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Evaluating Planting Green and Herbicides for Integrated Weed Management and Their Effect on Soil Properties in Corn and Soybean in Nebraska

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Evaluating Planting Green and Herbicides for Integrated Weed Management and Their Effect on Soil Properties in Corn and Soybean in Nebraska

by

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Evaluating Planting Green and Herbicides for Integrated Weed Management and Their Effect on Soil Properties in Corn and Soybean in Nebraska

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Producers across the Midwest are finding new ways to implement cover crops into cropping systems and the practice of “Planting Green” is one of the newest uses of cover crops. When planting green, producers plant their row crops into actively growing cover crops and terminate the cover crop at time of planting or shortly after planting. This practice would allow for higher biomass accumulation of the cover crop and could aid in weed management of herbicide-resistant weeds. The objective of the first two studies was to evaluate planting green and its effect on soil-applied residual herbicides, weed management, dicamba/glyphosate-resistant soybean yield, soil chemical and physical properties and economics in soybean. Treatments consisted of two different cover crop termination timings, three different herbicide application timings, and three different herbicides within each application and termination timing. All soil-applied herbicides controlled giant foxtail 79% to 99% in 2021 and 2022, and controlled Palmer amaranth 99% in 2021 and 53% to 73% in 2022. Thus, we can conclude that soil-applied herbicides are not affected by planting green. Pyroxasulfone/sulfentrazone fb dicamba and imazethapyr/saflufenacil/pyroxasulfone fb dicamba both consistently controlled Palmer amaranth above 90% in both years when paired with Planting Green in soybean. In 2021, soybean yields varied among termination timings and herbicide programs but PRE fb LPOST treatments provided the most consistent yields (3,324 kg ha^{-1} to 4,613 kg ha^{-1}). In 2022 due to compounding weather factors, all planting green treatments yielded higher than earlier terminated treatments. The second study was conducted in corn and in 2022 PRE fb Late POST herbicide programs combined with Planting Green provided the highest amount of Palmer amaranth control at 28 days after Late POST application: 92% to 97% control. Treatments that contained glyphosate or a residual grass-killing herbicide were most effective on giant foxtail in corn and soybean. In 2021, all planting green treatments yielded lower than earlier terminated treatments in corn. In 2022, a starter fertilizer application was made, and yields were significantly higher than the year before and the highest yielding treatment was acetochlor/clopyralid/mesotrione fb dicamba/mesotrione with planting green at 14,189 kg ha^{-1}.

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CHAPTER 1: INTRODUCTION AND OBJECTIVES

Introduction

Cover Crops

The implementation of cover crops has increased over 50% in between the years of 2012 and 2017 in the United States but adoption of year over year has only been about 2.5% in Nebraska (Wallander n.d.). In 2017 there was a total 6.2 million ha of cover crops planted in the United States and a majority of cover crops planted were rye or wheat (Wallander n.d.). There are many programs and incentives that organizations and the federal government have rolled out to provide producers an economic incentive to plant cover crops to achieve sustainable agricultural practices. Even with the programs and incentives the adoption of cover crops for some producers bring up hesitancies such as a lack of immediate economic return (Smith et al. 2020). The potential benefits of cover crops are: weed suppression, reduction of soil erosion, cycling of nutrients, water quality, and the improvement of overall soil fertility (Snapp et al. 2005) and therefor producers have looked for multiple ways to implement cover crops into their farming practices. A nonmarket benefit that could occur from cover crops reducing weed populations is reducing selection pressure and herbicide resistance in row crops (Bunchek et al. 2020) and this should be considered when producers are implementing an integrated weed management program. Researchers have conducted studies on cover crops from species to planting timing to termination timing and its affects upon weed suppression. Most researchers have concluded that biomass of one species tends to have more affect upon weed suppression than species diversity (Smith et al. 2020) and that planting cover crops species earlier after fall harvest allows for higher biomass production (Ruis et al. 2020) and thus better weed suppression.

Cover Crop Termination

When addressing the termination of cover crops there has been research on the method of termination: tillage, chemically, mowing, or crimping. The method and the timing of cover crop termination are decisions that need to be made together. A later termination allows for higher biomass accumulation which provides greater weed suppression through competition (Mirsky et al. 2013). Though the higher accumulation of biomass is needed for weed suppression it also means that the plant is growing and taking up nutrients and moisture from the soil that may be necessary for the succeeding cash crop. The timing of termination of cover crop is important and will depend on region and farming practices. Cover crop residues also provide a mat-like covering of the soil surface which can lower evaporation and loss of soil moisture if terminated at the correct timing (Bavougian et al. 2019).

Planting Green

Planting green is the practice of planting a row crop into an actively growing and green cover crop and then terminating the cover crop at time of planting or shortly after planting (Reed et al. 2019). The normal termination of cover crops in the Midwest usually occurs days or weeks before planting row crops (Oliveira et al. 2019). This new practice of planting green is being done in hopes of accumulating more biomass from the cover crop which can help aid in weed suppression (Nord et al. 2012) and slow down herbicide resistance in certain weeds. Other benefits that are hypothesized to occur from greater biomass accumulation are improvements in soil health properties such as aggregate stability, water infiltration, organic matter, and nutrient cycling (Blanco-Canqui and Ruis 2020). With the possible benefits of planting green there are some possible challenges of implementing planting green into farming practices. One of the biggest challenges is possible yield loss due to: nutrient tie up, disease and insect infestations, lack of soil moisture, and stand loss. Planting green may force producers to look at a system approach instead of just planting cover crops and terminating them later than normal.

Herbicide Resistance

Glyphosate has been and continues to be the most highly used herbicide across the implementation of glyphosate-resistant (GR) soybean and corn hectares (Zea mays L.) in the United States (Heap 2023). With the evolution of GR crops there has been more applications of glyphosate multiple times a year and have relied less upon soil applied-residual herbicides to control weeds (Burgos et al. 2006, Young 2006) and thus resulted in the evolution of GR weeds (Beckie 2006). Worldwide, there are 169 weed biotypes resistant to acetolactate synthase (ALS) inhibitors, 14 weed biotypes resistant to PPO-inhibitors, three to HPPD inhibitors, 41 to synthetic auxins, and 14 to Very Long-Chain Fatty Acid Synthesis (Heap 2023). There is an estimated loss more than US$100 billion and 10% yield loss worldwide due to herbicide resistant weeds (Appleby 2000). With the continuing rise of herbicide-resistant (HR) weeds there is a need for integrated weed management programs that help slow down the spread.

Soil Physical and Chemical Properties

The health of a soil can be defined by its physical, chemical, and biological properties. Organic matter is a soil health indicator that can be related to all three categories of properties (Moore et al. 2014) and therefor it is important to understand the effects on organic matter of any new farming practice. Some physical properties that are important to understand are water infiltration, aggregate stability, compaction, and bulk density (Amézketa 1999, Blake 1965, Tate III 1987). The use of cover crops can have potential benefits over long periods on soil properties (Blanco-Canqui and Francis 2016, Blanco-Canqui and Ruis 2020). Time is the biggest effect on the response of soils to any new practice such as cover crops; similar results were seen in changing from conventional tillage to a no-till management practice (Rhoton 2000). In a short term study such as two years, the effects of cover crops on these properties have been highly variable (Blanco-Canqui et al. 2015) and thus a long-term study of any new implementation of cover crops is necessary to understand the effects of said practice.

OBJECTIVES

1. Evaluate the effects of Planting Green on soil-applied residual herbicides, weed suppression, yield, and economics in dicamba/glyphosate-resistant soybean.
2. Evaluate the effects of Planting Green on soil-applied residual herbicides, weed suppression, yield, and economics in glyphosate/glufosinate-resistant corn.
3. Evaluate the effects of Planting Green on soil chemical and physical properties in soybean.

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Chapter 2:

Integrating fall-planted cereal rye (*Secale cereale* L.) cover crop with herbicides for reducing Palmer amaranth (*Amaranthus palmeri*) seed production in soybean under planting green conditions

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Abstract

Cover crops are usually terminated prior to planting the cash crop that follows; however, “planting green” is an alternative approach that allows growers to plant cash crops into an actively growing, green cover crop that is then terminated after the establishment of the cash crop. The objectives of this study were (1) to determine whether planting soybean in actively growing cereal rye and terminating 2 weeks after planting (WAP) soybean is more effective for suppressing summer annual weeds compared with terminating 2 weeks before planting (WBP) soybean; and (2) to evaluate an integrated effect of herbicide programs and cereal rye termination timing on Palmer amaranth control, biomass, seed production, soybean grain yield, and cost-benefit ratio. Field experiments were conducted in southcentral Nebraska from 2020 to 2022. Preemergence (PRE) herbicide with 2 WAP termination of cereal rye provided > 95% Palmer amaranth control in 2021 and varied from 88% to 98% in 2022 at 28 d after PRE. A PRE herbicide fb (followed by) late-postemergence (LPOST) herbicide with 2 WAP termination of cereal rye controlled Palmer amaranth 85% to 92% in 2021 compared with 97% to 99% control 28 d after LPOST herbicide application in 2022. Weed density and biomass were relatively higher with 2 WBP cereal rye termination compared with 2 WAP

termination regardless of the herbicide program. PRE fb LPOST herbicide programs integrated with 2 WAP termination of cereal rye reduced Palmer amaranth seed production to less than 9,100 seeds plant^{-1} in 2021 and no seed production in 2022. Terminating cereal rye 2 WAP was an integral part of Palmer amaranth and giant foxtail suppression, density and biomass reduction, but that it affected soybean yield in 2021 compared with terminating cereal rye 2 WBP, while in 2022, hail and windstorms had a confounding effect on soybean stand and yield.

Introduction

Soybean is the second most grown crop in Nebraska, with an estimated 2.2 million ha planted in 2021 (USDA-ERS 2021). Soybean production in Nebraska ranked fifth in the United States, with production of approximately 9.5 trillion kg in 2021 (USDA-ERS 2021) and an average soybean yield of 4,237 kg ha^{-1} (USDA-NASS 2021). One of the major obstacles to optimum soybean yield is competition with weeds (Vivian et al. 2013). Early-season weed control in soybean is required to achieve optimum grain yields (Hock et al. 2005), and if weeds are not controlled in soybean, yield reductions in the range of 8% to 55% have been reported from soybean emergence up to the beginning of seed formation (R5) (Van Acker et al. 1993).

To combat weed control issues, multiple herbicide-resistant soybean has been developed and rapidly adopted by growers (de Sanctis et al. 2021a; McDonald et al. 2021). This technology began with glyphosate-resistant soybean to allow POST glyphosate applications during the growing season; however, the evolution of glyphosate-resistant weeds has created a challenge for growers (Striegel and Jhala 2022). For example, six broadleaf weeds have evolved resistance to glyphosate in Nebraska as of 2023, including common ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), horseweed (*Erigeron canadensis* L.*)*, kochia [*Bassia scoparia* (L.) A.J. Scoot)], Palmer amaranth, and waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Saueer] (Anonymous 2023; Heap 2022). Several producers control weeds in soybean in the early growing season by applying PRE herbicides (Sarangi and Jhala 2018): for example, a statewide survey in 2015 indicated that 59% of soybean producers use soil-applied residual herbicides to control glyphosate-resistant weeds in Nebraska (Sarangi and Jhala 2018).

Weed competition with crops can reduce crop growth and yield (Teasdale and Mohler 2000), and if weeds are controlled during the early-season, the crops can close their canopy and compete with late-emerging weeds (Rajcan and Swanton 2001). One specific weed control method does not often provide complete control of weeds (Datta and Knezevic 2013), and a multidisciplinary approach (defined as integrated weed management) is imperative for reducing herbicide selection pressure (Bunchek et al. 2020) and weed seed bank addition (Striegel and Jhala 2022).

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

In recent years, growers have started to plant cash crops such as soybean directly into actively growing cover crops (known as “planting green”), then terminate the cover crop at the time of planting (Grint et al. 2022b) or a few days after planting (Reed et al. 2019). Planting green is in contrast to the dominant practice of terminating cover crops at least two weeks prior to planting (Oliveira et al. 2019). This practice could provide much-needed early-season weed suppression if cover crops produce abundant biomass (Grint et al. 2022a). According to a survey conducted in 2017, the most commonly grown cover crop in Nebraska is cereal rye (Butts and Werle 2017), which is due to its winter hardiness, high biomass production, and high germination rate (Curran 2010). The recommended seeding rate of cereal rye is 67 kg ha^{-1} (Lesoing 2019); however, growers usually drill cereal rye at 33 to 45 kg ha^{-1} to reduce the cost of seeds (Grubinger 2021). The competition created by the practice of planting green could suppress the emergence and growth of summer annual weeds such as Palmer amaranth and waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Sauer] (Bezuidenhout et al. 2012) and crop residues can also create a competitive environment and conserve soil moisture (Mirsky et al. 2013, Teasdale and Mohler 1993). An adequate amount of cover crop biomass (around 4,600 kg ha^{-1}) can sufficiently suppress weeds (Finney et al. 2016). However, the effect of planting green has been variable among crops: some studies reported that planting green can reduce corn yield (Grint et al. 2022a) but not soybean yield (Montgomery et al. 2018, Reed et al. 2019), and Osipitan et al. (2018) specifically reported no effect when planting green was used for weed suppression.

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

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

Materials and Methods

Study Location

This study was conducted at the University of Nebraska–Lincoln's South-Central Agricultural Lab (SCAL) near Harvard, NE (40.52°N, 98.05°W) during 2020 to 2022. The soil at the experimental site was silt loam (58% silt, 17% sand, and 25% clay), with a soil organic matter content of 3.4%, and pH 6.8. The site was under a lateral irrigation system. The experiment was established after corn harvest in 2020 and after soybean harvest in 2021. The study was conducted in a no-till cropping system with crop residue left on the surface post-harvest through the following growing season. The most common weeds at the research site were Palmer amaranth and giant foxtail. Cereal rye (Elbon cereal rye, GreenCover Seed, Bladen, NE) was drilled after soybean harvest in the fall of 2020 and 2021 with 20.32 cm row spacing, 3.2 cm seeding depth, and a seeding rate of 95.32 kg ha^{-1}. Glyphosate/dicamba-resistant soybean (NK S30-M9X) with a 2.7 maturity group at a rate of 330,000 seeds ha^{-1} at a depth of 3.0 cm and 76.2 cm width between rows was planted on May 12, 2021 and May 18, 2022. Field experiments were conducted under linear irrigation. The second-year study was repeated at the same site and using the same plot to evaluate two-year treatment effect.

Experimental Design and Treatments

The experimental design was a factorial randomized complete block design (RCBD) with four replications. Individual plots were 3 m wide and 9 m long with four soybean rows spaced 0.76 m apart. The three factors were cereal rye termination timing, herbicide application timing, and herbicide. Termination of cereal rye occurred two weeks before planting (WBP) or two weeks after planting (WAP) with an application of glyphosate at 1,260 g ae ha^{-1} + COC 1% v/v + ammonium sulfate 3% v/v. Soybean plants were non-emerged when 2 WBP termination treatments were terminated. In 2021, soybean plants were at the V1 crop stage when terminated 2 WAP (Figure 2-1) and were at the VC stage in 2022. The three herbicide timings consisted of pre-emergence (PRE), early POST (EPOST), and PRE followed by (fb) late POST (LPOST) (Table 2-1). In addition, a non-treated control (cereal rye present), a weed-free control, and weed and cereal rye present treatments were included for comparison (Table 2-1). The non-treated control had cereal rye present due to a missed termination in the fall of both years, but the presence of cereal rye throughout the growing season allows it to be closely compared to a true non-treated control with weeds present during the entire growing season. In total there were two termination timings, three herbicide application timings, and three different herbicides within each herbicide timing.

Herbicide was applied using a handheld CO_2-pressurized backpack sprayer equipped with AIXR 110015 flat-fan nozzles (TeeJet® Technologies, Spraying Systems Co., Wheaton, IL 60187) spaced 51 cm apart and calibrated to deliver 140 L ha^{-1} at 276 kPa at a constant speed of 4.8 km h^{-1}. Dicamba-containing treatments were applied with TTI 11005 flat-fan nozzles (TeeJet® Technologies). PRE herbicides were applied two days after soybean planting, early POST herbicides were applied 31 days after PRE (DAPRE), and late POST herbicides were applied 40 DAPRE herbicide application.

Data Collection

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

Cereal rye biomass was collected at each termination timing from two randomly placed 0.5 m^2 quadrats per plot. Planting occurred during the same week in 2021 and 2022; therefore, biomass collection at each termination timing was taken within the same week in both years. The growth stage of cereal rye was determined using the Zadoks Scale (Zadoks et al. 1974). Cereal rye was at the 21 to 32 growth stage when terminated 2 WBP compared with 49 to 59 growth stage in the 2 WAP termination. Palmer amaranth estimated seed production was collected by sampling two female plants from between the middle two rows. To record estimated seed production, 1,000 seeds were counted from each sample and mass weighed, after which the entire sample mass was taken, and estimations made from the 1,000 seed weight. Based on the weed densities in each plot at the time of Palmer amaranth seed collection, direct correlations were made to estimate the number of seeds per female plant. Soybean was harvested from the middle two rows with a plot combine and yields were adjusted to 13% moisture content and converted into kg ha^{-1}.

Economic Analysis

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

$$\text{Gross Profit (US\$)} = (R - W) \qquad [1]$$

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

$$\text{Benefit / Cost Ratio (US\$ / US\$)} = \frac{(R_T - R_C)}{W} \qquad [2]$$

where R_T is the gross revenue, R_C is the gross revenue for the nontreated control, and W is the cost of the weed management program, including the cost of herbicide, adjuvant, and application (Sarangi and Jhala 2019). The gross revenue was calculated by multiplying soybean grain yield for each treatment by an average price ($0.51 kg ha^{-1}) received for soybean in the spring 2022 and October 2022. Herbicide and custom application prices were sourced from three independent commercial sources in Nebraska (Central Valley Ag Cooperative, Frontier Cooperative, and

Nutrien Ag Solutions) and averaged out as follows: PRE herbicide at US$17.30 ha^{-1}, non−dicamba-containing POST herbicide at US $18.94 ha^{-1}, and dicamba-containing POST herbicide at US $31.71 ha^{-1}.

Statistical Analysis

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

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

Results and Discussion

Year-by-treatment interaction for Palmer amaranth ($P = 0.0002$) and giant foxtail ($P < 0.0001$) control estimates were significant; therefore, data are presented by year. Cereal rye termination timing was significant ($P = 0.0007$), resulting in separation of termination timings when analyzing weed control and density of Palmer amaranth ($P < 0.0001$) and giant foxtail ($P < 0.0001$). Herbicide ($P < 0.0001$) and herbicide application timing ($P < 0.0001$) were significant for Palmer amaranth ($P < 0.0001$) and giant foxtail ($P < 0.0001$) control. Year-by-treatment interaction for soybean yield was significant ($P < 0.0001$); therefore, data are presented by year. Hail and windstorms in June 2022 reduced soybean stand up to 70% in plots where cereal rye was terminated 2 WBP compared with up to

15% soybean stand reduction in plots where cereal rye was terminated 2 WAP (data not shown).

Temperature and Precipitation

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

Cereal Rye Biomass Production

Cereal rye biomass was affected by termination timing. In 2021, cereal rye produced 1,950 kg ha^{-1} biomass at 2 WBP termination compared with greater than 6 times biomass of 12,775 kg ha^{-1} at 2 WAP termination (Figure 2-2). Similarly, in 2022 cereal rye biomass was 2,750 kg ha^{-1} at 2 WBP termination compared with 11,290 kg ha^{-1} at 2 WAP termination (Figure 2-2). Similarly, Grint et al. (2022a) reported that cereal rye biomass increased greater than 6 times when terminated two weeks after planting soybean compared to cereal rye terminated at soybean planting in field studies conducted in Wisconsin. Similar results of cereal rye biomass accumulation at different termination timings have been reported (Keene et al. 2017; Ruis et al. 2017). Some studies revealed that a mixture of cover crop species leads to better weed suppression (Döring et al. 2012; Linares et al. 2008); however, studies in last 10 years conclude that total cover crop biomass production is essential for weed suppression rather than a cover crop mixture (Finney et al. 2016; MacLaren et al. 2019; Smith et al. 2014).

Soybean Stand Count

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

Palmer amaranth and Giant Foxtail Control

PRE herbicides evaluated in this study controlled Palmer amaranth 85% to 99% 14 DAPRE (Table 2-3). Although statistically similar with 2 WBP cereal rye termination, 2 WAP termination combined with PRE herbicide controlled Palmer amaranth 97% to 99% 14 DAPRE (Table 2-3) and giant foxtail 91% to 99% (data not shown). The greater amount of biomass from cereal rye due to 2 WAP termination contributed to greater Palmer amaranth control 14 DAPRE, which has also been observed in other studies (Bunchek et al. 2020, Montgomery et al. 2018, Schramski et al. 2021, Wiggins et al. 2017). Weed control varied by year and cereal rye termination timing at 28 DAPRE. Termination of cereal rye 2 WBP paired with PRE herbicides provided 79% to 98% control of Palmer amaranth in 2021 (Table 2-3) and 68% to 97% control of giant foxtail (data not shown), whereas 2 WAP termination of cereal rye with PRE herbicides controlled Palmer amaranth 95% to 99% (Table 2-3) and giant foxtail 81% to 96% (data not shown). Similar results have been reported where Palmer amaranth is suppressed by soil-applied residual herbicides and late terminated cover crops (Perkins et al. 2021). In 2022, there was a consistent decline in Palmer amaranth control, except for the flumioxazin/pyroxasulfone/metribuzin with 2 WAP termination of cereal rye (95% to 98% control). PRE herbicides provided 80% to 99% control of Palmer amaranth 42 DAPRE in 2021 (Table 2-3) and 62% to 97% control of giant foxtail (data not shown). Although not statistically different, 2 WBP termination of cereal rye controlled Palmer amaranth 80% to 99% (Table 2-3) compared to consistent control of 98% to 99% with 2 WAP termination (Table 2-3). In 2022, a consistent trend of decreased control compared with 2021 was observed. PRE herbicides with 2 WBP termination of cereal rye provided 46% to 73% control of Palmer amaranth (Table 2-3). Montgomery et al. (2018) reported that at least one POST herbicide application is needed to obtain the highest weed control and soybean yield.

Palmer amaranth and giant foxtail control was variable in EPOST herbicide programs compared with the PRE-only herbicide program. Palmer amaranth control was 11% to 50% when EPOST herbicides were paired with 2 WBP termination of cereal rye at 14 DAEPOST in 2021 (Table 2-4; Figure 2-2). In contrast, EPOST herbicides with 2 WAP termination of cereal rye provided 79% to 98% control of Palmer amaranth (Table 2-4; Figure 2-3). At 28 DAEPOST, EPOST herbicides and 2 WBP termination timing-controlled Palmer amaranth 14% to 68% in 2021 and 66% to 99% in 2022 (Table 2-4). When there was no graminicide or glyphosate in the POST herbicide, control of giant foxtail ranged from 5% to 91% at 14 DAEPOST, 2% to 86% 28 DAEPOST, and 4% to 82% 42 DAEPOST (data not shown). With the addition of glyphosate, giant foxtail control ranged from 79% to 99% at 14 DAEPOST, 75% to 92% at 28 DAEPOST, and 56% to 87% at 42 DAEPOST (data not shown). Palmer amaranth control 42 DAEPOST varied between years (Table 2-4). EPOST herbicides and 2 WAP termination of cereal rye provided 69% to 97% control of Palmer amaranth in 2021 at 42 DAEPOST; and 95% to 99% control in 2022 (Table 2-4 and Figures 2-3 and 2-4).

Palmer amaranth control varied between years in PRE fb LPOST herbicide programs regardless of cereal rye termination timing (Table 2-5). PRE fb LPOST herbicide programs with 2 WBP termination of cereal rye controlled Palmer amaranth 60% to 97% at 14 DALPOST (Table 2-5). PRE fb LPOST herbicide programs with 2 WAP termination of cereal rye provided 63% to 99% control of Palmer amaranth at 14 DALPOST; and 85% to 99% control at DALPOST in both years (Table 2-5). The PRE fb

LPOST herbicide program with cereal rye termination 2 WAP provided better control of Palmer amaranth and giant foxtail in this study compared to the same herbicide program with cereal rye terminated 2 WBP. This might be due to the additional biomass from the 2 WAP cereal rye termination that suppressed weeds earlier in the season, which is critical for soybean. A study conducted in Pennsylvania reported better control of slug when cereal rye was terminated 5 days after planting corn/soybean compared with terminating 2 weeks before planting the cash crop (Gall et al. 2022). Results of this study are similar to literature reporting that termination of the cover crop after crop planting provides better weed suppression (Grint et al. 2022b, Rosa et al. 2021). Reduced control of Palmer amaranth or giant foxtail in PRE fb LPOST herbicides with 2 WBP termination of cereal rye in 2022 can be attributed to the hail and windstorm events in that year, which reduced soybean stand and leaf count. This led to a later canopy or absence of a canopy, resulting in less competition against weeds for light, water, and other resources (Nordby et al. 2007).

Palmer amaranth and Giant Foxtail Density

Palmer amaranth density and control were highly correlated (-0.8607678), as were giant foxtail density and control (-0.9324782) (Figure 2-6; Figure 2-7). Year by treatment ($P < 0.0001$) and treatment by cereal rye termination timing was significant ($P < 0.0002$). The treatment by herbicide and herbicide timing were also significant ($P < 0.0001$) for both factors. The termination of cereal rye 2 WAP with herbicide programs reduced density of Palmer amaranth and giant foxtail. PRE herbicides with cereal rye termination 2 WAP reduced Palmer amaranth density to 0 and 3 plants m^{-2} and 0 giant foxtail plants m^{-2} in 2021 and 2022, respectively (data not shown). The glyphosate-containing POST herbicide program reduced giant foxtail density to 8 and 5 plants m^{-2} in 2021 and 2022, respectively (data not shown). Herbicide programs that did not include glyphosate showed a giant foxtail density of 8 to 54 plants m^{-2} in both years (data not shown). The most effective program for reducing Palmer amaranth density was a PRE fb LPOST herbicide program (1 plant m^{-2}) for both years. Although PRE herbicide programs resulted in the lowest density of giant foxtail at 14 and 28 d after treatment; an application of PRE-only herbicide combined with either termination timing of cereal rye was not effective for season-long weed control, especially in the case of Palmer amaranth, which has multiple emergence patterns and can emerge until the end of August in southcentral Nebraska (Chahal et al. 2021). Weed density was relatively higher in each herbicide program with 2 WBP cereal rye termination compared with 2 WAP termination. A study in Wisconsin reported that cereal rye cover crop terminated at crop planting reduced weed density by 31% and reduced weed biomass by 61% compared with no cover crop (Grint et al. 2022b). An observation of reduced density in the 2 WAP termination in combination with herbicides alludes to less variability when attempting to reduce Palmer amaranth and giant foxtail densities. Such reduction in Palmer amaranth density has been observed in other studies (Montgomery et al. 2018; Wiggins et al. 2015; 2016; 2017).

Palmer amaranth & Giant Foxtail Biomass

PRE herbicides with 2 WBP termination of cereal rye limited weed (Palmer amaranth and giant foxtail) biomass to 0 to 5.45 g m^{-2} in 2021 and 5.22 to 16.19 g m^{-2} in 2022 at EPOST herbicide application timing (Table 2-6). Pyroxasulfone/sulfentrazone was the only PRE herbicide that did not result in weed biomass lower than 1 g m^{-2} in 2021, and each PRE herbicide with 2 WBP cereal rye termination timing averaged weed biomass above 5 g m^{-2} in 2022 at EPOST herbicide application timing (Table 2-6). With the termination of cereal rye 2 WAP, weed biomass was reduced to between 0 g m^{-2} to 0.03 g m^{-2} in 2021 and between 0.145 g m^{-2} to 5.22 g m^{-2} in 2022 (Table 2-6). At 21 DAEPOST, PRE herbicides with 2 WBP termination of cereal rye limited weed biomass between 27.8 g m^{-2} to 88.3 g m^{-2} in 2021 and 25.41 g m^{-2} to 25.59 g m^{-2} in 2022 (Table 2-6). PRE herbicides with 2 WAP termination of cereal rye limited weed biomass to between 35.1 g m^{-2} to 45.35 g m^{-2} in 2021 and between 17.53 g m^{-2} to 36.11g m^{-2} in 2022 at 21 DAEPOST (Table 2-6). EPOST herbicides with 2 WBP termination of cereal rye reduced weed biomass to between 12.08 g to 24.91 g in 2021 and between 1.32 g m^{-2} to 10.87 g m^{-2} in 2022 (Table 2-7). Dicamba + glyphosate reduced biomass to 1.32 g m^{-2} (Table 2-7) in 2022. At 2 WAP termination of cereal rye, weed biomass was reduced to between 0 g m^{-2} to 0.09 g m^{-2} in 2021 and 0.09 g m^{-2} to 0.27 g m^{-2} in 2022 (Table2- 7). In a study in Wisconsin, Grint et al. (2022b) reported that cereal rye cover crop terminated at crop planting reduced weed biomass by 61% compared to without a cover crop. At 21 DAEPOST, EPOST herbicides with 2 WBP termination of cereal rye limited biomass to 22.55 g to 89.9 g m^{-2} in 2021 and 3.72 g m^{-2} to 51.55 g m^{-2} in 2022 (Table 2-7). Dicamba + glyphosate reduced weed biomass to 3.72 g m^{-2} and was the most effective of the herbicides paired with 2 WBP termination of cereal rye (Table 2-7). EPOST herbicides with 2 WAP termination of cereal rye at 21 DAEPOST limited weed biomass to 5.05 g to 20.1 g in 2021 and 5.03 g m^{-2} to 8.86 g m^{-2} in 2022 (Table 2-7). Dicamba + acetochlor was the most consistent EPOST herbicide when combined with 2 WAP termination of cereal rye at 21 DAEPOST (Table 2-7). PRE fb LPOST herbicide programs with 2 WBP termination of cereal rye limited weed biomass to 1.01 g m^{-2} to 3.16 g m^{-2} in 2021 and 2.19 g m^{-2} to 20.53 g m^{-2} in 2022 at EPOST herbicide application timing (Table 2-8). Flumioxazin/metribuzin/pyroxasulfone fb dicamba consistently reduced weed biomass (1.38 g m^{-2} and 2.19 g m^{-2}, respectively) at EPOST in 2021 and 2022 (Table 2-8). When cereal rye was terminated 2 WAP, weed biomass was limited to 0.02 g m^{-2} to 0.11 g m^{-2} in 2021 and 0.1 g m^{-2} to 0.36 g m^{-2} in 2022 (Table 2-8), with no difference among PRE fb LPOST herbicide programs. At 21 DAEPOST, PRE fb LPOST herbicide programs with 2 WBP termination of cereal rye limited weed biomass to 41.8 g m^{-2} to 72.7 g m^{-2} in 2021 and 25.72 g m^{-2} to 47.21 g m^{-2} in 2022 (Table 2-8). When paired with 2 WAP termination of cereal rye, these programs limited weed biomass to 3.8 g m^{-2} to 99.6 g m^{-2} in 2021 and 16.54 g m^{-2} to 27.21 g m^{-2} in 2022. At EPOST herbicide application timing, programs had lower weed biomass when paired with 2 WAP termination of cereal rye (Figure 2-4). In PRE herbicide treatments used with 2 WAP termination of cereal rye, lower weed biomass amounts were observed during both observation timings a majority of the time, as has also been reported in other experiments (Bunchek et al. 2020).

Palmer amaranth Seed Production

Palmer amaranth seed production was reduced the most by a PRE fb LPOST herbicide program in both years, with 6,400 to 9,078 seeds female $plant^{-1}$ in 2021 (Table 2-9). Other herbicide programs ranged from 14,000 to 21,000 seeds $plant^{-1}$ in 2021. In 2022, EPOST and PRE fb LPOST herbicide program showed great reduction in Palmer amaranth seed production, with many of the treatments having no seed production (Table 9). PRE fb LPOST herbicide programs with 2 WAP termination of cereal rye limited seed production to 0 seeds $plant^{-1}$ in 2022 (Table 2-9). Across both years, the least effective treatment to reduce Palmer amaranth seed production was a PRE-only herbicide combined with 2 WBP cereal rye termination (Table 2-9). In most cases, 2 WAP termination of cereal rye reduced Palmer amaranth seed production compared with the same herbicide program with the 2 WBP termination, indicating the importance of planting green to reduce the Palmer amaranth seedbank. Palmer amaranth seed production can vary depending on the crop competition and control methods adopted in the field; for example, de Sanctis et al. (2021a) reported that nontreated plots with crop competition (soybean) produced 25,800 to 34,000 seeds female plant^{-1} in a two-year study conducted in Nebraska. Webster and Grey (2015) have reported up to 832,000 seeds per female plant without crop competition, while Sosnoskie et al. (2014) indicated that Palmer amaranth can produce up to 1.6 million seeds in cotton (*Gossypium hirsutum* L.) field.

Soybean Yield

Year-by-treatment interaction for soybean grain yield was significant (P = 0.0015); therefore, data are presented separately for both years. Soybean yield in 2021 was higher compared to 2022 due to the hail and windstorm that occurred in June 2022. Dicamba plus glyphosate applied EPOST with 2 WAP cereal rye termination was the only treatment that increased yield from 2021 to 2022, from 3,713 kg ha^{-1} to 3,838 kg ha^{-1} (Table 2-10). In 2021, yields varied between termination timings and herbicide application timings. Several herbicide programs with the 2 WBP termination timing produced similar yields (3,486 kg ha^{-1} to 4,830 kg ha^{-1}) and programs with the 2 WAP termination timing produced similar yields in the range of 3,324 kg ha^{-1} to 4,891 kg ha^{-1} (Table 2-10). Cereal rye terminated 2 WBP usually yielded higher than the 2 WAP termination in 2021 (Table 2-10) and visual differences of yellowing and stunting were observed in the 2 WAP termination (Figure 2-5). A recent study in Pennsylvania also reported reduction in corn yield when cereal rye was terminated 5 d after planting corn compared with terminating 2 weeks before planting corn (Gall et al. 2022). Grint et al. (2022a) reported that corn yield was lower at the southcentral Wisconsin study site when cereal rye was terminated 2 weeks after planting corn. However, in contrast, multi-year/location field studies in Pennsylvania reported no effect of planting green on soybean grain yield (Reed et al. 2019), though the cover crop species and termination timings were variable in this study. In 2022, herbicide programs with 2 WAP termination of cereal rye produced higher yield than 2 WBP termination paired with herbicide programs, apart from dicamba plus glyphosate, which had a soybean yield of 2,393 kg ha^{-1} (Table 2-10). The difference in yield was expected due to the hail and windstorm events in 2022. As stated above, the biomass from the later termination timing seemed to protect the soybean plants, and yields correlated (Table 2-10).

Economic Analysis

Gross profit was lower in 2022 because of the reduction in soybean grain yield due to the hail and windstorm compared with soybean grain yield in 2021. Gross profit ranged from US $642 to $2,116 ha^{-1} in 2021 and $207 to $1,966 ha^{-1} in 2022 (Table 2-11). The total cost of PRE-only and PRE fb LPOST herbicide programs with the cereal rye cover crop were higher than that of an EPOST herbicide program. EPOST programs ranged from $157 to $187 ha^{-1}, whereas PRE herbicide programs ranged from $186 to $241 ha^{-1}, while PRE fb LPOST herbicide programs were the most expensive, ranging from $246 to $301 ha^{-1} (Table 2-11).

Benefit/cost ratios varied between years, herbicide programs, and termination timings (Table 2-11). Reduction in soybean grain yield in 2022 due to the hail and windstorm in June resulted in a lower benefit/cost ratio compared with 2021. Across herbicide programs, EPOST herbicide programs had the highest average benefit/cost ratio in 2021 (5.7) and 2022 (1.29) due to better performance of dicamba fb glyphosate with both the 2 WBP and the 2 WAP termination timing in 2021 (8.29 and 5.47, respectively) and 2022 (2.16 and 6.28, respectively) (Table 2-11). Dicamba plus acetochlor added to the higher average benefit/cost ratio across EPOST herbicide programs with both termination timings in 2021 but struggled to add value in 2022 when paired with the 2 WBP termination of cereal rye. The benefit/cost ratio for PRE herbicides with either termination ranged from between 2.1 to 6.18 in 2021 and between -2.82 to 1.10 in 2022. The PRE fb LPOST herbicide programs with either termination timing of cereal rye ranged from between 2.62 to 5.11 in 2021 and -2.06 to 3.92 in 2022 (Table 2-11). Dicamba plus glyphosate consistently added value both years with cereal rye terminated 2 WAP (5.47 in 2021 and 6.28 in 2022) (Table 2-11). This can be attributed to the relatively lower cost of POST herbicides and the consistent soybean yield produced in both years. EPOST herbicide programs with 2 WBP termination of cereal rye provided the highest benefit/cost ratio in 2021; while in 2022, EPOST herbicide programs with 2 WAP cereal rye termination resulted in the highest benefit/cost ratio. EPOST herbicide programs used under normal irrigated conditions and stress-induced situations provide the highest benefit/cost ratio and should therefore be considered as a weed management program in dicamba/glyphosate-resistant soybean.

Practical Implications

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

Due to the increasing number of herbicide-resistant weeds and their widespread occurrence, interest in cover crops is growing across the Midwestern United States.

Results of this study indicated that soybean grain yields from a POST-only herbicide program with cereal rye terminated 2 WAP provided the highest benefit and the best return on investment. Cover crops should not be used alone and should be aided by additional weed control options such as herbicides as observed in this study due to the ability of Palmer amaranth to emerge, produce seeds, and reduce soybean yield after terminating cereal rye if not controlled. Planting green could be integrated into soybean production as observed in this study specifically to reduce the seed production of Palmer amaranth; however, soil moisture, disease and insect pressure, and the effect on grain yield should be carefully considered when implementing planting green in soybean production fields.

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Table 2-1. Herbicide programs, application timings, and rates used for weed control in dicamba/glyphosate-resistant soybean in field experiments conducted near Harvard, NE in 2021 and 2022.

Herbicide program	**Timing**[a]	**Rate**[a] (g ai/ae ha-1)	**Trade name**	**Manufacturer** [b]	**Adjuvants** [a,c]
Nontreated Control					
Weed Free Control: Dicamba + Acetechlor	EPOST	560 + 840	XtendiMax + Warrant	Bayer	DRA + WC
Weed and Cereal Rye Free Control: Pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	Fall PRE EPOST	245 + 1,260 fb 1,260 + 556 fb 560	Authority XL + Roundup Powermax fb Roundup Powermax + Fierce MTZ fb XtendiMax	FMC + Bayer + Valent + Bayer	COC + AMS + DRA + WC
Pyroxasulfone/sulfentrazone	PRE	292	Authority Supreme	FMC	-
Flumioxazin/pyroxasulfone/metribruzin	PRE	475	Fierce MTZ	Valent	-
Imazethapyr/saflufenacil/pyroxasulfone	PRE	215	Zidua Pro	BASF	-
Dicamba + glyphosate	EPOST	560 + 1,260	XtendiMax+ Roundup PowerMax	Bayer	DRA + WC
Fomesafen/S-Metalachlor	EPOST	1,480	Prefix	Syngenta	NIS
Dicamba + acetochlor	EPOST	560 + 840	Xtendimax+ Warrant	Bayer	DRA + WC
Pyroxasulfone/sulfentrazone fb dicamba	PRE fb LPOST	292 + 560	Authority Supreme fb Xtendimax	FMC, Bayer	DRA + WC
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	PRE fb LPOST	556 + 560	Fierce MTZ fb Xtendimax	Valent, Bayer	DRA + WC
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	PRE fb LPOST	215 + 560	Zidua Pro fb Xtendimax	BASF, Bayer	DRA + WC

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

[b] Bayer CropScience, Research Triangle Park, NC; BASF Corporation, Research Triangle Park, NC; FMC Corporation, Philadelphia, PA; Syngenta Crop Protection, LLC., Greensboro, NC; Valent USA Corporation, Walnut Creek, CA.

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

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

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

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

[a] Data were obtained from National Oceanic and Atmospheric Administration (NOAA 2022).

Table 2-3. Effect of cereal rye termination timing and PRE herbicides on Palmer amaranth control in dicamba/glyphosate-resistant soybean at 14, 28, 42 DAPRE in field experiments conducted near Harvard, NE in 2021 and 2022.

			Rate	**Palmer amaranth control**[a,b,c]					
				14 DAPRE		28 DAPRE		42 DAPRE	
Herbicide program	**Cereal rye termination**[a]	**Application timing**[a]	g ae or ai ha^{-1}	2021	2022	2021	2022	2021	2022
				%					
Nontreated (cereal rye present)	NA	NA		85 a	99 a	65 b	50 c	67 b	70 b
Weed Free Control: Dicamba + Acetochlor	NA	EPOST	560 + 840	99 a	99 a	96 a	98 a	96 a	92 a
Weed and cereal rye free control: Pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	NA	Fall, PRE fb EPOST	245 + 1,260 fb 1,260 + 556 fb 560	99 a	97 a	97 a	93 a	99 a	90 a
Pyroxasulfone/sulfentrazone	2 WBP	PRE	292	85 a	99 a	79 a	56 c	98 a	59 bc
Pyroxasulfone/sulfentrazone	2 WAP	PRE	292	98 a	99 a	99 a	88 ab	99 a	53 bc
Flumioxazin/pyroxasulfone/metribuzin	2 WBP	PRE	475	99 a	97 a	98 a	80 ab	99 a	73 b
Flumioxazin/pyroxasulfone/metribuzin	2 WAP	PRE	475	99 a	99 a	95 a	98 a	99 a	60 bc
Imazethapyr/saflufenacil/pyroxasulfone	2 WBP	PRE	215	95 a	89 a	83 a	69 bcbc	91 a	46 c
Imazethapyr/saflufenacil/pyroxasulfone	2 WAP	PRE	215	99 a	97 a	99 a	89 ab	99 a	73 b

[a] Abbreviations: DAPRE, days after preemergence herbicide application; fb, followed by; NA, not applicable; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

[b] Means presented within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at $P \leq 0.05$.

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

Table 2-4. Effect of cereal rye termination timing and EPOST herbicide programs on Palmer amaranth control at 14, 28, 42 DAEPOST in dicamba/glyphosate-resistant soybean near Harvard, NE in 2021 and 2022.[c]

Herbicide program [a]	**Cereal rye termination** [a]	**Application timing** [a]	**Rate** [a]	**Palmer amaranth control** [a,b,c]					
			g ae or ai ha^{-1}	14 DAEPOST[a,b]		28 DAEPOST[a,b]		42 DAEPOST[a,b]	
				2021	2022	2021	2022	2021	2022
				%					
Nontreated control (cereal rye present)	NA	NA	NA	48 b	77 b	45 c	63 b	59 c	55 b
Weed-free control: Dicamba + Acetechlor	NA	EPOST	560 + 840	96 a	92 a	96 a	98 a	63 c	87 a
Weed- and rye-free control: Pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	NA	Fall, PRE fb EPOST	245 + 1,260 fb 1,260 + 556 fb 560	99 a	90 ab	97 a	67 b	99 a	72 ab
Dicamba + glyphosate	2 WBP	EPOST	560 + 1,260	50 b	86 a	68 c	66 b	80 abc	63 b
Dicamba + glyphosate	2 WAP	EPOST	560 + 1,260	93 a	97 a	93 ab	93 a	71 b	99 a
Fomesafen/S-Metolachlor	2 WBP	EPOST	1,480	11 c	96 a	14 d	94 a	23 d	94 a
Fomesafen/S-Metolachlor	2 WAP	EPOST	1,480	79 ab	84 b	73 bc	96 a	69 bc	95 a
Dicamba + acetochlor	2 WBP	EPOST	560 + 840	50 b	99 a	60 c	99 a	86 ab	99 a
Dicamba + acetochlor	2 WAP	EPOST	560 +840	98 a	99 a	95 a	99 a	97 a	99 a

[a] Means presented within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at $P \leq 0.05$.

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

[c] Abbreviations: DAEPOST, days after early postemergence herbicide application; EPOST, early postemergence; fb, followed by; NA, not applicable; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

Table 2-5. Effect of cereal rye termination timing and PRE fb LPOST herbicide programs on Palmer amaranth control at 14, 28, 42 DAPRE and 14, 28 DALPOST in dicamba/glyphosate-resistant soybean near Harvard, NE in 2021 and 2022. [c]

Herbicide program [a]	**Cereal rye termination**[a]	**Application timing**[a]	**Rate** [a]	**Palmer amaranth control** [a,b,c]									
			g ae or ai ha^{-1}	14 DAPRE[a,b]		28 DAPRE[a,b]		42 DAPRE[a,b]		14 DALPOST[a,b]		28 DALPOST[a,b]	
				2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
				%									
Nontreated control (cereal rye present)	NA	NA	NA	84 a	80 b	70 b	60 b	72 b	65 b	40 c	45 c	59 b	45 b
Weed-free control: Dicamba + Acetechlor	NA	EPOST	560 + 840	85 a	99 a	96 a	98 a	96 a	92 a	63 b	98 a	63 b	87 a
Weed- and rye-free control: Pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	NA	Fall, PRE fb EPOST	245 + 1,260 fb 1,260 + 556 fb 560	99 a	97 a	97 a	67 b	99 a	90 a	99 a	98 a	99 a	72 a
Pyroxasulfone/sulfentrazone fb dicamba	2 WBP	PRE fb LPOST	292 + 560	96 a	90 a	71 b	90 a	98 a	67 b	60 b	71 b	90 a	71 abc
Pyroxasulfone/sulfentrazone fb dicamba	2 WAP	PRE fb LPOST	292 + 560	99 a	99 a	95 a	87 a	99 a	93 a	92 a	99 a	92 a	99 a
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WBP	PRE fb LPOST	556 + 560	99 a	99 a	99 a	94 a	99 a	98 a	91 a	97 a	91 a	97 a
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WAP	PRE fb LPOST	556 +560	98 a	99 a	99 a	91 a	99 a	97 a	92 a	97 a	92 a	97 a
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WBP	PRE fb LPOST	215 + 560	89 a	99 a	84 ab	65 b	94 a	69 b	85 a	75 ab	97 a	75 a
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WAP	PRE fb LPOST	215 + 560	99 a	99 a	99 a	92 a	99 a	98 a	63 ab	84 ab	85 a	99 a

[a] Means presented within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at $P \leq 0.05$.

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

[c] Abbreviations: DALPOST, days after late postemergence herbicide application; DAPRE, days after preemergence herbicide application; fb, followed by; NA, not applicable; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

Table 2-6. Effect of PRE herbicides and cereal rye termination timing on weed biomass in dicamba/glyphosate-resistant soybean in field experiments conducted near Harvard, NE in 2021 and 2022.

Herbicide program [a]	**Cereal rye termination**[a]	**Application timing**[a]	**Rate**[a]	**Weed biomass**[a,b,c,d]			
			g ae or ai ha^{-1}	EPOST		21 DAEPOST	
				2021	2022	2021	2022
				g m^{-2}			
Nontreated control (rye present)	NA	NA		11 d	22.5 e	25 c	37.5 e
Weed-free control: Dicamba + Acetechlor	NA	EPOST	560 + 840	0.58 ab	2.04 bc	13.23 b	13.53 bc
Weed- and rye-free control: Pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	NA	Fall, PRE fb EPOST	245 + 1,260 fb 1,260 + 556 fb 560	0.5 ab	6.88 d	0.78 a	3.52 a
Pyroxasulfone/sulfentrazone	2 WBP	PRE	292	5.45 c	16.19 de	88.3 g	25.59 d
Pyroxasulfone/sulfentrazone	2 WAP	PRE	292	0 a	0.37 a	45.35 e	17.53 c
Flumioxazin/pyroxasulfone/metribruzin	2 WBP	PRE	475	0 a	5.22 cd	27.8 c	25.41 d
Flumioxazin/pyroxasulfone/metribruzin	2 WAP	PRE	475	0 a	5.22 cd	39.5 d	36.11 e
Imazethapyr/saflufenacil/pyroxasulfone	2 WBP	PRE	215	0 a	13.96 de	54.45 f	26.71 d
Imazethapyr/saflufenacil/pyroxasulfone	2 WAP	PRE	215	0 a	0.15 a	35.1 d	23.4 cd

[a] Abbreviations: DAEPOST: days after early postemergence herbicide application; EPOST, early postemergence; fb, followed by; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

[b] Data for each year were log transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.

[c] All weed species are combined for biomass data.

[d] Means presented within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at $P \leq 0.05$.

Table 2-7. Effect of EPOST herbicides and cereal rye termination timing on weed biomass in dicamba/glyphosate-resistant soybean in field experiments conducted near Harvard, NE in 2021 and 2022.

Herbicide program[a]	**Cereal Rye termination**[a]	**Application timing**[a]	**Rate**[a]	**Weed biomass**[a,b,c,d]			
				EPOST[a,b,d]		21 DAEPOST[a,b,d]	
			g ae or ai ha^{-1}	2021	2022	2021	2022
				g m^{-2}			
Nontreated control (rye present)	NA	NA	NA	0.64 ab	2.935 ab	25 d	38.19 d
Weed-free control: Dicamba + Acetechlor	NA	EPOST	560 + 840	0.58 ab	2.04 ab	13.23 bc	13.53 c
Weed- and rye-free control: Pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	NA	Fall, PRE fb EPOST	245 + 1,260 fb 1,260 + 556 fb 560	0.5 ab	6.88 cd	0.78 a	3.52 a
Dicamba + glyphosate	2 WBP	EPOST	560 + 1,260	24.91 d	1.32 ab	22.55 cd	3.72 a
Dicamba + glyphosate	2 WAP	EPOST	560 + 1,260	0 a	0.14 a	20.1 cd	5.255 ab
Fomesafen/S-Metolachlor	2 WBP	EPOST	1,480	12.36 c	4.76 bc	89.9 f	36.36 d
Fomesafen/S-Metolachlor	2 WAP	EPOST	1,480	0 a	0 a	15.2 c	5.03 ab
Dicamba + acetochlor	2 WBP	EPOST	560 + 840	12.08 c	10.87 d	57.15 e	51.55 e
Dicamba + acetochlor	2 WAP	EPOST	560 +840	0 a	0.27 a	5.05 b	8.86 bc

[a] Abbreviations: DAEPOST, days after early postemergence herbicide application; EPOST, early postemergence; fb, followed by; NA, not applicable; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

[b] Data for each year were logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.

[c] All weed species were combined for biomass data.

[d] Means presented within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at $P \leq 0.05$.

Table 2-8. Effect of PRE fb LPOST herbicide programs and cereal rye termination timing on weed biomass in dicamba/glyphosate-resistant soybean in field experiments conducted near Harvard, NE in 2021 and 2022.

Herbicide program[a]	Cereal Rye termination[a]	Application timing[a]	Rate[a] g ae or ai ha^{-1}	Weed biomass [a,b,c,d]			
				EPOST[a,b,d]		21 DAEPOST[a,b,d]	
				2021	2022	2021	2022
				g m^{-2}			
Nontreated control (cereal rye present)	NA	NA	NA	0.64 ab	13.93 c	25 d	37.19 d
Weed-free control: Dicamba + Acetechlor	NA	EPOST	560 + 840	0.58 ab	2.04 ab	13.23 c	13.53 b
Weed- and rye-free control: Pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	NA	Fall, PRE fb EPOST	245 + 1,260 fb 1,260 + 556 fb 560	0.5 ab	6.88 bc	0.78 a	3.52 a
Pyroxasulfone/sulfentrazone fb dicamba	2 WBP	PRE fb LPOST	292 + 560	3.16 c	20.53 d	41.8 ef	25.72 c
Pyroxasulfone/sulfentrazone fb dicamba	2 WAP	PRE fb LPOST	292 + 560	0.06 a	0.1 a	44.3 ef	16.54 bc
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WBP	PRE fb LPOST	556 + 560	1.38 bc	2.19 ab	72.7 f	47.21 d
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WAP	PRE fb LPOST	556 +560	0.11 a	0.36 a	99.6 g	27.21 c
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WBP	PRE fb LPOST	215 + 560	1.01 abc	12.35 c	62.95 f	25.88 c
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WAP	PRE fb LPOST	215 + 560	0.02 a	0.32 a	3.8 ab	27.21 c

[a] Abbreviations: DAEPOST, days after early-postemergence herbicide application; EPOST, early postemergence; fb, followed by; LPOST, late postemergence; NA, not applicable; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

[b] Data for each year were logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data

[c] All weed species are combined for biomass data.

[d] Means presented within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at $P \leq 0.05$.

Table 2-9. Effect of herbicide programs and cereal rye termination timing on Palmer amaranth seed production plant^{-1}in glyphosate/dicamba-resistant soybean near Harvard, NE in 2021 and 2022.

Herbicide program^{a}	Cereal rye termination^{a}	Application timing^{a}	Rate^{a}	Estimated Palmer amaranth seed count^{b,c}	
			g ae or ai ha^{-1}	Seeds plant^{-1}	
				2021	2022
Nontreated control (rye present)	NA	NA	NA	13,142 bcde	10,500 b
Weed-free control: Dicamba + Acetechlor	NA	EPOST	420 + 820	17,942 de	0 a
Weed- and rye-free Control: Pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	NA	Fall, PRE fb EPOST	245 + 1,260 fb 1,260 + 556 fb 560	0 a	7,860 a
Pyroxasulfone/sulfentrazone	2 WBP	PRE	292	18,037 de	7,423 ab
Pyroxasulfone/sulfentrazone	2 WAP	PRE	292	16, 109 abcd	7,026 ab
Flumioxazin/pyroxasulfone/metribruzin	2 WBP	PRE	475	16, 770 cde	9,055 ab
Flumioxazin/pyroxasulfone/metribruzin	2 WAP	PRE	475	15,326abcde	7,103 b
Imazethapyr/saflufenacil/pyroxasulfone	2 WBP	PRE	215	21,1137 cde	9,543 b
Imazethapyr/saflufenacil/pyroxasulfone	2 WAP	PRE	215	16, 822 abc	5,685 ab
Dicamba + glyphosate	2 WBP	EPOST	560 + 1,260	17,642 abcd	8,171 ab
Dicamba + glyphosate	2 WAP	EPOST	560 + 1,260	14,216 abcd	0 a
Fomesafen/S-Metolachlor	2 WBP	EPOST	1,480	15,908 e	0 a
Fomesafen/S-Metolachlor	2 WAP	EPOST	1,480	14,790 bcde	0 a
Dicamba + acetochlor	2 WBP	EPOST	560 + 840	14, 832 abcd	0 a
Dicamba + acetochlor	2 WAP	EPOST	560 +840	0 a	0 a
Pyroxasulfone/sulfentrazone fb dicamba	2 WBP	PRE fb LPOST	292 + 560	7,196 ab	23,632
Pyroxasulfone/sulfentrazone fb dicamba	2 WAP	PRE fb LPOST	292 + 560	9,078 ab	0 a
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WBP	PRE fb LPOST	556 + 560	6,473 ab	0 a
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WAP	PRE fb LPOST	556 +560	6,561 ab	0 a
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WBP	PRE fb LPOST	215 + 560	8,505 ab	4,943 a
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WAP	PRE fb LPOST	215 + 560	7,130 ab	0 a

[a] Abbreviations: EPOST, early postemergence; fb, followed by; LPOST, late postemergence; NA, non-applicable; PRE, preemergence; WBP, weeks before planting, WAP, weeks after planting.

[b] Means presented within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at $P \leq 0.05$.

[c] Year-by-treatment interaction for estimated Palmer amaranth seed plant-1 were significant, therefore data were separated by year.

Table 2-10. Effect of herbicide programs and cereal rye termination timing on soybean yield in dicamba/glyphosate-resistant soybean in field experiments conducted near Harvard, NE in 2021 and 2022.

Herbicide program^c	Cereal rye termination^c	Application timing^c	Rate^c	Soybean yield^{ab}	
			g ae or ai ha^{-1}	Kg ha^{-1}	
				2021	2022
Nontreated control (cereal rye present)	NA	NA	NA	226 d	235 e
Weed-free control: Dicamba + Acetechlor	NA	EPOST	560 + 840	2,174 c	1,941 abcde
Weed- and rye-free control: Pyroxasulfone/sulfentrazone + glyphosate fb glyphosate + flumioxazin/pyroxasulfone/metribuzin fb dicamba	NA	Fall, PRE fb EPOST	245 + 1,260 fb 1,260 + 556 fb 560	4,875 a	2,104 abcde
Pyroxasulfone/sulfentrazone	2 WBP	PRE	292	2,480 bc	515 de
Pyroxasulfone/sulfentrazone	2 WAP	PRE	292	3,500 abc	1,934 abcde
Flumioxazin/pyroxasulfone/metribruzin	2 WBP	PRE	475	3,614 abc	391 de
Flumioxazin/pyroxasulfone/metribruzin	2 WAP	PRE	475	4,891 a	2,182 abcde
Imazethapyr/saflufenacil/pyroxasulfone	2 WBP	PRE	215	3,486 abc	821 dce
Imazethapyr/saflufenacil/pyroxasulfone	2 WAP	PRE	215	3,424 abc	2,099 abcde
Dicamba + glyphosate	2 WBP	EPOST	560 + 1,260	4,830 a	2,393 abcde
Dicamba + glyphosate	2 WAP	EPOST	560 + 1,260	3,713 abc	3,838 a
Fomesafen/S-Metolachlor	2 WBP	EPOST	1,480	2,652 bc	400 de
Fomesafen/S-Metolachlor	2 WAP	EPOST	1,480	3,694 abc	2,934 abc
Dicamba + acetochlor	2 WBP	EPOST	560 + 840	4,631 ab	240 e
Dicamba + acetochlor	2 WAP	EPOST	560 +840	4,331 ab	2,791 abc
Pyroxasulfone/sulfentrazone fb dicamba	2 WBP	PRE fb LPOST	292 + 560	4,613 ab	1,075 dce
Pyroxasulfone/sulfentrazone fb dicamba	2 WAP	PRE fb LPOST	292 + 560	3,350 abc	2,526 abcd
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WBP	PRE fb LPOST	556 + 560	4,499 ab	461 de
Flumioxazin/pyroxasulfone/metribuzin fb dicamba	2 WAP	PRE fb LPOST	556 +560	3,324 abc	2,875 abc
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WBP	PRE fb LPOST	215 + 560	4,316 ab	1,602 bcde
Imazethapyr/saflufenacil/pyroxasulfone fb dicamba	2 WAP	PRE fb LPOST	215 + 560	3,741 abc	3,582 ab

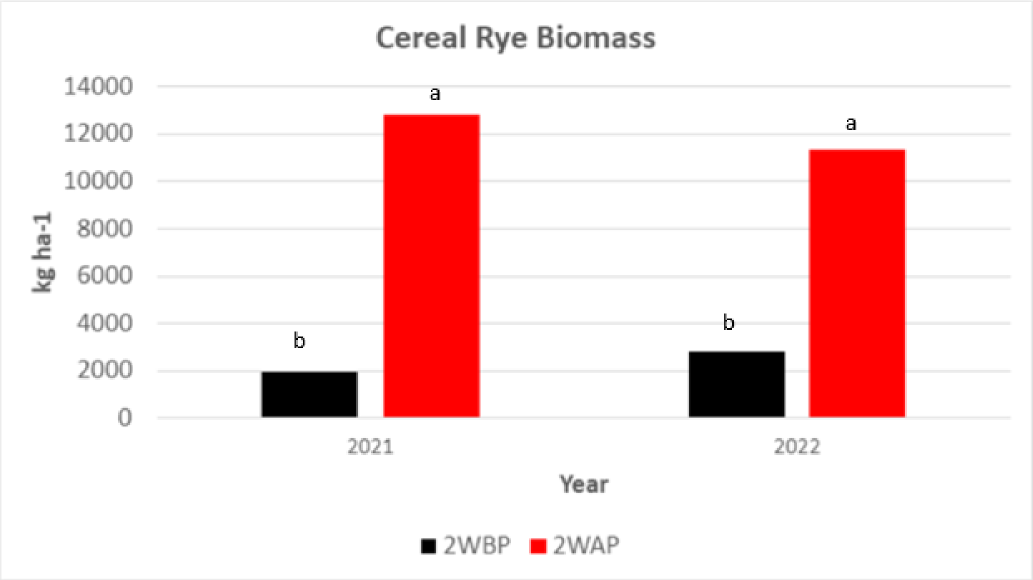
Table 2-11. Effect of herbicide programs and cereal rye termination timing on gross profit margin and benefit/cost ratio in dicamba/glyphosate-resistant soybean in field experiments conducted near Harvard, NE in 2021 and 2022.

Herbicide program + Termination timing	Weed management program cost						Gross profit margin		Benefit/cost ratio	
	PRE	EPOST	LPOST	APP[b]	Rye[a]	Total	2021	2022	2021	2022
PRE	\$ ha^{-1}									
Nontreated control (cereal rye present)	-	-	-	-	99	99	115	120	-	-
Weed-free control	-	56	-	32	99	187	934	1,001	1.56	0.74
Weed/Rye-free control*	141	45	-	68	99	431	2,116	1,207	3.42	0.80
Pyroxasulfone/sulfentrazone + 2 WBP	92	-	-	17	99	208	1,080	276	2.10	-2.82
Pyroxasulfone/sulfentrazone + 2 WAP	92	-	-	17	99	208	1,518	1,000	4.21	0.66
Flumioxazin/pyroxasulfone/metribruzin + 2 WBP	125	-	-	17	99	241	1,401	207	3.15	-2.72
Flumioxazin/pyroxasulfone/metribruzin + 2 WBP	125	-	-	17	99	241	2,131	1,104	6.18	1.00
Imazethapyr/saflufenacil/pyroxasulfone + 2 WBP	70	-	-	17	99	186	1,518	414	4.70	-2.41
Imazethapyr/saflufenacil/pyroxasulfone + 2 WAP	70	-	-	17	99	186	1,488	1,069	4.55	1.11
EPOST										
Dicamba+glyphosate + 2 WBP	-	45	-	32	99	176	2,101	1,242	8.29	2.16
Dicamba+glyphosate + 2 WAP	-	45	-	32	99	176	1,605	1,966	5.47	6.28
Fomesafen/S-metolachlor + 2 WBP	-	40	-	19	99	157	1,138	207	3.15	-4.16
Fomesafen/S-metolachlor + 2 WAP	-	40	-	19	99	157	1,171	1,518	3.36	4.16
Dicamba+acetochlor + 2 WBP	-	56	-	32	99	187	2,014	138	7.34	-3.87
Dicamba+acetochlor + 2 WAP	-	56	-	32	99	187	1,868	1,449	6.56	3.14
PRE fb LPOST										
Pyroxasulfone/sulfentrazone fb Dicamba + 2 WBP	92	-	29	49	99	268	2,014	552	5.11	-1.16
Pyroxasulfone/sulfentrazone fb Dicamba + 2 WAP	92	-	29	49	99	268	1,459	1,311	3.04	1.67
Flumioxazin/pyroxasulfone/metribruzin fb Dicamba + 2 WBP	125	-	29	49	99	301	1,955	241	4.36	-2.06
Flumioxazin/pyroxasulfone/metribruzin fb Dicamba + 2 WBP	125	-	29	49	99	301	1,430	1,484	2.62	2.06
Imazethapyr/saflufenacil/pyroxasulfone fb Dicamba + 2 WBP	70	-	29	49	99	246	1,868	828	4.97	-0.14
Imazethapyr/saflufenacil/pyroxasulfone fb Dicamba + 2 WAP	70	-	29	49	99	246	1,634	1,828	4.03	3.92

[a] Abbreviations: APP, application cost; fb, followed-by; EPOST, early postemergence; LPOST, late postemergence; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

[b] Cereal rye seed price + termination cost.

Figure 2-1. Soybean plants at V1 crop stage at 2 weeks after planting cereal rye termination.



[a]Means presented for each bar with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at $P \leq 0.05$.

Figure 2-2. Effect of termination timing of cereal rye on cumulative biomass in 2021 and 2022 in a study conducted near Harvard, NE. Cereal rye termination timings: 2 weeks before planting (WBP), 2 weeks after planting (WAP), no termination timing (NA).

Figure 2-3. Weed control in dicamba + glyphosate with 2 weeks before planting termination of cereal rye at 14 days after early postemergence herbicide application.

Figure 2-4. Weed control in dicamba + glyphosate with 2 weeks after planting termination of cereal rye at 14 days after early postemergence herbicide application.

Figure 2-5. The 2 WAP termination of cereal rye treatment provided effective weed supression, but there is an observed yellowing and stunting of the soybean compared to the 2 WBP termination of cereal rye treatment to the right.

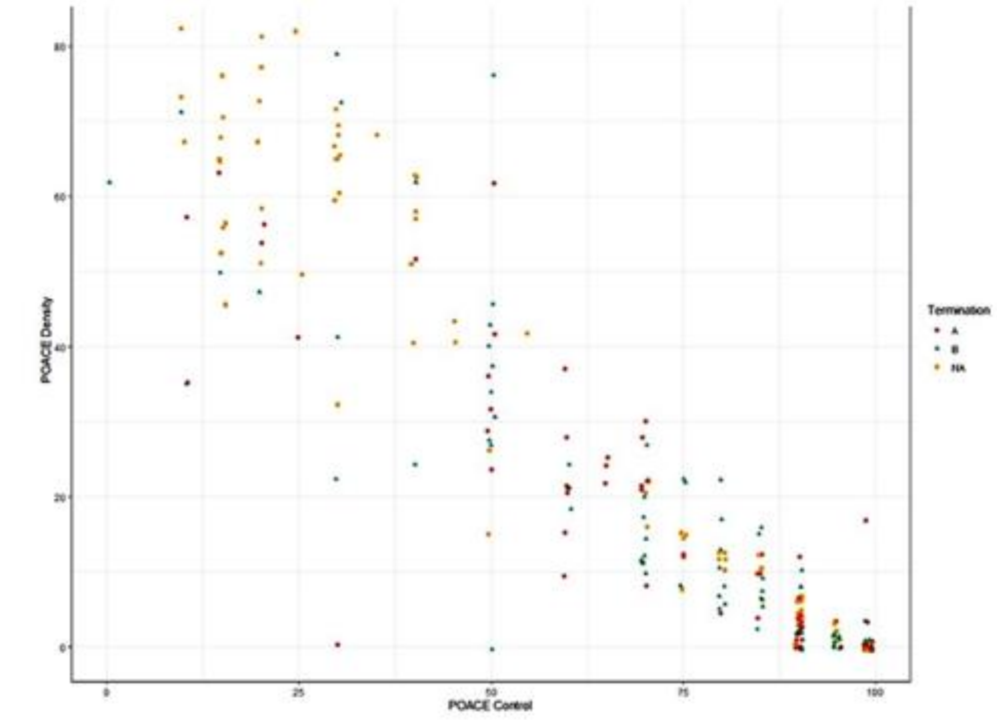


Figure 2-6. Correlation between giant foxtail (POACE) control and density in field experiments conducted in 2021 and 2022 (-0.9324782). Cereal rye termination timing: 2 weeks before planting (B), 2 weeks after planting (A), no termination timing (NA).

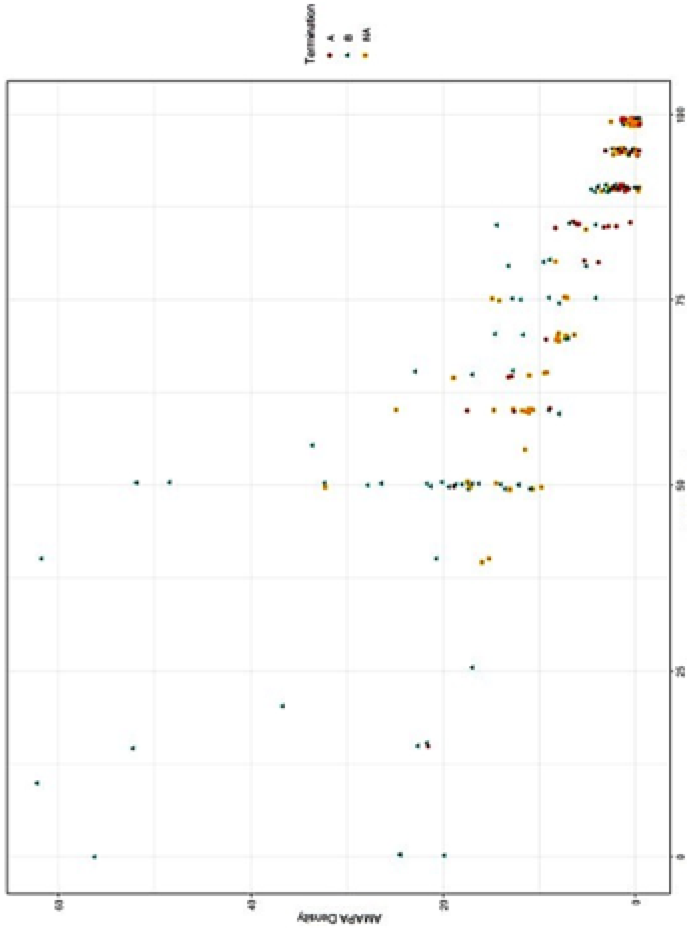


Figure 2-7. Correlation between Palmer amaranth (AMAPA) control and density in field experiments conducted in 2021 and 2022 (-0.8607678). Cereal rye termination timing: 2 weeks before planting (B), 2 weeks after planting (A), no termination timing (NA).

Chapter 3:

Integrating Cereal Rye (*Secale cereale* L.) with Herbicides for Weed Management in Corn under PG Conditions in Nebraska

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Abstract

The integration of cover crops has increased recently in corn-based cropping systems in Nebraska. Planting green is when a producer plants a cash crop into an actively growing cover crop and then terminates at time of planting or in the first couple weeks after planting. The objectives of this study were to: determine the effect of planting green on residual herbicide efficacy, weed suppression, corn yields, and cost-benefit ratio. Field experiments were conducted from 2020 to 2022 in southcentral Nebraska. Three different herbicides or herbicide combinations were used in each herbicide program [PRE, Early POST, and PRE followed-by (fb) Late POST], and each of those had termination timings of 2 weeks before planting (2 WBP) or 2 weeks after planting (2 WAP). PRE herbicide programs paired with 2 WAP provided 81% to 98% control of giant foxtail and 87% to 97% control of Palmer amaranth in 2021 at 28 days after PRE (DAPRE) compared with 99% control of giant foxtail and 93%-99% control of Palmer amaranth in 2022. In 2021, there was a missed application of fertilizer at planting and in 2022 there was no irrigation until July 1 and there was a hail event in June. There is an assumption that these are compounding factors that effected yields in both years. In 2021 2 WBP termination treatments yielded higher than 2 WAP termination. The 2 WBP yielded between 15,604 kg ha^{-1} and 17,956 kg ha^{-1} and the 2 WAP termination treatments yielded between

12,306 kg ha^{-1} and 15,535 kg ha^{-1}. In 2022, yields were reduced in all treatments but the 2 WAP termination treatments yielded higher with yields between 11,230 kg ha^{-1} and 13,651 kg ha^{-1} compared to the 2 WBP, 7,801 kg ha^{-1} to 13,517 kg ha^{-1}. In conclusion, proper fertility with plating green can lead to excellent weed control and higher yields than an earlier terminated cereal rye. In 2022, PRE fb LPOST/2 WAP program provided highest yield and full season weed control, but economics must be factored into combining planting green and herbicides. Planting green provided greater weed suppression but due to confounding factors in both years, it is yet to be determine on how it affects corn yield and benefit/cost ratio.

Introduction

Nebraska is the third largest corn producing state in the United States behind Iowa and Illinois with an estimated 4 million ha of corn planted in 2021 (USDA-NASS 2022). A majority of corn is used for grain and a minority is used for silage (USDA-NASS 2022). Corn is a grass (*Poaceae*) species that exhibits quick growth habits that flourish in hot days and colder nights which fits the climate of many Midwestern states including Nebraska. Corn production is a main commodity alongside the production of soybean in Nebraska (USDA-NASS. 2017) and producers predominately rotate between the two or practice continuous corn (Striegel et al. 2020; Yu et al. 2018). Corn is the most grown crop in Nebraska and one of the most limiting factors of a successful corn production is competition from weeds. In crop production fields, there can be emergence of weeds from early spring through the fall which creates a challenge for producers (Ogg and Dawson 1984). The common practice of soybean and corn rotations can create restrictiveness when it comes to chemical control of summer annual weeds such as common lambsquarters (*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* Modik.), common ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), kochia (*Bassia scoparia* L.), Palmer amaranth (*Amaranthus palmeri* S. Wats.), and waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Saueer], and *Poaceae* species. The development of commercial hybrids that exhibit resistance to multiple herbicides has given producers options of how to chemically control weeds in corn production. Often times, producers rely only upon herbicides for weed management that has resulted into selection pressure and the evolution of herbicide-resistant weeds (Kniss 2018) which has led to a continuous rise in herbicide-resistant weeds (McDonald et al. 2021).

In Nebraska, six broadleaf weeds have been confirmed resistant to glyphosate: common ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), horseweed (*Erigeron canadensis* L.), kochia (*Bassia scoparia* L.), Palmer amaranth (*Amaranthus palmeri* S. Wats.), and waterhemp [*Amaranthus tuberculatus (*Moq.) J.D. Saueer] (Anonymous 2022). Other broadleaf weed species such as redroot pigweed (*Amaranthus retroflexus* L.) has evolved resistance to atrazine and two grass species Johnsongrass (*Sorghum halapense* L.) and shattercane (*Sorghum bicolor* L.) have evolved resistance to acetolactate synthase (ALS) inhibitors (Anonymous 2022). In 2021, a total of three weeds have been confirmed resistant to HPPD-inhibitors, 41 to synthetic auxins, 169 to ALS inhibitors, and 14 to very long-chain fatty acid synthesis-inhibitors worldwide (Heap 2023). These are the top four herbicides applied preemergence (PRE) in Nebraska; and 74% of corn producers use soil-applied residual herbicides to manage glyphosate-resistant weeds (Sarangi & Jhala, 2018). In addition, HPPD-inhibitor-resistant Palmer amaranth and waterhemp; and 2,4-D-resistant waterhemp has been reported in Nebraska (Anonymous 2022). Several biotypes of Palmer amaranth and waterhemp are multiple herbicide-resistant and they are widespread (Jhala et al. 2014; (Mausbach et al. 2021). Therefore, herbicide options are limited for management of herbicide-resistant weeds in corn and soybean production fields. Other forms of weed control such as mechanical control in the form of a rotary hoe reduced weed density by 39% to 57% compared to a nontreated in a study conducted in Pennsylvania (Bates et al. 2012). Mechanical weed control no longer occurs once crop has grown to a height where equipment destroys established crop. In addition, mechanical weed control is not preferred when a producer is a no-till; thus, limiting the use of mechanical weed control for summer annual weed management. A survey conducted in 2015 reported that 61% of growers in Nebraska have adopted no-till production systems (Sarangi and Jhala 2018).

Other weed control options are being explored in corn production across the Midwest such as the use of cover crops (cover crops). A well-established cover crop during the early spring can work as a weed suppressor before, during, and shortly after planting. Cover crops can suppress weeds through competition for light, moisture, nutrients, and space (Mirsky et al. 2013). Some cover crop can suppress weeds through allelopathic effects (Hutchinson and McGiffen 2000). Cover crop adoption has increased 50% from 2012 to 2017 in the United States but does vary by region (USDA-ERS 2021). For example, adoption in eastern states such as Maryland, Pennsylvania, Virginia, and Georgia is higher than midwestern and western states. A few states such as Colorado, New Mexico, Washington, Wyoming have even seen a decline in cover crop adoption (USDA-ERS 2021). This could be due to limited moisture these states receive from rainfall. Nebraska's rate of adoption is ~2.5% compared with the 33% adoption rate in Maryland-being the state with highest adoption of cover crops in the United States (USDA-ERS 2021). It is important to note that Nebraska ranked fifth in cover crop area as of 2017 with 303,475 hectares whereas Maryland did not rank in the top five (USDA-ERS 2021). The greatest use of cover crops throughout the United States has been seen in corn silage and cotton (*Gossypium herbaceum L.*) fields but to achieve greater adoption there must be expansion into other commodities; therefore, increase in adoption from 2012 to 2017 has been from greater adoption in field corn and soybean (USDA 2017 EIB 222). Many benefits that lead to adoption are seen as longer-term benefits such as: reduction in soil erosion, nutrient cycling, water quality, and soil health (Smith et al.

2020). Greater adoption could occur if quicker return on investment occurred in weed management (Nicholas et al. 2020).

‘Planting green’ is planting a row crop into a green actively growing cover crops and terminating at or after planting (Reed et al. 2019). The conventional use of cover crops is to establish during the fallow period of winter and to terminate before planting a cash crop (Oliveira et al. 2019), but this tends to result in lower biomass accumulation and minimum suppression of summer annual weeds. Therefore, there has been an adoption of planting green which allows for greater biomass accumulation and weed suppression. Planting green could provide weed suppression into the growing season that may help as an aid to other weed control methods. An actively growing cover crop can create a highly competitive environment for light, water, space, and nutrients (Bezuidenhout et al. 2012) and leftover plant residues can provide similar effects (Mirsky et al. 2013, Teasdale and Mohler 1993). Cereal rye (*Secale cereale* L.) is commonly used in the practice of planting green in the Midwest (Butts and Werle 2017) because of its winter hardiness, success of establishment, and its ability to produce copious amount of biomass to suppress weeds (Curran 2010).

As with any new practice, the risks and benefits need to be researched to implement the “planting green” practice in commercial production fields. Allelopathy, soil water use, pest transfer, and N immobilization while using cover crops in corn are among the list of potential concerns (Koehler-Cole et al. 2020). Allelopathy is a process that uses secondary metabolites to change soil properties to alter the growth of seedlings (Bennet & Klironomos 2019). Laboratory and field studies have shown that allelopathy affects small-seeded species more than large-seeded (Koehler-Cole et al. 2020; Liebman and

Sundberg 2006) which may allude to less of an influence upon corn and soybean (Koehler-Cole et al. 2020). Cover crops can use moisture needed for row crop growth and are a much better fit for humid regions of the United States such as the eastern half of Nebraska, but the semi-arid region of western Nebraska is more likely to experience limitation of cover crop usages due to water usage (Nielsen et al. 2015). Because cereal rye and corn both are grass species, they can often share pests such as insects or diseases. A cover crop may become a "green bridge" for pests and allow them to increase or maintain their population and transfer it to the new crop (Smiley et al. 1991). Cereal rye is a nutrient scavenger meaning that it can find nutrients in the soil that other crops have often left, and it tends to use a substantial amount of nitrogen. As a result, N can be tied up in the cereal rye crop due to a high C:N and not be available for a following corn crop (Jahanzad et al. 2016) and might result in yield reduction.

The objectives of this study were to: 1) evaluate planting green and non-planting green practices in combination with multiple herbicide programs (PRE, Early POST, and PRE followed by Late POST) and their impact on weed management, 2) evaluate interactions between pre-emergence herbicides and cereal rye as a cover crop, and 3) determine the effect of planting green on corn yield, and cost/benefit ratio.

Materials and Methods

Study Location

Research was conducted at the University of Nebraska-Lincoln's South-Central Agricultural Lab (SCAL) near Harvard, NE (40.52°N, 98.05°W) in 2020-2022. The soil at the experimental site was silt loam (58% silt, 17% sand, 25% clay content), soil organic matter of 3.4%, and pH of 6.8. In both years, experiments were conducted under linear irrigation, although in 2022 the irrigation was not available until July 1. In 2020-2021 The experiment was established after soybean in 2020-2021; and after the previous year's corn in 2021-2022. This location is a no-till cropping system. The most common weeds at the research site were Palmer amaranth and giant foxtail. Cereal rye (Elbon Cereal Rye, GreenCover Seed) was drilled on October 23, 2020 and November 15, 2021 with 20.32 cm row spacing, 3.2 cm seeding depth, and a seeding rate of 95.32 kg ha^{-1}. Glyphosate and glufosinate-resistant corn planted at a rate of 84,000 seeds ha^{-1} at a depth of 4.5 cm and 76.2 cm width between rows on May 7, 2021, and May 16, 2022.

Experimental Design and Treatments

This study was designed as a factorial randomized complete block design (RCBD) with four replications. Individual plots were 3 m wide and 9 m long with four corn rows spaced 0.76 m apart. The three factors that made up a treatment in this study were: (1) cereal rye termination timing, (2) herbicide termination timing, and (3) herbicide type. Termination timing of the cereal rye occurred twice: two weeks before planting (2 WBP) or two weeks after planting (2 WAP). Cereal rye was terminated using glyphosate at 1,260 g ae ha^{-1} + crop oil concentrate (COC) 1% v/v + ammonium sulfate (AMS) 3% v/v. In 2021 and 2022, corn plants were non-emerged when 2 WBP termination treatments were terminated. In 2021 and 2022, corn plants were V1 when 2 WAP termination treatments were terminated (Figure 3-1). The three herbicide timings in the study were pre-emergence (PRE), early POST (EPOST), and PRE followed (fb) late POST (LPOST) (Table 3-2). Herbicide type and timing together are defined as a program. In addition, a nontreated control (rye present), weed free control, and weed and cereal rye free control treatments were included (Table 3-2). Cereal rye was present in the nontreated control due to a missed termination in the fall both years, but this treatment can be comparable to a nontreated because of the presence of cereal rye throughout the season compared to weeds being present throughout the season.

Herbicides applications were made with a handheld CO_2-pressurized backpack sprayer equipped with AIXR 110015 flat-fan nozzles (TeeJet® Technologies, Spraying Systems Co., Wheaton, IL 60187) spaced 51 cm apart and calibrated to deliver 140 L ha^{-1} at 276 kPa at a constant speed of 4.8 km h^{-1}. Dicamba-containing treatments were applied with TTI 11005 flat-fan nozzles (TeeJet® Technologies). The PRE herbicides were applied the day of planting corn, EPOST herbicides were applied 39 days after PRE (DAPRE), and LPOST herbicides were applied 40 DAPRE in 2021. In 2022, PRE herbicides were applied the day after planting corn, EPOST herbicides were applied 20 DAPRE, and LPOST herbicides were applied 35 DAPRE.

Data Collection

Weed control was estimated through visual observations of weed injury and growth suppression at 14, 28, and 42 days after treatment (DAT) on a scale of 0% to 100%, where no control is equal to 0% and total control of weeds in a treatment is equal to 100%. Weed density of observed weed species were collected from two 0.5 m^2 quadrats $plot^{-1}$ from the two middle corn rows at 14 DAT, 28 DAT, and 42 DAT. Weed biomass (0.5 m^2) was collected on the day of early POST herbicide application and 21 days after early POST (DAEPOST) herbicide application by clipping plants in two 0.5 m^2 quadrats

plot^{-1} at the ground, drying them at 64 C for 8-10 days until they reached a constant mass and then weighing each sample.

Cereal rye biomass was collected at both termination timings from two randomly placed 0.5 m^2 quadrats plot^{-1}. Fresh biomass was recorded in grams (g) plot^{-1} and converted to kg ha^{-1}. Cereal rye biomass at 2 WBP termination was taken at stage 21 to 32 (10-35 cm tall) and 2 WAP termination was taken at stage 49 to 59 (90-140 cm tall) using the Zadoks scale (Zadoks et al. 1974). Palmer amaranth seed production was collected by sampling two plants from between the middle two rows. To record estimated seed production, 1,000 seeds were counted from each sample weighed (g) and then the whole sample was weighed, and estimations of total seed count plant^{-1} were made from the 1,000 seed weight. Corn was harvested from the middle two rows with a plot combine and yields were adjusted to 15.5% moisture content. An economic analysis was taken of cereal rye use and herbicide programs to determine the profitability of each treatment. Gross profitability was calculated for each program using the following equation (Sarangi and Jhala 2019):

$$\text{Gross Profit } (\$) = (R-W) \qquad [1]$$

Where, R is the gross revenue which was calculated by multiplying the corn yield for each treatment by the average price of corn in Nebraska in 2021 and 2022, and W was the weed management program cost which includes the cost of cereal rye, herbicide, adjuvant, and application. Benefit/cost ratio for each program was calculated using an equation as well (Sarangi and Jhala 2019):

$$\text{Benefit/Cost Ratio } (\$/\$) = (R_T - R_C) / W \qquad [2]$$

where R_T is overall gross revenue, R_C is gross revenue for nontreated control, and W is the cost of the weed management program which includes the cost of cereal rye seeds, herbicide, adjuvant, and application (Sarangi and Jhala 2019). Herbicide prices were estimated from spring 2022 prices and an October corn price (\$0.27 kg ha^{-1}) was used for calculations. Custom application of herbicide prices were sourced from three independent sources in Nebraska in 2021: PRE herbicide: \$17.30 ha^{-1}, non−dicamba-containing POST herbicide: \$18.94 ha^{-1}, and dicamba-containing POST herbicide: \$31.71 ha^{-1}.

Statistical analysis

Statistical analysis was performed using PROC GLIMMIX procedure in SAS statistical software 9.4. The interaction of year x treatment was significant for all experimental variables except for PRE herbicide treatment control of Palmer amaranth at 14, 28, and 42 DAPRE. When year x treatment was significant then years were analyzed separately and when the year by treatment was not significant then data from each year were combined. In the combined and single-year models, herbicide type and timing, and termination timing were considered a fixed effect that was nested within year. The replication nested within year was considered the random effect. Discrete variables (e.g. corn yield, Palmer amaranth seed production, cereal rye biomass, weed biomass, and weed density) were fit into a mixed linear model with gaussian (link = “density”) error distributions. Continuous variables (e.g weed control), were fit to a linear mixed effect model with gaussian (link = “density”) error distribution (Striegel and Jhala 2022). It was assumed to be a normal distribution on all variables except for weed biomass which was log transformed and then back-transformed for mean comparison. For discrete and continuous variables there was a selection of the final model based upon fit statistics such as Akaike information criterion (AIC) values with gaussian error distributions.

Before conducting ANOVA, normality was tested by normal QQ plots and then ANOVA was performe[ST1]d [ST2]using the “PROC ANOVA” package using Type III tests and when differences were indicated for treatment effects, multiple comparisons were conducted using Tukey-Kramer’s HSD test with a 95% confidence interval and LS Means were compared. To determine the significance of termination timing; contrast analyses were performed comparing termination timing of 2 WBP to 2 WAP and NA. Likewise to determine herbicide type differences and significances, contrast analyses were performed to compare herbicide timing of PRE only to EPOST, PRE fb LPOST, and control. Lastly, herbicide types were subject to contrast analyses to determine significance by comparing each herbicide within each herbicide timing and termination timing.

Results and Discussion

Herbicide-by-year interaction was significant for Palmer amaranth ($P < 0.0001$) and giant foxtail control ($P = 0.0003$); therefor data were presented by year. Termination-by-treatment effects were significant for both termination timings; therefore, data were presented by year ($P = 0.0025$ & $P = 0.0005$). Herbicide type had a significant effect on control of both weed species ($P = 0.0032$ & $P = 0.0312$). Termination by year and herbicide by year were significant for corn yields; therefore, years were separated ($P < .0001$ & $P < .0001$).

Temperature and Precipitation

Growing conditions in 2021 varied from those in 2022 but both were drier than the 30-year average (Table 3-1). A drier May than average was recorded in both years. The rainfall occurred after planting and allowed for planting to occur in the first week of May in 2021. In 2022, rainfall occurred earlier in May that pushed planting 7 to 10 days later than the previous year but then remained dry until the end of May and beginning of June. Irrigation was not available in 2022 until July 1; therefore, rainfall accumulation should be considered when assessing this study's results in 2022 (Table 3-1). Cumulative precipitation was 287 mm and 209 mm, respectively in 2021 and 2022, which is below the 30-year average (Table 3-1). The drier than average summer influenced reproduction, respiration, and photosynthesis processes in corn. In 2021 and 2022, the average temperature was 21 C from May through September which is equal to the 30-year average for the Harvard, NE (Table 3-1). A hail and windstorm occured on June 7 in 2022 that reduced corn plant stand up to 15% and reduced leaf number on some corn plants. Data for the winter months were recorded to help understand cereal rye growth (Table 3-1). On average, November and December were warmer than the 30-year average, but November had higher precipitation than the 30-year average (Table 3-1). In the spring, January, and February in 2021 were colder than normal temperature, but January had higher precipitation. March was warmer than normal and had higher precipitation than the 30-yr average (Table 3-1). In 2022, January and March were colder than average, but February was warmer, and only March had higher precipitation total than the 30-year average.

Cereal Rye Biomass

There was greater cereal rye biomass is seen in the 2 WAP termination which is to be expected as it has been observed in other studies (Keene et al. 2017, Ruis et al. 2017). In 2021, 2 WBP termination of cereal rye accumulated 1,950 kg ha^{-1} of cereal rye biomass compared with 12,775 kg ha^{-1} with 2 WAP termination (Figure 3-2). In 2022, greater biomass was produced in 2 WBP than in 2021 at 2,756 kg ha^{-1} but less biomass was produced in the 2 WAP termination of cereal rye with 11,291 kg ha^{-1} (Figure 3-2). This was also observed in a similar study in soybean at the same research site and other studies that have conducted multiple termination timings of cover crops (Grint et al. 2022; Montgomery et al. 2018).

Corn Stand Count

Stand counts were taken two weeks after emergence in both 2021 and 2022 and showed similar results. Years were not significantly different in weed/rye free treatment and 2 WBP termination (P 0.13980) therefor they were combined. Comparisons made for this observation were between three different termination timings, weed/rye free (no cover crop), 2 WBP termination, and 2 WAP termination. The rye/weed free treatment had a mean count of 76,640 plants hectare^{-1} (data not shown). The treatment that was terminated 2 WBP had 72,333 plants hectare^{-1} and had significantly more plants than the later terminated treatment which had 57,694 plants hectare^{-1} (data not shown). The weed/rye free treatment and the 2 WBP terminated treatment had no significant difference (P 0.09322), but the 2 WAP treatment was significantly lower than either of those two treatments ($P < .0001$) (data not shown).

Palmer amaranth and Giant Foxtail Control

Year was not significant for PRE herbicides for Palmer amaranth control; therefore, data were combined (P = 0.0778), but was significant for giant foxtail control (P = 0.0003). PRE herbicides provided 94% or higher control of Palmer amaranth 14 DAPRE (Table 3-3) compared with 82% or higher control of giant foxtail (data not shown). PRE herbicides varied in Palmer amaranth control (85% to 98%) 28 DAPRE (Table 3-3). Giant foxtail control at 28 DAPRE was variable (75% to 99%) over both years (data not shown). PRE herbicides paired with 2 WBP, controlled Palmer amaranth 98% to 99% 14 DAPRE, 85% to 91% 28 DAPRE, and 84% to 85% 42 DAPRE (Table 3-3). Giant foxtail control was 82% to 99% 14 DAPRE, 75% to 99% 28 DAPRE, and 75% to 99% 42 DAPRE (data not shown). PRE herbicides paired with 2 WAP controlled Palmer amaranth 94% to 98% 14 DAPRE, 90% to 98% 28 DAPRE, and 90% to 94% 42 DAPRE (Table 3-3). Giant foxtail control was 90% to 97% 14 DAPRE, 82% to 99% 28 DAPRE, and 79% to 99% 42 DAPRE (data not shown). Control of Palmer amaranth and giant foxtail early in the season affected equally by termination timing soil-applied residual herbicides along with a pre-plant termination of cover crops have been able to suppress Palmer amaranth in other studies as well (Perkins et al. 2021). Although each termination timing and herbicide program was not significant, there is observed longer control from the later termination timing paired with a PRE herbicide which in previous research has been confirmed that early season weed control is affected by cover crop biomass accumulation (Ateh and Doll 1996; Fisk et al. 2001; Teasdale 1996). PRE herbicide programs along with either termination timing provided ≥ 80% control (Table 3-3). Even though PRE herbicides and cover crops were able to control Palmer amaranth and giant foxtail up to

42 days, this weed management method is not designed for season long control and this has been observed in other studies (Wiggins et al. 2016).

EPOST herbicide programs combined with 2 WBP termination did not provide the level of Palmer amaranth control that PRE herbicides did at each observation, but dicamba/mesotrione + acetochlor and acetochlor/mesotrione did provided above 83% control in three out of six observations in two years (Table 3-4). Similar results were seen in giant foxtail control from EPOST herbicide programs (data not shown). Dicamba plus glyphosate provided highest control when combined with 2 WAP termination of cereal rye and over 90% control was observed in five out of six observations across two years (data not shown). Dicamba plus glyphosate with 2 WBP termination of cereal rye provided above 91% Palmer amaranth control in both years at 14 days after EPOST (DAEPOST) but failed to control giant foxtail any more than 86% in any following observations. Acetochlor/mesotrione with 2 WAP termination of cereal rye provided 99% at 14, 28, and 42 DAT in 2022 (data not shown). Treatments with 2 WBP termination of cereal rye provided lower level (44% to 91%) of giant foxtail control, but those with 2 WAP termination of cereal rye had higher level (65% to 99%) of giant foxtail control compared to 2 WBP termination of cereal rye (data not shown). EPOST herbicide programs paired with 2 WAP termination had more than 64% control in 2021 and 86% control of Palmer amaranth (Table 3-4). Acetochlor/mesotrione provided consistently ≥ 94% control in three out of the six observations (Table 3-4). Herbicide program that included glyphosate was the most effective for controlling giant foxtail with either termination timing (data not shown) and EPOST herbicides did not control Palmer amaranth better than other herbicide systems and this could be due to Palmer amaranth height or density when applications were made. Based upon other research that integrates herbicides and cover crops there should be a POST application integrated into the weed management program to help control summer annual weeds (Montgomery et al. 2018, Wiggins et al. 2015, 2017).

PRE fb LPOST herbicide programs contained similar results in observations after PRE herbicide applications. Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor was not different than other treatments for controlling Palmer amaranth 14 DAPRE (Table 3-5). One observation in 2021, showed lower control of giant foxtail from the treatment at 14 DAPRE when combined with 2 WAP termination (data not shown). At 28 DAPRE, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor had lower Palmer amaranth control than other PRE herbicides (Table 3-5) but was not different than other PRE herbicides for giant foxtail control (Table 3-8). At 42 DAPRE, years were significantly different; therefore, data were separated for Palmer amaranth control (Table 3-5). At 28 days after LPOST (DALPOST), LPOST herbicides with 2 WBP termination of cereal rye provided 83% to 95% in 2021 and 81% to 92% Palmer amaranth control in 2022 (Table 3-5). The effect of planting green varied control of Palmer amaranth in both years (Table 3-5). LPOST herbicide combined with 2 WAP termination of cereal rye controlled Palmer amaranth 65% to 90% in 2021 and 92% to 97% in 2022 (Table 3-5). Control of giant foxtail varied across years at 28 DALPOST. Acetochlor/clopyralid/mesotrione fb dicamba provided 67% to 70% control across both years (data not shown). The 2 WBP termination of cereal rye provided 33% to 99% control across both years compared with 71% to 99% control of giant foxtail with 2 WAP termination (data not shown). PRE fb LPOST herbicides paired with 2 WAP termination provided more consistent control of

Palmer amaranth and giant foxtail. The data are consistent with (Wiggins et al. 2017) which observed better weed control of Palmer amaranth when a POST application was made after a PRE application in treatments that had cover crop terminated three weeks before planting. PRE herbicides provided the best control within a reasonable time frame (42 days) and has been found in other studies when combined with a later terminated cover crop to have significant reduction in waterhemp species density and emergence (Perkins et al. 2021). Although this is observed, a PRE herbicide even when paired with planting green are not suggested to be a season long weed control practice and a POST herbicide is suggested when using cover crops (Montgomery et al. 2018, Wiggins et al. 2015, 2016). Another study also suggest that cover crops that are terminated at planting or after could impact the effectiveness and fate of soil-applied residual herbicides (Whalen et al. 2020). Therefore, a POST applied herbicide must be used to combat season long control of Palmer amaranth and giant foxtail and a combination of a broadleaf and grass herbicides will give greatest control across the two species that were observed in this study. Although PRE fb LPOST herbicide programs in many observations provided higher weed control with 2 WAP termination there was little to no differences in some EPOST herbicides with 2 WAP termination in weed control and therefore economic analysis should be taken into consideration when implementing cover crops into corn management decisions.

Palmer amaranth & Giant Foxtail Biomass

In 2021 and 2022, cereal rye terminated 2 WBP had consistently higher biomass at EPOST herbicide application timing which is expected because of a lack of ground cover (Table 3-7, Figure 3-3 and 4). Program with PRE herbicides applied had lower biomass in both termination timings (Table 3-6). The lowest cover crop accumulation of biomass in both years occurred in herbicide programs that were paired with 2 WAP termination of cereal rye. At 21 DAEPOST, biomass was highest in PRE herbicides with either termination timing in both years (Table 3-6). EPOST and PRE fb LPOST had lower weed biomass when paired with 2 WAP cereal rye termination compared with 2 WBP termination (Table 3-7; Table 3-8). In both years, lowest biomass at 21 DAEPOST was in programs with the PRE fb LPOST herbicide with 2 WAP termination of cereal rye (Table 3-8). The same herbicide program with an earlier termination timing had similar weed biomass as other herbicide programs that were paired with the 2 WBP termination timing; therefore, herbicide application timing had limited effect on weed biomass compared with cereal rye termination timing.

Palmer amaranth and Giant Foxtail Density

Palmer amaranth densities were lower in 2022 than in 2021 in most treatments (data not shown). The greatest reduction in density of Palmer amaranth and giant foxtail in both years came from acetochlor/mesotrione (1 plant m^{-2}) applied PRE with 2 WAP termination of cereal rye 28 DAT (data not shown). This same treatment provided low densities of giant foxtail (0 plant m^{-2}) at 28 DAT (data not shown). Many PRE herbicides provided lower densities of giant foxtail (0 plant m^{-2}), and this could be due to a later emergence of giant foxtail compared with Palmer amaranth. Palmer amaranth densities were reduced the most when PRE fb LPOST herbicides were applied which correlates to weed control observed. In Figure 3-5, a high correlation is shown between Palmer amaranth control and density: -0.8607678; where 1 is directly correlated. Similar correlations were observed in giant foxtail density and control. A -0.9324782 correlation between giant foxtail control and density was observed (Figure 3-6). Herbicide programs that included glyphosate were the most effective for reducing giant foxtail densities and some additional reduction was observed with any treatment that contained acetochlor which provides residual control. Cereal rye termination at 2 WAP reduced density of giant foxtail and Palmer amaranth in most cases; only 3 out of 9 herbicide programs in 2021 had higher densities when 2 WAP termination of cereal rye was used (data not shown). In 2022, every herbicide program that contained 2 WAP termination of cereal rye had lower Palmer amaranth and giant foxtail densities (data not shown). The most consistent PRE fb LPOST treatment was acetochlor/clopyralid/mesotrione fb dicamba/mesotrione which reduced Palmer amaranth density to 3 and 2 plants m^{-2} in respective years and reduced giant foxtail densities to 7 plants m^{-2} in each year (data not shown).

Palmer amaranth Seed Production

Palmer amaranth seed production in 2021 was lowered the most by PRE fb LPOST herbicide programs (Table 3-9). Palmer amaranth seed production ranged from 4,011 seeds to 10,242 seeds female plant^{-1} (Table 3-9). Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor fb dicamba/mesotrione with both termination timings lowered seed production below 5,000 seeds female plant $^{-1}$ and it was the most consistent in reducing seed production across herbicide programs in 2021 (Table 3-9). Dicamba/mesotrione + acetochlor with 2 WAP termination of cereal rye was the only treatment with no seed production of Palmer amaranth in 2021 (Table 3-9). In 2022 all but one PRE fb LPOST herbicide program (atrazine/bicyclopyrone/mesotrione/*S*-metolachlor fb dicamba/mesotrione with 2 WBP termination) were able to reduce seed production to zero (Table 3-9). A PRE followed by a POST herbicide with multiple sites of action integrated with cereal rye for weed suppression and reduction in Palmer amaranth seed production could be considered as a possible weed management strategy as the evolution of herbicide-resistant weeds increased throughout the Midwest. Similar results have been observed in other studies (Montgomery et al. 2018, Wiggins et al. 2017). In 2022 a POST-only treatment of dicamba/mesotrione fb acetochlor combined with 2 WAP termination of cereal rye reduced seed population to zero; therefore, should be considered for Palmer amaranth seedbank management strategies (Table 3-9). A reduction in seed production lowers the possibility of herbicide resistance and should be considered as added value which was also observed in other studies ((Owen et al. 2015, Riar et al. 2013).

Corn Yield

Year by treatment interaction was significant for corn yield; therefore, yield data are presented for each year. Corn yield was lower in 2022 compared with 2021 due to hail and windstorm in early June and the lack of irrigation available until July 1, 2022. The only two treatments that increased in yield from 2021 to 2022 were acetochlor/clopyralid/mesotrione with 2 WAP cereal rye termination from 9,789 kg ha^{-1} (2021) to 11,295 kg ha^{-1} (2022) and acetochlor/mesotrione with 2 WAP cereal rye termination from 11,322 kg ha^{-1} (2021) to 14,208 kg ha^{-1} (2022) (Table 3-10). In 2021, a missed application of 10-34-0 fertilizer at time of planting seemed to influence yields as the treatments with 2 WBP termination of cereal rye yield higher in every treatment. These differences were visually apparent in 2021, where stunting and reduced corn plant vigor were observed (Figure 3-7). In 2022, an application of starter fertilizer (10-34-0 at

46.8 l/ha) at time of planting seemed to influence corn growth, development, yields particularly under planting green conditions. The 2 WAP termination of cereal rye yielded higher than the 2 WBP termination. Although most treatments were statistically similar, there were a few treatments that showed greater yields in 2021. Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor fb dicamba/mesotrione with 2 WBP, acetochlor/clopyralid/mesotrione fb dicamba/mesotrione with 2 WBP, and isoxaflutole/thiencarbazone-methyl + atrazine fb dicamba/mesotrione with 2 WBP yielded above 16,000 kg ha^{-1} (Table 3-10). Similarly, these herbicide programs with 2 WAP termination of cereal rye, yielded highest in 2021 (13, 831 kg ha^{-1} to 15,275 kg ha^{-1}) (Table 3-10). In 2022, most PRE followed POST herbicide programs and certain only-POST herbicide programs with 2 WAP cereal rye termination were similar for corn yield with acetochlor/mesotrione and acetochlor/clopyralid/mesotrione fb dicamba/mesotrione with 2 WAP termination timing provided the highest corn yield of 14,208 and 14,189 kg ha^{-1}, respectively (Table 3-10). The data in 2021 when there was no added nitrogen management was also observed in a meta-analysis that showed no positive yield increase when a grass cover crop was followed by corn but there were other environmental services that were beneficial (Miguez and Bollero 2005).

Economic Analysis

The gross profit in 2022 was lower than 2021 due to lower corn yield because of a hailstorm in June 2022 and lack of irrigation in early season and limited rainfall. Gross profit ranged from $1,022 to $4,577 ha^{-1} in 2021 and $1,272 to $3,836 ha^{-1} in 2022 (Table 3-11). A total cost for PRE-only and PRE fb LPOST herbicide programs paired with a cereal rye cover crop terminated 2 WAP averaged higher than that of an EPOST-only program. The cost of EPOST herbicide program ranged from \$198 to \$241 ha^{-1} and PRE-only programs costed \$225 to \$247 ha^{-1}; and PRE fb LPOST programs ranged from \$298 to \$327 ha^{-1} (Table 3-11). Benefit/cost ratios varied between years, herbicide programs, and termination timings. The reduction in yields in 2022 reduced benefit/cost ratios in most treatments compared with 2021 (Table 3-11). Across herbicide programs, a few EPOST herbicide programs had the highest cost/benefit ratio in 2021 and 2022 (Table 3-11). Dicamba/mesotrione + acetochlor applied EPOST with 2 WBP termination of cereal rye (11.72) in 2021 and acetochlor/mesotrione (10.62) in 2022 had the highest cost/benefit ratio. In 2021, a starter fertilizer was not applied that led to lower yields in 2 WAP termination of cereal rye treatments and therefor those have lower cost/benefit ratios (Table 3-11). In 2022, which was observed as a drier year than average (Table 3-1) but the starter fertilizer application was made at corn planting, and the treatments with 2 WAP termination of cereal rye had higher yields and resulted in higher cost/benefit ratios (Table 3-11). In 2022, the highest ratio was observed in acetochlor/mesotrione applied EPOST with 2 WAP termination of cereal rye (Table 3-11), but more consistent cost/benefit ratios were observed in both years for PRE fb LPOST herbicide programs with either termination timing of cereal rye (Table 3-11). An EPOST only herbicide with 2 WAP program in both years provided the most consistent and higher cost/benefit ratios (Table 3-11).

Practical Implications

Results of this study indicate that terminating cereal rye 2 WAP in a corn cropping system can be implemented when the proper systematic management decisions are made. The implementation of irrigation and a starter fertilizer at the time of planting were two necessary farming practices that would allow for this practice to be economical and sustainable in a Nebraska corn production system and it could reduce herbicide usage because EPOST herbicide integrated with planting green provided economical weed management. There is an indication that soil-applied herbicides and planting green do not negatively affect weed control when combined but further research should be conducted to confirm whether the herbicide or cereal rye biomass is the determining factor. The highest level of giant foxtail and Palmer amaranth control was observed a PRE fb LPOST herbicide program combined with 2 WAP termination of cereal rye. The combination of two passes of herbicide with multiple sites of action and the cereal rye biomass provided more than adequate weed control in both weed species. Although this was the result of weed management programs, it is not the most economical management program.

Results of this study found that yields of EPOST herbicides and PRE fb LPOST herbicides combined with 2 WAP termination of cereal rye (when proper farming practices mentioned above were practiced) were comparable. Therefore, the lower cost of POST herbicides with 2 WAP terminated cereal rye with a comparable yield to a PRE fb LPOST herbicide program with cereal rye could give producers a better economical return. POST herbicides with multiple sites of action that can provide foliar as well as residual activity are recommended. Moisture, cover crop biomass, disease and insect pressure, and weed pressure should be considered when implementing this practice (Bunchek et al. 2020). Fields that lack soil moisture, have soil fertility issues, or have higher known disease and insect pressure should be carefully considered before implanting planting green into corn production system in Nebraska. The critical period of cover crop termination should be research in detail to determine the effect upon corn yield. Due to the compounding factors of weather and management miscues in both years there was limitations on this study and there is unknown effects of planting green on corn yield or cost/benefit ratio but increased weed suppression was observed when planting green was implemented with herbicide applications.

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Table 3-1. Herbicide program, application timing, and rates used for weed control in glyphosate/glufosinate-resistant corn in field experiments conducted near Harvard, NE in 2021 and 2022.

Herbicide program	Timing[a]	Rate[a]	Trade Name	Manufacturer[b]	Adjuvants[a,c]
		(g ai/ae ha^{-1})			
Nontreated Control					
Weed Free Control: Dicamba + Acetechlor	EPost	560 + 840	Diflexx + Warrant	Bayer	DRA + WC
Weed and Cereal Rye Free Control: Flumioxazin + glyphosate fb glyphosate + atrazine/bicyclopyrone/mesotrione/S-Metolachlor fb dicamba/mesotrione + glyphosate	Fall PRE EPOST	245 + 1,260 fb 1,260 + 556 fb 560	Valor SX + Roundup Powermax fb Roundup Powermax + Acuron fb Diflexx + Glyphosate	Valent Bayer Syngenta Bayer	COC + AMS + DRA + WC
Isoxaflutole/thiencarbazone-methyl + atrazine	PRE	130 + 560	Corvus + AAtrex 4L	Winfield	
Acetochlor/mesotrione	PRE	2700	Harness Maxx	Bayer	
Acetochlor/clopyralid/mesotrione	PRE	2300	Resicore	BASF	
Dicamba + glyphosate	EPost	420 + 1,260	Diflexx + Roundup Powermax	Bayer	DRA + WC
Acetochlor/mesotrione	EPost	2700	Harness Maxx	Bayer	NIS
Dicamba/mesotrione + acetochlor	EPost	900 + 820	Diflexx Duo + Warrant	Bayer	DRA + WC
Isoxaflutole/thiencarbazone-methyl + atrazine fb dicamba/mesotrione	PRE fb LPost	130 + 560 fb 900	Corvus + AAtrex 4L fb Diflexx Duo	Winfield, Bayer	DRA + WC
Atrazine/bicyclopyrone/mesotrione/S-metolachlorfb dicamba/mesotrione	PRE fb LPost	2900 fb 900	Acuron fb Diflexx Duo	Bayer	DRA + WC
Acetochlor/clopyralid/mesotrione fb dicamba/mesotrione	PRE fb LPost	2300 fb 900	Resicore fb Diflexx Duo	Corteva, Bayer	DRA + WC

[a] Abbreviations: ai, active ingredient; ae, acid equivalent, AMS, ammonium sulfate (N-Pak AMS Liquid, Winfield United, LLC. St. Paul, MN); COC, crop oil concentrate; DRA, drift reducing agent (Intact, Precision Laboratories, Waukegan, IL); EPOST, early POST-emergence, fb, followed by; LPOST, late POST-emergence; NIS, nonionic surfactant (Induce, Helena Chemical, Collierville, TN); WC, water conditioner (Class Act Ridion, Winfield United, Arden Hills, MN).

[b] Bayer CropScience, Research Triangle Park, NC; BASF Corporation, Research Triangle Park, NC; Corteva AgriScience, Indianapolis, IN; FMC Corporation, Philadelphia, PA; Syngenta Crop Protection, LLC., Greensboro, NC; Valent USA Corporation, Walnut Creek, CA.

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

Table 3-2. Monthly mean air temperature and total precipitation during the 2021 and 2022 corn growing seasons (May to September) and cereal rye growing season (November to March) along with the 30 year average at the research site near Harvard, NE.[a]

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

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

[a] Data were obtained from National Oceanic and Atmospheric Administration (“NOAA” 2022).

Table 3-3. Effects of cereal rye termination timing and PRE herbicide programs on Palmer amaranth control at 14, 28, 42 DAPRE in glyphosate/glufosinate-resistant corn near Harvard, NE in 2021 and 2022.

Herbicide Program [c]	**Cereal rye Termination** [c]	**Application Timing** [c]	**Rate**	**Palmer Amaranth Control**[a,b,c]		
			g ai/ae ha-^{1}	14 DAPRE[a,b]	28 DAPRE[a,b]	42 DAPRE[a,b]
					%	
Nontreated Control (Rye Present)	NA	NA	NA	96 a	93 a	98 a
Weed Free Control: Dicamba + Acetechlor	NA	EPOST	420 + 820	94 a	98 a	97 a
Weed and Cereal Rye Free Control: Flumioxazin + glyphosate fb glyphosate + atrazine/bicyclopyrone/mesotrione/S-Metolachlor fb dicamba/mesotrione + glyphosate	NA	Fall, PRE fb EPOST	72 + 1260 fb 1260 + 2900 + 1260	99 a	94 a	95 a
Isoxaflutole/thiencarbazone-methyl + atrazine	2 WBP	PRE	130 + 560	99 a	85 a	85 a
Isoxaflutole/thiencarbazone-methyl + atrazine	2 WAP	PRE	130 + 560	98 a	90 a	90 a
Acetochlor/mesotrione	2 WBP	PRE	2700	98 a	91 a	84 a
Acetochlor/mesotrione	2 WAP	PRE	2700	98 a	98 a	93 a
Acetochlor/clopyralid/mesotrione	2 WBP	PRE	2300	99 a	86 a	86 a
Acetochlor/clopyralid/mesotrione	2 WAP	PRE	2300	94 a	95 a	94 a

[a] Means presented within each column with no common letter(s) are significantly difference according to Tukey-Kramer's LSD test at $P \leq 0.05$.

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

[c] Abbreviations: DAPRE, days after PRE herbicide application; fb, followed by; NA, not applicable; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

Table 3-4. Effects of cereal rye termination timing and EPOST herbicide programs on Palmer amaranth control at 14, 28, 42 EPOST in glyphosate/glufosinate-resistnat corn near Harvard, NE in 2021 and 2022.

Herbicide Program [a]	**Cereal Rye Termination** [a]	**Application Timing** [a]	**Rate** [a]	**Palmer Amaranth Control** [a,b,c]					
			g ai/ae ha-[1]	14 EPOST[a,b]		28 EPOST[a,b]		42 EPOST[a,b]	
				%					
				2021	2022	2021	2022	2021	2022
Nontreated Control (Rye Present)	NA	NA	NA	89 a	98 a	80 ab	98 a	73 abc	85 ab
Weed Free Control: Dicamba + Acetechlor	NA	EPOST	420 + 820	98 a	98 a	97 a	97 a	79 ab	98 a
Weed and Cereal Rye Free Control: Flumioxazin + glyphosate fb glyphosate + atrazine/bicyclopyrone/mesotrione/S-Metolachlor fb dicamba/mesotrione + glyphosate	NA	Fall, PRE fb EPOST	72 + 1260 fb 1260 + 2900 + 1260	98 a	89 a	99 a	89 b	98 a	91 ab
Dicamba + glyphosate	2 WBP	EPOST	420 + 1260	52 bc	90 a	54 bc	53 c	65 bc	28 d
Dicamba + glyphosate	2 WAP	EPOST	420 + 1260	64 ab	86 a	65 abc	65 bc	80 ab	49 cd
Acetochlor/mesotrione	2 WBP	EPOST	2700	31 c	86 a	46 c	91 ab	58 c	89 a
Acetochlor/mesotrione	2 WAP	EPOST	2700	74 ab	99 a	71 abc	94 a	70 abc	96 a
Dicamba/mesotrione + acetochlor	2 WBP	EPOST	900 + 820	85 a	83 a	88 a	76 abc	70 abc	67 bc
Dicamba/mesotrione + acetochlor	2 WAP	EPOST	900 + 820	75 ab	97 a	79 ab	95 a	84 a	95 a

[a] Means presented within each column with no common letter(s) are significantly difference according to Tukey-Kramer's LSD test at $P \leq 0.05$.

[b] Year-by-treatment interaction for Palmer amaranth control 14, 28, and 42 DAEPOST were significant, therefore data were separated for both years.

[c] Abbreviations: DAEPOST, days after early postemergence herbicide application; EPOST, Early POST; fb, followed by; NA, not applicable; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

Table 3-5. Effects of cereal rye termination timing and PRE fb herbicide programs on Palmer amaranth control at 14, 28, 42 DAPRE and 14, 28 DALPOST in glyphosate/glufosinate-resistant corn near Harvard, NE in 2021 and 2022.

Herbicide Program [a]	Cereal Rye Termination[a]	Application Timing[a]	Rate [a]	Palmer Amaranth Control [a,b,c]							
			g ai/ae ha^{-1}	14 DAPRE[a,b]	28 DAPRE[a,b]	42 DAPRE[a,b]		14 DALPOST[a,b]		28 DALPOST[a,b]	
				2021/2022	2021/2022	2021	2022	2021	2022	2021	2022
				%							
Nontreated Control (Rye Present)	NA	NA	NA	96 a	94 a	80 a	98 a	60 ab	98 a	73 ab	85 a
Weed Free Control: Dicamba + Acetechlor	NA	EPOST	420 + 820	94 a	98 a	97 a	97 a	74 ab	99 a	79 ab	98 a
Weed and Cereal Rye Free Control: Flumioxazin + glyphosate fb glyphosate + atrazine/bicyclopyrone/mesotrione/S-Metolachlor fb dicamba/mesotrione + glyphosate	NA	Fall, PRE fb EPOST	72 + 1260 fb 1260 + 2900 + 1260	98 a	94 a	99 a	89 a	96 a	97 a	98 a	91 a
Isoxaflutole/thiencarbazone-methyl + atrazine fb dicamba/mesotrione	2 WBP	PRE fb LPOST	130 + 560 fb 900	98 a	75 b	99 a	78 a	75 ab	78 a	85 a	89 a
Isoxaflutole/thiencarbazone-methyl + atrazine fb dicamba/mesotrione	2 WAP	PRE fb LPOST	130 + 560 fb 900	98 a	93 a	99 a	93 a	81 a	96 a	80 ab	96 a
Atrazine/bicyclopyrone/mesotrione/S-metolachlor fb dicamba/mesotrione	2 WBP	PRE fb LPOST	2900 fb 900	99 a	94 a	99 a	79 a	87 a	74 a	95 a	92 a
Atrazine/bicyclopyrone/mesotrione/S-metolachlor fb dicamba/mesotrione	2 WAP	PRE fb LPOST	2900 fb 900	95 a	98 a	98 a	95 a	77 ab	98 a	65 b	97 a
Acetochlor/clopyralid/mesotrione fb dicamba/mesotrione	2 WBP	PRE fb LPOST	2300 fb 900	94 a	91 a	99 a	79 a	59 b	78 a	83 ab	81 a
Acetochlor/clopyralid/mesotrione fb dicamba/mesotrione	2 WAP	PRE fb LPOST	2300 fb 900	99 a	98 a	98 a	91 a	82 a	96 a	90 a	92 a

[a] Means presented within each column with no common letter(s) are significantly difference according to Tukey-Kramer's LSD test at $P \leq 0.05$.

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

[c] Abbreviations: DALPOST, days after late postemergence herbicide; DAPRE, days after PRE herbicide application; fb, followed by; NA, not applicable; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

Table 3-6. Effect of PRE herbicide programs and cereal rye termination timing on weed biomass (g) at EPOST herbicide application and 21 DAEPOST in glyphosate/glufosinate-resistant corn near Harvard, NE in 2021 and 2022.

Herbicide Program [a]	**Cereal Rye Termination** [a]	**Application Timing** [a]	**Rate** [a]	**Total Weed Biomass** [a,b,c,d]			
				EPOST[a,b,d]		21 DAEPOST[a,b,d]	
				2021	2022	2021	2022
				$\mathrm{g\ m^{-1}}$			
Nontreated Control (Rye Present)	NA	NA	NA	0.01 a	0.14 a	9.93 ab	1.97 ab
Weed Free Control: Dicamba + Acetechlor	NA	EPOST	420 + 820	0.00 a	1.48 bc	3.85 a	0.00 a
Weed and Cereal Rye Free Control: Flumioxazin + glyphosate fb glyphosate + atrazine/bicyclopyrone/mesotrione/S-Metolachlor fb dicamba/mesotrione + glyphosate	NA	Fall, PRE fb EPOST	72 + 1260 fb 1260 + 2900 + 1260	0.01 a	3.20 d	2.83 a	5.09 c
Isoxaflutole/thiencarbazone-methyl + atrazine	2 WBP	PRE	130 + 560	0.20 b	2.03 c	40.80 d	30.62 gh
Isoxaflutole/thiencarbazone-methyl + atrazine	2 WAP	PRE	130 + 560	0.00 a	0.93 ab	7.30 ab	20.38 ef
Acetochlor/mesotrione	2 WBP	PRE	2700	0.11 a	4.58 e	34.85 cd	37.28 h
Acetochlor/mesotrione	2 WAP	PRE	2700	0.00 a	0.28 a	27.80 c	12.81 d
Acetochlor/clopyralid/mesotrione	2 WBP	PRE	2300	0.27 b	0.70 a	39.00 d	14.52 d
Acetochlor/clopyralid/mesotrione	2 WAP	PRE	2300	0.00 a	0.41 a	41.90 d	26.62 f

[a] Abberviations :, DAEPOST: days after early-POST herbicide application; EPOST, early POST; fb, followed by; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

[b] Data for each year were log transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.

[c] All weed species are combined for biomass data.

[d] Means presented within each column with no common letter(s) are significantly difference according to Tukey-Kramer's LSD test at $P \leq 0.05$.

Table 3-7. Effect of EPOST herbicide programs with both termination of cereal rye timings on weed biomass (g) at EPOST herbicide application and 21 DAEPOST in glyphosate/glufosinate-resistant corn near Harvard, NE in 2021 and 2022.

Herbicide program[a]	Cereal Rye Termination[a]	Application Timing[a]	Rate[a]	Total Weed Biomass [a,b,c,d]			
				EPOST[a,b,d]		21 DAEPOST[a,b,d]	
				2021	2022	2021	2022
				g plot^{-1}			
Nontreated Control (Rye Present)	NA	NA	NA	0.01 a	0.14 a	9.93 d	1.97 ab
Weed Free Control: Dicamba + Acetechlor	NA	EPOST	420 + 820	0.00 a	1.48 b	3.85 b	0.00 a
Weed and Cereal Rye Free Control: Flumioxazin + glyphosate fb glyphosate + atrazine/bicyclopyrone/mesotrione/S-Metolachlor fb dicamba/mesotrione + glyphosate	NA	Fall, PRE fb EPOST	72 + 1260 fb 1260 + 2900 + 1260	0.01 a	3.20 c	2.83 b	33.35 f
Dicamba + glyphosate	2 WBP	EPOST	420 + 1260	12.23 ab	0.17 a	11.20 e	24.2 e
Dicamba + glyphosate	2 WAP	EPOST	420 + 1260	0.11 a	0.16 a	0.30 a	24.20 e
Acetochlor/mesotrione	2 WBP	EPOST	2700	28.35 b	0.09 a	67.8 g	13.42 d
Acetochlor/mesotrione	2 WAP	EPOST	2700	0 a	0 a	2.75 b	0.59 b
Dicamba/mesotrione + acetochlor	2 WBP	EPOST	900 + 820	19.76 b	2.82 c	35.20 f	36.39 g
Dicamba/mesotrione + acetochlor	2 WAP	EPOST	900 + 820	0.05 a	0.23 a	6.15 c	5.55 c

[a] Abberviations: DAEPOST, days after early postemergence herbicide application; EPOST, early POST; fb, followed by; NA, not applicable; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

[b] Data for each year were logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.

[c] All weed species were combined for biomass data.

[d] Means presented within each column with no common letter(s) are significantly difference according to Tukey-Kramer's LSD test at $P \leq 0.05$.

Table 3-8. Effect of PRE fb LPOST herbicide programs with both termination of cereal rye timings on weed biomass (g) at EPOST herbicide application and 21 DAEPOST in glyphosate/glufosinate-resistant corn near Harvard, NE in 2021 and 2022.

Herbicide program[a]	**Cereal Rye Termination**[a]	**Application Timing**[a]	**Rate**[a]	**Total Weed Biomass** [a,b,c,d]			
				EPOST[a,b,d]		21 DAEPOST[a,b,d]	
				2021	2022	2021	2022
				g plot $^{-1}$			
Nontreated Control (Rye Present)	NA	NA	NA	0.01 a	0.14 a	9.93 d	1.97 b
Weed Free Control: Dicamba + Acetechlor	NA	EPOST	420 + 820	0.00 a	1.48 d	3.85 b	0.00 a
Weed and Cereal Rye Free Control: Flumioxazin + glyphosate fb glyphosate + atrazine/bicyclopyrone/mesotrione/S-Metolachlor fb dicamba/mesotrione + glyphosate	NA	Fall, PRE fb EPOST	72 + 1260 fb 1260 + 2900 + 1260	0.01 a	3.20 f	2.83 a	33.35 g
Isoxaflutole/thiencarbazone-methyl + atrazine fb dicamba/mesotrione	2 WBP	PRE fb LPOST	130 + 560 fb 900	0.09 a	4.07 g	18.40	19.77 e
Isoxaflutole/thiencarbazone-methyl + atrazine fb dicamba/mesotrione	2 WAP	PRE fb LPOST	130 + 560 fb 900	0.00 a	0.42 b	4.10 b	6.11 c
Atrazine/bicyclopyrone/mesotrione/S-metolachlor fb dicamba/mesotrione	2 WBP	PRE fb LPOST	2900 fb 900	0.17 a	6.26 h	16.65 e	6.47 c
Atrazine/bicyclopyrone/mesotrione/S-metolachlor fb dicamba/mesotrione	2 WAP	PRE fb LPOST	2900 fb 900	0.00 a	0.00 a	3.00 a	0.00 a
Acetochlor/clopyralid/mesotrione fb dicamba/mesotrione	2 WBP	PRE fb LPOST	2300 fb 900	0.53 b	1.87 e	24.70 f	23.99 f
Acetochlor/clopyralid/mesotrione fb dicamba/mesotrione	2 WAP	PRE fb LPOST	2300 fb 900	0.00 a	0.67 c	5.30 c	12.82 d

[a] Abbreviations: DAEPOST, days after early-POST herbicide application; EPOST, early POST; fb, followed by; LPOST, late POST; NA, not applicable; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

[b] Data for each year were logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data

[c] All weed species are combined for biomass data.

[d] Means presented within each column with no common letter(s) are significantly difference according to Tukey-Kramer's LSD test at $P \leq 0.05$.

Table 3-9. Effect of herbicide program and cereal rye termination on estimated Palmer amaranth seeds plant^{-1} in glyphosate/glufosinate-resistant corn in 2021 and 2022 near Harvard, NE.

Herbicide Program[a]	Cereal Rye Termination[a]	Application Timing[a]	Rate[a]	Estimated Palmer Amaranth Seed Count[b,c]	
			g ae or ai ha^{-1}	seeds plant^{-1}	
				2021[ab]	2022[ab]
Nontreated Control (Rye Present)	NA	NA	NA	12,969 ab	2,798 a
Weed Free Control: Dicamba + Acetechlor	NA	EPOST	420 + 820	12,586 ab	0
Weed and Cereal Rye Free Control: Flumioxazin + glyphosate fb glyphosate + atrazine/bicyclopyrone/mesotrione/S-Metolachlor fb dicamba/mesotrione + glyphosate	NA	Fall, PRE fb EPOST	72 + 1260 fb 1260 + 2900 + 1260	1,247 a	6,407 a
Isoxaflutole/thiencarbazone-methyl + atrazine	2 WBP	PRE	130 + 560	9, 372 ab	9,852 a
Isoxaflutole/thiencarbazone-methyl + atrazine	2 WAP	PRE	130 + 560	9,085 ab	9,348 a
Acetochlor/mesotrione	2 WBP	PRE	2700	8,548 ab	8,303 a
Acetochlor/mesotrione	2 WAP	PRE	2700	10,300 ab	8,731
Acetochlor/clopyralid/mesotrione	2 WBP	PRE	2300	10,643 ab	7,733 a
Acetochlor/clopyralid/mesotrione	2 WAP	PRE	2300	11,133 b	8,631 a
Dicamba + glyphosate	2 WBP	EPOST	420 + 1260	16,810 ab	6,797 a
Dicamba + glyphosate	2 WAP	EPOST	420 + 1260	9,493 ab	10,113 a
Acetochlor/mesotrione	2 WBP	EPOST	2700	12,831 b	5,630 a
Acetochlor/mesotrione	2 WAP	EPOST	2700	7,702 ab	0
Dicamba/mesotrione + acetochlor	2 WBP	EPOST	900 + 820	14,555 ab	6,765 a
Dicamba/mesotrione + acetochlor	2 WAP	EPOST	900 + 820	0 a	0 a
Isoxaflutole/thiencarbazone-methyl + atrazine fb dicamba/mesotrione	2 WBP	PRE fb LPOST	130 + 560 fb 900	9,267 ab	0 a
Isoxaflutole/thiencarbazone-methyl + atrazine fb dicamba/mesotrione	2 WAP	PRE fb LPOST	130 + 560 fb 900	8,450 ab	0 a
Atrazine/bicyclopyrone/mesotrione/S-metolachlor fb dicamba/mesotrione	2 WBP	PRE fb LPOST	2900 fb 900	4,011 a	2,406 a
Atrazine/bicyclopyrone/mesotrione/S-metolachlor fb dicamba/mesotrione	2 WAP	PRE fb LPOST	2900 fb 900	4,993 a	0 a
Acetochlor/clopyralid/mesotrione fb dicamba/mesotrione	2 WBP	PRE fb LPOST	2300 fb 900	10,242 ab	0 a
Acetochlor/clopyralid/mesotrione fb dicamba/mesotrione	2 WAP	PRE fb LPOST	2300 fb 900	8,892 ab	0 a

[a] Abberviations: EPOST, early POST; fb, followed by; LPOST, late POST; NA, non-applicable; PRE, preemergence; WBP, weeks before planting, WAP, weeks after planting.

[b] Means presented within each column with no common letter(s) are significantly difference according to Tukey-Kramer's LSD test at $P \leq 0.05$.

[c] Year-by-treatment interaction for estimated Palmer amaranth seed plant-1 were significant, therefore data were separated by year.

Table 3-10. Effect of herbicide program and cereal rye termination timing on corn yield in glyphosate/glufosiante-resistant corn in field experiments conducted in 2021 and 2022 near Harvard, NE.

Herbicide Program[c]	Cereal Rye Termination Timing[c]	Application Timing[c]	Rate[c]	Corn Yield[ab]	
			g ae or ai ha^{-1}	Kg ha^{-1}	
				2021[b,c]	2022[b,c]
Nontreated Control (Rye Present)	NA	NA	NA	6,221 ef	4,712 f
Weed Free Control: Dicamba + Acetechlor	NA	EPOST	420 + 820	3,786 f	6,648 ef
Weed and Cereal Rye Free Control: Flumioxazin + glyphosate fb glyphosate + atrazine/bicyclopyrone/mesotrione/S-Metolachlor fb dicamba/mesotrione + glyphosate	NA	Fall, PRE fb EPOST	72 + 1260 fb 1260 + 2900 + 1260	15,809 ab	12,299 ab
Isoxaflutole/thiencarbazone-methyl + atrazine	2 WBP	PRE	130 + 560	14,744 abc	6,408 ef
Isoxaflutole/thiencarbazone-methyl + atrazine	2 WAP	PRE	130 + 560	11,802 bcd	9,647 abcde
Acetochlor/mesotrione	2 WBP	PRE	2700	15,741 abc	8,608 bcde
Acetochlor/mesotrione	2 WAP	PRE	2700	12,788 abcd	10,572 abcd
Acetochlor/clopyralid/mesotrione	2 WBP	PRE	2300	14,682 abcde	6,851 cdfe
Acetochlor/clopyralid/mesotrione	2 WAP	PRE	2300	9,789 de	11,295 abcd
Dicamba + glyphosate	2 WBP	EPOST	420 + 1260	14,467 abcd	4,613 f
Dicamba + glyphosate	2 WAP	EPOST	420 + 1260	13,201 abcd	11,265 abcd
Acetochlor/mesotrione	2 WBP	EPOST	2700	13,184 abcd	10,938 abcd
Acetochlor/mesotrione	2 WAP	EPOST	2700	11,322 cd	14,208 a
Dicamba/mesotrione + acetochlor	2 WBP	EPOST	900 + 820	15,075 abc	5,115 ef
Dicamba/mesotrione + acetochlor	2 WAP	EPOST	900 + 820	12,696 abcd	11,830 ab
Isoxaflutole/thiencarbazone-methyl + atrazine fb dicamba/mesotrione	2 WBP	PRE fb LPOST	130 + 560 fb 900	16,804 ab	13,716 a
Isoxaflutole/thiencarbazone-methyl + atrazine fb dicamba/mesotrione	2 WAP	PRE fb LPOST	130 + 560 fb 900	15,275 abc	13,952 a
Atrazine/bicyclopyrone/mesotrione/S-metolachlor fb dicamba/mesotrione	2 WBP	PRE fb LPOST	2900 fb 900	16,952 a	12,687 ab
Atrazine/bicyclopyrone/mesotrione/S-metolachlor fb dicamba/mesotrione	2 WAP	PRE fb LPOST	2900 fb 900	14,435 abcd	13,893 a
Acetochlor/clopyralid/mesotrione fb dicamba/mesotrione	2 WBP	PRE fb LPOST	2300 fb 900	16,532 ab	11,374 abc
Acetochlor/clopyralid/mesotrione fb dicamba/mesotrione	2 WAP	PRE fb LPOST	2300 fb 900	13,831 abcd	14,189 a

[a] Means presented within each column with no common letter(s) are significantly difference according to Tukey-Kramer's LSD test at $P \leq 0.05$.

[b] Year-by-treatment interaction corn yield were significant; therefore, data were separated for both years.

[c] Abbreviations: DAPRE, days after preemergence herbicide application; fb, followed by; WBP, weeks before planting; WAP, weeks after planting.

Table 3-11. Herbicide program and COVER CROP establishment and termination cost and effect of herbicide and COVER CROP on gross profit margin and benefit/cost ratios in glyphosate/glufosinate-resistant soybean near Harvard, NE in 2021 and 2022.

Herbicide Program + Termination	Weed management program cost						Gross profit margin		Benefit/cost ratio	
	PRE	EPOST	LPOST	APP[b]	Rye[a]	Total	2021	2022	2021	2022
	$ ha^{-1}									
Nontreated Control (Rye Present)	-	-	-	-	99.02	99.02	1,679.67	1,272.24	-	-
Weed Free Control	-	77.95	-	31.71	99.02	208.62	1,022.22	1,794.96	-3.15	2.51
Weed/Rye Free Control*	150.05	48.63	-	67.95	99.02	365.65	4,268.43	3,320.73	7.08	5.60
PRE										
Isoxaflutole/thiencarbazone-methyl + atrazine + 2 WBP	109.14	-	-	17.30	99.02	225.46	3,980.88	1,730.16	10.21	2.03
Isoxaflutole/thiencarbazone-methyl + atrazine + 2 WAP	109.14	-	-	17.30	99.02	225.46	3,186.54	2,604.69	6.68	5.91
Acetochlor/mesotrione + 2 WBP	123.50	-	-	17.30	99.02	239.82	4,250.07	2,324.16	10.72	4.39
Acetochlor/mesotrione + 2 WAP	123.50	-	-	17.30	99.02	239.82	3,452.76	2,854.44	7.39	6.6
Acetochlor/clopyralid/mesotrione + 2 WBP	131.23	-	-	17.30	99.02	247.55	3,964.14	1,849.77	9.23	2.33
Acetochlor/clopyralid/mesotrione + 2 WAP	131.23	-	-	17.30	99.02	247.55	2,643.03	3,049.65	3.16	7.18
EPOST										
Dicamba + glyphosate + 2 WBP	-	68.07	-	31.71	99.02	198.80	3,906.09	1,245.51	11.24	-0.13
Dicamba + glyphosate + 2 WAP	-	68.07	-	31.71	99.02	198.80	3,564.27	3,041.55	9.48	8.9
Acetochlor/mesotrione + 2 WBP	-	123.50	-	18.94	99.02	241.46	3,559.68	2,953.26	7.79	6.96
Acetochlor/mesotrione + 2 WAP	-	123.50	-	18.94	99.02	241.46	3,056.94	3,836.16	5.70	10.62
Dicamba/mesotrione + acetochlor + 2 WBP	-	73.33	-	31.71	99.02	204.06	4,070.25	1,381.05	11.72	0.53
Dicamba/mesotrione + acetochlor + 2 WAP	-	73.33	-	31.71	99.02	204.06	3,427.92	3,194.10	8.57	9.42
PRE fb LPOST										
Isoxaflutole/thiencarbazone-methyl + atrazine fb dicamba/mesotrione + 2 WBP	109.14	-	48.63	49.01	99.02	305.80	4,537.08	3,703.32	9.34	7.95
Isoxaflutole/thiencarbazone-methyl + atrazine fb dicamba/mesotrione + 2 WAP	109.14	-	48.63	49.01	99.02	305.80	4,124.25	3,767.04	7.99	8.19
Atrazine/bicyclopyrone/mesotrione/S-metolachlor fb dicamba/mesotrione + 2 WBP	101.89	-	48.63	49.01	99.02	298.55	4,577.04	3,425.49	9.70	7.21
Atrazine/bicyclopyrone/mesotrione/S-metolachlor fb dicamba/mesotrione + 2 WAP	101.89	-	48.63	49.01	99.02	298.55	3,897.45	3,751.11	7.43	8.3
Acetochlor/clopyralid/mesotrione fb dicamba/mesotrione + 2 WBP	131.23	-	48.63	49.01	99.02	327.89	4,463.64	3,070.98	8.49	5.49
Acetochlor/clopyralid/mesotrione fb dicamba/mesotrione + 2 WAP	131.23	-	48.63	49.01	99.02	327.89	3,734.37	3,831.03	6.27	7.8

[a] Abbreviations: APP, application cost; fb, followed-by; EPOST, Early POST; LPOST, Late POST; PRE, preemergence; WBP, weeks before planting; WAP, weeks after planting.

[b] Rye seed price + termination cost

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

Figure 3-1. Corn plants at V1 crop stage at 2 WAP termination timing.

Figure 3-2. Effect of cereal rye termination timing [2 weeks before planting (WBP) or 2 weeks after planting (2 WAP) on cereal rye biomass accumulation in field experiments conducted in 2021 and 2022 in corn near Harvard, NE.

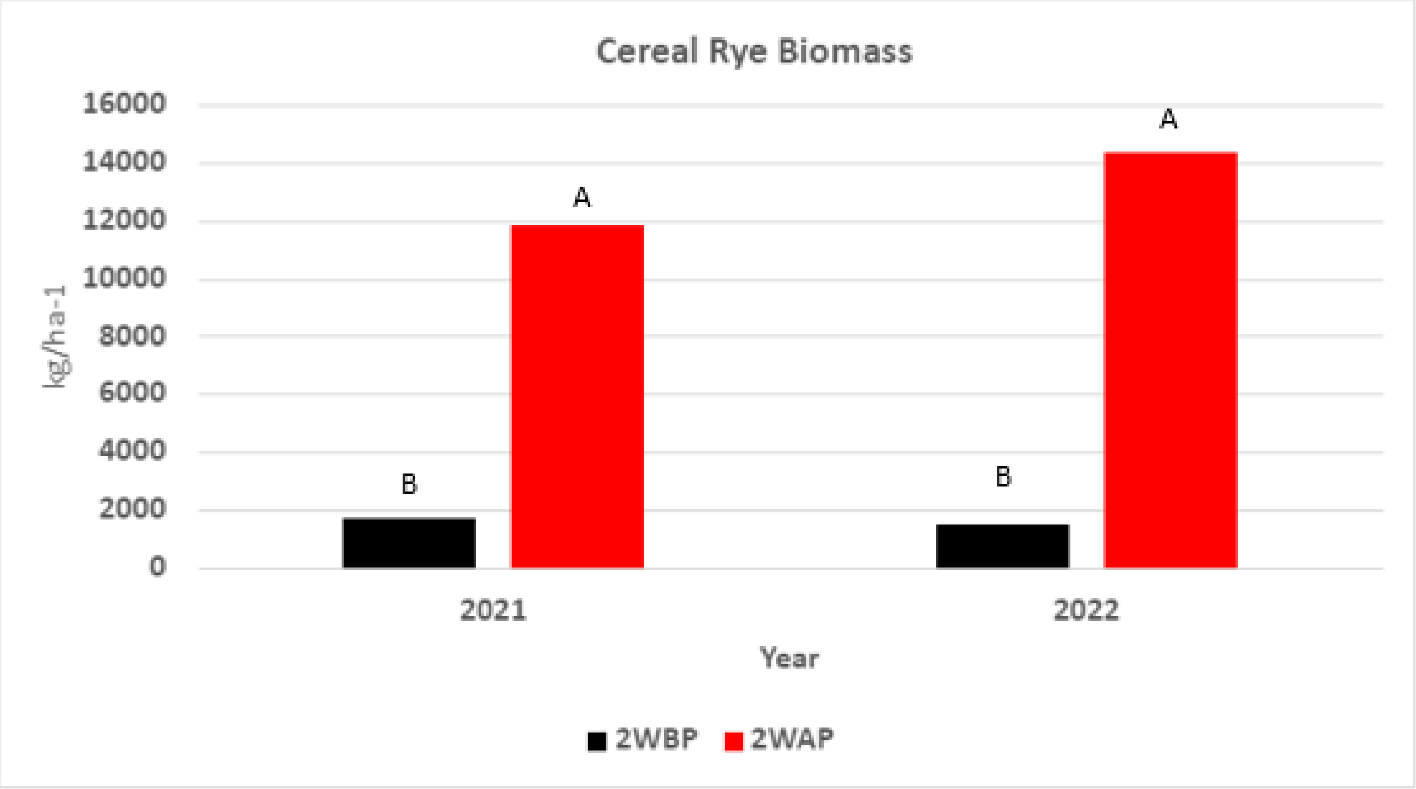

Figure 3-3. Dicamba/mesotrione + acetochlor with 2 weeks before planting termination treatment at 14 DAEPOST application.

Figure 3-4. Dicamba/mesotrione + acetochlor with 2 WAP termination treatment at 14 DAEPOST application.

Figure 3-5. Correlation between Palmer amaranth (AMAPA) control and density in field experiments conducted in 2021 and 2022. (Correlation = -0.8868911). Cereal rye termination timing: 2 weeks before planting (B) or 2 weeks after planting (A), no termination timing (NA).

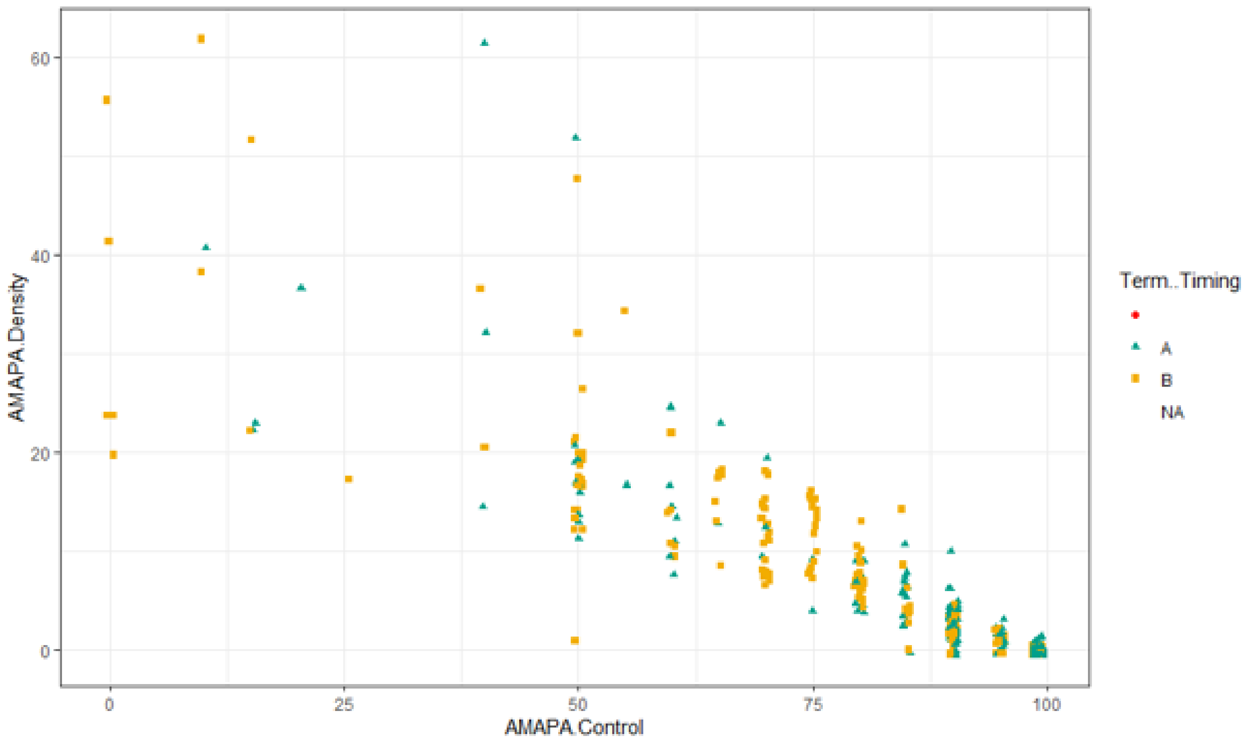

Figure 3-6. Correlation between giant foxtail (POACE) control and density in field experiments conducted in 2021 and 2022 (Correlation = -0.9286299). Cereal rye termination timing: 2 weeks before planting (B), 2 weeks after planting (A), no termination timing (NA).

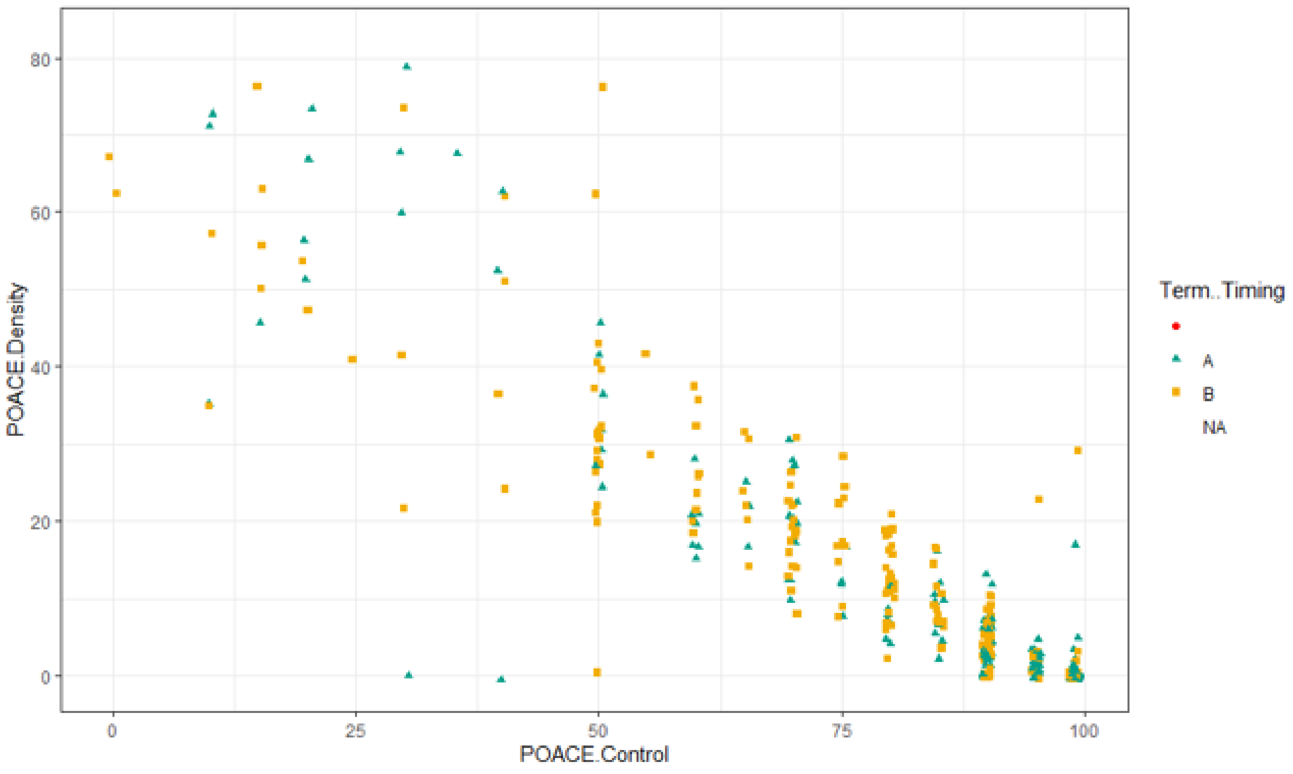

Figure 3-7. Observed stunting and decrease in crop vigor in corn in 2 WAP termination treatments (center) in comparison to 2 WBP termination treatments (left and right) in 2021.

Chapter 4:

Impact of planting green on soil properties under irrigated no-till soybean

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Abstract

Planting green refers to the practice of planting a row crop into an actively growing cover crop (CC) and terminating it at or after row crop planting. Because it allows greater CC biomass accumulation than early-terminated CC, planting green could have more beneficial impacts on soil properties, erosion control, nutrient cycling, weed suppression, and other soil ecosystem services. The objectives of this 2-yr study were to evaluate the impact of planting green on soil properties (bulk density, wet aggregate stability, sorptivity, particulate organic matter, organic matter, nutrients, and others) and soybean (*Glycine max* L.) yield in an irrigated no-till soybean system in south central Nebraska. Treatments were cereal rye (*Secale cereale* L.) CC terminated 2 wk before planting (2WBP), CC terminated 2 wk after planting (2WAP) soybean, and no CC. On average, CC produced 2.35 Mg ha^{-1} of biomass for 2WBP and 12.03 Mg ha^{-1} for 2WAP. Both 2WBP and 2WAP reduced N concentration by 48% (31.1 vs 59.7 mg kg^{-1}) but had no effect on other soil properties compared with no CC. Despite the abundant CC biomass production, terminating 2WAP had little to no effect on most soil properties in the short term (2 yr). Wet aggregate stability increased as CC biomass production increased, while soil sorptivity (initial water infiltration) increased as wet aggregate stability increased. Cover crop termination timing had inconsistent effects on soybean yield. In general, after 2 yr, planting green had no effect on most soil properties or soybean yield, warranting long-term studies on this topic.

Introduction

In 2021, 35.4 million hectares (ha) of soybean were planted in the United States, 2.2 million of which were in Nebraska (USDA-NASS, 2022). Among the 2.2 million ha of soybean grown in Nebraska, about 50% (1.11 million ha) are irrigated and the rest are rain-fed (USDA-NASS, 2022). Thus, supporting soybean production via maintenance or improvement in soil health, fertility, and productivity is vital. The introduction of CCs in soybean production systems can be a potential strategy for improving soil properties and productivity. However, the literature shows that CCs could have inconsistent effects on soil properties and crop yields, particularly in the short-term (Blanco-Canqui et al., 2015; Finney et al., 2017; Poeplau & Don, 2015; Vukicevich et al., 2016).

One of the leading factors that may affect CC benefits is CC biomass production (Ruis et al., 2019). Previous studies found that increased CC biomass production can result in improved bulk density (Duiker & Curran 2005), water infiltration (Blanco-Canqui et al., 2015), and water holding capacity (Basche et al., 2016) and increased soil organic C accumulation (Poeplau & Don, 2015), among others. Cover crop management influences CC biomass production. For instance, CC planting dates (Ruis et al., 2020) and termination dates (Ruis et al., 2019) determine the amount of CC biomass produced, provided that other factors such as climate are favorable. Lengthening the CC growing season via late termination increases CC biomass accumulation (Ruis et al., 2019). For example, one study found that CC accumulated about 1.75 Mg ha^{-1} of biomass for every 10 days of extra CC growth in a humid and mild region (Nord et al., 2012) .

While several studies have evaluated the effect of CC planting and termination dates on soil properties and crop yields (Ruis et al., 2017; Ruis et al., 2020; Koehler-Cole et al., 2020), little is known about the implications of "planting green" on soil properties and crop yields (Acharya et al., 2022). Planting green is defined as planting a row crop into an actively growing CC such as cereal rye and terminating the CC at the time of main crop planting or after (Reed et al., 2019). Because CC impacts soil properties and crop yields vary depending upon CC termination dates, planting green could have more positive impacts on soil properties compared with typical termination times due to the increased amount of biomass resulting from terminating the CC after the main crop planting. For example, in Nebraska, CCs are typically terminated in spring 2 or 3 wk before planting corn or soybean. The early termination limits CC growth and thus biomass production due to cold temperatures during early spring (Oliveira et al., 2019). Research on the effects of different CC termination dates, including planting green, on soils and crops is necessary so that researchers and producers can effectively integrate planting green into soybean-based crop production systems.

Particulate organic matter, soil organic matter, and aggregate stability are some soil properties that are sensitive indicators of changes in soil health (Moore et al., 2014). For instance, an increase in soil particulate organic matter concentration can improve soil aggregation, nutrient storage and availability, and soil biological activities, among other processes. Similarly, soil aggregate stability, which is a sensitive soil physical property, influences water infiltration, root growth, microbial activity, aeration, and soil erosion (Amézketa, 1999). However, how planting green affects the above soil health parameters and others is unclear, as studies on planting green and soils are mostly unavailable. A 2-

yr planting green study in Iowa found that a cereal rye CC terminated 6 or 12 d after planting corn increased CC biomass production compared with CC terminated 17 or 3 d before planting corn (Acharya et al. 2022). Cover crop biomass production can gradually increase as the number of days until CC termination increases. The same study by Acharya et al. (2022) found that in both years the no-CC treatment produced the greatest corn yield while the 12-d after planting corn termination treatment produced the lowest yield, suggesting that planting green may contribute to reduced corn yield.

Further, previous CC research on soils under typical CC termination timing in Nebraska suggests that CCs may or may not improve soil properties, especially in the short term (< 3 yr) and when CC biomass production is low (< 2 Mg ha-1; Ruis et al., 2017; Sharma et al., 2018; Sindelar et al., 2019). Research also shows that changes in soil properties are often observed only near the soil surface (< 10 cm; Sharma et al., 2018). Quantifying potential changes in soil properties due to planting green can provide valuable information about planting green as a CC management practice in the U.S. Midwest. Thus, the objectives of this 2-yr study were to evaluate the impact of planting green on soil properties (bulk density, wet aggregate stability, sorptivity, particulate organic matter, organic matter, nutrients, and others) and soybean yield in an irrigated no-till soybean system in south-central Nebraska. Our hypothesis was that planting green would rapidly improve soil properties due to potential greater biomass production relative to early-terminated CCs (typical practice) in the region.

1. MATERIALS AND METHODS

1.1. Study Location and Experimental Design

This 2-yr study was conducted on an experiment established at the University of Nebraska-Lincoln's South Central Agricultural Lab (SCAL) near Harvard, NE (40.52°N, 98.05°W) in fall 2020. The soil at the experimental site was silt loam (58% silt, 17% sand, 25% clay content) with an organic matter concentration of 3.7% and pH of 6.8. The experiment was established after corn harvest in 2020 and was then managed under no-till continuous soybean during the 2-yr study with crop residues left on the soil surface post-harvest (Table 4-1). Soybean (main crop) was sprinkler irrigated, but the CC was never irrigated.

The study experiment was a randomized complete block design with four replications. The treatments were No CC, CC terminated 2 weeks before planting (2WBP) soybean, and CC terminated 2 wk after planting (2WAP) soybean. Thus, the experiment had a total of 12 plots. Each plot was 3-m wide and 9-m long with four soybean rows spaced 76.2-cm apart. Cereal rye (Elbon Cereal Rye, GreenCover Seed) CC was drilled in fall after crop harvest in both years. Cereal rye was seeded at a rate of 95.32 kg ha^{-1} in 20.32 cm row spacing and to 3.2 cm seeding depth (Table 4-1). Planting occurred during the same week in 2021 and 2022 (Table 4-1). The staging of cereal rye was conducted using the Zadok's Scale (Zadoks et al., 1974). Cereal rye growth stages were taken at the time of biomass collection, and plants were at stage 21-32 when biomass was collected at 2WBP and stage 49 to 59 when collected at 2WAP. Cover crops were terminated using glyphosate at 1,260 g ae ha^{-1} + crop oil concentrate (COC) 1% v/v + ammonium sulfate

(AMS) 3% v/v. Glyphosate- and dicamba-resistant soybean was planted at a rate of 330,000 seeds ha^{-1} to a 3.8-cm depth and in 76.2-cm row spacing. Soybean was planted on May 12, 2021 and May 18, 2022 (Table 4-1). The soybean crop was at the V1-V2 stages in both years when the CC was terminated at 2 WAP.

1.2. Data Collection

We measured the following soil properties in this study: soil bulk density; wet aggregate stability; sorptivity (initial water infiltration); pH; and concentrations of particulate organic matter, organic matter, and total C, N, P, and K. Soil samples were collected 2 wk after the 2WAP CC termination in the summer of 2021 and 2022. Five soil cores were taken with a 1.9-cm diameter hand probe from each plot at 0-5 cm, 5-10 cm, and 10-20 cm depths. Soil samples were composited by depth in each plot, sealed in ziplock bags, transported to the laboratory, and weighed. Next, a fraction of the soil sample was weighed, dried at 105° C for 24 h, and weighed again to determine gravimetric water content and soil bulk density by the core method (Blake & Hartge, 1986).

Wet aggregate stability was determined using the wet sieving method (Nimmo & Perkins, 2002). Fifty grams of air-dried soil sample passed through 8-mm sieves were placed on top of a column of sieves with openings of 4.75, 2.00, 1.00, 0.50, and 0.25 mm. The top sieve (4.75 mm sieve) contained filter paper to hold the sample for saturation via capillarity for 10 min. The filter paper was then removed and the soil samples were mechanically sieved for 10 min. The aggregates from each sieve were transferred into pre-weighed beakers, dried at 105°C for 2 d, and weighed. The amount of dry aggregates and the sieve sizes were used to compute the mean weight diameter of water-stable aggregates (Nimmo & Perkins, 2002).

Another fraction of the air-dried soil sample was gently crushed, passed through 2-mm sieves, and analyzed for chemical properties including total C, organic matter, N, P, and K concentrations, and pH. Any visible crop residues were removed from the sample before analysis. Total organic C concentration was determined by the dry combustion method on samples milled on a roller mill (Nelson & Sommers, 1996). Soil P concentration was measured by the Mehlich-3 extraction procedure (Frank et al. 2015). One gram of soil sample was mixed with 10 mL of the extracting solution, shaken for 5 min, and transferred to test tubes for the analysis using Lachat QuickChem (Lachat Instruments, Loveland, CO). Potassium concentration was determined by the ammonium acetate method (Warncke & Brown, 1998). Two grams of soil sample were mixed with 20 mL of 1 N ammonium acetate solution, shaken for 5 min, and filtered for the analysis via inductively coupled plasma (iCAP 6000 series, Thermo Scientific, Waltham, MA). Soil pH was measured on soil and water slurry in a 1:1 ratio (Peters et al., 2015).

To determine particulate organic matter concentration, 30 g of soil from each sample were dispersed with 5 g L^{-1} sodium hexametaphosphate for at least 24 h and then the mix was washed through 53-μm sieves (Cambardella et al. 2001). The remaining sample on top of the 53-μm sieves was dried at 60°C until a constant mass was reached. After weighing, the samples were then ashed at 450° C in a muffle furnace for 4 h. Particulate organic matter concentration was then calculated as the difference between sample mass after drying and ashing. Soil organic matter concentration was analyzed by loss on ignition (Combs & Nathan, 1998). Briefly, 5 g of air-dry soil were oven dried at 105°C for 2 h, weighed, heated to 360°C for another 2 h, and weighed again to compute soil organic matter concentration.

Soil sorptivity was determined using the method outlined by Smith et al. (1999). Three steel rings (9.75 cm diam. by 10 cm height) were inserted into the soil at three locations within each plot and 75 ml of water added. The time needed to infiltrate the 75 mL of water was recorded to compute sorptivity as per Eq. [1]:

$$S = \frac{h}{t^{\frac{1}{2}}} \qquad [1]$$

where S is sorptivity (cm $s^{-1/2}$), h is the height of water (cm), and s is time (s).

Soybean yield was determined by harvesting the middle two rows of each plot and then adjusting the yield to 13.5% moisture content.

2.3 Statistical Analysis

Statistical analysis of the data was preformed using SAS PROC GLIMMIX in SAS 9.4. The data on all soil properties were normally distributed. Year and CC termination treatments were considered as fixed effects, while replication was the random effect in the model. If year × treatment interaction was not significant, data were averaged across both years. When differences in treatments were significant, a multiple comparison test was conducted using Tukey-Kramer’s HSD test with a 95% confidence interval and LS means were then compared. Also, correlation analysis among soil properties and cover crop biomass yield was performed using PROC CORR in SAS to determine any relationships among the study variables.

2. RESULTS AND DISCUSSION

2.1. Temperature and Precipitation

Growing conditions differed between the 2021 and 2022 growing seasons. Sufficient rain and snowfall occurred in fall 2020 and winter 2021, which resulted in adequate CC emergence and growth for the 2020-2021 CC growing period (Table 4-2). However, below-average rain and snow in fall 2021 and winter 2022 (Table 4-2) hindered the emergence of the CC; and a viable CC stand was not successful until the spring months of 2022. Soybean was planted within the normal planting time in the region in both years. Soybean was irrigated in both years to compensate for the lower precipitation during the study years compared with the 30-yr average (Table 4-1). In 2022, soybean was not irrigated until July 1 due to the installation of a new linear irrigation system. In both years (2021 and 2022), the average temperature was 21° C during the growing season, which is similar to the 30-yr average for the site. A weather event to note is a hail and windstorm that occurred on June 7, 2022 when soybean was at V1 to V2 growth stage and adversely impacted soybean stand and growth.

2.2. Cereal Rye Biomass Production

Cover crop termination treatments affected CC biomass production as expected. In 2021, on average, CC terminated 2WBP accumulated 1.95 Mg ha^{-1} of biomass, while CC terminated 2WAP accumulated 12.78 Mg ha^{-1} (Figure 4-1). In 2022, on average, CC terminated 2WBP accumulated 2.75 Mg ha^{-1} of biomass, while CC terminated 2WAP accumulated 11.29 Mg ha^{-1} (Figure 4-1). Averaged across both years, CC produced 2.35

Mg ha^{-1} of biomass for the 2WBP treatment and 12.03 Mg ha^{-1} for the 2WAP treatment (Figure 4-1).

Cover crop terminated 2WAP produced more biomass than cover crop terminated 2WBP due to the four additional weeks of growth for the 2WAP CC treatment. Cover crop under the 2WAP treatment was terminated about 4 wk later than the typical CC termination time in the region. In the study region, temperatures and rainfall can be optimal during April and May (Table 4-2). Thus, delaying CC termination can lead to rapid growth in CCs such as cereal rye.

Note that CC biomass production under the 2WAP treatment rose by about 5 times (2.35 vs 12.03 Mg ha^{-1}) relative to the 2WBP treatment. The 2WAP treatment increased CC biomass production by 9.68 Mg ha^{-1} compared with the 2WBP treatment. This increase is much larger that the increase in CC biomass production reported in previous studies on late CC termination (Ruis et al., 2017). For example, a 3-yr study in our region found that cereal rye CC produced 0.75 Mg ha^{-1} of biomass when terminated 2-3 weeks (mid-April) before corn planting and 1.60 Mg ha^{-1} of biomass when terminated at corn planting, indicating that late CC termination increased CC biomass amount by 0.85 Mg ha^{-1} only (Ruis et al., 2017). The greater CC biomass production in our study than in the study by Ruis et al. (2017) occurred because the CC in our study was terminated 2 wk later (2WAP). Thus, our results suggest that planting green can be a strategy to boost CC biomass production. However, how the increased CC biomass production affects soils and crop yields deserves discussion.

2.3. Soil Physical Properties

Cereal rye CC termination treatments (No CC, 2WBP, and 2WAP) had no effect on soil bulk density (*p* = 0.76), wet aggregate stability (*p* = 0.215), or sorptivity (*p* = 0.204) in any year (Table 4-3). However, year had an effect on wet aggregate stability (*p* = 0.0003) and sorptivity (*p* = 0.0003) but not on bulk density. Results indicate that year affected soil physical properties more than CC termination treatment. Both wet aggregate stability and sorptivity decreased from 2021 to 2022 in all treatments. The year-to-year fluctuation in dynamic soil properties such as wet aggregate stability and sorptivity is not uncommon, especially in temperate regions. Differences in freezing-thawing and wetting-drying from year to year can differently impact soil properties near the soil surface (Dagesse, 2011).

The lack of CC termination timing impacts on bulk density is not surprising. Studies found that CCs generally have small or effects on soil bulk density in temperate regions (Villamil et al. 2006: Hubbard et al. 2013). Cover crops often alter soil bulk density in the long-term (>10 yr) if CC biomass production is high (Blanco-Canqui et al., 2011). While CC termination timing on soil bulk density was not significant, the numerical values of bulk density slightly decreased (from 1.13 to 1.09 Mg m^{-3}) under CCs. The decreasing trend in bulk density suggests that bulk density in the study soil may decrease with the continued use of planting green in the long term. A decrease in bulk density can increase soil porosity and reduce risks of compaction relative to fields without planting green.

Similarly, although not statistically significant, wet aggregate stability increased with both 2WBP and 2WAP treatments compared with no CC in both years (Table 4-3). The increasing trend in wet aggregate stability was larger with 2WAP than with 2WBP treatment. Thus, similar to soil bulk density, the tendency for improved aggregate stability after 2 yr suggests that this property can improve under planting green in the long term. Cover crops can increase wet aggregate stability, especially in the long term (> 10 yr, (Blanco-Canqui et al., 2011; Steele et al., 2012).

Further, the correlation analysis showed that wet aggregate stability was the only soil property correlated ($p = 0.067$) with CC biomass production (Fig. 2A). Across both years, wet aggregate stability increased as the amount of CC biomass increased (Fig. 2A). This significant correlation suggests that CCs could maintain or improve soil aggregate stability probably due to their abundant canopy cover, which slows and intercepts raindrops, thereby reducing their erosive energy (Adetunji et al., 2020, Wassenaar et al., 2005). The correlation analysis also showed that sorptivity, which is the initial water infiltration, increased as wet aggregate stability increased ($p = 0.0037$; Fig. 2B). While CC termination timing did not affect sorptivity in the short term (2 yr), the positive correlation between sorptivity and aggregate stability suggests that planting green could increase sorptivity in the long term if CCs significantly increase wet aggregate stability, which promotes macroporosity. Previous studies in the region also found that CCs may have limited effects on soil sorptivity in the short term (< 4 yr) even when CCs produce large amounts of biomass (about 4 Mg ha^{-1}; Ruis et al., 2020)**.**

In this study, CC produced as high as 12.78 Mg biomass ha^{-1} under planting green (2WAP) but did not affect soil physical properties after 2 yr. One reason for the limited effect of planting green on the soils in this study may be the initial soil conditions. The study site had been managed under no-till for decades before the CC study initiation. Thus, because soil properties may have already been improved, it could take more than 2 yr for planting green to induce further changes in soil properties in this and similar soils. For example, bulk density ranged from 1.08 to 1.13 Mg m^{-3}, which was near optimum for highly productive silt loam soils in no-till. Also, the initial organic matter (3.7%) in the study soil was higher than for most agricultural soils. Most croplands have organic matter concentration below 3% on a global scale (Oldfield et al., 2019, Yang et al. 2017). Plowed or degraded soils with less than ideal soil properties may respond more rapidly to planting green than soils under long-term no-till management (Olson et al., 2014).

2.4. Soil Chemical Properties

Similar to the impacts on soil physical properties, CC treatments had no impact on soil chemical properties ($p > 0.10$) except for total N ($p < 0.10$; Table 4-4). Cover crop treatments did not affect pH, particulate organic matter, organic matter, or total C, P, and K, though they did reduce total N concentration. The year × CC termination interaction was significant for total N. In 2021, both 2WBP and 2WAP treatments reduced total N concentration by 48% (31.1 vs 59.7 mg kg^{-1}) but not in 2022 (Table 4-4). Data on pH, particulate organic matter, organic matter, and total C, P, and K were averaged across both years as year × CC interaction was not significant for these properties (Table 4-4).

Total particulate organic matter tended to increase with both CC termination treatments compared with no CC (Table 4-4). While the correlation between particulate organic matter and wet aggregate stability was not significant ($p > 0.10$) after 2 yr, the increased trend in particulate organic matter under planting green suggests that its positive influence on soil aggregation may develop over the long term. The role of particulate organic matter in binding soil particles and promoting soil aggregation is well recognized (Cambardella et al., 2001). Previous CC studies showed that labile organic matter (i.e., particulate organic matter, water-extractable organic matter) often increase 3 or more years after CC introduction (Ruis et al., 2020).

The lack of CC termination treatment effect on particulate organic matter, soil organic matter concentration, and soil C in this study could be due to the already high organic matter levels in the study soil mentioned earlier. Other studies observed that organic matter concentration can increase only 3 or 5 yr after CC adoption (Dabney et al., 2001, Olson et al., 2014, Sainju et al., 2002). The reduction in total N concentration with CCs in one of the 2 yr can have important connotations for N management. It suggests that the practice of planting green can reduce nitrate leaching and potentially contribute to N use efficiency (O'Reilly et al., 2012). One potential reason for increases of total N is that crops tend to use less N in drier years, and both of these years were drier than the 30-yr average (Table 4-2). Another potential reason is that soybean residues can put N credits back into the soil. These two reasons combined could have led to higher N values. Long-term monitoring of planting green impacts on nitrate leaching and other soil processes is needed to better evaluate the effect of planting green on nitrate leaching, soil C, and other soil chemical and fertility properties.

2.5. Soybean Yield

Cover crop termination and year had a significant effect ($p < 0.05$) on soybean yield. Also, the CC termination × year interaction was significant ($p = 0.0015$), indicating that CC effect depended on the year. Table 4-4 shows that soybean yield in 2021 was about 2.2 times higher than in 2022. The yield decrease in 2022 was due to a hail and windstorm that occurred in early June in 2022 at the V1-V2 soybean growth stage. Cover crop termination treatments had no effect on soybean yield in 2021, but the 2WBP treatment reduced yield in 2022. The adverse impact of CC (2WBP treatment) on soybean yield in 2022 should be interpreted with caution due to the compounding effect of the hail and windstorms, which reduced soybean stand and growth in all CC treatments. The large fluctuation in soybean yield from year to year due to unexpected weather events strongly suggests the need for long-term studies to better assess planting green effects crop yields.

In 2021, while differences in soybean yield among CC treatments were not significant, soybean yield ascended in this order: No > 2WBP > 2WAP. This trend suggests that CCs, particularly planting green (2WAP), could reduce crop yields. Indeed, in 2021, visual differences of soybean yellowing and stunting were observed in the 2WAP treatment. Cover crops under 2WAP most likely depleted moisture and immobilized nutrients. Other studies also found that high biomass accumulation for non-legume CCs could reduce crop yields in some cases (Acharya et al., 2022, Ficks et al., 2023, Wallace et al., 2021). A recent field-scale analysis across the U.S. Corn Belt reported that CCs can reduce soybean yield by 3.5% in years with low precipitation and warm temperatures in spring (Deines et al. 2023). However, results indicate that in 2022, the year with abnormal weather, planting green (2WAP) tended to increase soybean yield relative to 2WBP and no CC treatments (Table 4-4). The abundant CC biomass in the 2WAP treatment may have protected the soybean stand from the hail and windstorm, leading to better soybean stand.

One may expect that an improvement in soil properties such as soil organic matter concentration could translate into increased crop yields, particularly in soils with relatively low initial organic matter. For example, Oldfield et al. (2019) discussed that soil productivity increases as soil organic matter concentration increases, although it can plateau as organic matter concentration reaches (3.4%). However, in this study, CCs had no effect on most soil properties, including organic matter concentration, in the short term. Thus, the need for a longer-term planting green study cannot be overemphasized for determining definitive conclusions about the effects of planting green on soils and crop production.

3. CONCLUSIONS

Our research on planting green conducted under an irrigated no-till soybean system in the western U.S. Corn Belt for 2 yr generated initial findings about the potential implications of early (2 wk before planting soybean) and late (2 wk after planting soybean) cereal rye CC termination on soil properties and soybean yield. Results show that the abundant amount (12 Mg ha^{-1}) of CC biomass that was produced under planting green had limited or no significant effect on most soil properties in the short term. Our hypothesis that planting green would rapidly improve soil properties due to high biomass accumulation relative to lower amounts of biomass produced under typical CC management practices in the region was not supported by the data.

In addition, results show that planting green does not reduce soybean yields, yet planting green contributed to nitrate scavenging, particularly in the first year. Further, the significant positive correlation between wet soil aggregate stability and CC biomass production can be early indicators of the soil benefits of planting green. In general, the limited or no impacts of planting green on soil properties and soybean yield in the short term suggest the need for long-term future research on planting green to improve soil properties while reducing negative impacts on crop yields.

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TABLE 4-1 Management of main crop (soybean) and cereal rye cover crop (CC) for the planting green experiment near Harvard, NE during 2020-2022.

Year	Date	Field Operations
2020	Oct. 16	Cover crop drilled at 95.32 kg ha^{-1} with a no-till drill
	Dec. 6	Glyphosate applied to terminate weed in no-CC treatments
2021	Apr. 1	Herbicide maintenance applied
	Apr. 24	Cover crop terminated by glyphosate 2 wk before planting
	Apr. 24	Cover crop biomass collected 2 wk before planting soybean
	May 12	Dicamba/glyphosate-resistant soybean planted at 330,000 seeds ha^{-1}
	May 26	Cover crop terminated by glyphosate 2 wk after planting soybean
	May 26	Cover crop biomass collected 2 wk after planting soybean
	Jun. 14	Soil samples collected at 0-5 cm, 5-10 cm, 10-20 cm depths
	Jun. 14	Soil sorptivity measured under field conditions
	Nov. 10	Soybean harvested
	Nov. 15	Cover crop drilled at 95.32 kg ha^{-1} with a no-till drill
2022	Mar. 28	Glyphosate applied to terminate weed in no-CC treatments
	Apr. 28	Herbicide maintenance applied
	Apr. 28	Cover crop terminated by glyphosate 2 wk before planting
	Apr. 28	Cover crop biomass collected 2 wk before planting soybean
	May 18	Dicamba/glyphosate-resistant soybean planted at 330,000 seeds ha^{-1}
	May 31	Cover crop terminated by glyphosate 2 wk after planting soybean
	May 31	Cover crop biomass collected 2 wk after planting soybean
	Jun. 14	Soil samples collected at 0-5 cm, 5-10 cm, 10-20 cm depths
	Jun. 14	Soil sorptivity measured under field conditions
	Oct. 13	Soybean harvested

TABLE 4-2 Mean temperature and precipitation in 2020-2022 for the planting green experimental site near Harvard, NE.

	Mean air temperature, °C				Monthly precipitation, mm			
Month	**2020**	**2021**	**2022**	**30-yr**	**2020**	**2021**	**2022**	**30-yr**
January	-2.3	-0.9	-3.7	-3.4	22	34	8	15
February	-0.1	-9.6	-2.6	-1.3	3	16	0	21
March	6.1	7.2	4.2	4.6	43	30	36	34
April	9.7	11.2	11.9	10.3	57	13	22	65
May	15.4	15.7	16.2	16.4	52	87	105	136
June	25.3	23.1	22.8	22.6	43	43	56	107
July	25.2	23.3	24.0	24.7	53	51	100	105
August	24.5	23.5	22.7	23.4	15	58	17	98
September	18.4	21.1	21.6	18.9	30	66	41	57
October	10.2	11.8	11.6	11.8	5	17	15	60
November	7.3	6.6	7.2	4.3	42	10	36	35
December	0.0	2.3	1.8	-1.5	16	6	25	25
Average	***11.0***	***11.3***	***11.50***	***10.90***	***381***	***432***	***460***	***756***

TABLE 4-3 Effect of planting green on soil physical properties for the experiment near Harvard, NE in 2021 and 2022. Means with common letter within each column are not significantly different.

Treatment	**Bulk Density ($Mg\ m^{-1}$)**		**Mean Weight Diameter of Water-stable Aggregates (mm)**		**Sorptivity ($cm\ s^{-1}$)**	
	2021	2022	2021	2022	2021	2022
No Cover Crop	1.13a	1.13a	1.01a	0.68a	0.12a	0.10a
2WBP[a]	1.09a	1.08a	1.40a	0.84a	0.11a	0.08a
2WAP[b]	1.12a	1.10a	1.49a	1.07a	0.12a	0.10a

[a] 2WBP = Cover crop terminated two weeks before planting soybean.
[b] 2WAP = Cover crop terminated two weeks after planting soybean (planting green).

TABLE 4-4 Effect of planting green on soil chemical properties and soybean yield for the experiment near Harvard, NE in 2021 and 2022. Means with common letter within each column are not significantly different. The year × treatment interaction was significant only for total N.

Treatment	**Total N (mg kg^{-1})**		**Particulate Organic Matter (mg g^{-1})**	**Total C (g kg^{-1})**	**Organic Matter (g kg^{-1})**	**P (mg kg^{-1})**	**K (mg kg^{-1})**	**Soybean Yield (Mg ha^{-1})**	
	2021	2022						2021	2022
No CC	59.67a	78.67a	9.70a	20.46a	40.17a	123a	478a	4.87a	2.11a
2WBP[a]	33.89b	64.56a	9.87a	20.07a	40.10a	91.30a	451a	3.92a	0.96b
2WAP[b]	28.3b	75.78a	10.60a	19.58a	30.98a	104.56a	470a	3.77a	2.7a

[a] 2WBP = Cover crop terminated two weeks before planting soybean.

[b] 2WAP = Cover crop terminated two weeks after planting soybean (planting green).

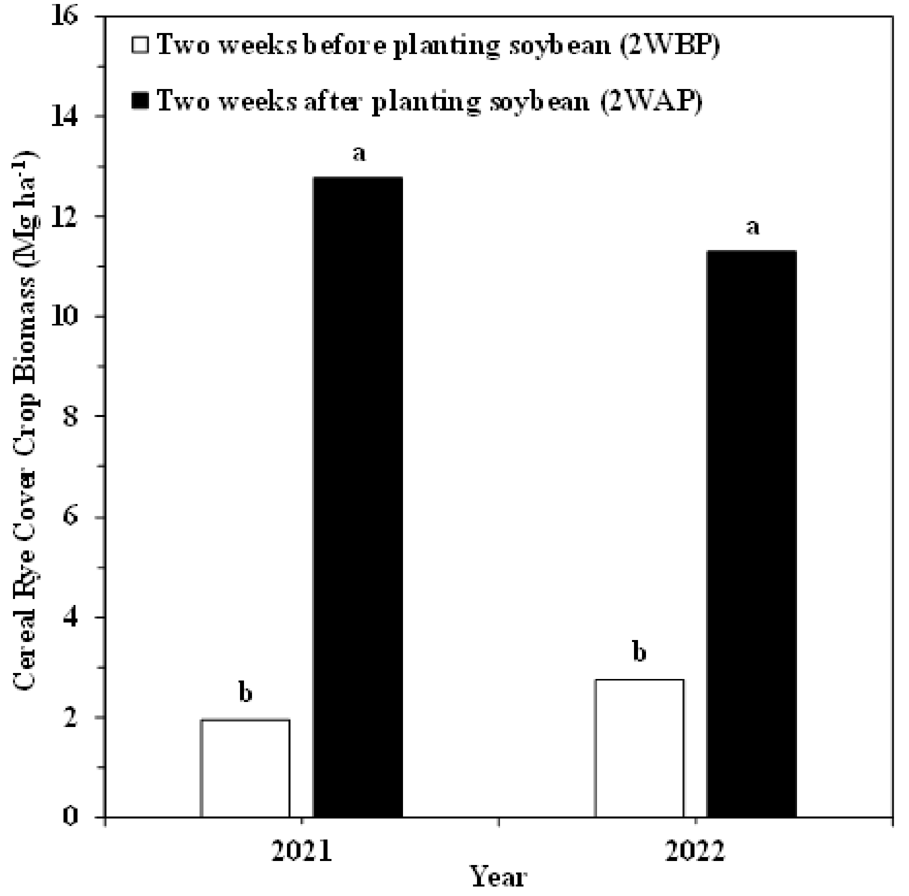

Figure 4-1. The effect of cereal rye cover crop termination timing on biomass accumulation for the planting green experiment conducted near Harvard, NE in 2021 and 2022.

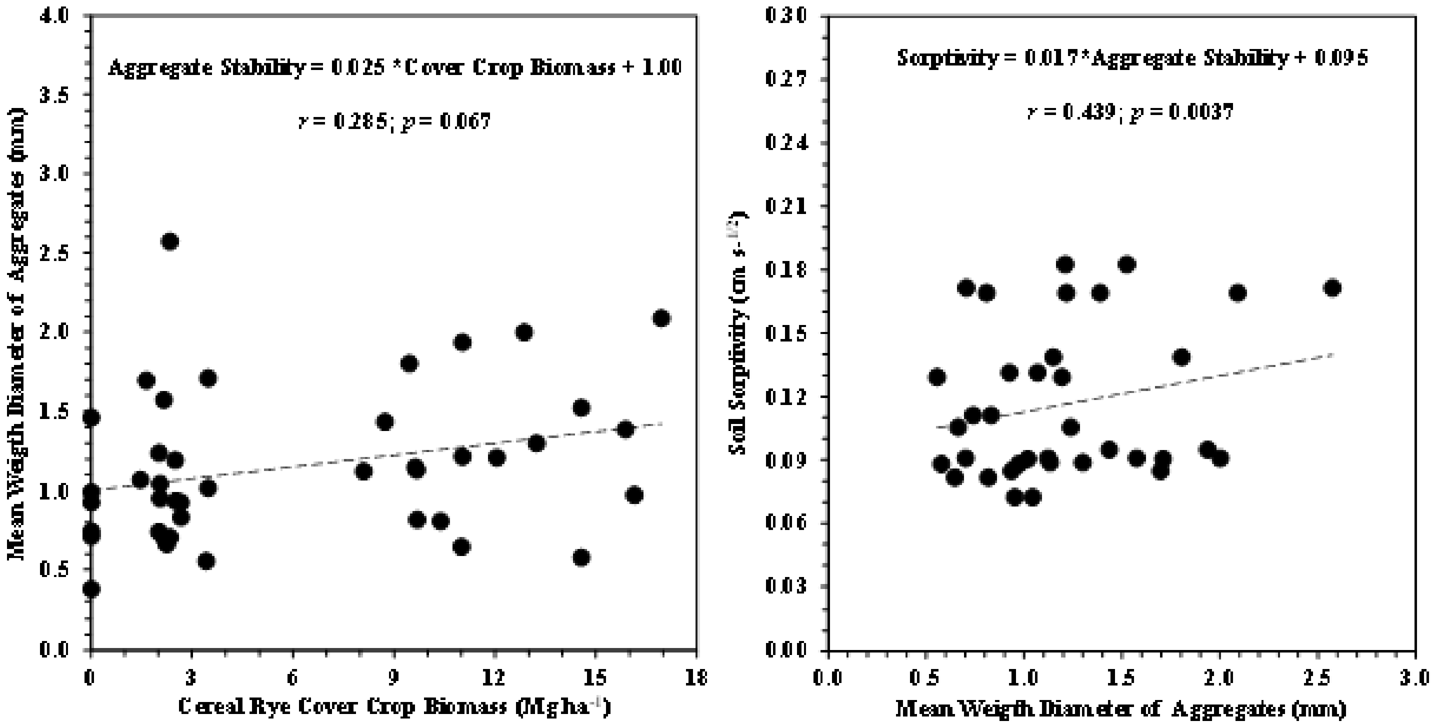

Figure 4-2. Relationship of wet aggregate stability expressed as mean weight diameter of aggregates with A) cereal rye biomass production and B) soil sorptivity across 2 yr for the planting green experiment conducted near Harvard, NE in 2021 and 2022.