Postemergence herbicide application was initiated when 20% of *Amaranthus* spp. plants reached 10 cm in height within a treatment, similar to Perkins et al. (2021), who evaluated the number of days until *Amaranthus* spp. reached 10 cm in height as the threshold for postemergence control with most herbicides available for soybean. Because postemergence applications were initiated by *Amaranthus* spp. height, applications varied across treatments within each site-year. The respective dates of postemergence herbicide application by treatment are available in Supplementary Tables S2 and S3. The postemergence herbicide mixture was composed of glufosinate (Liberty®, 655 g ai ha^{-1}, BASF), 2,4-D choline (Enlist One®, 1,095 g ae ha^{-1}, Corteva Agriscience, Indianapolis, IN), clethodim (Select Max®, 102 g ai ha^{-1}, Valent U.S.A.), microencapsulated acetochlor (Warrant®, 1,261 g ai^{-1}, Bayer CropScience), and ammonium sulfate at 2,200 g ha^{-1}. All herbicide applications (cereal rye termination, preemergence, and postemergence) were delivered with a CO_2-pressurized backpack sprayer equipped with a 3-m handheld boom fitted with six nozzles (TTI 110015 for cereal rye termination and preemergence application and AIXR 110015 for postemergence application, TeeJet® Technologies, Denver, CO) on 50-cm spacing calibrated to deliver 140 L ha^{-1} of spray solution.

Cereal Rye, *Amaranthus* spp., Soybean, and Weather Data Collection

Aboveground cereal rye biomass was determined at each termination timing by clipping cereal rye plants at the soil surface from three 0.1-m^2 quadrats randomly placed in each plot immediately before termination. Biomass samples were placed in paper bags and dried at 65 C for 7 d to determine cereal rye biomass (in Mg ha^{-1}). *Amaranthus* spp. density was collected at the time of postemergence herbicide application by counting the number of emerged *Amaranthus* spp. plants in two 0.25-m^2 quadrats randomly placed in each plot. *Amaranthus palmeri* was evaluated in KS-E 2021, KS-C 2021, KS-E 2022, and AR 2022, and *A. tuberculatus* in the other site-years. *Amaranthus palmeri* and *A. tuberculatus* density data were combined for analysis due to the intrinsic similarities between the two species and also to their similar response to preemergence herbicides and the use of cereal rye for weed suppression (Palhano et al. 2018; Perkins et al. 2021; Steckel 2007; Webster et al. 2016). Because postemergence herbicide applications were initiated on a case by case basis when 20% of *Amaranthus* spp. plants within a treatment reached 10 cm in height, the days between each soybean planting time and postemergence T application were quantified to assess differences across treatments. Soybean stand was quantified by counting the number of plants from 2 m of the two center rows of each plot at the time of harvest. Soybean yield (adjusted to 13% moisture content) was determined by harvesting the two center rows of each plot with a plot combine at physiological maturity.

Daily precipitation (mm) and minimum, maximum, and average air temperature (C) from cereal rye planting to soybean harvest of each experimental year were collected from weather stations adjacent to the experimental areas. The temperature data were used to estimate daily growing degree days (GDD) from cereal rye planting until each termination time using Equation 1:

$$GDD = \frac{T_{max} + T_{min}}{2} - T_{base} \quad [1]$$

where T_{max} and T_{min} are the maximum and minimum daily temperatures, respectively; and T_{base} is the base temperature at which cereal rye's physiological activity and growth occur, set at 4.4 C (Mirsky et al. 2011). Thus, for days on which the mean temperature was lower than T_{base}, GDD accumulation was assumed to be zero.

Statistical Analyses

All statistical analyses were performed in R statistical software v. 4.2.1 (R Core Team 2022). Data processing and visualization were

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performed with the TIDYVERSE collection of packages (Wickham et al. 2019), and specific details about other packages are provided in each section.

Cereal rye biomass data were analyzed with a linear mixed-effects model using the LME4 package (Bates et al. 2015). Cereal rye termination time, soybean planting time, and use of a preemergence herbicide were treated as fixed effects, and block nested within site-year was treated as a random effect in the model. *Amaranthus* spp. density data were analyzed with a generalized linear mixed model using the GLMMTMB package (Brooks et al. 2017) following a generalized Poisson distribution. Cover crop management, soybean planting time, and use of a preemergence herbicide were treated as fixed effects, and block nested within site-year was treated as a random effect in the model. Days to postemergence herbicide application data were analyzed with a linear mixed-effects model using the LME4 package (Bates et al. 2015). Cover crop management, soybean planting time, and use of a preemergence herbicide were treated as fixed effects, and site-year was treated as a random effect in the model.

Block was not nested within site-year as a random effect in this particular model to ensure proper replication of the data, because all four experimental units of a treatment at each site-year were sprayed on the same date. Soybean stand and yield were analyzed with a linear mixed-effects model using the LME4 package (Bates et al. 2015). Cover crop management, soybean planting time, and use of a preemergence herbicide were treated as fixed effects, and block nested within site-year was treated as a random effect in the model. Model assumptions of normality and homogeneity of variance were assessed by visual inspection of residuals. No transformation was necessary. When a significant interaction or main effect was observed ($P < 0.05$), fitted models were used to obtain estimated marginal means, which were separated using Fisher's LSD test at $\alpha = 0.05$ (EMMEANS package; Lenth 2022).

Piecewise structural equation models (SEMs) were fit using the PIECEWISESEM package (Lefcheck 2016) to evaluate the effects of cereal rye termination, cereal rye biomass production, soybean planting time, use of a preemergence herbicide, and soybean stand on *Amaranthus* spp. density and soybean yield. Models were fit following a similar approach to Wallace et al. (2021), who adopted SEM to evaluate the effects of cover crop and weed management on corn and soybean yield. The goal of fitting SEMs was to understand how the management practices adopted in this study affected cereal rye biomass production and, consequently, how cereal rye biomass affected *Amaranthus* spp. and soybean responses. Because the SEMs revolved around cereal rye biomass production, the no-till treatment was not directly included in the models. Instead, the no-till treatment was used to standardize *Amaranthus* spp. density and soybean yield response to alternative treatments using a relative response index (RRI; Equation 2) adapted from Williams et al. (1998):

$$\mathrm{RRI} = (P_{\mathrm{r}} - P_{\mathrm{cn}}) \;/\; (P_{\mathrm{r}} + P_{\mathrm{cn}}) \qquad [2]$$

where P_{r} represents plant response (*Amaranthus* spp. density and soybean yield) in a cereal rye treatment (cereal rye early-term and cereal rye plant-green), and P_{cn} represents plant response (*Amaranthus* spp. density and soybean yield) in the absence of cereal rye cover crop (no-till), which was given by the average of the four observations of each variable in the no-till treatment of each site-year. An RRI value greater than 0 indicates that the cereal rye increased plant response; if equal to 0, the cereal rye had no effect on plant response; and if lower than 0, it decreased plant response.

SEMs were composed of structured linear equations fit using the LME4 package (Bates et al. 2015). For the *Amaranthus* spp. density SEM model, two structured linear equations were included: (1) the additive effect of cereal rye termination and soybean planting time on cereal rye biomass and (2) the interaction of cereal rye biomass and use of a preemergence herbicide with the additive effects of cereal rye termination and soybean planting time on *Amaranthus* spp. RRI. As for the soybean yield SEM model, three structured linear equations were included: (1) the additive effect of cereal rye termination and soybean planting time on cereal rye biomass, (2) the linear relationship between cereal rye biomass and soybean stand, and (3) the additive effect of cereal rye termination time and soybean stand on soybean RRI. Structured linear equations were fit with block nested within site-year as a random effect using either a random intercept or random intercept and slope specification. Fitted structured linear models were compared through Akaike's information criterion to select the best model for inclusion in the SEM (Wallace et al. 2021; Zuur et al. 2009). Fitted SEMs underwent a test of directed separation and were evaluated with Fisher's C statistic (Lefcheck 2016; Wallace et al. 2021). This function tests the assumption of conditional independence, which identifies significant relationships among unconnected variables in the full model using a predetermined significance threshold ($\alpha = 0.05$). Fisher's C is derived from the P of all linear models in the basis set, and the overall model fit is indicated by a $P > 0.05$ (Lefcheck 2016; Wallace et al. 2021). Standardized regression coefficients (Byrnes et al. 2011) and significant levels ($P < 0.05$) for path coefficients were obtained to determine the directionality and relative strength of explanatory variables. Marginal (R^2_{m}) and conditional (R^2_{c}) coefficients of determination are reported for each component model. R^2_{m} describes the proportion of the variance in the response explained by the model's fixed effect(s) only, and R^2_{c} describes the proportion of the variance in the response explained by the model's random and fixed effect(s) components (Lefcheck 2016).

Results and Discussion

Aboveground Cereal Rye Biomass at Termination

Cereal rye biomass was affected by termination ($P < 0.001$) and soybean planting times ($P < 0.001$) main effects (Table 3). Delaying cereal rye termination until soybean planting (plant-green) or delaying soybean planting time (late soybean) increased cereal rye biomass production by 33% and 41%, respectively (Table 3). The increase in cereal rye biomass production by the planting green termination time corroborates previous studies reporting the benefits of this practice for increasing cereal rye biomass accumulation (Hodgskiss et al. 2022; Reed and Karsten 2022; Schramski et al. 2021). On average, across soybean planting times and site-years, the planting green treatment resulted in a 13-d delay in cereal rye termination compared with the early termination. This delay led to an increase of 2.1 Mg ha^{-1} in cereal rye biomass within the specified 13-d window, equivalent to a daily increment of 0.16 Mg ha^{-1}. This rate of biomass increase aligns with findings from other studies exploring the feasibility of the planting green system. Reed and Karsten (2022) and Schramski et al. (2021) observed a daily increase rate of 0.20 and 0.17 Mg ha^{-1} of cereal rye biomass over nearly a 2-wk period in late spring,

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Table 3. Aboveground cereal rye biomass (Mg ha^{-1}) at termination

Main effect	Cereal rye biomass[a]
Cereal rye termination time	— Mg ha^{-1} —
Early-term	4.2 (0.71) b
Plant-green	6.3 (0.71) a
Soybean planting time	— Mg ha^{-1} —
Early soybean	3.9 (0.71) b
Late soybean	6.6 (0.71) a
	P-value
Cereal rye termination (T)	<0.001
Soybean planting (SB)	<0.001
Preemergence herbicide (PRE)	0.413
T × SB	0.835
T × PRE	0.628
SB × PRE	0.222
T × SB × PRE	0.868

[a]Means followed by standard errors in parentheses. Means followed by the same letter within the column of each main effect indicate no statistical difference by the Fisher's protected LSD test ($\alpha = 0.05$).

respectively. Hodgskiss et al. (2022) observed a daily increase rate of 0.11 Mg ha^{-1} over a 3-wk window.

The main purpose of the planting green system is to delay cereal rye termination to optimize biomass production and achieve desired biomass levels for effective suppression of late-emerging *Amaranthus* spp. In a previous study, Nunes et al. (2024) reported that 5.2 Mg ha^{-1} of cereal rye biomass was required to reduce *A. tuberculatus* density by 50%. Considering 5.2 Mg ha^{-1} of cereal rye biomass to be the desired biomass level for effective *Amaranthus* spp. suppression, the adoption of the planting green system surpassed this biomass threshold when averaged over all site-years. Nonetheless, there were 8 site-years (AR 2022, IA 2021, IL 2021, IN 2022, KY 2021, KY 2022, MO 2022, and ND 2021) in which this practice did not lead to adequate cereal rye biomass production (<5.2 Mg ha^{-1}) regardless of the soybean planting time. The lack of response in cereal rye biomass production by the planting green system in some site-years indicates that other factors besides termination time play an important role in biomass production. Cereal rye planting date has been suggested to affect cereal rye growth during the fall and biomass production during the spring (Mirsky et al. 2011; Nord et al. 2011; Schramski et al. 2021). Out of the 8 site-years that did not achieve 5.2 Mg ha^{-1} of cereal rye biomass, 4 site-years (AR 2022, IA 2021, IN 2022, and MO 2022) had the cereal rye planted after November 4, which could be one of the factors driving the lower biomass production in these site-years (Table 2). Another aspect to consider is the precipitation between cereal rye planting and termination. The site-year ND 2021 had the lowest accumulated precipitation (142 mm) between cereal rye planting and the latest termination (planting green at the late soybean planting time) time across site-years (Supplementary Figure S3). The accumulated precipitation in ND 2021 was 482 mm lower than the average accumulated precipitation (624 mm) for the same period in the other 7 site-years with biomass production <5.2 Mg ha^{-1}. The low precipitation likely hindered cereal rye growth in this site-year (Reed et al. 2019). Additionally, issues with cereal rye establishment due to high corn residue from the previous crop were reported to influence cereal rye stand and final biomass production in KY 2021 (TL and JN, personal observation).

One of the main drivers for cereal rye biomass production is GDD accumulation (Baraibar et al. 2020; Mirsky et al. 2011). Our data show that for all site-years, cereal rye biomass production and GDD accumulation had a positive linear relationship (Figure 1; Supplementary Figure S4). Delaying cereal rye termination increased GDD accumulation and cereal rye biomass production. However, our data do not indicate that the site-years with the largest GDD accumulation also resulted in the highest cereal rye biomass production. In a meta-analysis compiling studies investigating the effect of cover crop biomass on weed suppression, Nichols et al. (2020) reported model simulations suggesting that extending the cereal rye growth window (early planting and late termination dates) could lead to higher cereal rye biomass production. Their model also suggested that cereal rye biomass production would follow a latitudinal gradient, with northern midwestern states requiring a longer window to achieve 5 Mg ha^{-1} of cereal rye biomass than southern states. The linear relationship between cereal rye biomass production and GDD accumulation supports the findings from Nichols et al. (2020) that extending the window for cereal rye growth could lead to higher biomass production. Nonetheless, our data do not support a latitudinal gradient, with southern midwestern states presenting higher biomass production than northern midwestern states. The lack of a latitudinal gradient for cereal rye biomass production indicates that farmers in the northern midwestern states (e.g., Wisconsin) can successfully grow cereal rye and produce adequate levels of biomass for effective weed suppression.

Amaranthus spp. Density and Time of Postemergence Application

Analysis of *Amaranthus* spp. density at the time of postemergence application revealed the main effect of cover crop management ($P < 0.001$) and the interaction between preemergence herbicide and soybean planting time ($P = 0.019$) as significant effects (Table 4). For the main effect of cover crop management, the highest *Amaranthus* spp. density was observed in the no-till (average of 41 plants m^{-2}), whereas cereal rye early-term (34 plants m^{-2}) and cereal rye plant-green (23 plants m^{-2}) reduced *Amaranthus* spp. density by 16% and 44%, respectively (Table 4). Adopting the planting green system increased cereal rye biomass production (Table 3) and resulted in the lowest *Amaranthus* spp. density when compared with no-till and cereal rye early-term (Table 4). The *Amaranthus* spp. suppression provided by the planting green system corroborates previous research indicating that cereal rye can effectively suppress weeds and that weed suppression is correlated with cereal rye biomass production (Cornelius and Bradley 2017; Hodgskiss et al. 2022; Nord et al. 2011; Nunes et al. 2024; Ryan et al. 2011; Schramski et al. 2021).

As for the interaction between preemergence herbicide and soybean planting time, the YES PRE treatment reduced *Amaranthus* spp. density by 62% and 74% when compared with NO PRE in the early and late soybean planting times, respectively (Table 4). Moreover, *Amaranthus* spp. density in the YES PRE treatment was 36% lower in the late soybean planting time (14 plants m^{-2}) when compared with early planting (23 plants m^{-2}; Table 4). The effectiveness of flumioxazin plus pyroxasulfone on *Amaranthus* spp. control corroborates previous research investigating the adoption of these preemergence herbicides for weed control in soybean production (Duenk et al. 2023; Ferrier et al. 2022; Perkins et al. 2021). The lower *Amaranthus* spp. density in the late soybean planting time compared with early planting can be attributed to a combination of factors involving cereal rye biomass

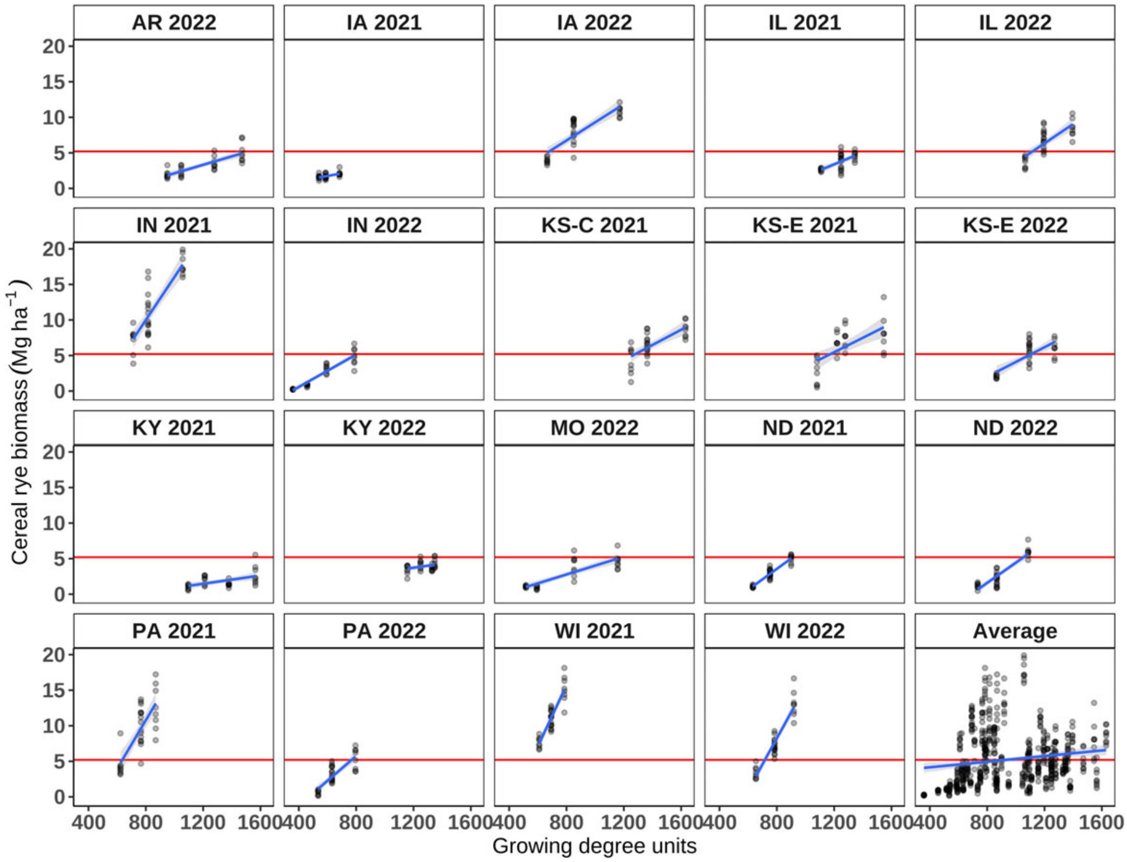

Figure 1. Effect of growing degree days (GDD; $T_{\text{base}} = 4.4$ C) on cereal rye aboveground biomass (Mg ha^{-1}) production at termination across site-years. GDD calculated from cereal rye planting to termination. The figure indicates the GDD accumulated between the earliest (early termination ahead of early soybean planting) to the latest (planting green termination at the late soybean planting) cereal rye termination dates. Points indicate the raw observations of cereal rye biomass collected at each termination time. Lines indicate the response in biomass accumulation as a function of GDD. Cereal rye termination times progress from the earliest to the latest. Red horizontal line indicates the level of 5.2 Mg ha^{-1} of cereal rye biomass. The average panel represents the data of all 19 site-years combined.

production, *Amaranthus* spp. emergence period, and the timing of herbicide applications in the study. First, delaying soybean planting time led to a 41% increase in cereal rye biomass production compared with early planting (Table 3). Because cereal rye biomass is correlated with *Amaranthus* spp. suppression (Nunes et al. 2024), a higher cereal rye biomass level in the late planting time likely reduced *Amaranthus* spp. density beyond the effect of the preemergence herbicides. A second factor that likely influenced *Amaranthus* spp. density was the combination of *Amaranthus* spp. emergence period and the timing of herbicide applications in the study. *Amaranthus* spp. is known to start emerging in mid-May in most U.S. soybean production regions (Chahal et al. 2021; Nunes et al. 2024; Werle et al. 2014). Thus, considering that *Amaranthus* spp. emergence started mid-May in most site-years and that the average late soybean planting time was May 25 across site-years (Table 2), it is plausible that the preemergence herbicides were at a higher concentration in the soil at the onset of *Amaranthus* spp. emergence in the late planting time. Additionally, all treatments received an application of glyphosate (1,262 g ae ha^{-1}) and glufosinate (655 g ai ha^{-1}) at soybean planting. This herbicide application likely controlled emerged *Amaranthus* spp. seedlings at the late soybean planting time to a greater extent when compared with average early planting, which was May 7 across site-years (Table 2).

For days between each soybean planting time to postemergence herbicide application, the main effects of cover crop management, soybean planting time, and preemergence herbicide were all significant ($P < 0.001$; Table 5). The main effect of cover crop management revealed an additional benefit of the planting green system for *Amaranthus* spp. management. Besides reducing *Amaranthus* spp. density (Table 4), planting green also delayed the time for a postemergence herbicide application by 2 and 4 d when compared with cereal rye early-term and no-till, respectively (Table 5). A similar result was reported by Wiggins et al. (2017), who observed that cover crops delayed the time for *A. palmeri* to reach 10 cm in height. Delaying soybean planting time required the postemergence herbicide application to be initiated 7 d earlier compared with early planting relative to the crop planting date (Table 5). As previously discussed, *Amaranthus* spp. emergence period likely played an important role in this study. It is plausible that because *Amaranthus* spp. emergence usually starts mid-May (Werle et al. 2014), planting soybean at this time point (average late soybean planting date May 25 across site-years) favors a shorter window for postemergence applications relative to the planting date. Whereas, with earlier soybean planting dates (average early soybean planting date May 7 across site-years), there is extra time between soybean planting and the onset of *Amaranthus* spp. emergence, thus extending the window for a postemergence application relative to the soybean planting date.

As for the effect of a preemergence herbicide, the application of flumioxazin and pyroxasulfone at soybean planting delayed the need for a postemergence herbicide application by 6 d compared

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Table 4. *Amaranthus* spp. density (plants m^{-2}) at the time of postemergence herbicide application[a]

	Preemergence herbicide[b]			
Soybean planting time	NO PRE		YES PRE	
	— plants m^{-2} —			
Early soybean	60 (13) a	A	23 (5) a	B
Late soybean	55 (12) a	A	14 (3) b	B
Cover crop main effect				
Cover crop management	*Amaranthus* spp. density[c]			
	— plants m^{-2} —			
No-till	41 (9) a			
Cereal rye early-term	34 (8) b			
Cereal rye plant-green	23 (5) c			
	P			
Cover crop management (CC)	<0.001			
Soybean planting (SB)	0.285			
Preemergence herbicide (PRE)	<0.001			
CC × SB	0.108			
CC × PRE	0.392			
SB × PRE	0.019			
CC × SB × PRE	0.595			

[a]Means followed by the standard errors in parentheses. The top of the table illustrates the interaction between preemergence herbicide and soybean planting, with the main effect of cover crop management given below.
[b]Means followed by the same lowercase letters indicate no statistical difference between soybean planting time within preemergence herbicide, and the same uppercase letters indicate no statistical difference between preemergence herbicide within soybean planting time by the Fisher's protected LSD test ($\alpha = 0.05$).
[c]Means followed by the same letter within the cover crop management main effect column indicate no statistical difference by the Fisher's protected LSD test ($\alpha = 0.05$).

Table 5. Days between each soybean planting time and postemergence (POST) herbicide application[a]

Cover crop management	Days to POST
No-till	37 (2) c
Cereal rye early-term	39 (2) b
Cereal rye plant-green	41 (2) a
Soybean planting	Days to POST
Early soybean	43 (2) a
Late soybean	35 (2) b
Preemergence herbicide	Days to POST
NO PRE	36 (2) b
YES PRE	42 (2) a
	P-value
Cover crop management (CC)	<0.001
Soybean planting (SB)	<0.001
Preemergence herbicide (PRE)	<0.001
CC × SB	0.446
CC × PRE	0.062
SB × PRE	0.672
CC × SB × PRE	0.528

[a]Means followed by the standard errors in parentheses. Means followed by the same letter within the column of each main effect indicate no statistical difference by the Fisher's protected LSD test ($\alpha = 0.05$).

with NO PRE (Table 5). Our findings corroborate similar research by Perkins et al. (2021), who reported that flumioxazin and pyroxasulfone reduced *Amaranthus* spp. density and increased the number of days for emerged plants to reach 10 cm in height. Knezevic et al. (2019) reported that the application of a preemergence herbicide delayed weed emergence and delayed the critical time for weed removal in soybean. According to

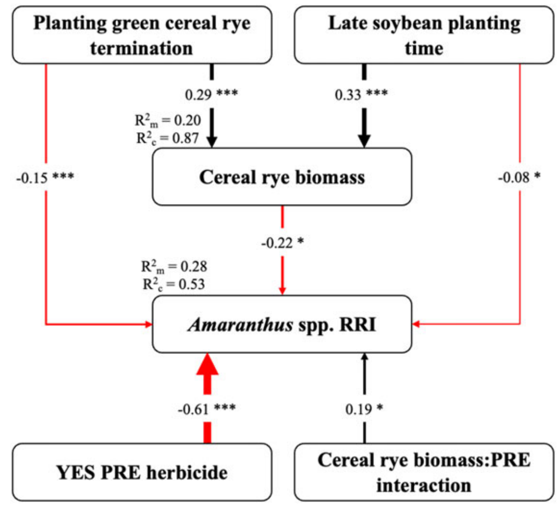

Figure 2. Path diagram of significant direct and indirect predictors influencing *Amaranthus* spp. density relative response index (RRI). Arrows indicate the directionality of the effect. Red and black arrows indicate negative and positive relationships, respectively. The thickness of the arrows is scaled based on the magnitude effect of the standardized path coefficient. Standardized path coefficients are provided for each relationship, followed by the respective significance level (*$P < 0.05$; ***$P < 0.001$). Marginal (R^2_m) and conditional (R^2_c) coefficients of determination, describing the proportion of the variance explained by the model's fixed and random plus fixed effects, respectively, are provided for each component model.

Knezevic et al.'s (2019) findings, the critical time for weed removal based on a 5% soybean yield reduction ranged from V1 to V6 and from V4 to R5 without and with preemergence herbicide, respectively. Additionally, Ulusoy et al. (2021) observed that the adoption of effective preemergence herbicides delayed the critical time for postemergence weed control in corn, reducing the need for multiple postemergence applications and providing alternative sites of action for managing glyphosate-resistant weeds.

SEM for *Amaranthus* spp

Our best-fit SEM detected significant relationships among cereal rye termination time, soybean planting date, cereal rye biomass production, and herbicide inputs on the RRI of *Amaranthus* spp. density (Fisher's $C = 2.3$, $P = 0.31$; Figure 2). The RRI corresponds to the relative change in *Amaranthus* spp. fitness in terms of density when cereal rye was adopted compared with no-till. For clarity, *Amaranthus* spp. fitness will be the nomenclature used to describe the changes in RRI. Delaying cereal rye termination (standardized coefficient effect: 0.29) and soybean planting (standardized coefficient effect: 0.33) time positively affected cereal rye biomass production and negatively affected *Amaranthus* spp. fitness. The additive effect of delaying cereal rye termination and soybean planting explained 20% ($R^2_m = 0.20$) of the variation in cereal rye biomass production, whereas site-years explained 67% ($R^2_c = 0.87$). The negative relationship of cereal rye termination (standardized coefficient effect: −0.15) and soybean planting (standardized coefficient effect: −0.08) time with *Amaranthus* spp. fitness likely reflects the effects of delaying soybean planting on the onset of *Amaranthus* spp. emergence, as previously discussed. Increasing cereal rye biomass (standardized coefficient effect: −0.22) and adopting preemergence herbicides (standardized coefficient effect: −0.61) presented a negative relationship with *Amaranthus* spp. fitness and were the two predictors that most

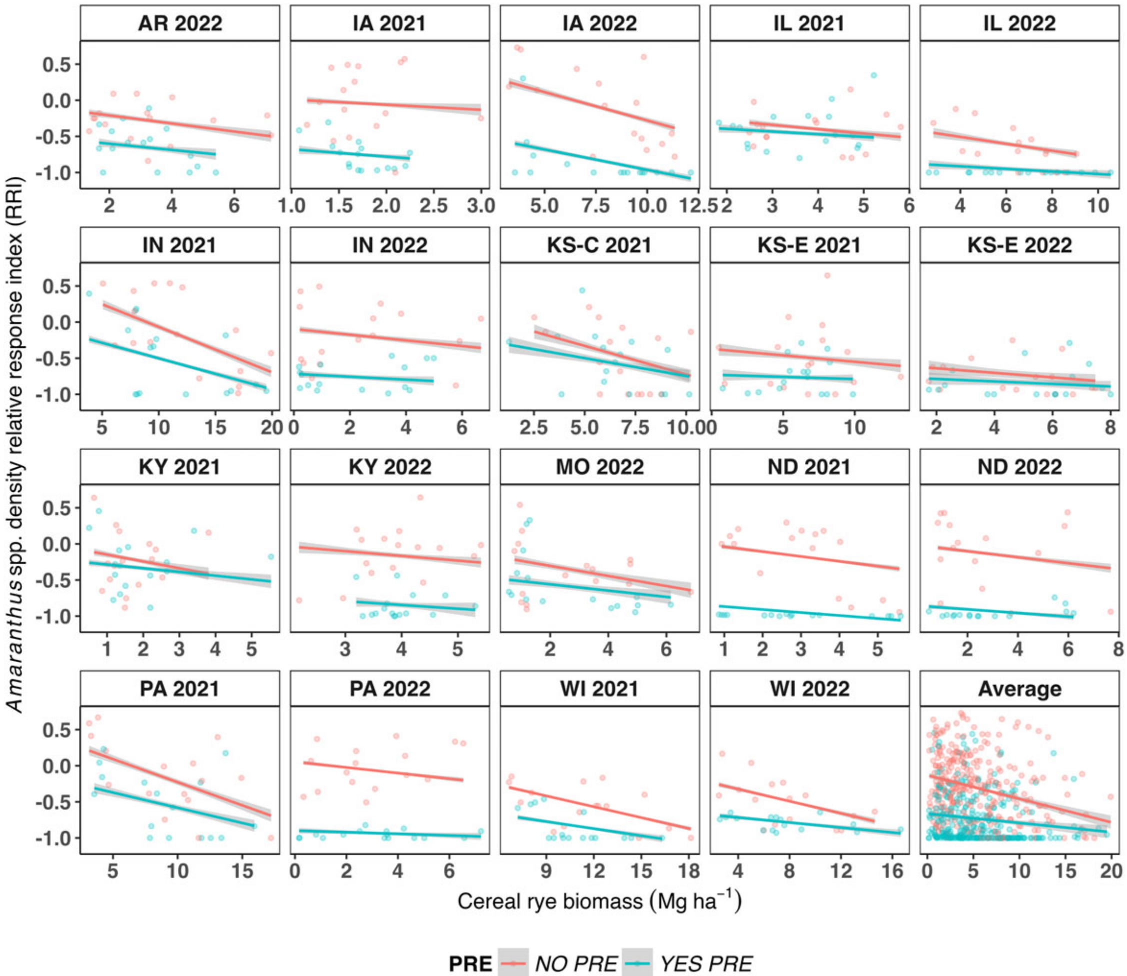

Figure 3. Effect of aboveground cereal rye biomass (Mg ha^{-1}) on *Amaranthus* spp. density relative response index (RRI) with and without the preemergence herbicide across site-years. The average panel represents the data of all 19 site-years combined. A positive RRI indicates that the adoption of cereal rye cover crop is increasing plant response, whereas a negative value indicates that the cereal rye cover crop is decreasing plant response.

affected this response variable. The effect of postponing cereal rye termination time and soybean planting date, increasing cereal rye biomass production, and applying preemergence herbicides, accounted for 28% ($R^2_m = 0.28$) of the variation in *Amaranthus* spp. fitness, whereas site-years accounted for 25% ($R^2_c = 0.53$). The effect of cereal rye biomass and preemergence herbicides on *Amaranthus* spp. fitness is illustrated in Figure 3. Increasing cereal rye biomass lowered *Amaranthus* spp. fitness with and without preemergence herbicides. The negative effect of these two predictors on *Amaranthus* spp. fitness indicates that they reduced plant response by lowering RRI close to −1.

Overall, the *Amaranthus* spp. SEM captured the results presented in Tables 3 and 4 and illustrated them as path diagrams displaying how cereal rye termination and soybean planting times affect cereal rye biomass accumulation and, consequentially, how biomass accumulation and preemergence herbicides affect *Amaranthus* spp. density. Nonetheless, the *Amaranthus* spp. SEM illustrated an intriguing result by showing that the interaction between cereal rye biomass and preemergence herbicides had a positive relationship on *Amaranthus* spp. fitness, whereas their individual effects had a negative relationship on *Amaranthus* spp. fitness (Figure 2). The interaction between cereal rye biomass and preemergence herbicides was evaluated and deemed significant when fitting the structured linear equation used in the SEM. The interaction portrays the differences between NO PRE and YES PRE under low and high cereal rye biomass levels (Figure 3). When cereal rye biomass is low and close to 0, there is a larger difference between NO PRE and YES PRE on *Amaranthus* spp. fitness compared with high levels of biomass (>15 Mg ha^{-1}). This is expected to an extent, considering that *Amaranthus* spp. suppression is correlated with the increase in cereal rye biomass (Nunes et al. 2024). Hence, under high levels of cereal rye biomass, the importance of preemergence herbicides for *Amaranthus* spp. control is diminished due to the suppression provided by the cover crop. The change in the preemergence herbicide response according to the level of cereal rye biomass is likely the reason for the interaction to result in a positive standardized coefficient. Although the individual effects of cereal rye biomass and preemergence herbicides can be easily assessed, when combined, the interaction effect exceeds the sum of their individual importance.

Soybean Stand at the End of the Season and Yield

The analysis of soybean stand revealed a significant interaction of cover crop management and soybean planting time ($P = 0.024$) (Table 6). No-till treatment presented the highest soybean stand in

Table 6. Soybean stand (plants m^{-1}) at the end of the season and soybean yield (kg ha^{-1})[a]

	Soybean stand				Soybean yield			
	Soybean planting time							
Cover crop management	Early soybean		Late soybean		Early soybean		Late soybean	
	— plants m^{-1} —				— kg ha^{-1} —			
No-till	18 (1) a	A	19 (1) a	A	3,729 (252) a	A	3,708 (252) a	A
Cereal rye early-term	18 (1) a	A	17 (1) b	A	3,874 (252) a	A	3,611 (252) a	B
Cereal rye plant-green	16 (1) b	A	15 (1) c	B	3,437 (252) b	A	3,022 (252) b	B
	P							
Cover crop management (CC)	<0.001				<0.001			
Soybean planting (SB)	0.003				<0.001			
Preemergence herbicide (PRE)	0.847				0.289			
CC × SB	0.024				0.012			
CC × PRE	0.634				0.298			
SB × PRE	0.980				0.911			
CC × SB × PRE	0.953				0.923			

[a]Means followed by the standard errors in parentheses. Means followed by the same lowercase letters indicate no statistical difference between cover crop management within soybean planting time, and the same uppercase letters indicate no statistical difference between soybean planting time within cover crop management by the Fisher's protected LSD test ($\alpha = 0.05$).

both soybean planting times with no differences in stand between early and late plantings, averaging 18 plants m^{-1}. The cereal rye early-term (average of 17 plants m^{-1}) only reduced soybean stand in the late soybean planting time by 1 plant compared with no-till. Cereal rye plant-green reduced soybean stand when compared with no-till by 2 and 4 plants in the early (16 plants m^{-1}) and late (15 plants m^{-1}) planting times, respectively. Due to their reduction in soybean stand compared with no-till, both cereal rye treatments presented a lower stand in the late soybean planting time compared with early planting (Table 6). The difference in soybean stand between soybean planting times is likely due to the increase in cereal rye biomass production by the late planting date (Table 3). High cover crop biomass has been previously attributed to hindering crop establishment and reducing the final crop stand (Gross et al. 2022; Mischler et al. 2010). Establishing soybean under high levels of cereal rye biomass can be challenging due to the physical barrier created by the cover crop mulch, which makes it difficult for the planter units to slice residue, place the seed at a uniform planting depth, and close the seed furrow (Gross et al. 2022; Mirsky et al. 2013). To minimize the negative effects of planting soybean under high cereal rye biomass, proper planter setup is crucial. Hence, planters should be equipped with the appropriate coulters, planting unit gauge wheels, row cleaners, downforce pressure on planter units, and effective closing wheels to ensure accurate seed placement (Mirsky et al. 2013). Precipitation before soybean planting is an additional factor to consider when establishing soybean over cereal rye. The water used by cereal rye before its termination can deplete soil moisture in the topsoil profile (0 to 8 cm; Reed and Karsten 2022). Under dry-weather spells, the lower soil moisture due to cereal rye water use can negatively affect soybean establishment by reducing germination, causing uneven plant emergence, and increasing plant stress early in the season (Helms et al. 1996).

The analysis of soybean yield also revealed a significant interaction of cover crop management and soybean planting time ($P = 0.012$) (Table 6). No-till and cereal rye early-term resulted in the highest soybean yield levels in both soybean planting times. No differences in soybean yield between no-till and cereal rye early-term were observed. Conversely, cereal rye plant-green reduced soybean yield when compared with no-till and cereal rye early-term in both soybean planting times. Soybean yield reduction

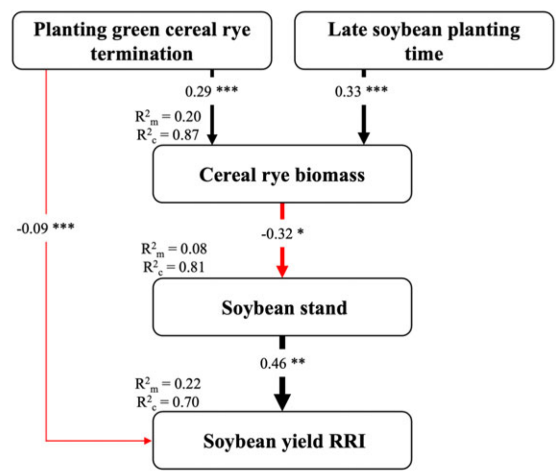

Figure 4. Path diagram of significant direct and indirect predictors influencing soybean yield response index (RRI). Arrows indicate the directionality of the effect. Red and black arrows indicate negative and positive relationships, respectively. The thickness of the arrows is scaled based on the magnitude effect of the standardized path coefficient. Standardized path coefficients are provided for each relationship, followed by the respective significance level (*$P < 0.025$; **$P < 0.007$; ***$P < 0.000$). Marginal (R^2_m) and conditional (R^2_c) coefficients of determination, describing the proportion of the variance explained by the model's fixed and random plus fixed effects, respectively, are provided for each component model.

ranged from 8% to 18%, with the greatest reductions in the late soybean planting. No-till was the only treatment to maintain a similar soybean yield level in both soybean planting times. Cereal rye early-term and plant-green reduced soybean yield by 7% and 12%, respectively, when soybean planting was delayed. The reduction in soybean yield by the cereal rye treatments in the late soybean planting is likely a consequence of the lower soybean stand recorded in these two treatments (Table 6). Reductions in soybean stand when planting green have been previously reported to result in lower soybean yields (Hodgskiss et al. 2022; Kannberg et al. 2024; Liebl et al. 1992; Nunes et al. 2023). Despite some studies reporting soybean yield reductions when planting green, there are numerous studies showing no negative effect of this practice on yield (Ficks et al. 2022; Fisher and Sprague 2022; Gross et al. 2022; Reed et al. 2019; Schramski et al. 2021). Studies reporting no

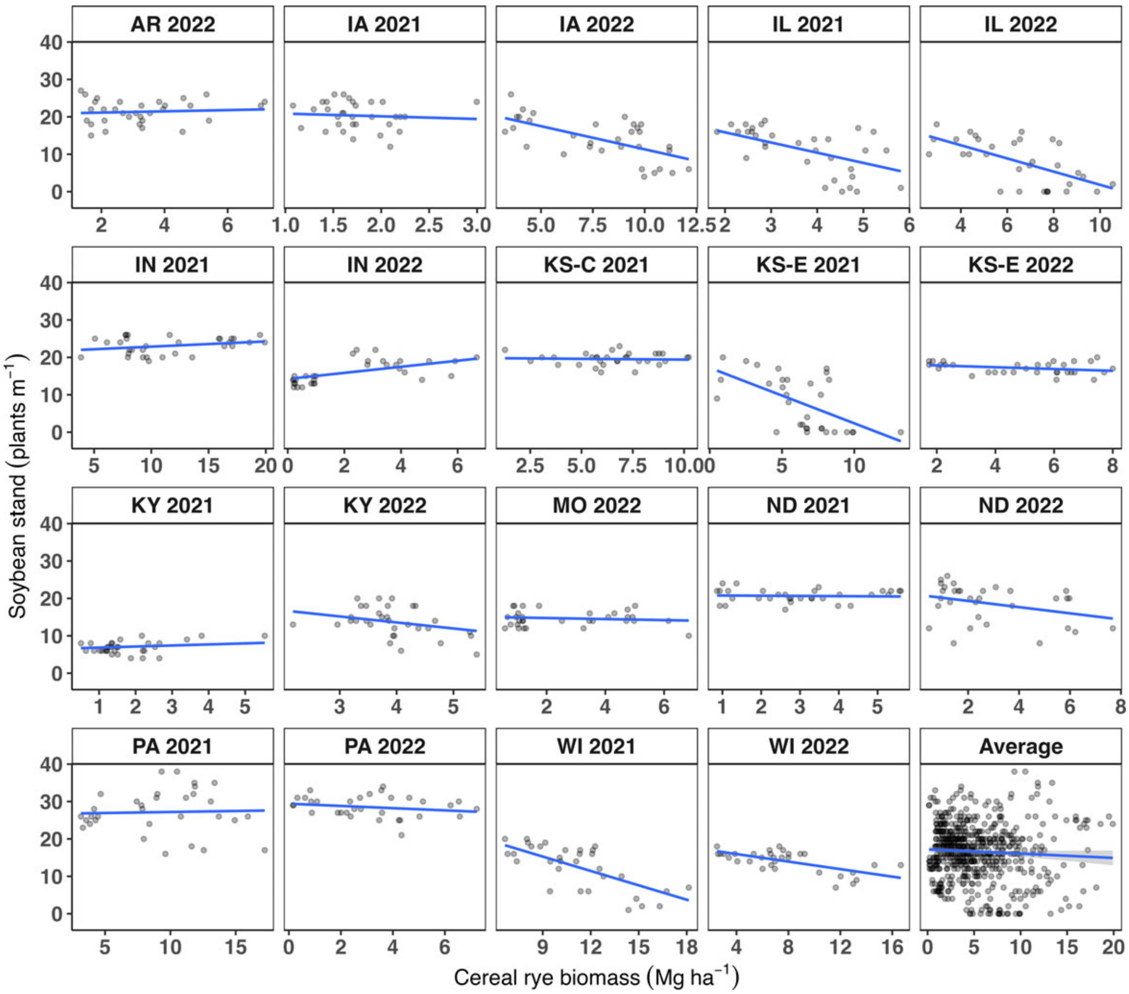

Figure 5. Effect of aboveground cereal rye biomass (Mg ha^{-1}) on soybean stand (plants m^{-1}) across site-years. The average panel represents the data of all 19 site-years combined. Note that the *x* axis is set to vary freely for each site-year for better visualization of trends.

negative impact of planting soybean green on yield demonstrate why soybean is often considered more resilient to this system when compared with other cash crops, such as corn (Grint et al. 2022; Reed et al. 2019).

SEM for Soybean Yield

Our best-fit SEM detected significant relationships among cereal rye termination time, soybean planting date, cereal rye biomass production, and soybean stand on the RRI of soybean yield (Fisher C = 12.5, P = 0.129; Figure 4). The RRI corresponds to the relative change in soybean fitness in terms of yield when cereal rye was adopted compared with no-till. For clarity, soybean fitness will be the nomenclature used to describe the changes in RRI. The structured linear equation explaining cereal rye biomass production in the soybean SEM model was the same as previously presented in the *Amaranthus* spp. SEM. Thus, the results were identical and are not discussed. Soybean stand was solely affected by cereal rye biomass, which had a negative relationship (standardized coefficient effect: −0.32) with stand and accounted for 8% ($R^2_m = 0.08$) of the variation explaining this response variable, whereas site-years accounted for 73% ($R^2_c = 0.81$). Delaying cereal rye termination (standardized coefficient effect: −0.09) and soybean stand (standardized coefficient effect: 0.46) were the only two predictors to directly influence soybean fitness. Their additive effect explained 22% ($R^2_m = 0.22$) of the variation in soybean fitness, whereas site-years explained 48% ($R^2_c = 0.70$). A similar result was observed by Wallace et al. (2021), who reported a positive relationship between soybean population and yield. The lack of a direct effect of cereal rye biomass on soybean fitness indicates that the level of biomass has a negligible effect on yield potential if soybean establishment is successful. In other terms, soybean stand acts as a mediator of soybean yield. Conversely, if soybean establishment is unsuccessful and differences in soybean population are beyond the crop's capacity to compensate for stand losses (Gross et al. 2022), the likelihood of yield reduction is greater. This is evidenced when comparing the effect of cereal rye biomass on soybean stand in PA 2021 and WI 2021 (Figures 5 and 6). High levels of cereal rye biomass were recorded in both site-years, overall average of 9.1 and 11.2 Mg ha^{-1} in PA 2021 and WI 2021, respectively. Nonetheless, the increase in cereal rye biomass affected soybean stand only in WI 2021 due to extreme dry weather

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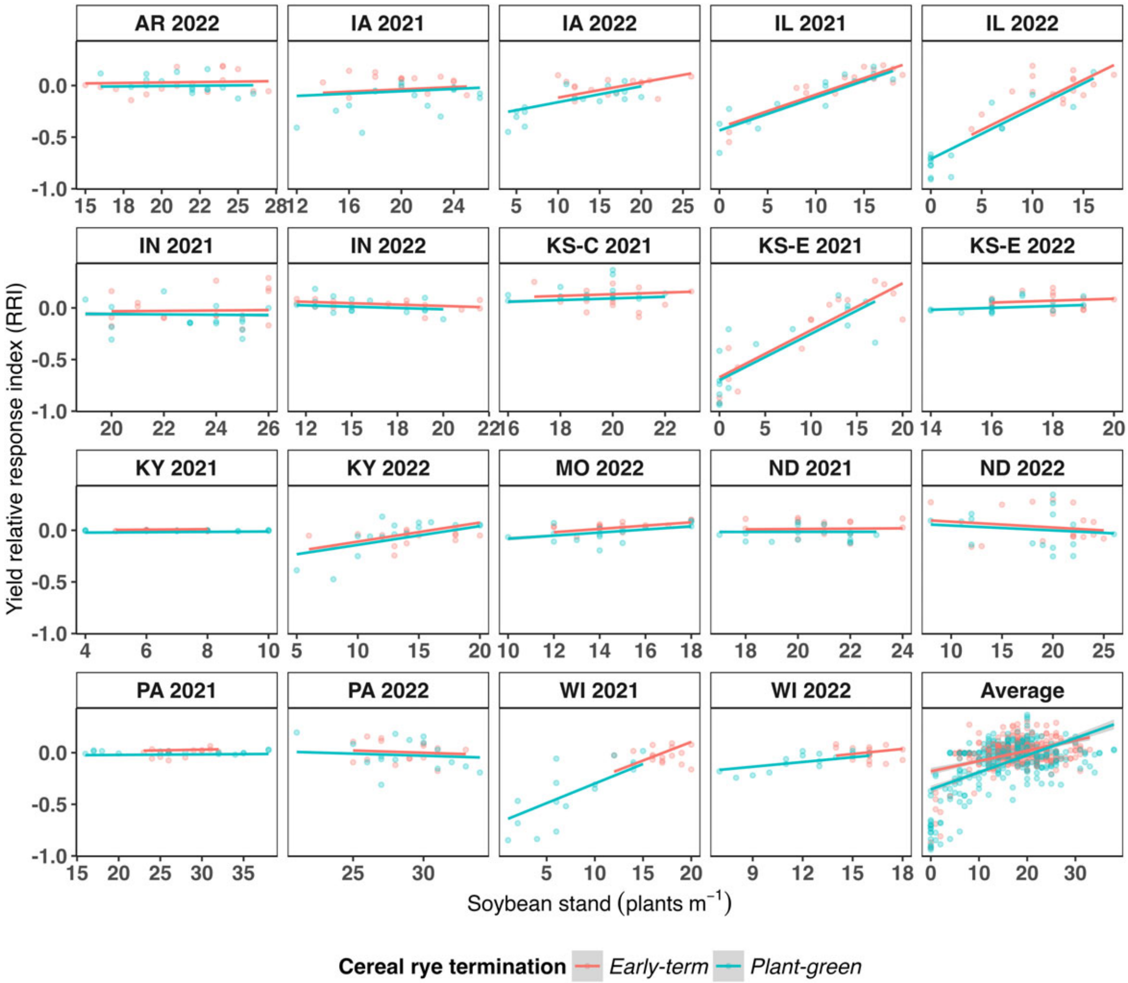

Figure 6. Effect of soybean stand (plants m^{-1}) on soybean yield relative response index (RRI) under the two cereal rye termination times across site-years. The average panel represents the data of all 19 site-years combined. A positive RRI indicates that the adoption of cereal rye cover crop is increasing plant response, whereas a negative value indicates that the cereal rye cover crop is decreasing plant response. Note that the *x* axis is set to vary freely for each site-year for better visualization of differences.

conditions at soybean planting in WI 2021 (Figure 7). The dry weather made soybean establishment particularly difficult under high levels of cereal rye biomass, which hindered soybean establishment and final crop stand. In contrast, higher precipitation in PA 2021 likely facilitated soybean establishment even under high levels of cereal rye biomass. Hence, no effect of cereal rye biomass on soybean stands in PA 2021.

Our results demonstrate that planting soybean green successfully increased cereal rye biomass production over a wide range of environmental conditions. The increase in cereal rye biomass production when planting green reduced *Amaranthus* spp. density by 44% compared with no-till. The use of a preemergence herbicide program also reduced *Amaranthus* spp. density and was the most important contributing factor for overall *Amaranthus* spp. control. Combining cereal rye cover crop and effective preemergence herbicides should be considered as part of integrated *Amaranthus* spp. management programs. Planting soybean green led to yield reductions of 8% and 18% at early and late soybean planting times, respectively. The reduction in soybean stand due to the increase in cereal rye biomass accumulation was the driving factor for the soybean yield penalty in this study. The fact that cereal rye biomass did not directly affect soybean yield is important information for farmers planting soybean green over cereal rye cover crop. Farmers should be aware that planters must be properly equipped to plant through high levels of cereal rye biomass and ensure proper soybean establishment. Environmental conditions should also be considered when planning for cereal rye termination and soybean planting. If dry weather is forecast, terminating cereal rye about 2 wk before soybean planting might be the best recommendation to avoid issues with soybean establishment and yield reductions. Our results show that even when soybean planting was delayed, terminating cereal rye before soybean planting resulted in yield levels similar to no-till. Future research should investigate more of the agronomic aspects of soybean production when planting green. For instance, the soybean population agronomically recommended to maintain maximum yield potential for different varieties should be reevaluated when planting soybean green. It is

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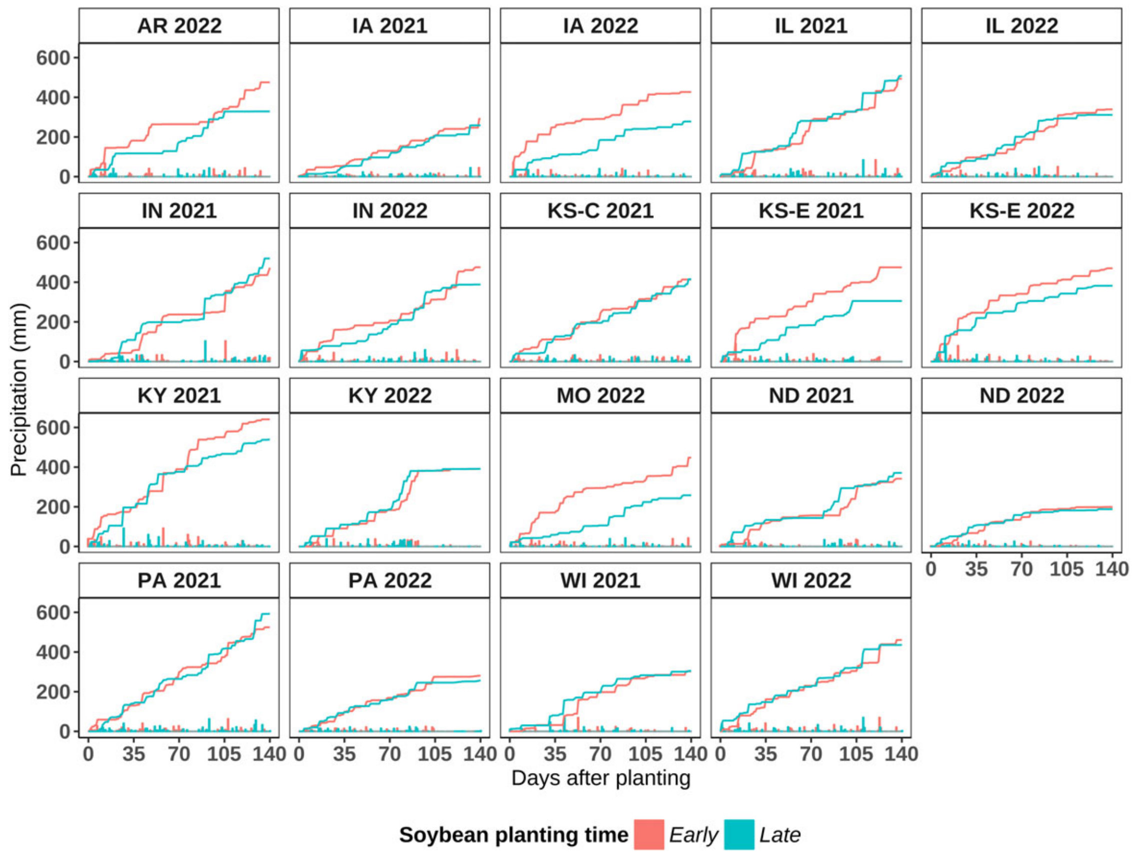

Figure 7. Cumulative precipitation (mm) from each soybean planting time to 140 d after planting across site-years. Lines represent the cumulated precipitation and bars represent the daily precipitation events.

unknown whether the soybean capacity to compensate for stand losses remains the same when planting green compared with a no-cover crop system. Covariates like maturity groups and planting dates should also be considered as part of such investigations.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wsc.2024.47

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