Influence of cover crop termination timing on weed suppression in soybean (*Glycine max*) and corn (*Zea mays*) in Kansas

by

Luke Isaiah Chism

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Approved by:

Co-Major Professor
Johanna “Anita” Dille

Approved by:

Co-Major Professor
Gretchen F. Sassenrath

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Abstract

Cover crops are becoming more commonly adopted throughout Kansas as a tool to help farmers manage weeds in soybean and corn crops. Though popularity continues to increase, there are still many questions and misunderstandings of the efficacy, profitability, and applicability of cover crops in real farm scenarios. More information is needed to provide quality recommendations to farmers and advisors in Kansas. The objectives of this research were to evaluate different cover crop (CC) termination timings relative to crop planting on weed suppression and grain yields in soybean and corn fields across various regions of Kansas. Additionally, the impact of residual herbicides at the time of CC termination on weed management in corn was evaluated. A total of 10 soybean and six corn on-farm and on-station field trials were conducted through the growing seasons of 2017 through 2020. Most sites had fall-seeded cereal (wheat, cereal rye, or triticale) as the CC, with one site using spring oat, which were terminated anywhere from 5 weeks before to 1 week after planting the cash crop. Cover crop termination was done with a glyphosate herbicide application at the appropriate timing. The results of all studies showed that delaying termination increased CC biomass at termination and reduced weed densities at 25 days after planting (DAP) the cash crop, especially compared to plots with no CC. For soybean, maximum CC biomass in 2018 was 989 g m^{-2} in western KS when seeded after wheat harvest and terminated 1 week after soybean planting. In 2019, the maximum CC biomass was 1619 g m^{-2} in eastern KS with a wet spring season. For corn at on-farm sites, where crop planting typically occurred between mid-April to mid-May, less total CC biomass was produced than before soybean which were planted later (late May to early June). In on-station studies, corn planting occurred later (late May to early June) and similar amounts of CC biomass were produced as in the soybean studies. By adding a residual herbicide at time of

CC termination in corn, weed density by 25 DAP was the same as CC terminated at planting with no residual herbicide across the on-station studies. No differences in corn stands were observed with use of CC at any termination timing in on-station studies. Corn yield differences were observed at two of the six locations: at Oak Hill 2019 in the on-farm study and at Ashland Bottoms 2020 in the on-station study. Lowest corn yields were observed when CC termination was 2 weeks before planting (WBP) at Ashland Bottoms 2020 and at 2 WBP and 1 week after planting at Oak Hill 2019. Across all soybean studies, no yield differences were observed across CC termination times. Yields at each site differed based on potential for that area of Kansas. In conclusion, CC can be terminated later to maximize the positive response of increased biomass and reduced weeds with minimal impact on soybean and corn yields.

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Dedication

To my wife Logan, daughter Lydia, and my parents.

Chapter 1 - Literature Review

Cover crops are a crop that is planted, not for the conventional purpose of harvesting grain, but rather for the purpose of covering the soil and providing a variety of benefits for the ecosystem and future cash crops. In 2017, there were 225,182 recorded hectares planted to cover crops in Kansas across 3,256 different farms (USDA-NASS 2017). The objective of this literature review is to describe the benefits and management of cover crops with a focus on weed suppression.

Benefits of Using Cover Crops

There are many benefits associated with using cover crops. Understanding the main goal for the cover crop is an important step in choosing the right cover crop species or mixture to plant. Some benefits can be seen within the first year of use, and many other benefits increase as cover crops are used over multiple years. Cover crops have reduced erosion, pollution, and nutrient leaching, and crop yield loss due to weeds and insects (SARE 2012). The benefits received from cover crops are dependent on the cropping system, location, and the cover crop species being used. Weed and insect populations can be reduced with cover crops, which can also reduce the total costs of herbicides and insecticides. Cover crops also can be a very effective tool in managing soil nutrients (SARE 2012). Legume species can fix atmospheric Nitrogen (N_2) into ammonia (NH_3). Atmospheric N_2 is an inert form of N that is not useful for plants; when it is transformed into NH_3 it becomes a viable source of N. Soil NH_3 is then available for the following cash crop to use, and the cover crop residue will continue to release NH_3 as it is broken down (Flynn and Idowu 2015). Cover crops can improve soil quality and health by increasing soil organic matter and diversifying soil microbial populations (Sharima et al. 2018).

Soil microbes are a key factor in nutrient cycling and are crucial for transforming plant matter into usable nutrients (Martínez-García et al. 2018).

Cover Crop Management

There are many different types of cover crop species that are used, each of which can serve a different purpose depending on the goal. The term 'cover crop' can entail a multitude of different species and their respective management practices including planting times, planting methods, and termination methods. Most common species are cool-season annual cereals such as rye (*Secale cereale* L.), triticale (*Triticosecale* W.), and wheat (*Triticum aestivum* L.). Other species include warm-season annual species like buckwheat (*Fagopyrum esculentum* L.), sorghum-sudangrass (*Sorghum bicolor* X *S. bicolor* var. s*udanense*), and millet species. Legumes include clover species (*Trifolium*), vetch species (*Vicia*), and peas (*Pisum*), while other non-legume broadleaf species include the brassicas such as radish (*Raphanus sativus)*, turnip (*Brassica rapa*), and canola (*Brassica napus*) (SARE 2012).

Planting times can depend on what the intended purpose of the cover crop is as well as harvest dates from the previous cash crop. Fall and spring are the most common times to plant; fall planting is ideal for spring weed suppression because it allows more time for cover crop establishment and provides season-long competition with winter annual weeds (Balkcom et al. 2023; Petrosino et al. 2015). Problems associated with fall-planted cover crops are timeliness and overwintering success rates (SARE 2019). Inclement weather conditions in the fall can sometimes delay cash crop harvest, in turn delaying planting times for cover crops. Both fall- and spring-planted cover crops can be used for grazing, while fall-planted species can provide more forage and biomass due to a longer growing season.

Weed Suppression with Cover Crops

The need for an integrated approach to weed management becomes more important as herbicide-resistant weed populations increase along with the increase of resistance to new herbicide modes of action (Heap 2025; Powles and Yu 2010). Additionally, the rate of herbicide resistance continues to develop faster than the rate of new herbicide discovery (Gaines and Busi 2021). Cover crops have been proven to be an effective form of weed suppression (Dorn et al. 2015). Cover crops have been used for decades but have received much more attention in recent years due to the need for an alternative method aside from herbicides for reducing weeds. There are multiple ways that cover crops improve weed control. Major factors include allelopathy between crop and cover crop species, and physical blockage which can reduce light, lowering soil temperature, and imposing competitive effects with a growing cover crop (Teasdale 1993).

Cover crops can reduce the density and biomass of weed species in fields, resulting in good weed control. The extent of suppression depends on the cover crop species. Hutchinson and McGiffen (2000) noted that the presence of a cowpea [*Vigna unguiculata* (L.) Walp.] cover crop resulted in 80 to 90% fewer weeds than bare ground plots at the time of desert pepper (*Capsicum annuum* L.) harvest in Southern California in 1997 and 1998, respectively. Cover crops species that consisted of either cereal rye, barley, wheat, or sorghum, that grew to a height of 40 to 50 cm, provided 95% weed control for 30 to 60 days in Michigan (Putnam et al. 1983). Smith et al. (2015) found that buckwheat and sorghum-sudangrass provided the most weed suppression among cover crop species; buckwheat provided 36 and 59% reduction in weed density in field studies in 2011 and 2012, respectively, and sorghum-sudangrass provided 25 and 40% reduction in weed density, respectively, compared to a no-cover control in field studies in New Hampshire. Buckwheat and sorghum-sudangrass had the highest biomass among cover crop species that also compared cereal rye, field pea (*Pisum sativum* L.), and hairy vetch (*Vicia villosa* Roth). Through their analysis, they concluded that the largest factor in weed suppression was greater cover crop biomass, irrespective of cover crop species. Mirsky et al. (2011) investigated cover crop biomass accumulation relative to termination timings, and a 37% increase in cover crop biomass was observed with each 10-day delay in termination in Pennsylvania. The results also showed that with each termination delay, both weed sizes and weed densities were reduced. This study favors the delay of cover crop termination to maximize cover crop biomass as well as maximizing weed suppression.

Allelopathy

Allelopathy is a process that affects seed germination, emergence, or plant growth due to a chemical produced by another plant or organism residing on or near that plant. Several cover crop species are known to produce allelopathic chemical compounds, and the amount can vary depending on the species. Compounds produced by the more common cover crop species can include phenolic acids and scopoletin in oat (*Avena sativa* L.) or hydroxamic acids in cereals such as rye, wheat, and triticale (Jabran and Farooq 2013). Differentiating between weed control from physical competition and allelopathic effects can be difficult to quantify. Soil factors such as levels of active carbon and nitrogen can also influence the efficacy and longevity of allelopathic chemicals and their ability to suppress weeds (Sturm et al. 2018).

Termination of cover crops

Terminating a cover crop is an essential step in cropping system management. It stops cover crop growth to minimize competitive interference with the following cash crop. Methods of termination include natural, chemical, and mechanical. Natural termination is typical in fall-planted cover crops that are not winter hardy, as they freeze out overwinter. Mechanical termination is often performed using mowers, roller-crimpers, and tillage equipment (Davis 2017). Chemical termination is a very common method, typically using glyphosate or a mixture including a synthetic auxin to kill the cover crop, that allows farmers to integrate a soil-residual herbicide with a one-pass approach. This can broaden the window of termination time compared to natural and mechanical methods. Chemical termination can be implemented both pre-plant and postemergence to the cash crop, assuming the crop is resistant to the herbicides being used. Cover crop termination timing varies with goals and geographies. To address weed control, later termination is often favored for the greater accumulation of cover crop biomass that is known to increase levels of suppression (Kumar et al. 2025).

The NRCS provides four different cover crop termination timing guidelines for different zones of the United States (USDA-NRCS 2019). These zones include zone 1: terminating 35 days or earlier before planting, zone 2: terminating 15 days or earlier before planting, zone 3: terminating at or before planting, and zone 4: terminating cover crop before cash crop emergence. These zones are specific to non-irrigated fields and are based on accumulated data specific to water availability. Prior to the 2018 Farm Bill, these guidelines had to be followed to qualify for crop insurance. Starting in the cropping year 2020, crop insurance was attached at the time of cash crop planting, and it would be reviewed under the Risk Management Agency (RMA) for following the rules of Good Farming Practice (GFP). If a claim was made on an insured cash crop, an Approved Insurance Provider (AIP) would research the management decisions that were made in preparation to make a final decision (USDA-NRCS 2019). These termination times need to be further explored across Kansas environments and the termination zones, to ensure that the given recommendations are suitable for local growers and can be part of "good farming practices".

Palmer Amaranth

Palmer amaranth (*Amaranthus palmeri* S. Wats.) is native to the areas of northwestern Mexico, California, New Mexico, and Texas (Ward et al. 2013). It is a C4 summer annual *Amaranthus* species. Palmer amaranth is a dioecious species, meaning that they produce male and female plants that can be differentiated by their physical feel in the field. The male inflorescence is soft, while the female inflorescence is rough and prickly due to the rigid bracts. Male plants produce large amounts of pollen, allowing for successful wind pollination (Ward et al. 2013). Female plants are prolific seed producers and can produce between 100,000 and 500,000 seeds (USDA-NRCS 2017). A survey conducted by the Weed Science Society of America has listed Palmer amaranth as the most troublesome weed in the United States (WSSA 2016). Because Palmer amaranth is a dioecious species, it must cross pollinate, which allows for more genetic variability, enabling herbicide resistance to develop at a relatively high rate (Sauer 1957).

Amaranthus Interference with Corn and Soybean

Corn and soybean are two of the most important and widely planted crops in the U.S. and in the state of Kansas. In 2025, there were 33.74 million hectares of soybean planted in the U.S. and 1.65 million hectares in Kansas. For corn, there were 38.5 million hectares planted nationally and 2.75 million hectares in Kansas (USDA - NASS, 2025).

Soybean yields are greatly impacted by increasing densities of *Amaranthus* species. In Manhattan and Topeka, KS, soybean yield loss due to weed competition was compared among Palmer amaranth, redroot pigweed [*A. retroflexus* (L.)], and common waterhemp [*A. tuberculatus* (Moq.) Sauer] with weed densities of 0.25, 0.5, 1, 2, 4, and 8 plants per m^{-1} row, with a weed-free check and two separate pigweed emergence times relative to soybean planting (Bensch et al. 2003) The most yield loss observed in all pigweed species was with the first pigweed emergence time and the highest pigweed density of 8 plants m^{-1} of row. Palmer amaranth reduced soybean yields the most by 78.7%, followed by common waterhemp with 56.2% and redroot pigweed with 38%. An experiment conducted in Arkansas showed that dryland soybean yield was reduced by 17, 27, 32, 48, 64, and 60% with increasing Palmer amaranth densities of 0.33, 0.66, 1, 2, 3.33, and 10 plants m^{-1} (Klingaman and Oliver 1994).

Corn yields are also impacted by competition with Palmer amaranth. Massinga and Currie (2002) conducted field studies in Garden City, KS and reported that as the density of Palmer amaranth increased, greater corn grain yield losses occurred. They also found that the timing of Palmer amaranth emergence relative to corn emergence influenced the degree of yield reduction. Palmer amaranth was present in densities ranging from 0.5 to 8 plants m^{-1} row, and the first emergence of Palmer amaranth coincided with corn emergence. Corn yields were reduced by 11 to 91% compared to a weed-free check. The second planting of Palmer amaranth emerged when the corn was between the four and seven leaf stages. These same densities of Palmer amaranth (0.5 to 8 plants m^{-1} of row) resulted in a yield loss of 7 to 35%. Grain yield losses of irrigated and dryland corn near Manhattan (Ashland Bottoms), KS were observed in 2005 and 2006 with different Palmer amaranth densities. Irrigated corn grain yields were reduced by 35 to 39% in 2005, and by 42 to 52% in 2026 with one and four Palmer amaranth plants m^{-1}

of row, respectively. In dryland corn there was 31 to 45% yield reduction in 2005 and 87 to 99% yield reduction in 2006 with one and four Palmer amaranth plants m^{-1} of row, respectively. The drastic increase in yield impact from Palmer amaranth in the 2006 dryland experiment was associated with the severe early season drought that took place in conjunction with the inherent soil property that had low water retention properties (Ruf-Pachta et al. 2013). Liphadzi and Dille (2002) conducted a study to determine corn yield loss from Palmer amaranth. In 2002 in Rossville, KS, corn yields were reduced by 13% from Palmer amaranth at 3 plants m^{-1} of row that escaped an application of isoxaflutole or flumetsulam. Near Manhattan (at Ashland Bottoms), KS, corn yields were reduced by 30% at the same weed density in plots that were not treated with herbicide. Smith (2021) conducted studies in Manhattan and Ottawa, KS comparing weed densities following different cover crop termination timings and different cover crop mixes in corn. At Manhattan in 2019 she found that triticale or a triticale-pea mix that was terminated 3 WBP reduced Palmer amaranth density by 100% at 1 WBP compared to no cover treatments with the same burndown. Weed densities between no cover and pea-only treatments were similar, which was thought to be due to lack of biomass provided by the pea cover crop. This study showed compelling evidence that using cover crops with appropriate management can effectively reduce weed densities in a corn cropping system.

Combining cover crops and residual herbicides can be an effective strategy for weed control. McCall (2018) studied the effects of different cover crops: winter wheat, spring oat, spring pea, and oat / pea mix, and residual herbicides on Palmer amaranth and horseweed [*Conyza canadensis* (L.) Cronquist] densities and biomass in a soybean cropping system near Manhattan, KS. Cover crops were terminated in May with glyphosate and 2,4-D and the plots with residual herbicides were treated with flumioxazin and pyroxasulfone. Palmer amaranth densities 10 weeks after cover crop termination were reduced by 69% with the use of residuals and the biomass was reduced by 95%. Palmer amaranth biomass was reduced in the winter wheat by 98% and in spring oat by 91% compared to no cover crop. In another study focusing on horseweed suppression, fall and spring treatments included fall-sown cereal rye, fall-applied residual herbicide, and no fall application compared to no spring application, a spring burndown only, and a residual applied early preplant or as a split-applied residual treatment. Fall-sown rye suppressed horseweed entirely. Fall herbicides suppressed horseweed density by 86% compared to no fall application. All treatments that included a rye cover crop had fewer weed numbers than those without. McCall (2018) concluded that cover crops were an effective weed suppression tool in soybean, when a spring burndown was included.

Conclusion

Weed control is an integral factor for successful crop production. Weeds that are herbicide resistant are becoming more prevalent in cropping systems throughout Kansas, demanding additional forms of weed control in conjunction with herbicides. Cover crops could reduce weed pressure, especially in scenarios where high amounts of cover crop biomass are produced. Cover crops can also impact corn and soybean yields. The goal of these studies was to access cover crop biomass, weed densities, and crop yields in response to different cover crop termination times in on-farm and on-station studies.

The objective for Chapter 2 was to assess the impact of cover crop termination timings relative to soybean planting on 1) cover crop biomass at time of termination, 2) weed density 25 DAP soybean, and 3) soybean yield on eight on-farm and two on-station locations over two growing seasons across Kansas.

The objectives for Chapter 3 were to 1) determine the impact of cover crop termination timing on cover crop biomass, weed densities, corn stand, and grain yield, and 2) compare the level of weed suppression from cover crops with or without soil-applied residual herbicide in corn across Kansas.

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Chapter 2 - Cover Crop Termination Timing Effect on Cover Crop Biomass Accumulation, Weed Density, and Soybean (*Glycine max*) Yield

Abstract

Herbicide resistance in weeds is evolving more rapidly than the development of new effective herbicides to combat these troublesome weeds. Integrated weed management is a critical approach to suppressing weeds in modern agriculture, and cover crops are one tool to help suppress weeds. On-farm and experiment station field trials were conducted in the growing seasons of 2017-2018 and 2018-2019 in seven counties across Kansas. The objective was to assess cover crop biomass, weed density, and soybean yield in response to different cover crop termination times relative to soybean planting. The 2017-2018 study had three termination times: two weeks before planting (2 WBP), at planting (AP), and one week after planting (1 WAP). The 2018-2019 study had an additional treatment of "no cover". Experiments were analyzed separately by year. The greatest cover crop biomass and lowest weed density was observed at the 1 WAP termination time. The average biomass across all locations for termination at 1 WAP was 766 g m^{-2}, ranging from the least, 256 g m^{-2}, to the greatest 1619 g m^{-2}. In contrast the average biomass accumulation was 152 g m^{-2} for 2 WBP and 503 g m^{-2} for AP. There was an inverse relationship between cover crop biomass and weed density in most cases, such that later termination times resulted in greater cover crop biomass and a lower weed density. No impact of termination times on soybean yields was observed in individual studies; different yields were observed among locations. In conclusion, weed density reduction was greatest with more cover crop biomass, which can be obtained by delaying the termination time to 1 WAP soybean.

Introduction

Soybean (*Glycine max* [L.] Merr.) is one of the most important crops in Kansas. In 2023, Kansas producers planted nearly 1.8 million hectares of soybean, with approximately 1.6 million hectares harvested (USDA-NASS 2025). Although there are many herbicide options for pre- and post-emergence weed control for soybean, weed resistance to those herbicides has developed at an alarming rate. For instance, Palmer amaranth (*Amaranthus palmeri* S. Watson), one of the most troublesome weeds in Kansas, has evolved resistance to many herbicides, including synthetic auxin, EPSPS, Photosystem II-, PPO-, and microtubule-inhibiting herbicides (SOA groups 4, 9, 5, 14, and 3, respectively) (Heap 2025). Due to the rising cases of weed resistance, it is becoming critical that alternative methods of weed control be explored to help slow the evolution of herbicide resistance and effectively provide weed suppression.

One alternative to herbicides is to utilize cover crops (CC). Cover crops have been shown to reduce weed densities due to CC biomass accumulation, which in turn competes effectively with weeds (Obour et al. 2022). In Kansas, it is quite common to use cereal grass crops as CC including cereal rye (*Secale cereale* L), winter wheat (*Triticum aestivum* L), and triticale (*X Triticosecale* W.) (Kumar et al. 2020). The high C:N ratio of cereal CC leads to establishment of a mulch layer due to their slower decay rates (Finney et al. 2016; Kumar et al. 2020), wider planting windows for both the winter and spring seasons, and lower relative seed costs compared to crops in the legume family (Snapp et al. 2005). Additionally, cereal CC have been shown to reduce the growth rates of weeds when compared to other CC that produce less biomass (Smith 2021; Wiggins et al. 2017).

Cereal CC are generally seeded in the fall or early spring and are usually terminated around soybean planting to avoid competition with the cash crop (Singer and Kohler 2005).

Common methods of termination in a no-tillage cropping system include chemically via herbicides, or mechanically with a roller-crimper and/or mowing (Davis 2017). To aid farmers in understanding when to terminate CC, the Natural Resource and Conservation Service (NRCS) has established national guidelines for cover crop termination based on local climate factors to minimize yield loss due to soil water use (USDA-NRCS 2019). In Kansas, all four zones of termination times can be found within the state, including a timing of 35 days or earlier before planting (Southwestern Kansas), 15 days or earlier before planting (West Central Kansas), at or before planting (East Central Kansas), and before crop emergence (Southeastern Kansas) (see Figures 2.1 and 3.1). Time of termination before crop planting increases from east to west, likely due to the decreasing annual rainfall gradient from east to west (Kansas Mesonet 2026).

The wide range of termination times provided by the NRCS could result in different weed suppression and soybean yield outcomes. Therefore, the objective of this study was to assess the impact of cover crop termination timings relative to soybean planting on 1) cover crop biomass at time of termination, 2) weed density 25 DAP soybean, and 3) soybean yield on eight on-farm and two on-station locations over two growing seasons across Kansas.

Materials and Methods

Field experiments were conducted in two growing seasons, 2017-2018 and 2018-2019 (referred to as “2018” and “2019”, respectively), at five locations each year, resulting in a total of ten field locations (Figure 2.1). Eight of the ten locations were located on farmer-owned fields, and two were on Kansas State University Experiment Fields. All but three were dryland locations with one irrigated location in 2018 and two in 2019. Information related to field trials can be found in Table 2. 1.

Soils were predominantly silt loam and varied from a fine sandy loam to a silty clay loam. Seeding rates for fall-seeded CC were cereal rye at 100 kg ha^{-1}, wheat at 90 kg ha^{-1}, and triticale at 110 kg ha^{-1}, while spring-seeded oat (*Avena sativa* L.) was seeded at 80 kg ha^{-1}. All CC were drilled with row spaced 19.05 cm apart. No additional fertilizer or herbicides were used in the CC.

The experimental design was a randomized complete block with four replications per location and termination timing being the sole treatment. In 2018, three CC termination timings were established: two weeks before planting (2 WBP), at soybean planting (AP), and one week after planting (1 WAP). In 2019, a fourth timing was added to mimic a "no cover" treatment (terminated approximately 5 weeks before soybean planting) for comparison. Within each field, individual plot sizes were 3.05 m wide and 7.62 m long. The termination method was chemical burndown consisting of glyphosate at 1420 g ae ha^{-1} (Roundup Powermax®, Bayer CropScience, St. Louis, MO), plus 2% v/v AMS. This solution was applied with a 1.98-m boom with four spray nozzles using a CO_2 pressurized backpack sprayer. Glyphosate was used because it is an effective non-selective herbicide used to terminate CC (Cornelius and Bradley 2017). Because it does not have soil-residual properties, weed control properties of the CC could be observed without the influence of chemical control.

Response variables collected included CC biomass at time of termination, weed density at 25 DAP soybean, and soybean yield. Cover crop biomass was collected from an area measuring 0.29 m^2 (area of 57.15 cm covering three rows by 50 cm of row length). All plant material within the sample area was harvested by cutting the above-ground biomass, which was dried at 60 C until constant moisture was achieved. Weed counts were observed in a single 0.25 m^2 quadrat randomly placed within each plot. After completion of all weed counts, the fields were released to the cooperating farmers. Most farmers made additional applications of herbicides following standard production practices to ensure that there was no yield loss due to weeds. To collect grain yield, soybean plants were hand-harvested from each field location by clipping four meters of the center two adjacent rows within each plot. Plants were threshed, grain weighed, and yields were corrected to 13% moisture content.

All data were analyzed using R 4.4.1 (R Core Team 2024). Data were analyzed separately by year, because the 2018 sites did not contain a "no cover" treatment. Linear mixed effects models were used to analyze the response variables of cover crop biomass, weed densities at 25 DAP, and soybean yields. Fixed effects were field location and termination timing, whereas the random effect was replication. Due to non-normality of data distribution, the analyses were conducted using a beta distribution within the glmmTMB package (Brooks et al. 2017) in R. Datasets were transformed with the logit transformation and automatically back transformed by the program for interpretation. ANOVA models were used with a Type III Wald chi-square test (Miranda et al. 2022) and the DHARMa (Hartig 2022) package was used to check all ANOVA assumptions. Tukey's Honest Significant Difference post-hoc test was used to determine differences among factors, and a confidence level of α=0.05 was selected. All post-hoc tests were conducted with the emmeans package (Lenth and Piaskowski 2025). To determine the relationships between weed density and CC biomass, regression analyses were performed for each location and year. To select between linear and exponential relationships, the model with the highest R^2 value was chosen for visualization.

Results and Discussion

Cover crop biomass at time of termination was influenced by an interaction between field location and termination timing for both 2018 and 2019 ($p < 0.0001$ for each year) (Figure 2.2). In general, greater CC biomass accumulations were observed for later termination timings, with the greatest CC biomass being collected at 1 WAP. Having an additional three weeks of CC growth substantially increased biomass. Biomass accumulation was very different across the five locations in 2018 and 2019. Soybean planting dates differed across the locations and years, ranging from May 6 to June 6 (Table 2.1), which influenced when the decision to terminate CC was made as compared to a standard CC growth stage across locations. The Sheridan County Irrigated field produced the least amount of CC biomass. The cooperator had irrigated the prior corn crop, which then delayed the time of CC planting until after corn harvest, towards the end of optimal winter cereal seeding dates (November 1, 2017), and they did not irrigate the growing CC. Conversely, the greatest CC biomass was produced in the Sheridan County Dryland field. Here the same cooperator planted the CC earlier (October 1, 2017) after a winter wheat crop that was harvested in mid-summer. Other studies have shown that cereal rye planted earlier in the fall has time to accumulate more biomass before termination in the spring (Balkcom et al. 2023). In 2019, the greatest biomass accumulation in fall winter cereal CC was observed at Ashland Bottoms with triticale producing 1619 g m^{-2} by 1 WAP, whereas the least amount of biomass in winter cereals by 1 WAP was at Oak Hill with cereal rye producing 449 g m^{-2}. Ashland Bottoms received more rainfall than the 30-yr average between October 1, 2018 and April 30, 2019, with 413 mm of precipitation (Kansas Mesonet 2025). The least biomass of any CC was at Isabel with spring oat producing 275 g m^{-2}, this was not surprising because spring oat was planted on March

5, 2019, in the early spring, meaning that the crop did not have as much time to develop biomass compared to the fall-seeded CC.

Over both years, weed density by 25 DAP of soybean was influenced by the interaction of location and termination timing ($p < 0.0001$ for both years) (Figure 2.3). Different soybean planting dates influenced the relative timing of weed emergence as well as having different weed species occurring across locations. Weed species were predominantly pigweeds, yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.], and large crabgrass [*Digitaria sanguinalis* (L.) Scop] across locations. At Ottawa, the pigweed species was waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] while the other locations were mostly Palmer amaranth. Overall, more weeds were observed in the soybean crop when the CC was terminated at 2 WBP and AP compared to 1 WAP. In other words, weed density was reduced by 58% between 2 WBP and AP, by 97% from 2 WBP to 1 WAP, and by 21% between AP and 1 WAP. The most weeds were observed in Ottawa when CC was terminated at 2 WBP with a 21% reduction in weed density when CC was terminated AP, and 98% by 1 WAP. In general, not as much CC was produced in Ottawa as other locations, resulting in less impact on weed density. Cover crops terminated at 1 WAP soybean, for both 2018 and 2019, resulted in the least weed densities, by an average reduction of 95% compared to the 2 WBP timing across locations (Figure 2.3). This is consistent with Mirsky et al. (2011), who found that later termination timings have greater CC biomass accumulations and overall lower weed densities. In 2019, when a fourth treatment of no cover was included, the weed density in absence of a CC showed how beneficial any CC could be, even if terminated at 2 WBP, which resulted in some degree of weed suppression. This was attributed to increased competition between weeds and CC, which has been shown to reduce weed densities compared to fallow fields (Gabriel and Quemada 2011).

A linear or exponential relationship was observed between weed density at 25 DAP and CC biomass produced by termination time at most locations in 2018 (Figure 2.4) and 2019 (Figure 2.5). In 2018 with three CC termination timings, as CC biomass increased, there was a linear decrease in weed density at three of the five locations. No relationship was observed at McPherson Dryland or Sheridan County Dryland, because no weeds were observed by 25 DAP in CC terminated AP or 1 WAP (Figure 2.3). In 2019 with three CC termination timings and a no-cover crop control, as CC biomass increased, there was either a linear (Isabel irrigated) or exponential decrease in weed density. Across all site years, delaying CC termination resulted in more CC biomass and lower weed densities. Results are consistent with Essman et al. (2023) who reported that termination at 3 WAP had fewer weeds than 1 WAP and 1 WBP, but also concluded that an effective herbicide plan was necessary to provide "adequate" weed control. Smith (2021) found a 44% decrease in weed density near Manhattan, KS when CC termination was delayed from 3 WBP to AP, where CC biomass production AP was 7,600 kg ha^{-1}. At Ottawa, KS, the AP termination timing only produced 2,500 kg ha^{-1} (32% of that in Manhattan) and no weed density response was observed with delayed termination (Smith 2021). This emphasizes the importance of greater CC biomass to influence weed density.

There were no differences in soybean yields because of CC termination times for each year and location; however, there were yield differences among years and locations (Table 2.2). Soybean yields from each location were compared to corresponding county average yields summarized by USDA-NASS (2025). In most cases, the dryland yields were lower than the county average with the one exception being Ashland Bottoms 2019. Conversely, irrigated locations for both years yielded more than the county average. These variations can partially be explained by the county averages being a combination of dryland and irrigated fields. In general, all locations received more precipitation than the 30-year average, except for the 2018 sites of Ottawa, Oak Hill and McPherson (Table 2.2). Garba et al. (2022) conducted a meta-analysis that showed CC can reduce soybean yields by up to 12% in some cases, whereas Deines et al. (2022) summarized that few studies found yield loss in soybean from the use of CC. An approach called "causal forest", that utilizes machine learning algorithms using satellite data, was used to compare soybean yields with and without CC. This study encompassed six states across the Midwest totaling 90,000 fields. An average of 3.5% yield loss was found in fields that used CC (Deines et al. 2022).

This current study in Kansas demonstrated that there were no impacts on soybean yield, in part due to sufficient rainfall throughout the CC and soybean growing seasons. This 2-year study across several locations demonstrates that, regardless of NRCS-labeled termination zones, later termination timings can be used to successfully increase CC biomass accumulation that results in reduced weed infestations. Additionally, soybean yields were not negatively impacted by CC termination timing in this study, even when terminating 1 WAP and outside of NRCS guidelines for a given zone. Because rainfall patterns were above normal for these two years, future studies should focus on assessing impacts on overall soybean stands and grain yields when precipitation is limited.

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Figures

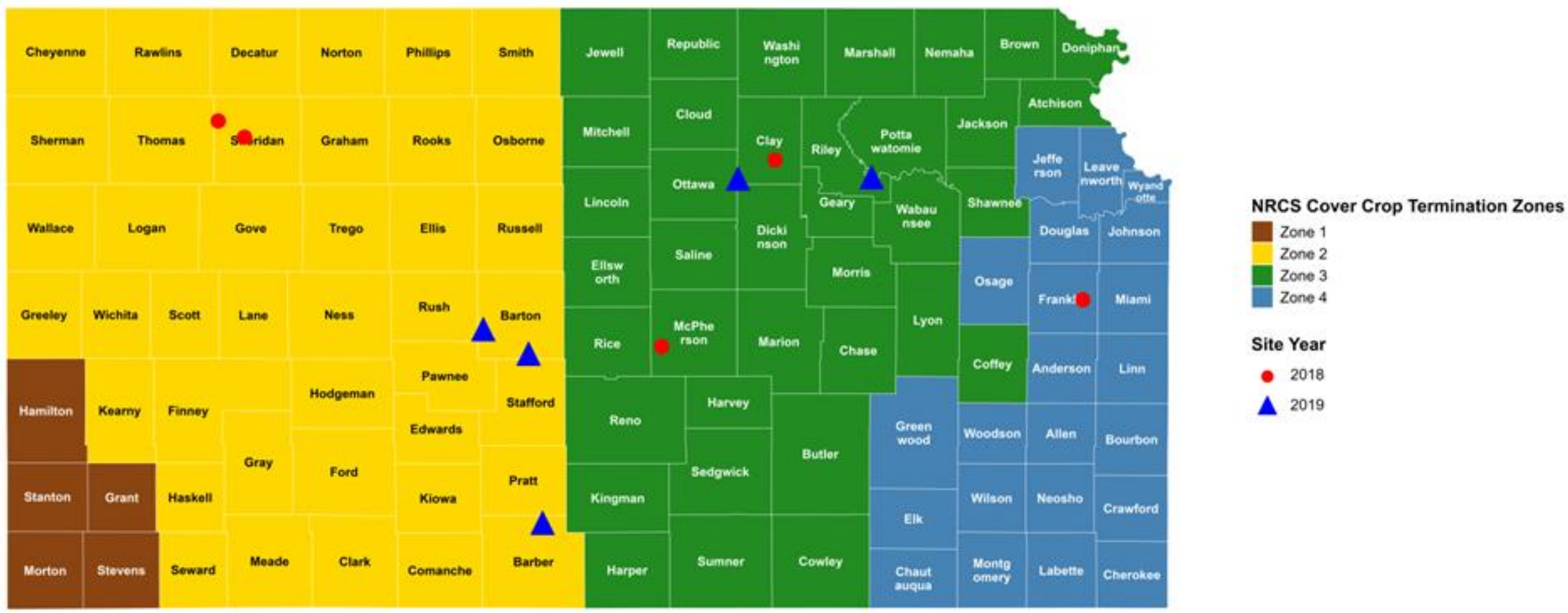

Figure 2.1 Map of Kansas with experiment locations for 2018 and 2019 as illustrated by the red circles and blue triangles, respectively. NRCS termination timing zones are depicted for each county with zones 1, 2, 3, and 4 corresponding to 35 days before planting, 15 days before planting, at or before planting, and before crop emergence, respectively (USDA-NRCS 2019).

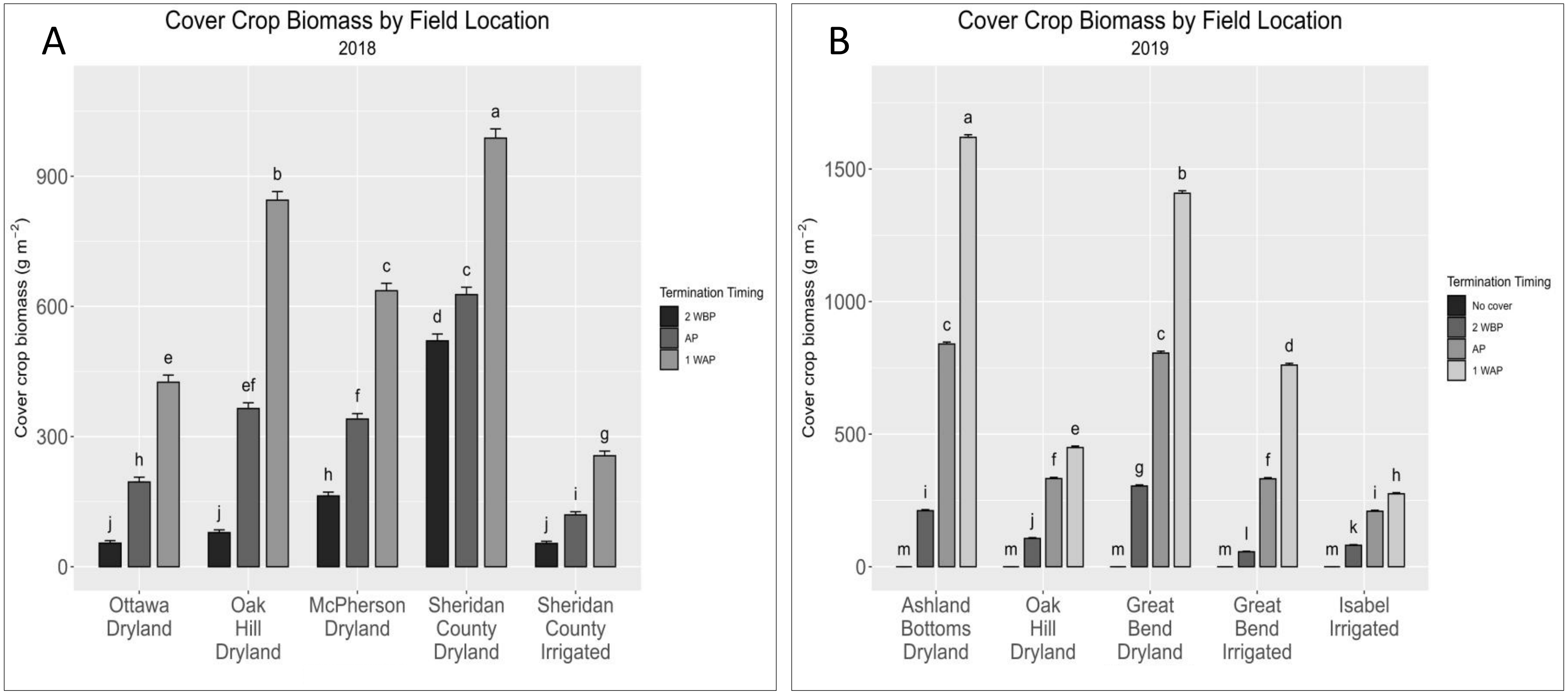

Figure 2.2 Relationship between cover crop biomass and termination timing relative to soybean planting for (A) 2018 and (B) 2019 field sites as they progress from east to west across Kansas. Biomass was analyzed with a two-way ANOVA followed by a Tukey Honest Significant Difference post-hoc test ($p<0.05$) for mean separation. Abbreviations: WBP, weeks before planting; AP, at plant; WAP, weeks after planting.

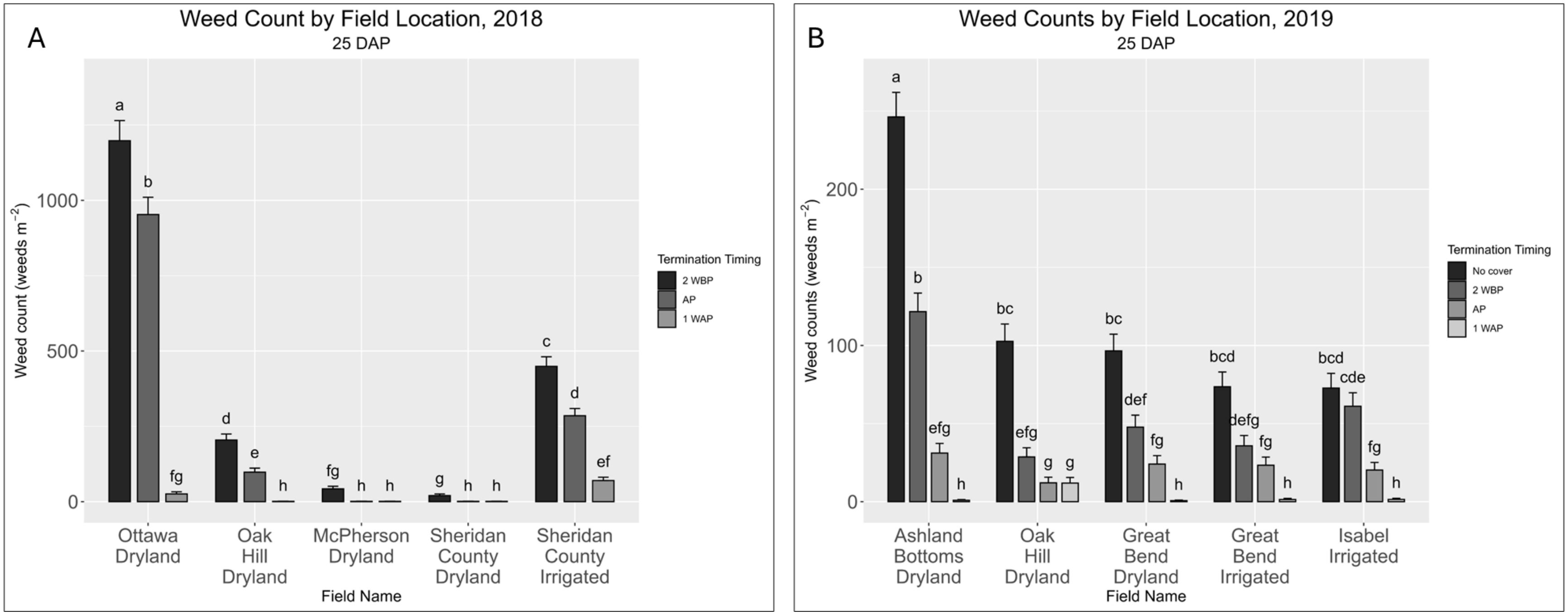

Figure 2.3 Relationship between weed count and cover crop termination timing relative to soybean planting for (A) 2018 and (B) 2019 field sites as they progress from east to west across Kansas. Weed counts were analyzed with a two-way ANOVA followed by a Tukey Honest Significant Difference post-hoc test ($p < 0.05$) for mean separation. Abbreviations: WBP, weeks before planting; AP, at plant; WAP, weeks after planting.

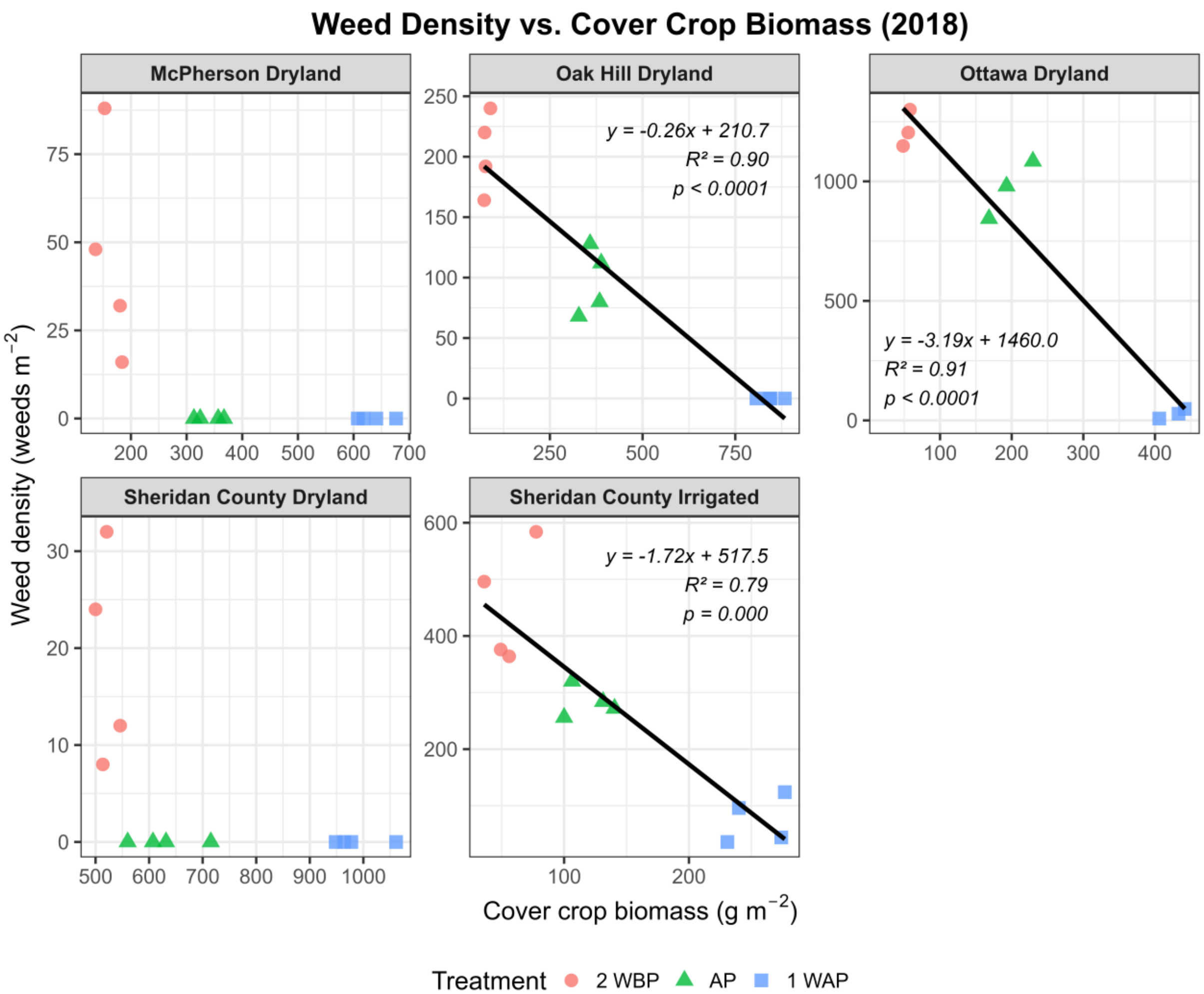

Figure 2.4 Points represent weed densities observed at 25 days after soybean planting in response to cover crop biomass produced by each termination timing in 2018 at field sites across Kansas. Solid line represents fit of linear model to relationship of weed density to cover crop biomass. Abbreviations: WBP, weeks before planting; AP, at plant; WAP, weeks after planting.

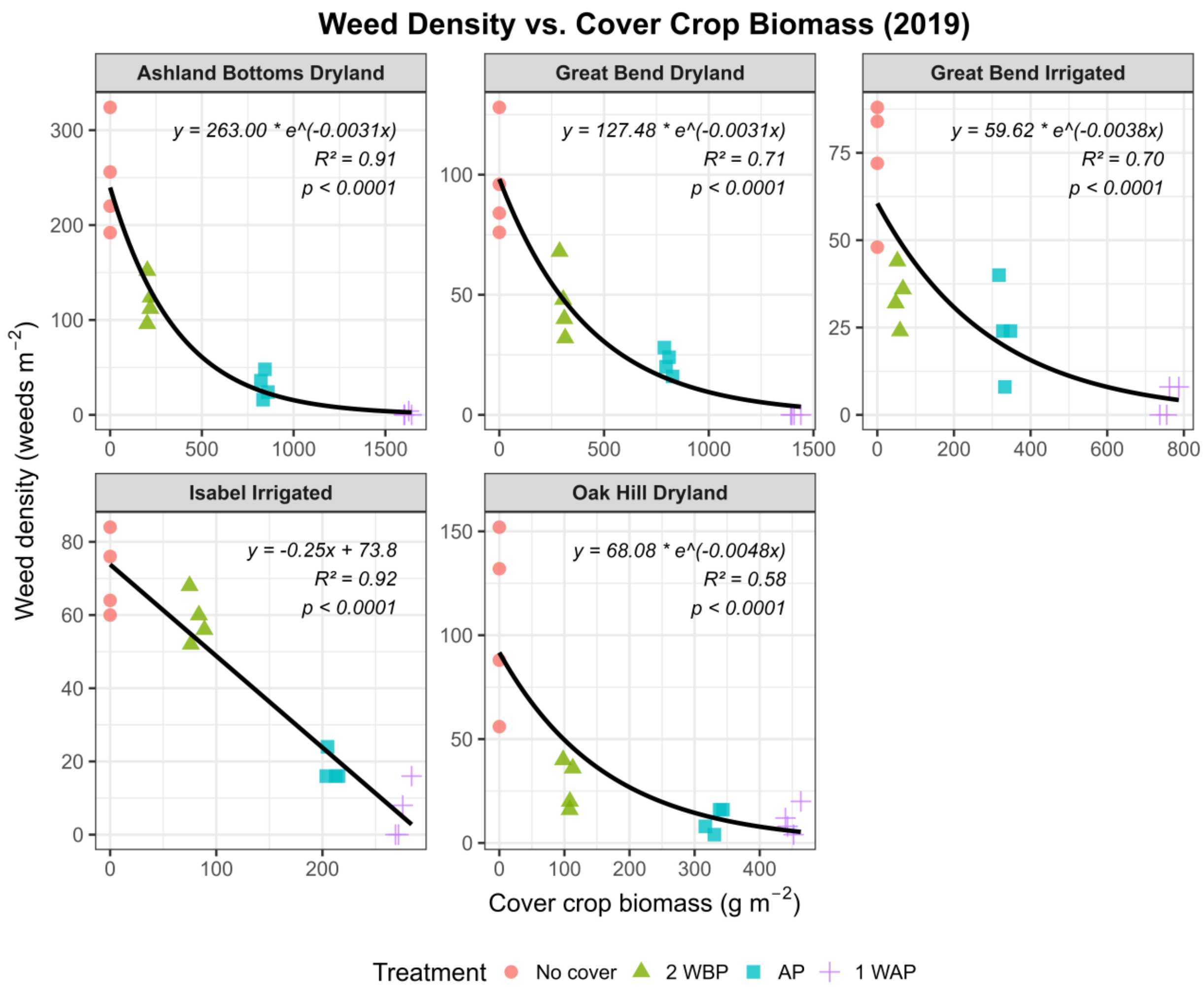

Figure 2.5 Points represent weed densities observed 25 days after soybean planting in response to cover crop biomass produced by each termination timing at 2019 field sites across Kansas. Solid line represents fit of linear or exponential model to relationship of weed density to cover crop biomass. Abbreviations: WBP, weeks before planting; AP, at planting; WAP, weeks after planting. .

Tables

Table 2.1 Summary of field information for 2018 and 2019 soybean cover crop termination studies across Kansas.

Year	Location	Coordinates	Tillage	Irrigation	Previous Crop	Cover Crop	Soybean Planting Date	Soil Type[a]	NRCS Termination Zone[b]
2018	Ottawa (KSU)	38.5380, -95.2427	Yes	No	Wheat	Wheat	5/6	Woodson Silt Loam	4
	Oak Hill	39.2334, -97.21	No	No	Wheat	Rye	5/13	Crete Silty Clay Loam	3
	McPherson	38.3031, -97.9359	No	No	Wheat	Rye	5/26	Tobin Silt Loam	3
	Sheridan County Dryland	39.4131, -100.6071	No	No	Wheat	Rye	5/12	Keith Silt Loam	2
	Sheridan County Irrigated	39.4263, -100.6091	No	Yes	Corn	Rye	5/12	Kuma Silt Loam	2
2019	Ashland Bottoms (KSU)	39.1205, -96.6374	Yes	No	Wheat	Triticale	6/6	Reading Silt Loam	3
	Oak Hill	39.2156, -97.2397	No	No	Wheat	Rye	5/11	Crete Silty Clay Loam	3
	Great Bend Dryland	38.3625, -98.8694	No	No	Wheat	Triticale	5/19	Taver Loam	2
	Great Bend Irrigated	38.3419, -98.8330	No	Yes	Corn	Rye	6/2	Kaski Loam	2
	Isabel	37.4876, -98.4903	No	Yes	Corn	Spring Oat	5/19	Clark Fine Sandy Loam	2

[a]Soil type information found at https://websoilsurvey.nrcs.usda.gov/app/

[b]NRCS termination zones found at https://www.nrcs.usda.gov/sites/default/files/2022-09/Termination_Guidelines_Designed_6.28_10.24am_%28002%29.pdf

Table 2.2 Mean (±SE) soybean yields for each location and corresponding county in 2018 and 2019 across Kansas. Growing season precipitation for cover crop (Oct 1 to April 30), soybean (May 1 to Sept 30), and total for the season for each location and 30-year county average are reported.

					Precipitation[a]			
Year	Location	County	Soybean Yield	County Yield	Cover crop season (Oct 1-April 30)	Soybean season (May 1-Sep 30)	Total season (Oct 1-Sep 30)	30-yr average[b]
			--------- $kg\ ha^{-1}$ --------		------------------------- mm -------------------------			
2018	Ottawa (KSU)	Franklin	2300 (110)	2900	271	368	639	990
	Oak Hill	Clay	1730 (80)	3100	170	562	732	809
	McPherson	McPherson	1030 (60)	3060	147	532	679	818
	Sheridan County Dryland	Sheridan	3250 (100)	4150	141	434	575	557
	Sheridan County Irrigated	Sheridan	4730 (110)	4150	141	434	575	557
2019	Ashland Bottoms (KSU)	Riley	4740 (170)	3100	413	789	1202	848
	Oak Hill	Clay	n/a[c]	3100	430	768	1198	809
	Great Bend Dryland	Barton	1930 (130)	2010	261	546	807	676
	Great Bend Irrigated	Barton	5080 (170)	2010	261	546	807	676
	Isabel Irrigated	Barber	4630 (170)	1800	396	564	960	729

[a] location and year-specific precipitation data found https://mesonet.k-state.edu/weather/historical/

[b] 30-year average precipitation data by county found at https://ksdata.ku.edu/ksdata/ksah/climate/17clim3.pdf

[c] Oak Hill yield data were not recorded in 2019.

Chapter 3 - Effect of Cover Crop Termination Time on Cover Crop Biomass, Weed Density and Corn (*Zea mays*) Yield

Abstract

Utilizing cover crops for assorted benefits including weed suppression is becoming more commonly adopted throughout Kansas. Some limitations remain in adoption in corn (*Zea mays*) production systems because of concerns about cover crop biomass reducing corn establishment, as well as reducing yield, especially where moisture is limited. Determining the most favorable termination time for cover crops is an important part of effectively managing them to ensure adequate corn yields as well as maximum weed suppression. The objectives of this research were to (1) determine the impact of termination time on cover crop biomass, weed density at 25 days after planting (DAP) corn, corn stand counts, and corn yield, and (2) compare the level of weed suppression from cover crops with or without soil-applied residual herbicides. Studies were established throughout Kansas in 2017-2018, 2018-2019 and 2019-2020 growing seasons. On-farm field experiments addressed objective 1 and had winter annual cover crops terminated at three or four different times relative to corn planting. Research station field experiments further addressed objective 2 and the use of residual herbicides applied at the same time as cover crop termination. Results indicated that delayed termination timings led to increased cover crop biomass accumulation and, in general, reduced weed densities. On-farm sites, where crop planting typically occurred between mid-April to mid-May, averaged 882 g m^{-2} of cover-crop biomass production. In on-station studies, corn planting occurred later (late May to early June) with a maximum of 1619 g m^{-2} of cover-crop biomass at Ashland Bottoms 2019 but less in 2020 with a drier spring. For on-station studies, excluding plots containing residual herbicide, the four weeks before planting termination resulted in an average of 74 weeds m^{-2}, while the at-planting

termination averaged 11 weeds m^{-2}. For all locations with residual applications, weed density was reduced compared to treatments containing no residual herbicide. Applying residual herbicide at all cover-crop termination times resulted in the same weed suppression 25 DAP as terminating the cover crop at planting with no residual herbicide. Generally, including cover crops for weed management prior to corn planting did not impact grain yields. This study showed that including at-planting and one week after planting cover-crop terminations can be successfully used to reduce weed densities without reducing corn yields.

Introduction

Corn is one of the most important crops grown in Kansas, with more than 2.77 million hectares planted and production valued at over $3.77 billion in 2023, making it the highest valued crop in the state (USDA-NASS 2026). One of the biggest challenges in corn production is weed control. Weeds can reduce corn yields by 50% or 148 billion kg each year across the United States and Canada, and 46% or 2.3 billion kg in Kansas (Soltani et al. 2017). Use of herbicides has been the main approach to managing weeds, but with ever increasing herbicide resistance, alternative methods of weed control are necessary to slow the evolution of resistant weeds (Harker 2013). Integrated weed management (IWM) can be defined as a "holistic approach to weed management that integrates different methods of weed control" to reduce weed pressures in cropping systems (Harker and O'Donovan 2013).

One principle of IWM is the use of cover crops (CC). Cover crops are a crop not taken to harvest but planted to fulfill other purposes such as weed suppression, erosion control, and improving soil health factors (SARE 2012). Specifically in corn, CC use has been shown to effectively reduce weed pressure and reduce reliance on chemical weed control (Grint et al.

2022; Osipitan et al. 2018). One of the most important factors in CC management is termination timing relative to cash crop planting. To prevent CC from competing with the cash crop, it is recommended to stop CC growth by chemical or mechanical means before planting (Qin et al. 2022). Terminating too early could reduce the ability of the CC to suppress weeds and promote soil health, whereas terminating too late can lead to concerns such as reduced crop emergence (Balkcom et al. 2016) and soil moisture depletion (Baxter et al. 2021).

Considering that IWM guidelines advise using multiple weed control methods to reduce overreliance on a single practice (Harker 2013), CC should be used with practices already shown to reduce weeds. One such practice is the use of residual herbicides, either pre-plant or early post-emergence. Whalen et al. (2019) concluded that although yields were often higher with treatments containing residual herbicides, significant CC biomass accumulation prevented the residual herbicide from reaching the soil. Pittman et al. (2019) demonstrated that several CC mixtures demonstrated good or better weed control than fall-applied residual herbicide applications. Often, residual herbicides are included in CC termination tank mixes (Maia et al. 2024), but to the best of our knowledge, this has yet to be extensively explored in Kansas cropping systems.

Winter annual species such as triticale (*X Triticoseacle*) and cereal rye (*Secale cereale* L) are commonly used CC for weed suppression. Winter annual cereals are preferred for their ability to produce more biomass than spring-planted species before cash crop planting. Winter annuals also fit well between cash crops in a common corn/soybean rotation sequence. Winter cereals have more time to establish and grow and can compete with winter annual and early emerging summer annual weeds (Balkcom et al. 2023; Grint et al. 2022). Weed suppression as influenced by CC, is measured as the reduction in both weed density and biomass. Cover crop biomass accumulation tends to be the most important factor to provide weed suppression (Grint et al. 2022; Mirsky et al. 2011; Petrosino et al. 2015). For fall-seeded CC, earlier fall planting and later spring termination increases the total biomass potential for CC. Generally, as CC biomass increases, subsequent weed densities and biomass decrease. Grint et al. (2022) found that fall-established cereal rye reduced weed density by 31% and weed biomass by 61% at the time of corn or soybean planting, relative to areas with no CC.

Guidelines for when to terminate CC relative to cash crops are based on recommendations developed by the National Resource Conservation Service (NRCS), which range from 35 days before planting, 15 days before planting, at cash crop planting, or just before emergence, based on county of residence (USDA-NRCS 2019). These guidelines provide information about how CC interact with the cash crop that may be insured. If an insurance claim is made, cover cropping management decisions will be reviewed by Risk Management Agency rules for Good Farming Practice determination to ensure that an insurance claim was not impacted by having a CC in place. These guidelines were generated based on research literature, plant growth, soil hydrology models and input from experts in CC management. The basis for the guidelines was to achieve CC conservation benefits while minimizing risk of reducing yield to the following crop due to soil water use.

Because all four NRCS cover-crop termination zones occur across Kansas, more localized data is needed to validate if these guidelines are appropriate for Kansas corn production. It is hypothesized that delaying CC termination to allow for maximum biomass accumulation will result in lower weed infestation and will not impact corn grain yields. Therefore, the objectives were to 1) determine the impact of CC termination timing on CC biomass, weed densities, corn stand, and grain yield, and 2) compare the level of weed suppression from CC with or without soil-applied residual herbicides in corn across Kansas.

Materials and Methods

Six site-years were established over three growing seasons, with three on-farm field sites and three on-station field sites (Table 3.1). In 2017-2018, one on-farm site was established near Rexford, KS. In 2018-2019, two on-farm sites included Great Bend and Oak Hill, with a third on-station site at the K-State Department of Agronomy Ashland Bottoms Research Farm near Manhattan, KS. In 2019-2020, on-station sites were established at Ashland Bottoms Research Farm and the K-State Department of Agronomy East-Central Kansas Research Farm near Ottawa, KS. Five sites were rainfed, and REX18 was irrigated via center pivot and this location was also strip-tilled prior to initiation of the study, thus leaving two of three rows of CC.

On-farm field sites were in a soybean-winter wheat-corn rotation sequence, with the exception of REX18 being soybean-corn rotation. Termination timing of CC was the main treatment at REX18, GB19, and OAK19, with three timings arranged in a randomized complete block design and four replications. Cover crops were bulk planted by the farmers using cereal rye at 100 kg ha^{-1} at REX18 and OAK19 and triticale at 110 kg ha^{-1} at GB19, using a drill with 19-cm spacing. Termination timings for REX18 were 2 weeks before planting (WBP), at planting (AP), 1 week after planting (WAP), and not terminated (NT). GB19 and OAK19 termination timings were 5 WBP, 2 WBP, AP, and 1 WAP.

On-station experiment sites at AB19, AB20, and OT20 had a main plot factor of presence or absence of CC and subplot factors as a two-way factorial of four termination timings and with or without residual herbicide, all arranged in a split-plot design with four replications. The CC was triticale, seeded using a John Deere 1590 no-till drill in rows spaced 19-cm apart at a rate of 100 kg ha^{-1}. On-station termination timings for AB19 were 5 WBP, 3 WBP, 1 WBP, and AP, while timings for AB20 and OT20 were 4 WBP, 3 WBP, 2 WBP, and AP.

Corn was planted the following spring in rows spaced 76 cm apart except for OAK19 where rows were spaced 38 cm apart. Cooperating farmers planted their desired corn hybrids at local recommended seeding rates. At AB19 the corn hybrid was Channel 209-15VT2PRIB (Bayer Crop Science, St. Louis, MO), and at AB20 and OT20 the corn hybrid was Dekalb 64-25 DGVT2PRIB (Bayer Crop Science, St. Louis, MO) seeded at 64,000 seed ha^{-1}. For on-station studies, 112 kg ha^{-1} of nitrogen and 22 kg ha^{-1} of phosphorus were broadcasted by hand pre-plant using urea and monoammonium phosphate fertilizers. At the V5 corn stage, an additional 56 kg ha^{-1} of nitrogen was applied via side-dress. No data on fertilizers applied was available for the on-farm studies.

Cover crops were chemically terminated with glyphosate (Roundup Powermax®, Bayer Crop Science, St. Louis, MO) at 1420 g ha^{-1} plus 2% liquid ammonium sulfate (N-Pak, WinField Solutions, LLC, St. Paul, MN). For the studies at AB19, AB20, and OT20, treatments that included a residual herbicide were sprayed with a tank mixture of glyphosate (1420 g ha^{-1}) + AMS and a pre-mix of s-metolachlor (600 g ha^{-1}) + atrazine (280 g ha^{-1}) + mesotrione (67.3 g ha^{-1}) + bicyclopyrone (16.8 g ha^{-1}) (Acuron®, Syngenta Crop Protection, Greensboro, NC). Herbicide applications were applied using a CO_2-pressurized backpack sprayer with a 1.5-m boom with four 8002VS nozzles (Teejet Technologies, Wheaton, IL) in a spray volume of 150 L ha^{-1} with an application pressure of 276 KPA.

For each site, CC biomass was sampled just prior to each termination timing by measuring 57.15 cm across three rows and 50 cm of row length (capturing an area of 0.29 m^2).

All CC biomass was clipped at the soil surface, placed in a bag, and dried at 60 C until constant weight was achieved. Weed counts and corn stand counts were taken 25 days after corn planting across all treatments. Weed counts were taken by randomly placing a single 0.25 m^2 quadrat within each plot and counting individual plants. Corn plant stand counts were taken from the center two rows of each plot, counting the number of plants from the beginning to the end of those rows. To estimate yield, corn was hand harvested by taking all ears from a four-m length of the center two rows of each plot, machine threshing the grain from the ears, and adjusting yields to 15.5% moisture content. On-station sites were harvested with a plot combine.

All data were analyzed using R 4.5.2 (R Core Team 2025). The three on-station location-years were analyzed separately from the three on-farm locations because of different experimental designs and treatments. Cover-crop biomass, weed counts, and grain yield data were analyzed for on-farm experiments as a randomized complete block design. For each measurement, the fixed effect was termination timing, and the random effect was replication. Because data met ANOVA assumptions of normality and homogeneity of variance, ANOVA analyses were analyzed using the lmerTest (Kuznetsova et al. 2017) package, and post hoc tests were conducted with the emmeans (Lenth and Piaskowski 2025) package. Tukey's Honest Significant Difference was used to determine differences among factors using a confidence interval of 0.05.

The on-station experiments were a split-plot arrangement of presence or absence of CC as whole plots and a factorial combination of termination timing and inclusion of residual herbicides as subplots. Linear mixed effects models were used to analyze the response variables of CC biomass, weed densities, corn stand counts, and grain yield. For the on-station studies with residual treatments, weed counts were analyzed with fixed effects being the combination of termination timing and residual, with random effects being replication nested within the combination of termination timing and residual. Due to the non-normal data distribution, these analyses were conducted using the glmmTMB (Brooks et al. 2017) package and by using a beta distribution. Data were transformed with the logit transformation and automatically back transformed for interpretation. ANOVA models were used with a Type III Wald chi-square test (Miranda et al. 2022), and the DHARMa (Hartig 2022) package was used to check all ANOVA assumptions. For cover crop biomass, data were analyzed as a randomized complete block design because treatments with no CC were not included in this analysis, and residual herbicide was not analyzed as a factor. Thus the fixed effect was termination timing and the random effect was replication. For corn stand counts and grain yield, only data from plots that had residual herbicide applied were analyzed to ensure that weed pressure did not confound results. These data were analyzed as a split-plot with fixed effects of CC and termination timing, and random effects included replication and replication-by-CC interaction.

Results and Discussion

Impact of termination timing on cover crop biomass

The amount of CC biomass produced was affected by termination timing at all three on-farm locations: REX18, GB19, and OAK19 ($p < 0.0001$ for each location). In general, CC biomass increased as termination times were delayed (Table 3.2). At REX18, the farmer wanted to explore the impact of not terminating (NT) the CC that remained between corn rows. This resulted in 14 times more biomass (sampled at 25 DAP) than when terminated at 2 WBP. At GB19, biomass increased by 4.5 times from 2 WBP to 1 WAP, with 1 WAP producing 882 g m^{-2}. At OAK19, biomass increased by 5.1 times from 2 WBP to 1 WAP, with 1 WAP producing

362 g m^{-2}. Rexford accumulated the least amount of biomass among the on-farm locations because the field was strip-tilled prior to any terminations, which removed approximately 33% of the cereal rye. While this field had irrigation, it was not used during the CC portion of the growing season, and Sheridan County received less rainfall than the other two more easterly locations (Table 3.2). At GB19 and OAK19, the CC was at the heading stage by 1 WAP, appropriate for terminating cereal rye. This indicated that the CC were close to their maximum biomass accumulation.

The amount of CC biomass also differed by termination timing at all three on-station locations ($p < 0.0001$ for each location) (Figure 3.2). For each location, the AP termination timing accumulated the most biomass (1630, 690, and 354 g m^{-2} for AB19, AB20, and OT20, respectively). Across site-years, less total CC biomass was produced at AB20 and OT20 by AP termination that occurred on May 19 and 20, respectively, compared to June 5 at AB19. Corn planting in 2019 was delayed due to excessively wet spring conditions where AB19 received 1202 mm of rainfall, significantly more than the 30-year average of 848 mm. This delay allowed for more CC biomass to be produced before AP termination. At AB19, biomass produced between 3 and 1 WBP was equivalent to the total produced by the AP termination at AB20. Total rainfall at AB20 was 983 mm and greater than the 30-year average (848 mm). At OT20, only 659 mm was received and much less than the 30-year average (990 mm) and resulted in overall less CC biomass being produced. Our research results for the on-station and on-farm locations were consistent with Grint et al. (2022) who found that CC biomass can be maximized by terminating at cash crop planting time. Generally, increases in winter annual CC biomass can lead to early season weed suppression, allowing cash crops to gain a competitive advantage against weeds (Teasdale 1996).

Impact of cover crop biomass on weed density on-farm

Differences in weed density at 25 DAP were observed among CC termination timings for each location ($p < 0.0001$ for all locations) (Table 3.3). Weed species observed were primarily Palmer amaranth (*Amaranthus palmeri* S. Wats.) and some grasses including yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.] and large crabgrass [*Digitaria sanguinalis* (L.) Scop). Weed densities were reduced as termination timings were delayed. In REX18, the greatest number of weeds were observed in the 2 WBP termination treatment, while significantly fewer weeds were counted in 1 WAP treatment, and the fewest weeds were found in NT. No cover treatment (terminated at 5 WBP) at GB19 and OAK19 had the greatest number of weeds, while the fewest weeds were observed in the latest termination time of 1 WAP. This aligns with Mirsky et al. (2011) who found that later cover crop termination times have greater CC biomass accumulations and fewer weeds by 25 DAP.

Impact of integrating cover crops and residual herbicides on weed density on-station

Weed density at 25 DAP was not affected by the three-way interaction of CC by termination time by residual herbicide for AB19 and AB20 (Table 3.4), but it was for OT20 ($p=0.0117$) (Table 3.5). For AB19, differences in weed density were observed for the interaction of termination time by residual herbicide ($p < 0.0001$) and the interaction of cover crop by residual herbicide ($p=0.004$). For AB20, differences in weed density were observed for the interaction of termination timing by residual herbicide ($p < 0.0276$) but not for the interaction of termination timing with CC (Table 3.4).

At AB19, all the CC and no cover crop treatments received a burndown application of glyphosate at the respective termination timing. In plots that received no residual herbicide with no cover crop, there were weeds present by 25 DAP corn in plots that were terminated at 5, 3, and 1 WBP (Table 3.4). By adding a residual herbicide, weed emergence was prevented between 5 WBP to AP. Burndown with glyphosate at corn planting, with or without a residual, effectively reduced weeds at 25 DAP, because these were not glyphosate-resistant weed populations. When adding a CC, even fewer weeds were observed by 25 DAP where residual herbicides were not applied. Cover crops reduced the weed infestation by 30% in the early termination times without residual herbicide in the burndown (data not shown). Combining CC with residual herbicides reduced the number of weeds at 25 DAP. The presence of a CC reduced weed density at AB19. There was an interaction effect on weed density, where the latest termination time and the use of a residual herbicide had the fewest weeds. The use of a residual herbicide had the greatest impact on weed density reduction of all treatments.

At AB20, there was no effect of CC presence on weed counts at 25 DAP. The interaction of termination timing with a burndown and no residual herbicide resulted in more Palmer amaranth at 25 DAP, when applied at 4, 3, and 2 WBP. The AP termination timing with no residual herbicide produced the same weed densities at the 4 WBP termination with residual herbicide. (Table 3.4). However, the 3 WBP, 2 WBP and AP termination times that included a residual herbicide produced the lowest weed densities. The reduced CC biomass in 2020 compared to 2019 possibly explains the lack of weed suppression attributed to CC in the second year.

At OT20, weed counts at 25 DAP were affected by timing of termination with fewer than 27 plants m^{-2} observed with the AP termination timings, and more than 60 plants m^{-2} at 4 and 3

WBP. Adding a residual herbicide reduced weeds observed 25 DAP from 120 m^{-2} with no residual to 20 m^{-2} with residual (Table 3.5). At OT20, CC did not affect weed densities, likely due to the lower CC biomass production at all four termination times (compared to the other studies).

Combining residual herbicides and CC has been explored previously, with mixed results. Whalen et al. (2019) concluded that soil-applied herbicides can be integrated into CC programs, but termination timing and biomass accumulation will influence how much herbicide reaches the soil. Similarly, Maia et al. (2025) reported that between 75 and 83% of the soil residual herbicides were intercepted by cereal rye that had been terminated by a roller-crimper but still reported that grass weed species were reduced due to the herbicide in some treatments. Additionally, Perkins et al. (2020) reported that combining residual herbicides with CC led to increased Palmer amaranth and/or waterhemp but still expressed concern that CC residue interfered with residual herbicide applications. It is possible that not all of the residual herbicide reached the soil (especially as CC biomass increased), but our data clearly showed that using residual herbicides with CC reduced weed infestations compared to using CC without residual herbicides. Because residual herbicides and CC are both important tools for integrated weed management (Maia et al. 2025), we argue that they can be used with one another to further reduce weed populations.

Impact of cover crops on corn production in on-farm and on-station studies

In the on-farm studies, no differences in corn yields were observed among CC termination timings at a given location, except for OAK19 (Table 3.2). At OAK19, yields from plots terminated 1 WAP were less than the no cover treatment (terminated 5 WBP) and AP, but were not less than 2 WBP termination timings. Overall yields varied by site-year. REX18 had the greatest average yield (14,120 kg ha^{-1}) likely due to irrigation, whereas GB19 had 5,400 kg ha^{-1} and OAK19 had 6,640 kg ha^{-1} average corn yields in dryland production (Table 3.2). These were similar to the county average yields in those years (USDA-NASS 2025).

No differences in corn stand count were observed among treatments for all studies established on KSU research farms. Average stand counts for AB19, OT20, and AB20 were 62,627, 64,325, and 60,850 plants ha^{-1}, respectively.

No differences in grain yield were detected at two of the three on-station locations, (AB19 and OT20). At AB20, corn yield differences were observed between the main effects of CC ($p < 0.0001$) and of termination timing ($p = 0.0006$) (Figure 3.3). At AB20, grain yields with CC were generally lower than those without. Treatments with and without CC resulted in a mean corn yield of 11,964 (±169) and 13,157 (±169) kg ha^{-1}, respectively. For the termination timings, 4 WBP, 3 WBP, and AP, corn yields did not differ, but the 2 WBP yield (11,663 (±238) kg ha^{-1}) was less than both 4 WBP and AP. More CC biomass at 2 WBP, coupled with deteriorating straw integrity, may have influenced corn establishment and therefore growth as compared to plots without CC, and resulted in lower corn yields as a result.

Our results for stand counts and yield are consistent with some studies, but conflict with others. The variation in stand counts was observed by Acharya et al. (2017). In 2014, they reported no corn stand count reductions in CC crops vs. no CC, but in 2015 all CC treatments resulted in lower stand counts. Smith (2021) observed reductions in corn stand counts in treatments with delayed CC termination timing. Because some studies report reductions in stand counts but not others, we suggest that stand count reductions are dependent on the growing season, and any crop stand losses due to CC treatments could be related to factors such as weather. Additionally, the correct planting equipment and settings are critical for stand establishment, because some equipment can handle high residue cropping systems more effectively than others (Maia et al. 2025).

Regarding yield, Acharya et al. (2017) reported that for 2014, the latest CC termination timing reduced corn yield, whereas in 2015, all yields were reduced compared to the no-rye treatment. A meta-analysis conducted by Marcillo and Miguez (2017) concluded that winter annual grass CC neither increased nor decreased corn yields. Our results generally support no yield reductions due to CC in corn, except for AB20. As stated before, proper planting equipment is critical to planting into high CC biomass residue. Further options for study on this topic include comparing different planter types and performances across a wide range of CC biomasses to assess stand count losses and yields.

Overall summary of using cover crops in corn

This multi-year study provides data to show that termination timing of CC has minimal impact of corn stands or yield but does show significant impact on reducing weed densities with later termination timings, specifically for Palmer amaranth. The NRCS guidelines on CC termination timings did not affect the yields except for OAK19, and AB20 where loss of yield was still minimal, yet the best weed suppression was observed when CC were terminated later than the NRCS recommended times.

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Figures

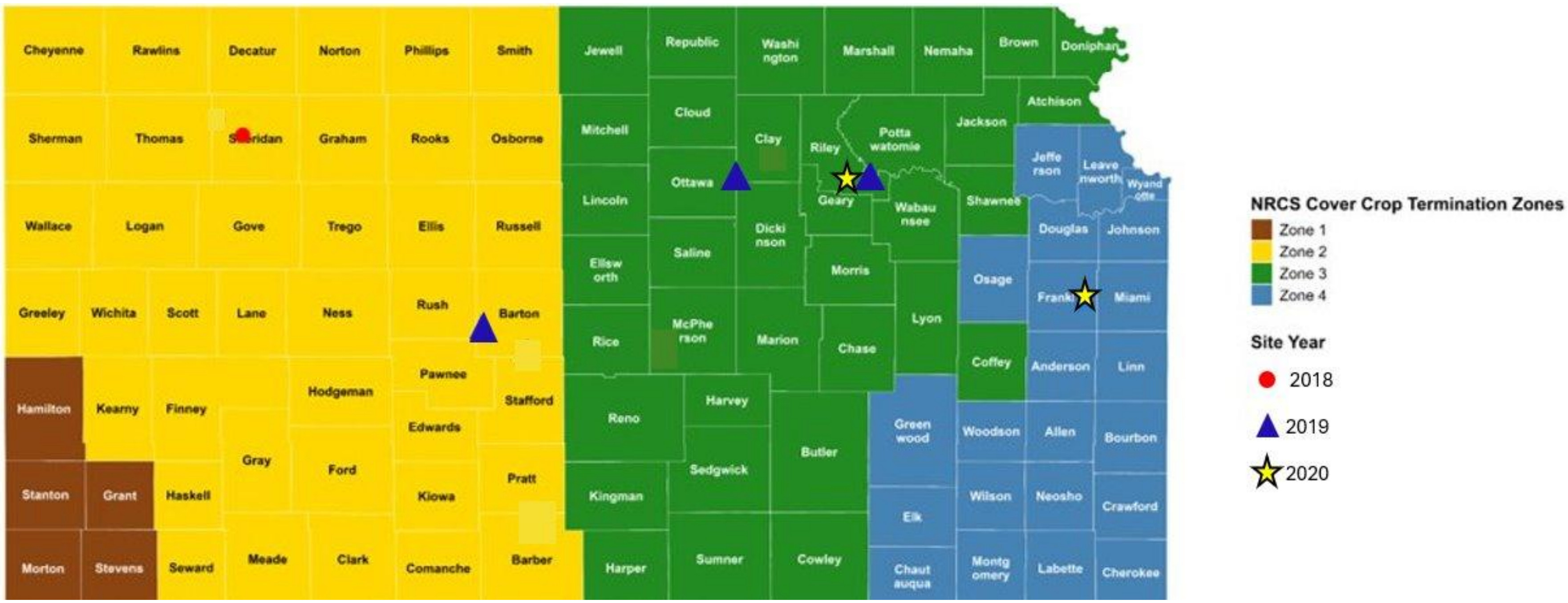

Figure 3.1 Map of Kansas with experiment locations for 2018 (red circles), 2019 (blue triangles), and 2020 (yellow stars). NRCS termination timing zones are depicted for each county with zones 1, 2, 3, and 4 corresponding to 35 days before planting, 15 days before planting, at or before planting, and before crop emergence, respectively (USDA-NRCS 2019).

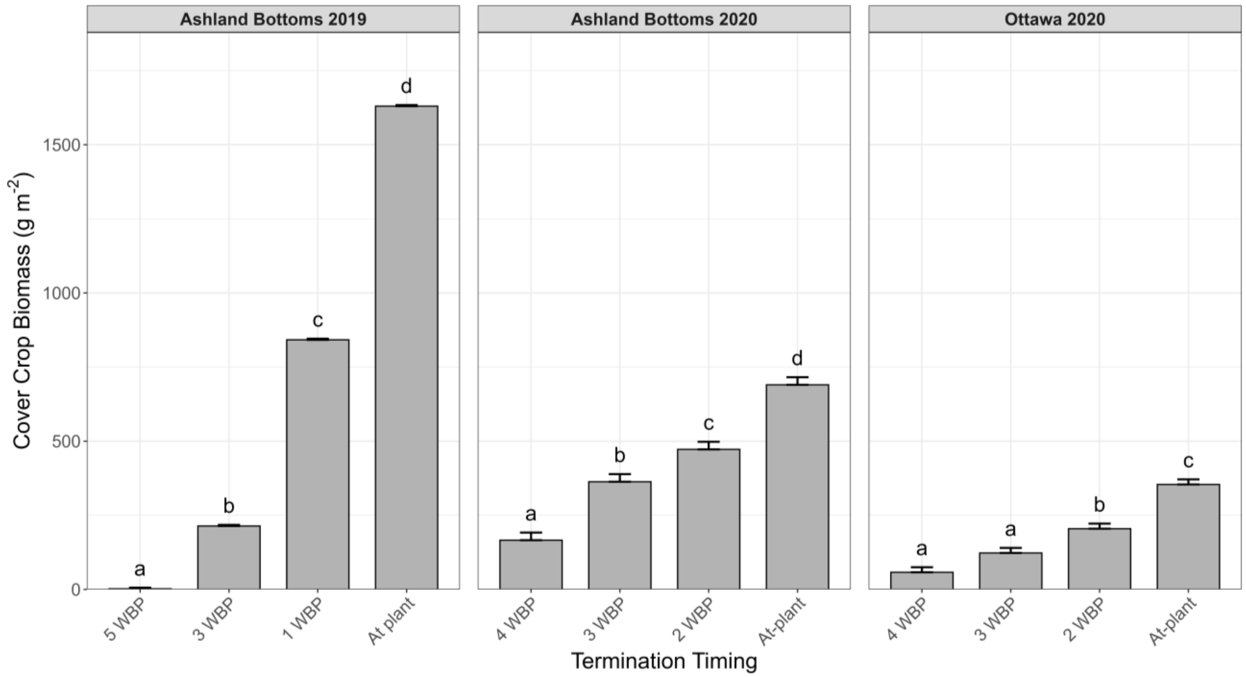

Figure 3.2 Effect of termination timing relative to corn planting on cover crop biomass (g m^{-2}) for Ashland Bottoms 2019, Ashland Bottoms 2020, and Ottawa 2020 on-station locations. Biomass was analyzed with a one-way ANOVA for each location followed by a Tukey Honest Significant Difference post-hoc test ($p < 0.05$) for mean separation.

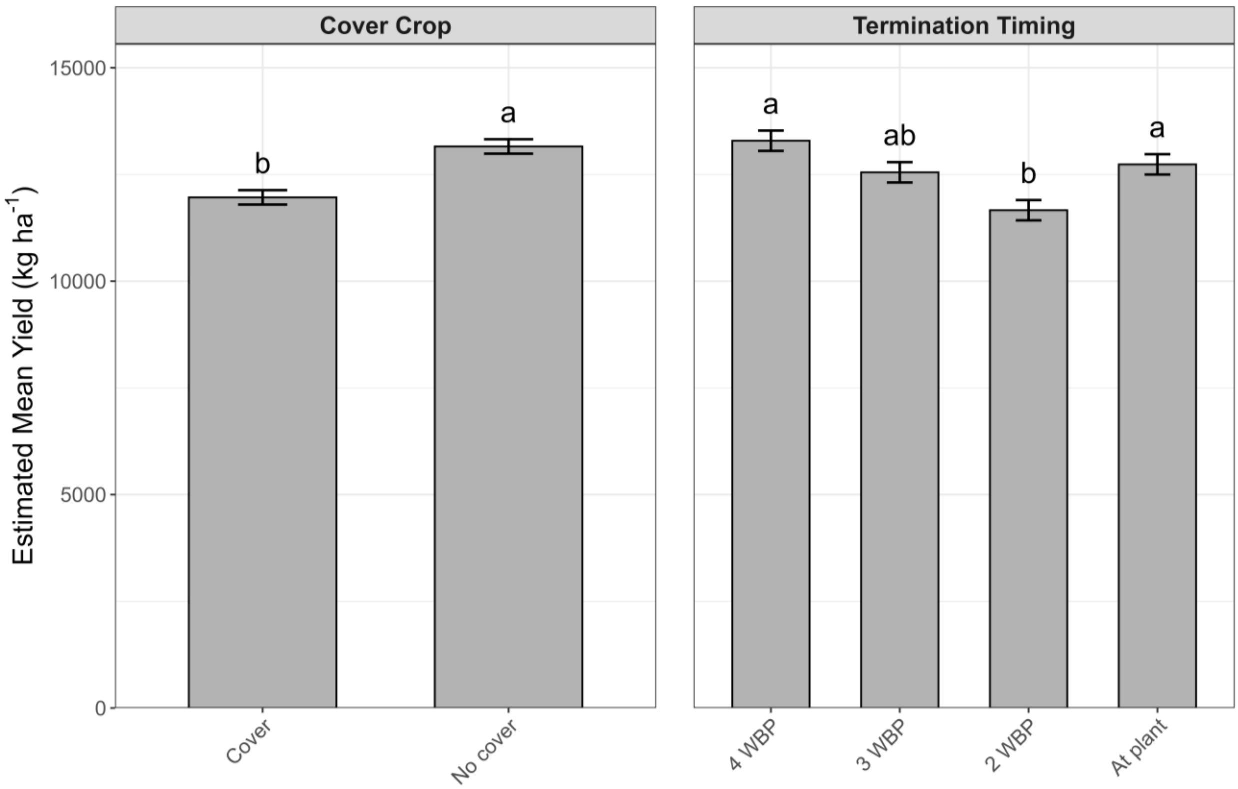

Figure 3.3 Corn grain yield as influenced by main effects of cover crop and termination timing relative to corn planting at the Ashland Bottoms 2020 on-station location. Grain yield was analyzed with a one-way ANOVA followed by a Tukey Honest Significant Difference post-hoc test ($p < 0.05$) for mean separation. Abbreviation: WBP, weeks before planting.

Tables

Table 3.1. Location-specific information including coordinates, previous crop, cover crop, corn planting date and soil series for each corn experiment in Kansas. Abbreviations: DC, double-crop

Year	Location	Location code	Coordinates	Previous crop	Cover crop	Corn planting date	Soil series[a]
2018	Rexford	REX18	39.3544, -100.8136	Soybean	Cereal rye	4/25/18	Keith silt loam
2019	Great Bend	GB19	38.3745, -98.8754	Wheat-fallow	Triticale	5/16/19	Taver loam
2019	Oak Hill	OAK19	39.2334, -97.2100	DC soybean	Cereal rye	4/19/19	Crete silty loam
2019	Ashland Bottoms	AB19	39.1205, -96.6374	Wheat-fallow	Triticale	6/5/19	Reading silt loam
2020	Ashland Bottoms	AB20	39.1205, -96.6374	Fallow	Triticale	5/20/20	Reading silt loam
2020	Ottawa	OT20	38.5380, -95.2427	Fallow	Triticale	5/19/20	Woodson silt loam

[a]Soil series information found at https://websoilsurvey.nrcs.usda.gov/app/.

Table 3.2 Precipitation received at each on-farm location during the cover crop and corn growing seasons, as well as season total and 30-year average in 2018 and 2019.

		Precipitation			
		Cover crop season	Corn season	Season	30-yr
Year	Location	(Oct 1- April 30)[a]	(May 1 – Sep 30)[b]	total[c]	Average[d]
		---------------------------------- mm -------------------------------			
2018	Rexford	87	343	430	518
2019	Great Bend	261	546	807	676
2019	Oak Hill	430	768	1198	809

[abc] Site/year specific data found at https://mesonet.k-state.edu/weather/historical/.

[d] 30-year average precipitation date by county found at https://ksdata.ku.edu/ksdata/ksah/climate/17clim3.pdf

Table 3.3 Mean (±SE) for cover crop biomass at termination (g m^{-2}), weed density at 25 days after corn planting (plants m^{-2}), and corn yield (kg ha^{-1}) for each on-farm location across Kansas in 2018 and 2019. Means followed by the same letter are not different at $\alpha = 0.05$ within site-years. Abbreviations: WBP, weeks before planting corn; AP, at planting; WAP, weeks after planting corn; NT, not terminated.

Year	Location	Termination timing	Cover crop biomass	Weed density	Corn grain yield
			g m^{-2}	plants m^{-2}	kg ha^{-1}
2018	Rexford	2 WBP	20 (2) c	445 (14) a	13,698 (1313)
		AP	36 (2) c	355 (24) b	14,764 (603)
		1 WAP	140 (10) b	177 (16) c	13,574 (236)
		NT	287 (9) a	62 (11) d	14,436 (639)
2019	Great Bend	5 WBP	9 (2) d	152 (7) a	4805 (1781)
		2 WBP	194 (8) c	64 (6) b	5518 (1172)
		AP	530 (9) b	54 (4) b	5780 (1000)
		1 WAP	882 (14) a	18 (5) c	5504 (1153)
2019	Oak Hill	5 WBP	4 (1) d	244 (9) a	7644 (1156) a
		2 WBP	71 (2) c	144 (7) b	6423 (1061) ab
		AP	175 (4) b	121 (6) b	7783 (296) a
		1 WAP	362 (6) a	48 (6) c	4690 (1388) b

Table 3.4 Mean (±SE) weed density at 25 days after corn planting as influenced by the two-way interactions of residual herbicide application and termination timing, and residual herbicide and cover crop in 2019, and the two-way interaction of residual herbicide and termination timing in 2020 for Ashland Bottoms, KS. Mean weed density followed by the same letter are not different at $\alpha = 0.05$ for each year. Abbreviations: WBP, weeks before planting corn; AP, at planting; WAP, weeks after planting corn

	Treatments				
Year	Residual herbicide	Termination timing	Cover crop	Weed Density	
				plants m^{-2}	
2019	No	5 WBP		181 (25)	a
	No	3 WBP		190 (25)	a
	No	1 WBP		120 (22)	a
	No	AP		6 (3)	b
	Yes	5 WBP		10 (4)	b
	Yes	3 WBP		7 (3)	b
	Yes	1 WBP		4 (2)	b
	Yes	AP		4 (2)	b
	No		No	112 (16)	a
	No		Yes	5 (2)	c
	Yes		No	51 (10)	b
	Yes		yes	7 (2)	c
2020	No	4 WBP		92 (19)	a
	No	3 WBP		109 (21)	a
	No	2 WBP		106 (21)	a
	No	At-Plant		29 (9)	b
	Yes	4 WBP		16 (6)	bc
	Yes	3 WBP		6 (2)	c
	Yes	2 WBP		5 (2)	c
	Yes	At-plant		5 (2)	c
			No	26 (5)	ns
			Yes	22 (4)	

Table 3.5 Mean (±SE) weed density at 25 days after corn planting as influenced by the three-way interactions of cover crop, residual herbicide application and termination timing in 2020 for Ottawa, KS. Mean weed density followed by the same letter are not different at $\alpha = 0.05$. Abbreviations: WBP, weeks before planting; AP, at planting.

Cover crop	Residual herbicide	Termination time	Weed Density	
			plants m^{-2}	
no	no	4 WBP	73 (31)	ab
no	no	3 WBP	286 (87)	a
no	no	2 WBP	82 (31)	ab
no	no	AP	87 (33)	ab
no	yes	4 WBP	6 (4)	c
no	yes	3 WBP	6 (4)	c
no	yes	2 WBP	5 (3)	c
no	yes	AP	4 (3)	c
yes	no	4 WBP	174 (57)	ab
yes	no	3 WBP	69 (28)	b
yes	no	2 WBP	104 (39)	ab
yes	no	AP	7 (4)	c
yes	yes	4 WBP	7 (4)	c
yes	yes	3 WBP	6 (4)	c
yes	yes	2 WBP	5 (3)	c
yes	yes	AP	7 (4)	c