On-farm evaluation of cover crop and residual herbicide integration for weed suppression in north-central Kansas

by

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Abstract

Palmer amaranth (*Amaranthus palmeri* S. Watson) and other herbicide-resistant weeds threaten the sustainability of no-till crop production in Kansas, where weed control relies mostly on herbicides. Cover crops (CC) can suppress weeds, but no single tactic provides consistent control, and local information on how to integrate CC with soil-residual herbicides within integrated weed management (IWM) programs is lacking for producers in rainfed north-central Kansas. The overall goal was to evaluate how CC and herbicide program combinations affect weed suppression, crop yield, and gross margin. Two on-farm studies were conducted in 2025 and 2026 at Oak Hill, KS. The objectives were to determine 1) the effects of cereal rye (*Secale cereale* L.) CC condition at herbicide application, dead (terminated 10 d before planting) or living (terminated at planting), soil-residual herbicides (dimethenamid-P or flumioxazin), and methylated seed oil (MSO) on Palmer amaranth suppression, soybean [*Glycine max* (L.) Merr.] yield, and gross margin, and 2) the effects of triticale (*Triticosecale* Wittm. ex A. Camus) -hairy vetch (*Vicia villosa* Roth) CC mixtures and rye CC, terminated with burndown herbicides with or without flumioxazin, compared with chemical fallow, on CC biomass, weed suppression, and late-planted corn (*Zea mays* L.) yield and gross margin. In the soybean study, flumioxazin delayed 10% Palmer amaranth emergence to 28 d after application, compared with 3 d with no residual herbicide, and reduced Palmer amaranth density at soybean canopy closure by 85 to 87% regardless of CC condition, including no CC in 2026. Dimethenamid-P did not differ from the control in emergence, and MSO did not improve either herbicide. Soybean yield was 8% greater with dead than with living CC only in 2025, which resulted in a \$70 ha^{-1} greater gross margin despite the \$44 ha^{-1} cost of the additional termination pass. Flumioxazin produced the same yield as dimethenamid-P but cost \$21 ha^{-1} less. In the late-planted corn study, rye CC

produced the most biomass in 2025 (11,630 kg ha^{-1}) but the least in 2026 (1,850 kg ha^{-1}), when a warm, dry spring required early termination. The triticale-hairy vetch mixtures produced similar biomass in both years. In 2025, all CC and herbicide program combinations reduced summer weed cover at corn planting by more than 99% relative to chemical fallow. In the 2026 season, only the triticale-hairy vetch mixtures terminated with flumioxazin consistently reduced weed cover and summer weed biomass (62 to 95%) relative to chemical fallow. Corn yield after CC was 25 to 35% less than after chemical fallow in 2025. In 2026 the triticale-hairy vetch mixtures yielded 500 kg ha^{-1} more than chemical fallow, but greater direct costs ($107 to $192 ha^{-1}) of CC mixtures resulted in less gross margin than chemical fallow in both years. Overall, the residual herbicide rather than CC condition or MSO drove Palmer amaranth control before soybean. Before late-planted corn, weed suppression was best when CC was integrated with an effective residual herbicide across years. Integrating CC with herbicides was more complex and more costly than herbicide-only programs in the short term. Producers who include CC in IWM programs should set clear goals for the CC, base management on the ecology of the dominant weed species and on their crop rotation, adjust herbicide programs to the CC, and consider additional CC uses, such as forage, to offset their short-term costs.

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Chapter 1 - Introduction and Literature Review

1.1 Weed Management in No-Till Production Systems

No-till production systems revolutionized U.S. Midwest row-crop agriculture by greatly reducing soil erosion (Triplett and Dick 2008). Crop residue left on the soil surface increases soil water storage and crop water-use efficiency and improves soil physical properties (Blanco-Canqui and Ruis 2020; Triplett and Dick 2008). Eliminating mechanical cultivation passes for weed control simplified operations and increased farmers' operational capacity and profitability.

No-till adoption was facilitated by a technological package of herbicide-resistant crops and herbicides, which brought ease for weed control (Duke and Powles 2008). Weeds are controlled with soil-applied residual herbicides before emergence (PRE) and foliar-applied herbicides after emergence (POST) (Norsworthy et al. 2012). Widespread herbicide use led to shifts in weed communities. Only 4 yr after glyphosate-resistant soybean *[Glycine max* (L.) Merr.] was introduced, glyphosate-resistant horseweed (*Erigeron canadensis* L.) was confirmed in no-till fields in Delaware (VanGessel 2001). Repeated use of herbicides with the same site of action (SOA) has since led to 550 unique resistance cases in 276 weed species, with resistance to 21 of 31 known SOA (Heap 2026), reducing the herbicide options available for satisfactory weed control.

Small-seeded species are better adapted to no-till systems and more likely to evolve herbicide resistance (Norsworthy et al. 2012; Osipitan et al. 2019). *Amaranthus* species stand out for their competitiveness and prolific seed production (Bravo et al. 2018; Jha 2008). Palmer amaranth (*Amaranthus palmeri* S. Watson) interference reduced corn (*Zea mays* L.) yield by 11 to 91% (Massinga et al. 2001) and grain sorghum *[Sorghum bicolor* (L.) Moench] yield by 1.8 to 3.5% for each additional plant per 15 m of row (Moore et al. 2004). A six-way SOA-resistant

Palmer amaranth population was confirmed in Kansas (Shyam et al. 2021), raising concerns among producers.

Herbicide resistance has increased weed management costs and herbicide use. Herbicide use intensity increased over 25 yr in major U.S. crops (Kniss 2017). Programs now require tank mixtures of two or more effective SOA and additional applications (Norsworthy et al. 2012). Mixtures can delay but not prevent resistance (Evans et al. 2016), and resistance management lowers profits in the short term but increases them in the long term (Livingston et al. 2016).

However, weed control may bring multiple problems for sustainable management. Chemical fallow leaves soil with little cover for months, increasing the risk of wind and water erosion; replacing fallow with cover crops (CC) in no-till reduced soil erodibility and runoff losses of sediment and nutrients (Blanco-Canqui et al. 2013). Across studies, CC reduced runoff volume by 10 to 98% and sediment loss by 22 to 100% (Blanco-Canqui 2018). Herbicides have been detected in groundwater and drinking water (Almberg et al. 2018; Ritter et al. 1994). Improper applications often result in off-target movement (drift), injuring sensitive crops and non-crop areas every year (Oseland et al. 2024; Soltani et al. 2020). These concerns have led to bans and lower allowed rates for some herbicides. Atrazine was banned in the European Union because of groundwater contamination (Sass and Colangelo 2006). In Wisconsin, atrazine use is prohibited in designated areas, and the maximum annual rate is limited to 0.84 to 1.12 kg ai ha^{-1} depending on soil texture (Wisconsin Administrative Code 2025). In addition, after new herbicide sites of action were introduced steadily from the 1950s to the mid-1980s, no herbicide with a new site of action was commercialized for major field crops until the late 2010s (Dayan 2019; Duke 2012). Together, these factors have reduced effective herbicide options and threaten the sustainability of no-till systems (Vencill et al. 2012).

Integrated weed management (IWM) combines chemical, cultural, mechanical, and biological tactics to reduce reliance on herbicides and slow resistance evolution (Harker and O'Donovan 2013; Swanton and Weise 1991). Rather than relying on a single highly effective tool, IWM is based on the concept of 'many little hammers', in which several partially effective tactics are combined so that their cumulative effect provides adequate control while reducing the selection pressure imposed by any single tactic (Liebman and Gallandt 1997). In no-till systems, this approach involves intensifying the crop rotation with cultural practices, such as cover crops, alongside chemical control to reduce reliance on herbicides (Petrosino 2010, p. 48). Among these tactics, cover crops align well with no-till principles and have gained attention for weed management (Kumar et al. 2020; Osipitan et al. 2019).

1.2 The Alternative Method of Weed Control: Cover Crops, Mechanisms, and Advantages

Cover crops are non-harvested crops, usually established in the fall and grown between summer cash crops in the U.S. Midwest (Blanco-Canqui and Ruis 2020; Osipitan et al. 2018). As a cultural practice, CC are well suited to no-till systems because their residue remains on the soil surface without soil disturbance (Kumar et al. 2020; Teasdale 1996). They are especially effective at suppressing small-seeded weeds, including herbicide-resistant *Amaranthus* species (Osipitan et al. 2019; Wiggins et al. 2016).

Cover crops suppress weeds by competing for light, water, and nutrients, releasing allelopathic compounds, physically impeding emergence, and modifying the soil environment (Creamer et al. 1996; Osipitan et al. 2019; Quintarelli et al. 2022). Competition and allelopathy act mainly while the CC is alive and shortly after termination (Rice et al. 2022; Teasdale 1996).

While growing, CC also suppress winter annual weeds that emerge with them, mainly through competition for soil nitrogen early in the season and for light later in the season, and this suppression is driven by CC biomass rather than by CC species diversity (MacLaren et al. 2019). Cover crop residue (mulch) provides the most consistent suppression of summer annual weeds (Osipitan et al. 2019; Teasdale 1996). The mulch acts as a physical barrier and reduces light transmittance, mean soil temperature, and daily temperature fluctuations (Teasdale 1993; Teasdale and Mohler 2000). The amount of CC biomass is the key driver of suppression: 3,300 to 6,600 kg ha^{-1} can suppress 50% or more of weed recruitment (Nichols et al. 2020; Osipitan et al. 2018; Weisberger et al. 2023).

Weed suppression by CC is species-specific. Large-seeded species have greater seed reserves to emerge through the mulch and depend less on light for germination than small-seeded species (Milberg et al. 2000; Seibert and Pearce 1993; Teasdale and Mohler 2000). At equal CC biomass, velvetleaf (*Abutilon theophrasti* Medik.) emergence was reduced by 26%, compared with 68% for redroot pigweed (*Amaranthus retroflexus* L.) (Mohler and Teasdale 1993). *Amaranthus* species need light and wide daily temperature fluctuations to break dormancy, and CC mulch reduces both (Jha 2008; Teasdale 1996). Cover crops mainly reduce weed emergence and density, but their effect on the biomass of surviving weeds is less certain. In the U.S. Southeast, CC reduced weed density but not weed biomass (Weisberger et al. 2023). Across the U.S., CC reduced weed biomass by 63% and density by 45% (Dong and Zeng 2024). For *Amaranthus* species, more CC biomass was needed to reduce weed biomass by 50% than weed density (5,352 vs 4,079 kg ha^{-1}) (Kumar et al. 2024). Cover crop residue can also delay weed emergence. Palmer amaranth needed 66 to 643 more growing degree days to reach 90% cumulative emergence after a CC mixture than in chemical fallow (Dhanda et al. 2024). Later-

emerging weeds cause smaller crop yield losses (Massinga et al. 2001), and delayed emergence may allow more time for other weed management practices. Cover crop residue can also make emerging weeds more susceptible to follow-up herbicide applications, possibly because seedlings deplete their seed reserves while growing through the residue (Teasdale et al. 2005).

The duration of weed suppression depends on residue persistence, which is driven by the carbon-to-nitrogen (C:N) ratio of the residue (Pittman et al. 2020; Swift et al. 1979). The C:N ratio varies by species and growth stage: legumes such as hairy vetch (*Vicia villosa* Roth) and clovers (*Trifolium* spp.) typically have C:N ratios of 10:1 to 20:1, whereas cereal rye (*Secale cereale* L.) and triticale (× *Triticosecale* Wittm. ex A. Camus) at reproductive stages reach 45:1 to 80:1 (Clark 2007). About 90% and 50% of surface residue decomposed after 1 yr for C:N ratios of about 20:1 and 80:1, respectively (Jahanzad et al. 2016; Schomberg et al. 1994). Low C:N residues therefore decompose faster and provide a shorter duration for weed suppression (Johnson et al. 2007; Poudel et al. 2020). Pittman et al. (2020) found that 50% suppression of redroot pigweed required residue C:N ratios of 9:1, 16:1, and 20:1 at 4, 6, and 8 wk after termination (WAT), respectively, showing that higher C:N extends the duration of suppression. Low C:N residues also release nitrate, which promotes germination of nitrate-sensitive species such as *Amaranthus* spp., whereas velvetleaf germination is not sensitive to nitrate (Brainard et al. 2006; Mohler et al. 2018). Accordingly, hairy vetch residue decreased the seed persistence of Powell amaranth (*Amaranthus powellii* S. Watson) but not of velvetleaf (Mohler et al. 2018).

Among CC options, winter cereal monocultures generally produce more biomass and greater weed suppression than mixtures (Baraibar et al. 2018; MacLaren et al. 2019). In the U.S. Northeast, cereal monocultures suppressed winter annual weed biomass by 83 to 100%, compared with 66 to 99% for diverse mixtures (Smith et al. 2020). In Arkansas, cereal rye

reduced Palmer amaranth emergence by 83% compared with no CC, mainly through the physical barrier of its residue (Palhano et al. 2018). Cereal rye is the most widely adopted CC because of its winter hardiness, high biomass production, high C:N ratio, and allelopathic benzoxazinoids (Chudzik et al. 2024; Oliveira et al. 2019; Rice et al. 2022). However, the weed suppression provided by CC depends on accumulating sufficient biomass, which varies with environment and management, and CC alone rarely provides adequate full-season weed control (Godar and Norsworthy 2025; Nichols et al. 2020; Ruis et al. 2019).

1.3 Cover Crop Disadvantages and Limitations

Cover crops alone do not provide adequate full-season weed control. Wiggins et al. (2016) found that CC reduced Palmer amaranth emergence by half compared with no CC, but did not adequately control it even when combined with PRE herbicides only. Nunes et al. (2024a) found that cereal rye reduced *Amaranthus* spp. density by 44%, whereas PRE herbicides reduced it by 68%, and concluded that combining both provided effective management. Loux et al. (2017) found that, at the end of the season, herbicide programs controlled 96% of Palmer amaranth compared with 29% without herbicides, and CC improved control only when herbicides were not used. Similarly, a CC terminated with a burndown plus a soil-applied residual herbicide reduced Palmer amaranth emergence by 82 to 94% compared with a bareground nontreated control, and more than the same CC terminated with burndown herbicides only (Dhanda et al. 2024). However, the CC benefit is not always evident once herbicides are used. Weed control with PRE herbicides was similar with and without cereal rye (Grint et al. 2022; Nunes et al. 2023b), and across 41 studies, CC did not affect *Amaranthus* spp. density or biomass when in-season herbicides were used (Kumar et al. 2024).

Cover crops are also a more complex tool than herbicides, because their performance depends on more specific site, management, and target weed species interactions. Biomass thresholds for weed suppression vary even within *Amaranthus* species. To reduce density by 50%, 4,079 kg ha^{-1} was needed across *Amaranthus* spp. in a meta-analysis of U.S. and Canadian studies (Kumar et al. 2024), whereas 5,200 kg ha^{-1} was needed for waterhemp *[Amaranthus* tuberculatus (Moq.) Sauer] in Wisconsin (Nunes et al. 2024b). For redroot pigweed, the biomass needed for 50% suppression increased from 2,800 kg ha^{-1} at 4 WAT to 6,610 kg ha^{-1} at 8 WAT (Pittman et al. 2020). Farmers report that CC add management complexity and require a whole-system approach (Chudzik et al. 2024; Roesch-McNally et al. 2018). Moreover, CC can have the opposite of the desired effect. With insufficient cereal rye biomass, the mulch does not suppress emergence but increases soil moisture, which increased waterhemp density compared with bare soil (Nunes et al. 2024b). Cereal rye residue increased giant foxtail (*Setaria faberi* Herrm.) and velvetleaf seed persistence in the soil by up to 12% (Hill et al. 2016).

The growing season is often too short to produce enough CC biomass. In the upper Midwest, the short window between corn harvest and soybean planting and cool spring temperatures limit cereal rye biomass (Grint et al. 2022; Nunes et al. 2024a). Cover crop biomass is greater in warmer and more humid regions and increases with a longer growing season (Ruis et al. 2019). Delaying termination until crop planting increased cereal rye biomass more than 6-fold (Grint et al. 2022), but high CC biomass can reduce crop stand and yield (Nunes et al. 2024a; Palhano et al. 2018). Water use by CC is another major concern, particularly in the water-limited western Corn Belt and Great Plains. Deines et al. (2023) observed that, across more than 90,000 Midwest fields, CC use was associated with average yield losses of 5.5% in corn and 3.5% in soybean, with larger losses under lower spring rainfall. In these water-limited

environments, CC may not produce enough biomass to provide their expected benefits, and their water use can reduce subsequent crop yields (Kumar et al. 2020; Nielsen et al. 2015). For example, replacing fallow with cover crops, annual forages, or short-season grain crops reduced winter wheat (*Triticum aestivum* L.) yields in dry years but had little effect in wet years, and cover crops or forages harvested by early June reduced wheat yield less than grain crops (Holman et al. 2017). However, CC effect on crop yield is not consistent. Across studies, winter grass CC such as cereal rye had a neutral effect on corn yield, whereas grass–legume mixtures terminated close to planting increased corn yield (Marcillo and Miguez 2017). In rainfed Wisconsin, soybean yield was not affected by cereal rye regardless of termination timing (Grint et al. 2022). In dryland western Kansas, grain sorghum yield after CC was reduced in only 1 of 3 yr (Simon et al. 2022).

Cost is one of the main barriers to CC adoption. Cover crops require seed and an additional drilling pass, which costs more than a herbicide application pass (Kansas Department of Agriculture and Kansas State University Land Use Survey Office 2026). The impact on short-term farm economics is likely the strongest disincentive for adoption of CC (Bergtold et al. 2019). In semiarid Kansas, net returns from CC left standing were no greater than those from chemical fallow (Simon et al. 2024). Farmers who successfully use CC still believe that greater economic incentives and more diverse markets are needed for wider adoption (Roesch-McNally et al. 2018).

Several factors can offset these limitations and increase CC adoption. Cover crops provide services beyond weed control: farmers widely agree that CC reduce soil erosion, and CC improve soil physical properties such as aggregate stability and water infiltration (Blanco-Canqui and Ruis 2020; Chudzik et al. 2024). Legume CC such as hairy vetch add nitrogen to the system

through biological fixation (Kaye et al. 2019; Poffenbarger et al. 2015). Cover crops can also be used as forage in integrated crop–livestock systems (Farney et al. 2018; Glaze-Corcoran et al. 2023). When grazed or hayed, CC can change the economic outcome. In western Kansas, net returns ranked grazed CC > hayed CC > fallow = standing CC (Simon et al. 2024), and net return increased with forage production (Obour et al. 2025). Financial incentives also promote adoption. Incentive programs doubled farmers' cropland with CC, and use remained 37% greater after participation ended (Chami et al. 2023). Private carbon markets are an emerging source of payments, but only 8.5% of CC users had enrolled in a carbon program by 2023 (CTIC et al. 2023), and payments mostly reach farmers who already use CC (Barbato and Strong 2023). These factors, especially the use of CC as forage, are relevant for how CC are integrated ahead of both soybean and cereal cash crops.

1.4 Cover Crops Preceding Soybean

Amaranthus species are particularly problematic in soybean because their emergence overlaps the early soybean growing season. The emergence period of Palmer amaranth varies among regions, populations, and years. In South Carolina, Palmer amaranth emerged from early May through mid-July, and more than 90% of its seasonal emergence occurred before soybean canopy closure (Jha and Norsworthy 2009). In a common garden study in western Kansas, populations from the south-central Great Plains had peak emergence between late April and early June, but emergence patterns differed among populations (Liu et al. 2022). Across the U.S. and Canada, uncontrolled weeds reduced soybean yield by 52% on average (Soltani et al. 2017). Palmer amaranth alone reduced soybean yield by 17 to 68% at densities of 0.33 to 10 plants m^{-1} of row in Arkansas (Klingaman and Oliver 1994) and by up to 79% in Kansas (Bensch et al. 2003). Without a PRE herbicide, weeds must be removed as early as the V1 to V2 soybean

stages to avoid yield loss (Knezevic et al. 2019). Applying a PRE herbicide at planting delays this critical time for weed removal, extending the weed-free period of the crop (de Sanctis et al. 2021; Knezevic et al. 2019).

Cereal rye CC fits well ahead of soybean. Apart from water use, few disadvantages have been reported for cereal rye preceding soybean, because soybean, as a legume, obtains much of its nitrogen from biological fixation and depends less on soil and fertilizer nitrogen than cereal crops, and it does not share major pests and diseases with cereal crops. However, rye residue can still affect soybean establishment and early growth through its effects on soil water, soil temperature, and seed–soil contact (Nunes et al. 2024a). Because soybean is normally planted later than corn, rye has more time to grow during spring, when most of its biomass accumulates. Rye biomass increased by about 2,000 kg ha^{-1} for each 10-d delay in spring termination (Mirsky et al. 2011). For these reasons, farmers often delay rye termination until near or after soybean planting, known as planting green (Essman et al. 2023; Reed et al. 2019). Planting green increased rye biomass by 94 to 181% (Reed et al. 2019) and reduced *Amaranthus* spp. density by 44% compared with no-till without CC (Nunes et al. 2024a), and soybean yield was not affected by termination date (Reed et al. 2019). Planting green also simplifies logistics, because CC termination and PRE herbicides can be applied in one pass at soybean planting (Nunes et al. 2023b). Herbicides remain crucial even under planting green (Kumar et al. 2024).

Integrating CC with soil-residual herbicides is a recommended approach for managing troublesome *Amaranthus* species in soybean (Loux et al. 2017; Nunes et al. 2023a; Whalen et al. 2020). Including a residual herbicide provides more consistent weed control than POST-only programs (Oliveira et al. 2017; Ribeiro et al. 2022). The choice of residual herbicide matters: Palmer amaranth needed 18 d to reach 10 cm with CC alone, compared with 33 to 35 d when

flumioxazin alone or with pyroxasulfone was applied over the CC (Perkins et al. 2021). Most studies apply residual herbicides at soybean planting, together with CC termination, and report effective *Amaranthus* spp. control (Nunes et al. 2023b, 2024a). In contrast, Whalen et al. (2020) found that residual herbicides applied with an earlier preplant burndown, 21 d before soybean planting, provided greater weed control (93%) than when applied 7 d before planting (60%). At termination, burndown herbicides are tank-mixed with residual herbicides. Burndown programs typically include glyphosate and glufosinate or auxin herbicides, which terminate the CC and control winter annual weeds (Monnig and Bradley 2007). The adoption of 2,4-D-resistant soybean (Enlist E3™, Corteva Agriscience, Indianapolis, IN) and dicamba-resistant soybean (Roundup Ready 2 Xtend®, Bayer CropScience, St. Louis, MO) has increased the use of auxin herbicides and glufosinate, which still provide effective Palmer amaranth control as part of herbicide programs because few resistant populations have been confirmed (Heap 2026; Miller and Norsworthy 2016). These tank mixtures commonly include adjuvants. Ammonium sulfate (AMS) is added to improve glyphosate (Polli et al. 2021) and glufosinate activity, and non-ionic surfactants improve spray coverage. Oil-based adjuvants such as methylated seed oil (MSO) are recommended with auxin herbicide esters and with protoporphyrinogen oxidase (PPO)-inhibiting herbicides that also have foliar activity, such as flumioxazin and fomesafen, to improve control of emerged weeds (Flexstar® label, Syngenta Crop Protection, Greensboro, NC; Valor® EZ label, Valent U.S.A. LLC, San Ramon, CA). Some oil-based adjuvants also increase spray droplet size and reduce drift potential (Basílio et al. 2024).

However, how to best integrate CC and residual herbicides remains uncertain. Cover crop biomass intercepts the herbicide spray, and the amount that reaches the soil decreases as biomass increases (Nunes et al. 2023a, 2023b; Smith et al. 2025). Standing cereal rye with 5,000 kg ha^{-1}

of biomass reduced herbicide deposition on the soil by 50% (Smith et al. 2025), and roller-crimped rye with 4,060 to 14,200 kg ha^{-1} intercepted 75 to 84% of the residual herbicides applied (Maia et al. 2025b). How much of the intercepted herbicide later reaches the soil depends on herbicide physicochemical properties (Krähmer et al. 2021; Smith et al. 2026), the amount and age of CC biomass (Banks and Robinson 1982; Dao 1991), the CC condition (living or dead) at application (Smith et al. 2026), and precipitation (Baker and Shiers 1989; Maia et al. 2025a). Results on weed control and yield are contrasting. Nunes et al. (2023a) found that rye biomass reduced sulfentrazone and S-metolachlor concentrations in the soil 25 d after application, and that soybean yield was reduced in all 3 yr when rye was terminated with a roller-crimper but in only 1 yr when terminated with glyphosate. In contrast, flumioxazin and pyroxasulfone soil concentrations rarely differed between early-terminated and living rye, and *Amaranthus* spp. control was not affected (Nunes et al. 2023b). Additional trade-offs may occur with PPO-inhibiting herbicides, which are key PRE residual herbicides in *Amaranthus* spp. programs in soybean (Perkins et al. 2021). These herbicides also have foliar activity, which is enhanced by MSO. When they are applied over a CC, part of the herbicide may be absorbed by CC tissue and contribute to CC termination rather than to soil-residual control. Whether this greater foliar uptake reduces their PRE activity is unknown. Weather further confounds these interactions, because PRE herbicides need adequate rainfall shortly after application to be effective (Landau et al. 2021). Together, these studies highlight complex interactions among environmental conditions, CC, herbicide properties, and adjuvants that are not yet well understood.

1.5 Cover Crops Preceding Cereal Cash Crops

Summer cereals like corn and grain sorghum face the same troublesome weeds as soybean. Without weed control, weed interference reduced yield by an average of 50% in corn (Soltani et al. 2016) and 47% in grain sorghum (Dille et al. 2020).

Winter cereal CC, particularly cereal rye, are the most common CC ahead of corn, but they have more disadvantages before a cereal cash crop than before soybean. Cereal rye residue with a high C:N ratio immobilizes soil nitrogen during decomposition. Corn yield after cereal rye was reduced by 20% when no nitrogen was applied, although not at the optimum nitrogen rate (Quinn et al. 2023), and in another study rye reduced corn nitrogen uptake by 16% and yield by 4.5% at one of three sites (Preza-Fontes et al. 2022). High rye biomass can also hinder corn establishment and early growth. Planting corn into living rye kept soil cooler and drier at planting and reduced corn yield in higher-yielding environments (Reed et al. 2019), and terminating rye at or after corn planting reduced yield by 16 to 22% (Godar et al. 2024). In addition, growing two grass species in succession can carry over pests and diseases. Cereal rye roots hosted *Fusarium* and *Pythium* species that caused corn seedling disease (Bakker et al. 2016), and cereal CC were frequently infected with wheat curl mite-transmitted viruses, serving as a bridge for wheat streak mosaic disease (Barman et al. 2026). This risk is relevant in Great Plains rotations where winter wheat precedes or follows a cereal cash crop, such as wheat–sorghum–fallow and corn–wheat sequences (Dhanda 2024). Grain sorghum may tolerate CC effects better than corn, because it is planted later and yields more than corn under drought and heat stress (Staggenborg et al. 2008). These limitations of cereal CC ahead of cereal cash crops have increased interest in CC mixtures.

Cover crop mixtures that combine cereals with legumes and other species can provide benefits that cereal monocultures cannot. As the proportion of hairy vetch in a vetch–rye mixture increased, CC nitrogen content increased from 64 to 181 kg ha^{-1} and the C:N ratio decreased from 83:1 to 16:1 (Poffenbarger et al. 2015). Mixtures can balance the nitrogen scavenging of cereals with the nitrogen supply of legumes (Kaye et al. 2019), and across studies, mixtures terminated close to planting increased corn yield by 30% (Marcillo and Miguez 2017). Mixtures also provide forage with greater nutritive value than cereal rye (Farney et al. 2018; Glaze-Corcoran et al. 2023; Obour et al. 2025). In southwestern Kansas, fall-sown triticale alone or mixed with legumes reduced kochia *[Bassia scoparia* (L.) A. J. Scott] density by 78 to 94% compared with chemical fallow (Petrosino et al. 2015). However, mixtures have limitations for weed control. They often produce less biomass and suppress weeds less than cereal monocultures (Baraibar et al. 2018; MacLaren et al. 2019; Smith et al. 2020). Their lower C:N residue decomposes faster (Pittman et al. 2020), and the nitrogen released can stimulate the emergence of nitrate-sensitive weeds such as *Amaranthus* spp. (Hill et al. 2016; Mohler et al. 2018). Mixtures can also be less profitable. In dryland Kansas, net return was greater with an oat–triticale mixture than with multispecies mixtures, because net return increased with forage production (Obour et al. 2025). Therefore, as with cereal CC, mixtures must be integrated with herbicides, and because mixtures are often less weed-suppressive than cereal monocultures, depending on their species composition, seeding rates, and biomass (Baraibar et al. 2018; MacLaren et al. 2019; Poffenbarger et al. 2015; Smith et al. 2020), this integration is even more critical for them to achieve sustainable weed management.

The combination of CC mixtures and herbicides creates opportunities to obtain the agronomic benefits of mixtures while maintaining weed control. Legume residue and residual

herbicides can act synergistically. Teasdale et al. (2005) found that hairy vetch residue alone reduced smooth pigweed (*Amaranthus hybridus* L.) emergence by 13% and metolachlor alone reduced it by 16%, whereas together they reduced it by 86%. In sweet corn, half rates of atrazine and metolachlor controlled redroot pigweed and Palmer amaranth regardless of the CC, including a rye–hairy vetch mixture (Burgos and Talbert 1996). In grain sorghum in Kansas, a triticale–winter pea–brassica mixture terminated with glyphosate plus a residual herbicide delayed and reduced glyphosate-resistant Palmer amaranth emergence by 42 to 56% compared with chemical fallow (Dhanda et al. 2024). Over 3 yr, the same combination reduced total weed density by 34 to 81% and weed biomass by 45 to 73% compared with chemical fallow, without reducing grain sorghum yield, although net returns were lower because of CC seed and planting costs (Dhanda 2024). However, few studies have evaluated CC mixtures with lower C:N ratios integrated with residual herbicides ahead of corn, and their effects on weed control, corn yield, and economics at the on-farm scale remain unknown.

1.6 Applicability of Integrated Weed Management

After decades of research, the strengths and limitations of herbicides and CC as weed control tools are well documented. Herbicide-only programs can be effective and inexpensive in the short term when no resistance is present but, even with best management practices, the evolution of herbicide resistance can only be delayed (Evans et al. 2016; Norsworthy et al. 2012; Vencill et al. 2012). Research from more than 30 yr ago to the present has concluded that IWM programs combining diverse control tactics are needed to ensure the medium- to long-term economic and environmental sustainability of weed management for producers (Harker and O'Donovan 2013; Kumar et al. 2020; Norsworthy et al. 2012; Swanton and Weise 1991).

However, how to best integrate CC and herbicides within IWM programs remains a challenge that is far from fully understood. Many studies combining cereal rye with soil-residual herbicides evaluated premixes or programs with multiple active ingredients (Loux et al. 2017; Nunes et al. 2023b; Whalen et al. 2020), rather than individual active ingredients. The role of commonly used adjuvants, such as MSO, which may increase herbicide retention on CC biomass, has also been largely overlooked. Furthermore, most CC research in Kansas has been conducted in semiarid western Kansas (Dhanda 2024; Petrosino et al. 2015; Simon et al. 2022), and local information on CC alternatives integrated with herbicides is lacking for producers in rainfed north-central Kansas.

On-farm research is an effective way to generate local information and to promote the adoption of more complex and sustainable practices. On-farm experimentation places farmers at the center of agricultural innovation through collaboration with researchers (Lacoste et al. 2022). In a survey of 255 farmers across the U.S. Midwest and South-Central regions, 66% of respondents reported a high likelihood (8 or higher on the survey scale) of adopting practices supported by on-farm research, compared with 26% for practices supported by research not conducted on-farm, and cover crops and no-till were at the forefront of the conservation practices adopted (Pires et al. 2024). To our knowledge, studies evaluating CC and herbicide integration in Kansas have been conducted mainly in small-plot experiments at research stations, such as near Manhattan (Petrosino 2010, pp. 47–74), including multistate studies with Kansas sites (Nunes et al. 2023b, 2024a), or in western Kansas (Dhanda et al. 2024; Petrosino et al. 2015; Simon et al. 2022, 2024), and on-farm studies assessing the weed control and economic outcomes of these IWM practices in north-central Kansas are lacking.

Therefore, the overall objective of this research was to evaluate how cover crops and herbicide program combinations affect weed suppression, crop yield, and gross margin on-farm in north-central Kansas. Two on-farm experiments were conducted over two growing seasons at Oak Hill, KS. Both experiments were established in a farm with an integrated cattle–grain system. The rotation implemented in the farm was a soybean–winter wheat–double-crop soybean or summer forage–corn rotation. Occasionally, late-planted corn was included. Cereal rye CC had been implemented for 7 yr in the rotation when wheat was not grown.

Study 1 (Chapter 2) integrated cereal rye CC, terminated before (rye CC dead condition) or at soybean planting (rye CC living condition), with soil-applied residual herbicides and MSO ahead of soybean. Its objectives were to determine the effects of combining cereal rye CC, soil-applied residual herbicides, and MSO on (i) Palmer amaranth suppression and (ii) soybean yield and gross margin. Study 2 (Chapter 3) integrated hairy vetch–triticale CC mixtures with herbicide termination programs, with or without a residual herbicide, ahead of late-planted corn, compared with chemical fallow and cereal rye CC. Its objectives were to evaluate the effects of these combinations on (i) CC biomass, (ii) winter and summer annual weed suppression, and (iii) late-planted corn yield and gross margin. Together, these studies provide local information for north-central Kansas farmers who are developing IWM programs on how to integrate CC and herbicides to maintain weed control while sustaining crop yield.

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Chapter 2 - Effects of Rye Cover Crop, Residual Herbicides and MSO Use on Palmer amaranth Control in Soybean

Abstract

Cereal rye (*Secale cereale* L.) cover crop (CC) and soil-residual herbicides help manage herbicide-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson) in soybean [*Glycine max* (L.) Merr.]. However, residual herbicides with both soil and foliar activity, such as flumioxazin, may be retained on living CC tissue and adding an adjuvant such as methylated seed oil (MSO) may increase this retention, resulting in less soil activity. On-farm studies in 2025 and 2026 at Oak Hill, KS, evaluated two CC conditions at application, dead (terminated 10 d before soybean planting) and living (terminated at planting), and five herbicide programs: no residual herbicide (control), dimethenamid-P (soil activity only) or flumioxazin (soil and foliar activity), each with or without MSO. A no-CC plot was added in 2026. Living CC produced up to 22% more biomass than dead CC in both years but spray interception did not differ between CC conditions. Flumioxazin-containing mixtures reduced early-season Palmer amaranth emergence in both years, and time to 10% emergence was delayed to 28 days after herbicide application, compared to 3 days with no residual herbicide. Emergence through dimethenamid-P-containing mixtures did not differ from the control. At soybean canopy closure, flumioxazin reduced Palmer amaranth density by 85 to 87%, and flumioxazin-containing mixtures had 18 to 29% of the biomass of dimethenamid-P-containing mixtures with either CC condition and 13% with no CC in 2026. There was no effect of CC condition, nor a consistent benefit of adding MSO on reducing Palmer amaranth density or biomass. Soybean yield was 8% greater with dead than living CC in 2025 but did not differ in 2026. Herbicide mixtures did not affect yield, but

flumioxazin cost \$21 ha^{-1} less than dimethenamid-P. In 2025, the dead CC condition had a \$70 ha^{-1} greater gross margin than the living CC condition, despite the \$44 ha^{-1} cost of its additional termination pass. Flumioxazin provided consistent Palmer amaranth control regardless of CC condition, including no CC in 2026, so its foliar activity did not reduce its soil-residual activity under living CC. Terminating CC before planting protected yield only in the year with more CC biomass and below-average rainfall.

Keywords: integrated weed management; planting green; spray interception; adjuvants; economics.

2.1 Introduction

Pigweed species such as Palmer amaranth (*Amaranthus palmeri* S. Watson) are major challenges for soybean crop production. They cause yield losses, increase production costs, and decrease farmer profits (Bravo et al. 2018; Oliveira et al. 2022; Soltani et al. 2017). Palmer amaranth is the most aggressive species within the genus. It is characterized by rapid growth, greater water-use efficiency, prolific seed production, and a high likelihood of evolving herbicide-resistant traits (Bensch et al. 2003; Brackenridge et al. 2024; Jha 2008; Sarangi et al. 2021). Soybean yield losses can be up to 80% due to Palmer amaranth interference (Bensch et al. 2003; Klingaman and Oliver 1994; Soltani et al. 2017). Multiple-herbicide-resistant Palmer amaranth populations are increasing in occurrence (Foster and Steckel 2022; Heap 2026; Kumar et al. 2019; Priess et al. 2022). Shyam et al. (2021) confirmed a six-way site-of-action resistant Palmer amaranth population in Kansas. This finding underscores the limited herbicide options available to soybean farmers and the need for alternative control approaches. Universities and

herbicide resistance management organizations have increased efforts to promote integrated weed management (IWM) programs that include diverse methods for weed control such as mechanical and cultural practices (Arsenijevic et al. 2022; Norsworthy et al. 2012; Oliveira et al. 2020).

Cover crops are an effective cultural practice for suppressing these small-seeded pigweed species through physical and ecological mechanisms that align with fundamentals of no-till production systems (Kumar et al. 2020; Osipitan et al. 2019). Accumulation of cover crop biomass is a key driver to suppress Palmer amaranth (Mirsky et al. 2011; Nunes et al. 2024a; Teasdale and Mohler 2000). Among cover crops (CC), cereal rye (*Secale cereale* L.) is widely adopted due to its winter hardiness, high biomass production, and potential allelopathic effects on weeds (Chudzik et al. 2024; Oliveira et al. 2019; Rice et al. 2022). In the U.S. Midwest, farmers often delay CC termination until near or after soybean planting to accumulate sufficient biomass for effective Palmer amaranth suppression (Essman et al. 2023; Mirsky et al. 2011; Nunes et al. 2023a; Reed et al. 2019). Meta-analysis studies indicated that 3,300 to 6,600 kg ha^{-1} of CC biomass can suppress Palmer amaranth recruitment by 50% or more, depending on site-specific environmental conditions (Nichols et al. 2020; Osipitan et al. 2018; Weisberger et al. 2023). Consequently, CC alone is not sufficient for consistent weed control. Integration with other weed control practices, such as herbicides, remains essential (Cornelius and Bradley 2017; Nichols et al. 2020; Norsworthy et al. 2012).

Combining the use of CC with soil-applied residual herbicides can be an effective and sustainable approach to manage troublesome pigweed species (Hand et al. 2021; Loux et al. 2017; Nunes et al. 2023a; Whalen et al. 2020). In general, including a soil-residual herbicide in programs has more consistent weed control than foliar-applied-only approaches (Oliveira et al.

2017; Ribeiro et al. 2022). By controlling weeds as they emerge, soil-applied herbicides reduce weed density and rate of weed growth, resulting in less competitive weeds against crops (Liphadzi and Dille 2006; Norsworthy et al. 2012). Flumioxazin and dimethenamid-P are two common soil-applied herbicides used for pigweed control programs in soybean (Hay et al. 2018). Flumioxazin has both good foliar activity and excellent soil-residual activity on small-seeded broadleaf weeds (Shaner 2014). Flumioxazin also has reach-back activity, which allows subsequent rain events to move the herbicide to the roots of weeds that have already emerged, providing control after emergence. In contrast, dimethenamid-P has soil-residual activity only. It controls germinating seedlings only and does not have reach-back activity. Dimethenamid-P, like others in its herbicide family, is highly effective on small-seeded grass and broadleaf weeds (Shaner 2014). Both herbicides can provide effective PRE control of pigweed species, including Palmer amaranth, although their efficacy varies with species, rate, rainfall for activation, soil properties, and population susceptibility (Hay et al. 2018; Shaner 2014). Both active ingredients have similar half-life in the soil but differ in other properties that determine their environmental fate (Shaner 2014). Dimethenamid-P has a moderate organic-matter sorption (Koc) value, low volatility, high water solubility, and low to moderate photostability (Lewis et al. 2016; Shaner 2014). Flumioxazin has a moderate to high Koc value, very low volatility, very low water solubility, and moderate photostability (Lewis et al. 2016; Shaner 2014). Flumioxazin's lower volatility and greater photostability may make it persist longer with no rain after application. Dimethenamid-P, in contrast, may need less rain for it to be washed off from residue and incorporated into the soil.

Combining CC with PRE herbicides also presents challenges. Herbicides applied over a CC can be intercepted by the crop, and the amount that reaches the soil decreases as CC biomass

cover on the soil increases (Nunes et al. 2023a, 2023b; Smith et al. 2025; Whalen et al. 2020). For example, roller-crimped cereal rye CC intercepted 75 to 84% of the residual herbicides applied when 4,060 to 14,200 kg ha^{-1} of CC biomass was present (Maia et al. 2025b). In another study, standing cereal rye CC with 5,000 kg ha^{-1} of biomass reduced herbicide deposition on the soil by 50% (Smith et al. 2025). The amount of intercepted herbicide that reaches the soil later depends on the physicochemical properties of the herbicide (Krähmer et al. 2021; Smith et al. 2026), the amount and age of CC biomass (Banks and Robinson 1982; Dao 1991), the CC condition (living or dead) at application (Smith et al. 2026), and precipitation (Baker and Shiers 1989; Maia et al. 2025a). Smith et al. (2026) reported that the amount of wash-off from living CC was greatest for pyroxasulfone and least for *s*-metolachlor, whereas *s*-metolachlor had the greatest amount of wash-off from aged residue that has more lignin. However, less herbicide in the soil does not always reduce weed control. In a multistate study, soil concentrations of flumioxazin and pyroxasulfone rarely differed between early-terminated and living CC, and *Amaranthus* spp. control did not differ when the herbicides were applied in a tank mix with glyphosate + glufosinate (Nunes et al. 2023b). An additional trade-off occurs with soil-applied herbicides that also have foliar activity, such as flumioxazin. Their foliar activity can speed up CC termination when applied with burndown herbicides, but the herbicide retained on CC tissue may not be available for soil-residual in-season control of Palmer amaranth. Together, these studies highlighted complex interactions among environmental conditions, CC, and herbicide physicochemical properties.

Timing of CC termination could be early, anytime from 10 or more days before cash crop planting (i.e., planting into brown/dead CC) or at planting (i.e., planting into green/living CC) (Nunes et al. 2023b). In both scenarios, opportunities exist to apply both burndown (foliar-

applied POST for termination) and soil-applied residual herbicides at one time, to provide operational advantages for farmers. To terminate before planting, a burndown program typically includes glyphosate and glufosinate, or auxin mimics (i.e., 2,4-D and dicamba). These herbicides terminate cereal rye effectively while also controlling glyphosate-resistant winter and early-spring annual weeds. In addition, glufosinate specifically accelerates CC dry-down. At planting, residual herbicides are commonly tank-mixed with burndown herbicides to control Palmer amaranth seedlings that have already emerged under the CC canopy (Norsworthy et al. 2012). Winter annual broadleaf weed species are effectively controlled when 2,4-D is included in these burndown programs (Monnig and Bradley 2007) and also provides effective Palmer amaranth control (Miller and Norsworthy 2016). Although 2,4-D-resistant Palmer amaranth populations have been confirmed in Kansas (Kumar et al. 2019), occurrence of resistant populations remains low (Hwang et al. 2023). The use of 2,4-D might also increase with adoption of 2,4-D-resistant soybean (Enlist E3™ soybean, Corteva Agriscience, Indianapolis, IN) due to less concern about herbicide carryover.

Oil-based adjuvants, such as methylated seed oil (MSO) or crop oil concentrate, are recommended to be mixed with 2,4-D ester formulations to improve foliar uptake and burndown activity. The MSO adjuvant is also recommended with soil-applied herbicides that have foliar activity, such as flumioxazin, to improve control of already emerged weeds. However, by increasing herbicide uptake on plant tissue, MSO may also increase the amount of herbicide retained on the CC canopy and reduce the amount that reaches the soil, especially with living CC.

It is not clearly understood how CC condition, residual herbicide, and MSO interact to affect season-long Palmer amaranth control in soybean under field conditions. Therefore, the

objectives of this study were, at an on-farm scale, to determine the effects of combining rye CC, soil-applied herbicides, and MSO on Palmer amaranth suppression and soybean yield and gross margin in north central Kansas over two growing seasons. We hypothesized that flumioxazin-based herbicide mixtures applied with living CC would result in less Palmer amaranth suppression, as a trade-off for increased foliar activity with the living CC.

2.2 Materials and Methods

2.2.1 Study Design and Treatments

On-farm experiments were established in the fall of 2024 and 2025 at Oak Hill, KS (39° 13’52.04” N; 97°12’19.55” W). Hereafter, the 2024–2025 and 2025–2026 growing seasons are referred to as 2025 and 2026, the years in which soybean was grown. Two neighboring field sites were used but were located on a Crete silty clay loam soil (fine, smectic, mesic Pachic Arguistolls) with 1 to 3% slopes (USDA-NRCS 2026). Fields were previously managed with winter cover crops, when wheat was not grown, for the last seven years. The trial followed corn harvest in a soybean-wheat/double-crop soybean-corn rotation. Cereal rye (‘Elbon’, Cisco Company, Indianapolis, IN) was drilled in rows spaced 19 cm apart, using a John Deere air drill 1890 seeder and 1910 cart (Deere & Company, Moline, IL) at a rate of 78 kg ha^{-1} on October 10, 2024, and October 3, 2025.

The experiment was a split-plot design with four blocks. Herbicide mixture was the whole-plot factor and CC condition was the subplot factor. Whole plots were 30 by 38 m and subplots were 15 by 38 m. Two CC conditions were dead and living at the time of herbicide mixture application. Rye in dead CC subplots were terminated at early anthesis, that is 10 d before soybean planting (DBP), while rye in living CC subplots was terminated at soybean

planting (Table 2.1). In 2026, a no-CC treatment was added and received dead and living termination applications as a sixth whole plot in each block to evaluate the residual herbicides in the absence of CC. In these plots, cereal rye was seeded but terminated early on March 20, 2026, with glyphosate (840 g ae ha^{-1}; Willowood Glypho 5, Willowood, Henderson, NV) to prevent further CC biomass accumulation. Foliar herbicides were included in all herbicide mixtures to terminate living CC subplots and applied to the dead CC subplots to control weeds that emerged during the 10-DBP window.

The five herbicide mixtures were no residual herbicide (control), dimethenamid-P alone (dime) or with MSO (dime + MSO), and flumioxazin alone (flumi) or with MSO (flumi + MSO). Dimethenamid-P (Outlook®, BASF Corporation, Research Triangle Park, NC) was applied at 842 g ai ha^{-1} and flumioxazin (Flumioxazin 51% WDG, RedEagle International LLC, Lakeland, FL) at 107 g ai ha^{-1}, and MSO (Fire Zone®, Helena Agri-Enterprises, Collierville, TN) was added at 0.5% v/v (0.7 L ha^{-1}). All herbicide mixtures, including the control, were tank-mixed with glyphosate (1,040 g ae ha^{-1}; Willowood Glypho 5) plus 2,4-D (770 g ae ha^{-1}; 2,4-D LV6®, Winfield Solutions, St. Paul, MN) and AMS (1.4 kg ha^{-1}).

In 2026, each no-CC treatment subplot was divided in half (15 by 19 m), and dime or flumi, both without MSO, were randomly assigned to each half. Thus, the no-CC treatment formed a split-split plot arrangement, with foliar program as the subplot and residual herbicide as the sub-subplot. The no-CC treatment did not include the no residual herbicide (control) treatment.

Soybean (2146E, Ohlde Seed Farms, Palmer, KS) was planted at 272,000 seeds ha^{-1} on June 2, 2025, and May 13, 2026, using a John Deere 1750 Max Emerge XP planter (Deere & Company, Moline, IL) with rows spaced 76 cm apart, a front roller crimper, and a vDrive

precision planting system. Herbicide mixtures were applied immediately after planting on the same day. All herbicides were applied with a Case IH Patriot 3340 sprayer (CNH Industrial, Racine, WI) equipped with a pulse-width modulation system and MR110-04 nozzles (Wilger Industries Ltd., Saskatoon, SK, Canada) spaced 52 cm apart on a 30 m-wide boom. The sprayer delivered 140 L ha^{-1} at 11 km h^{-1}, 400 kPa, and a 75% duty cycle.

2.2.2 Data Collection

Cover crop biomass was measured before termination of each CC condition: dead CC on May 23, 2025, and May 2, 2026, and living CC on June 2, 2025, and May 13, 2026 (Table 2.1). One 0.30 m^2 quadrat was placed per plot (three crop rows wide and 0.5 m long), and aboveground biomass was harvested by cutting plants at the base (1 cm above the soil surface). Samples were oven-dried at 58 °C until constant mass was reached.

Spray interception was determined by using water-sensitive cards (SpotOn® paper; Innoquest, Woodstock, IL, USA) at the time of herbicide mixture application. Four cards were placed per plot, except in no residual herbicide (control) plots, two above and two below CC biomass, to calculate the percentage of spray solution intercepted by CC canopy.

Cumulative emergence of Palmer amaranth was determined by counting and removing emerged seedlings from three permanently established 0.25 m^2 quadrats that were systematically placed in the center of each plot. In 2025, counts were taken at 21 and 35 days after herbicide mixture application (DAT) and in 2026, counts taken at 13, 21, and 38 DAT. Early-season emergence was expressed relative to the no residual herbicide (control) as the slope of cumulative emergence over DAT (% of the control per day).

Palmer amaranth final density and aboveground biomass were measured at 45 DAT in 2025 (soybean canopy), and at 50 DAT in 2026 (R1 soybean growth stage), just prior to farmer

POST application. All plants between the two center soybean rows (3.80 and 1.40 m long) were counted and two samples per plot (5.81 m² each in 2025 and 2.14 m² each in 2026) were harvested by cutting plants at the soil surface, placed in paper bags, and oven-dried at 58 °C to constant mass.

In 2026, soybean stand was counted at the R1 growth stage in 2.56 m of row in six dead CC, six living CC, and 12 no-CC plots, randomly selected so that the number of plots with CC equaled the number without CC, and converted to plants ha^{-1} with the 76-cm row spacing to evaluate establishment efficiency.

A POST application of glufosinate-ammonium (769 g ai ha^{-1}) plus clethodim (231 g ai ha^{-1}) (Willowood Glufosinate 280 SL and Willowood Clethodim 2EC, Willowood, Henderson, NV), AMS (2.8 kg ha^{-1}), and non-ionic surfactant (175 mL ha^{-1})(Brandt Super Wetter, Brandt Consolidated, Inc., Springfield, IL) was made by the farmer at ~56 DAT, after all weed assessments were done.

Soybean grain was harvested from the center 16 rows (12.2 m wide) by 43 m long (525 m²) of each subplot, except in the 2026 no-CC plots, where the center 16 rows (12.2 m wide) by 21.5 m long (262 m²) were harvested, with a John Deere S780 combine (Deere & Company, Moline, IL) on October 20, 2025, and October 24, 2026. Grain weight and moisture were recorded for each subplot, and yield was adjusted to 13% moisture.

Data on precipitation over the 2-yr period were recorded by using an on-farm rain gauge and air temperatures were obtained as 30-yr averages from the NOAA NCEI station at Clay Center, KS (USC00141559), located approximately 17 km from the study site (Table 2.2).

2.2.3 Economic Analysis

Direct costs were calculated for each herbicide mixture and CC condition combination (Table 2.3). Gross margin was calculated as income less direct costs and was compared only for factors that significantly affected soybean yield; thus differences in gross margin reflected differences in direct costs. Income was calculated with the model mean soybean yield of each CC condition, averaged over herbicide mixtures because they did not affect yield, and the soybean price. Because only the costs that differed among treatments were included, gross margin is a partial budget return above these weed management costs.

Income ($ ha^{-1}) = yield (kg ha^{-1}) × price ($ kg^{-1})

Direct costs included CC termination and herbicide mixture application costs in $ ha^{-1} and did not include cereal rye seed and its drilling pass, soybean seed and planting, fertilizer, the farmer POST application, harvest, or other production costs, which were the same for all treatments.

Direct cost ($ ha^{-1}) = Burndown herbicides + Residual herbicides + MSO + spraying pass

Burndown included all herbicides and adjuvants used for CC termination (Table 2.3). The dead CC condition received two spraying passes (10 DBP and at planting), whereas the living CC condition received one pass at planting. Herbicide, adjuvant, and soybean prices were provided by the cooperating farmer and represented 2026 cropping season costs near Clay Center, KS. The soybean price was \$0.435 kg^{-1}. The cost of each spraying pass was obtained from the Kansas custom rates survey (Kansas Department of Agriculture and Kansas State University Land Use Survey Office 2026).

2.2.4 Statistical Analysis

All responses analyzed inferentially were described with generalized linear mixed models (GLMMs), except Palmer amaranth biomass at canopy closure, which was described with a generalized additive model (GAM) with a gamma distribution: CC biomass with a gamma distribution, spray interception with a beta distribution, Palmer amaranth early-season cumulative density and final density at canopy closure with a negative binomial distribution, early-season emergence with a hurdle gamma distribution, and soybean yield with a Gaussian distribution. Fixed effects were herbicide mixture (HERB), CC condition (CC), year, and their interactions when estimable. Random effects corresponded to the split-plot structure within each year: block, whole plot (HERB) within block, and subplot (CC) within whole plot and block. In the 2026 no-CC whole plots, the sub-subplot replaced the subplot as the smallest random unit. Models with different interactions were fitted and evaluated based on residual diagnostics and on AIC and BIC. Significance was considered at $P < 0.05$.

CC biomass was described with a gamma distribution with a log link function. The linear predictor included CC and year as fixed effects, and block within year and whole plot within block and year as random effects (Appendix A, Eq. A.1).

Spray interception was described with a beta distribution with a logit link function, and the linear predictor included HERB, CC, year, and their interactions as fixed effects, and block within year, whole plot within block and year, and subplot within whole plot, block, and year as random effects (Appendix A, Eq. A.2). Two percentage interception values, calculated from the cards above and below the CC, were obtained per subplot.

Palmer amaranth early-season cumulative density (35 DAT in 2025 and 38 DAT in 2026) was described with a negative binomial distribution with a log link function and an offset for the

quadrat area to express estimates as plants m^{-2}, and the linear predictor included CC, HERB, their interaction, and year as fixed effects, and block within year, whole plot within block and year, and subplot within whole plot, block, and year as random effects (Appendix A, Eq. A.3). Only the ten treatment combinations present in both years were included. Cumulative density was used as the reference (100%) for early-season emergence, and results are presented in Appendix A (Table A.1).

Palmer amaranth early-season emergence was calculated as the slope of cumulative emergence against DAT, with the line forced through the origin (zero emergence at 0 DAT) and cumulative emergence expressed as a percentage of the mean cumulative emergence of the no residual herbicide (control) in the same year. Early-season emergence was described with a hurdle gamma distribution with a log link, which models separately whether Palmer amaranth emerged in a subplot and, when it did, the slope. The probability of no emergence was described as a function of HERB, and the linear predictor for the slope included HERB, year, CC, and the HERB × year and HERB × CC interactions as fixed effects, and block within year and whole plot within block and year as random effects (Appendix A, Eq. A.4).

Palmer amaranth final density at canopy closure was described with a negative binomial distribution with a log link and an offset for the sampled area (5.81 m^2 in 2025 and 2.14 m^2 in 2026), and the linear predictor included HERB, CC, year, and the CC × year interaction as fixed effects, and block within year, whole plot within block and year, and subplot (sub-subplot in no-CC plots) within whole plot, block, and year as random effects (Appendix A, Eq. A.5). This model included the 2026 no-CC plots, where CC had a third level (dime and flumi with no CC).

Palmer amaranth biomass at canopy closure was described with a gamma GAM with a log link function, and the linear predictor included HERB, CC, year, and their interactions as

fixed effects; block, whole plot, and subplot (sub-subplot in no-CC plots) as random effects with variances that differed by year; and a two-dimensional smooth function of block row and plot column, estimated for each year, to account for spatial variation across the field (Appendix A, Eq. A.6). In 2026, the no-CC plots were included as two additional herbicide levels (dime and flumi with no CC).

Soybean grain yield was described with a Gaussian distribution, and the linear predictor included HERB, CC, year, their interactions, and a linear trend along the harvest direction within year as fixed effects, and whole plot within block and year and subplot within whole plot, block, and year as random effects (Appendix A, Eq. A.7). The trend accounted for a west–east yield gradient across the fields. Soybean stand in 2026 was compared among CC conditions with a one-way ANOVA.

All analyses were done in R v. 4.4.2 (R Core Team 2024). GLMMs were fitted with the glmmTMB package (Brooks et al. 2017) and the GAM with the mgcv package (Wood 2017), both using restricted maximum likelihood; models compared with AIC and BIC were refitted by maximum likelihood. Model assumptions were checked with simulated quantile residuals using the DHARMa package (Hartig 2024). Fixed effects were tested with Type II Wald chi-square tests using the car package (Fox and Weisberg 2019) and with approximate F-tests for the GAM. Estimated marginal means were obtained with the emmeans package (Lenth 2025), back-transformed to the original scale, and compared within year with Tukey-adjusted pairwise comparisons and compact letter displays from the multcomp package (Hothorn et al. 2008). Early-season emergence of each herbicide mixture was compared with the no residual herbicide (control) within year with Dunnett-adjusted comparisons. Planned contrasts were evaluated within year to compare MSO with no MSO for each active ingredient, mixtures with flumi

compared to mixtures with dime, the dead with the living CC condition, and no CC with CC for dime and flumi in 2026. Contrasts were estimated on the log scale and back-transformed to ratios, except for early-season emergence, which was compared as differences. *P* values of planned contrasts were not adjusted for multiplicity. Figures were made with the ggplot2 package (Wickham 2016), and the tidyverse packages were used for data handling (Wickham et al. 2019).

2.3 Results and Discussion

Precipitation received during the cereal rye growing season, from October to termination (early May to June), was about 400 mm in 2025 and 300 mm in 2026, similar to the 30-yr average, but unevenly distributed (Table 2.2). February and March 2026 received less than the 30-yr average, and temperatures were warmer than average. These conditions likely accelerated cereal rye development and shortened the CC growing season by about 20 d, reducing the length of time that CC provided weed suppression.

Soybean was planted 20 days later in 2025 than in 2026 and therefore, the soybean growing season was shorter in 2025 (early June to September) as compared to 2026 (mid-May to September) (Table 2.2). Precipitation received during the 2025 soybean growing season was 268 mm and 24% less than the 30-yr average for the same period (353 mm), whereas precipitation in 2026 was 460 mm and was 6% greater than the 30-yr average (433 mm).

2.3.1 Total CC Biomass at Termination

Cover crop biomass varied by year ($P < 0.001$) and CC condition ($P < 0.001$) and no strong evidence for a relevant year x CC interaction was found. Living CC produced 21 to 22%

more biomass than dead CC in both years as dead CC was terminated 10 days earlier than the living CC. Living CC biomass was 10,300 ± 570 kg ha^{-1} in 2025 and 1,800 ± 90 kg ha^{-1} in 2026, and dead CC biomass was 8,100 ± 450 kg ha^{-1} in 2025 and 1,400 ± 70 kg ha^{-1} in 2026. Other studies have shown an increase of 2,100 kg ha^{-1} in CC biomass when delaying termination by 13 days (Nunes et al. 2024b) as seen in the 2025 results. It was observed that the delay in termination also corresponded to a shift in the phenological stage of the cereal rye, from early anthesis to early grain filling (Feekes 10.5.4), resulting in more volunteer cereal rye plants occurring by soybean harvest in 2025 (Appendix A, Figure A.1). Overall, there was 83% less CC biomass produced in 2026 as compared to 2025. The reduction in CC biomass observed in 2026 may be explained by the drier and warmer weather conditions of February and March 2026.

2.3.2 Spray Interception

Spray interception was affected by year ($P < 0.001$) and herbicide mixture ($P = 0.027$), but not by CC condition ($P = 0.425$) or any interaction ($P > 0.05$). Spray interception was greater in 2025 (72.1 ± 3.2%) than in 2026 (21.8 ± 2.3%), mainly because of more CC biomass in 2025. Although the herbicide mixture effect was significant, no differences in spray interception were detected among herbicide mixtures within a given year. Spray interception was similar for the dead and living CC conditions.

The difference in interception between years was consistent with the amount of CC biomass. Greater cereal rye biomass has been associated with less spray coverage and lower herbicide concentration on the soil (Nunes et al. 2023a; Whalen et al. 2020). In this study, CC was roller-crimped at soybean planting, immediately before herbicide mixture application. Under similar management, Smith et al. (2025) reported that roller-crimped cereal rye with more than

6,000 kg ha^{-1} of biomass reduced herbicide deposition on the soil by about 70%, whereas standing cereal rye with less than 2,000 kg ha^{-1} reduced deposition by about 35%. Similar levels were observed in this study, with 72.1% interception in 2025, more than 8,000 kg ha^{-1} of CC biomass, and 21.8% in 2026 where it was less than 1,800 kg ha^{-1}. Within each year, the greater biomass of the living CC condition did not increase spray interception, which may be because this difference was small compared with the difference between years.

2.3.3 Early-Season Palmer amaranth Density

In the no residual herbicide (control), Palmer amaranth density was 6 plants m^{-2} by 35 DAT in 2025 and 23 plants m^{-2} by 38 DAT in 2026. These values were used as 100% to compare the effects of herbicide mixtures and CC condition on early-season Palmer amaranth emergence. Early-season Palmer amaranth density by 35 DAT in 2025 and 38 DAT in 2026 for each herbicide mixture and CC condition combination, with means compared within year, are presented in Appendix A (Table A.1).

2.3.4 Early-Season Palmer amaranth Emergence

Early-season emergence was affected by herbicide mixture ($P = 0.012$) but not by year ($P = 0.420$), CC condition ($P = 0.690$), or interactions of herbicide mixture × year ($P = 0.922$) and herbicide mixture × CC condition ($P = 0.606$). Herbicide mixtures were compared within a year to keep inferences within contrasting weather scenarios. Only the ten treatment combinations present in both years were included (Figure 2.1).

In both years, flumi and flumi + MSO reduced early-season emergence compared with the no residual herbicide (control) ($P \leq 0.016$), whereas dime and dime + MSO did not differ

from the control ($P \geq 0.198$) (Figure 2.1). In 2025, flumi and flumi + MSO had less emergence by 35 DAT than dime + MSO and the no residual herbicide (control), and dime was intermediate. In 2026, flumi + MSO had less emergence by 38 DAT than all dimethenamid-P-containing mixtures and the no residual herbicide (control), whereas flumi differed only from dime + MSO and the no residual herbicide (control). Within each herbicide mixture, early-season emergence did not differ between the dead and living CC conditions in either year ($P \geq 0.112$). When contrasted, dimethenamid-P-containing mixtures had more early-season emergence than flumioxazin-containing mixtures, equivalent to about 60 and 49 percentage points more of the no residual herbicide (control) emergence by 35 DAT in 2025 and 38 DAT in 2026, respectively ($P < 0.001$).

Based on the estimated emergence rates, the fitted slopes indicate that 10% of the Palmer amaranth emergence in the no residual herbicide (control) would be reached at about 3 DAT with no residual herbicide, 4 to 9 DAT with dimethenamid-P-containing mixtures, and 28 DAT or later with flumioxazin-containing mixtures. This delay is important because the time of emergence relative to the crop determines the level of competition and the need for further weed management. In Kansas, Bensch et al. (2003) reported up to 79% soybean yield loss when Palmer amaranth emerged with soybean, but no significant yield loss when it emerged at soybean canopy closure. Our results partly agree with de Sanctis et al. (2021), who reported in an on-farm study in Nebraska that flumioxazin delayed the critical time of Palmer amaranth removal from the V1 to the V3 soybean stage in one year but not in the other, whereas the delay with flumioxazin-containing mixtures in this study occurred in both years. Although the critical time of removal was not measured, these results suggest that flumioxazin-containing mixtures may reduce early-season competition and delay the need for a POST herbicide application.

2.3.5 Palmer amaranth Final Density at Soybean Canopy

Palmer amaranth final density at soybean canopy closure was affected by additive effects of herbicide mixture ($P < 0.001$) and year ($P = 0.003$). There was no strong evidence of an interaction between CC condition and year ($P = 0.069$).

Palmer amaranth density was not affected by CC condition in either year (Table 2.4). From 2025 to 2026, Palmer amaranth density increased by 54% with dead CC and by 230% with living CC. In 2026, averaged over dime and flumi, no CC (3.0 ± 0.9 plants m^{-2}) had 67% more Palmer amaranth than dead CC and 6% more than living CC, but neither difference was significant ($P = 0.143$ and 0.858). Hereafter, analyses focused on the effect of herbicide mixtures within years.

In 2025, the no residual herbicide (control) had the highest Palmer amaranth density (3.0 ± 0.8 plants m^{-2}). Both flumi and flumi + MSO significantly differed and showed a suppression of 85 to 87% Palmer amaranth density versus the no residual herbicide (control). Remaining dimethenamid-P-containing herbicide mixtures showed 50 to 52% suppression; nonetheless, they were not different from the no residual herbicide (control) (Table 2.4). In 2026, the no residual herbicide (control) had 6.7 ± 1.9 plants m^{-2}, and herbicide mixtures showed the same differences and reduced Palmer amaranth density by similar proportions as in 2025 (Table 2.4). Including MSO did not change Palmer amaranth density with either flumi or dime in either year based on the contrast ($P > 0.05$).

Overall, Palmer amaranth density in this study was characterized as low compared with densities of more than 80 plants m^{-2} typically observed in small-plot university research fields (Nunes et al. 2023b; Perkins et al. 2021).-Palmer amaranth density was greater in 2026 than in

2025, which may be related to the greater precipitation during the 2026 soybean growing season and the much lower CC biomass. More CC biomass was produced than predicted by meta-analyses for consistent weed suppression in 2025 and less in 2026 (Nichols et al. 2020; Weisberger et al. 2023). In addition, the soybean canopy was still open at 50 DAT (R1 stage) in 2026, which allowed more sunlight to reach the soil between rows for a longer time and favored Palmer amaranth emergence (Jha and Norsworthy 2009).

The most consistent result for Palmer amaranth density was the difference between active ingredients. Flumi had less Palmer amaranth than dime with the dead CC condition, the living CC condition, and no CC, so the ranking of the active ingredients did not change with CC. In addition, Palmer amaranth density with no CC did not differ from that with CC (averaged over the dead and living CC conditions) for either dime or flumi ($P > 0.05$). These results agree with Nunes et al. (2023b), who reported similar *Amaranthus* spp. control with or without cereal rye when a flumioxazin + pyroxasulfone premix was applied and density was low.

2.3.6 Palmer amaranth Biomass at Soybean Canopy

Palmer amaranth biomass was affected by the interaction of herbicide mixture and year ($P < 0.001$) and herbicide mixture and CC condition ($P = 0.024$), whereas the three-way interaction was not significant ($P = 0.115$). Therefore, means were compared within each year. Biomass in the no residual herbicide (control) was 3.5 times greater in 2025 than in 2026. Biomass reductions were calculated relative to the treatment combination with the greatest Palmer amaranth biomass in each year (Figure 2.2).

In 2025, the greatest Palmer amaranth biomass at canopy closure was observed in the no residual herbicide (control) with the dead CC condition (109.2 ± 34.9 g m^{-2}), which did not differ

from the no residual herbicide (control) with the living CC condition (53.0 ± 17.0 g m^{-2}). All flumioxazin-containing mixtures had less Palmer amaranth biomass than the no residual herbicide (control) with either CC condition, reducing biomass by 92 to 98% relative to the no residual herbicide (control) with the dead CC condition. Dimethenamid-P-containing mixtures reduced Palmer amaranth biomass by 76 to 88% and differed from the no residual herbicide (control) with the dead CC condition, but not from the no residual herbicide (control) with the living CC condition (Figure 2.2).

In 2026, the greatest Palmer amaranth biomass at canopy closure was observed in the no residual herbicide (control) with the living CC condition (31.0 ± 8.1 g m^{-2}) and the dead CC condition (29.7 ± 7.9 g m^{-2}). These treatments did not differ from dime with no CC, which reduced Palmer amaranth biomass by 7 to 8%. All flumioxazin-containing mixtures, with the dead, living CC condition, or no CC, had less Palmer amaranth biomass than the no residual herbicide (control), reducing it by 79 to 90% versus the no residual herbicide (control) with the living CC condition. Flumi with the dead CC condition, the living CC condition, or no CC had the least biomass (3.2 to 4.5 g m^{-2}) and differed from all dimethenamid-P-containing mixtures and no residual herbicide (control) treatments. Dimethenamid-P-containing mixtures with either CC condition reduced Palmer amaranth biomass by 24 to 52% but did not differ from the no residual herbicide (control) (Figure 2.2).

Palmer amaranth biomass did not differ between the dead and living CC conditions in either year, within the no residual herbicide (control) or averaged across herbicide mixtures ($P > 0.05$; Figure 2.3). Presence of CC biomass suppresses weeds early in the season but to extend suppression to 8 weeks after CC termination, double the amount of biomass is required because suppression declines as the residue decomposes (Pittman et al. 2020). In addition, weeds that

emerge through the residue usually compensate with greater growth per plant, so late-season weed biomass is less affected than early-season emergence (Teasdale 1996). Therefore, any extra suppression from the living CC condition was likely gone by soybean canopy closure. For this reason, CC needs to be integrated with residual herbicides to extend Palmer amaranth control (Nunes et al. 2024b; Perkins et al. 2021).

Flumioxazin-containing mixtures had less Palmer amaranth biomass than dimethenamid-P-containing mixtures in both years and both CC conditions, averaged over MSO inclusion, with only 18 to 29% of the biomass ($P < 0.001$; Figure 2.4). The same difference occurred with no CC in 2026, where flumi had 13% of the Palmer amaranth biomass of dime ($P < 0.001$; Figure 2.4). These differences were likely related to the characteristics of each active ingredient rather than to the CC treatment. Dimethenamid-P only reduced emergence, whereas the reach-back activity of flumioxazin (Shaner 2014) may have further reduced Palmer amaranth growth later in the season (Liphadzi and Dille 2006). Active ingredients can also differ in how much herbicide is washed off from the CC residue and thus finally reaches the soil (Smith et al. 2025, 2026). For example, Nunes et al. (2023a) reported that cereal rye reduced the soil concentration of metolachlor by 60 to 91%, compared with 39 to 71% for sulfentrazone applied in the same premix. Dimethenamid-P belongs to the same SOA group as metolachlor, and the two have similar and different physicochemical properties (Lewis et al. 2016). Herbicide concentrations in soil and CC residue were not measured, so the causes remain unclear. Research on how these properties interact with weather after application to CC biomass would help explain the weed control obtained by combining residual herbicides and CC (Krähmer et al. 2021; Maia et al. 2025a; Smith et al. 2026). Including MSO did not affect Palmer amaranth biomass ($P > 0.05$), except for flumi with living CC in 2025, where MSO reduced Palmer amaranth biomass by 73% ($P = 0.004$). The

effect of including MSO was not clear and further research with different weather conditions and Palmer amaranth infestation levels are needed to determine when MSO may improve the performance of soil-applied residual herbicides applied to CC.

2.3.7 Soybean Yield

Soybean yield was affected by year ($P < 0.001$) but not by herbicide mixture ($P = 0.190$), CC condition ($P = 0.229$), or any interaction ($P \geq 0.161$). Yield was about 250 kg ha^{-1} greater in 2025 than in 2026 when averaged over treatments. Yield also decreased from west to east across the field in 2026 (133 kg ha^{-1} per harvest pass, about 1,500 kg ha^{-1} across the field), and this gradient was accounted for in the analysis, whereas no spatial pattern was observed in 2025.

Soybean yield was affected by CC condition in 2025, where the dead CC condition yielded 270 kg ha^{-1} (8%) more than the living CC condition (3,600 vs. 3,330 kg ha^{-1}; $P = 0.046$), whereas CC conditions did not differ in 2026 (3,210 kg ha^{-1} for both; $P = 0.988$) (Figure 2.5; Table 2.5). Within each CC condition, herbicide mixtures did not differ in yield in either year, including dime and flumi with no CC in 2026.

Flumioxazin- and dimethenamid-P-containing mixtures did not differ in yield, whether averaged over MSO inclusion and CC condition ($P \geq 0.196$) or within each CC condition ($P \geq 0.158$). In 2025, flumioxazin-containing mixtures yielded 3,180 to 3,660 kg ha^{-1} and dimethenamid-P-containing mixtures yielded 3,360 to 3,600 kg ha^{-1} across CC conditions. In 2026, flumioxazin-containing mixtures yielded 3,150 to 3,460 kg ha^{-1} and dimethenamid-P-containing mixtures yielded 2,960 to 3,220 kg ha^{-1}, including plots with no CC. Yield ranges overlapped in both years.

The yield reduction with the living CC condition occurred only in 2025, when living CC biomass exceeded 10,000 kg ha^{-1} and precipitation during the soybean growing season was 24% below the 30-yr average. Planting into living cereal rye can reduce soybean yield through water use by the CC and may have been the main cause of the yield differences observed in our study (Nunes et al. 2023a, 2024b). In 2026, CC biomass was below 2,000 kg ha^{-1} and precipitation was about average, and the living CC condition had no yield impact. Soybean stand at R1 was also similar among the dead CC, living CC, and no-CC conditions (274,000 ± 6,000, 260,000 ± 10,000, and 279,000 ± 8,000 plants ha^{-1}, respectively; $P = 0.331$), close to the desired seeding rate (272,000 seeds ha^{-1}). Nunes et al. (2024b) reported that reduced soybean stand under high CC biomass was a key factor in soybean yield loss when planting green, but planting into living CC did not reduce soybean stand in 2026. Herbicide mixtures did not affect yield, even though flumioxazin-containing mixtures reduced Palmer amaranth density and biomass. In general, Palmer amaranth density was relatively low in both years in this farmer's field, and the farmer POST application after the last weed assessment controlled the remaining Palmer amaranth, diminishing its effect on yield. Therefore, the yield difference between CC conditions was more likely related to CC effects on soil water or other factors not measured in this study than to early-season weed interference. However, this study was not designed to isolate these causes, and the low Palmer amaranth pressure may have limited our ability to detect yield responses to the herbicide mixtures and to estimate the yield loss or economic value of additional weed suppression.

2.3.8 Economics

Direct costs ranged from a low of \$43 ha^{-1} for the no residual herbicide (control) with the living CC condition to a high of \$118 ha^{-1} for dime + MSO with the dead CC condition (Table 2.6). The additional termination pass in the dead CC condition resulted in \$44 ha^{-1} more than the living CC condition; this cost was recovered with 102 kg ha^{-1} of additional soybean yield.

In 2025, the greater yield in the dead CC condition corresponded with a greater gross margin, that is \$70 ha^{-1} more than living CC (\$1,463 vs. \$1,393 ha^{-1}; Table 2.6). In 2026, yields did not differ between CC conditions, so the two conditions differed only in direct cost (\$44 ha^{-1} less with living CC). Because CC condition did not affect yield when analyzed across years (P = 0.229), the 2025 gross margin difference should be interpreted with caution. Flumi cost \$21 ha^{-1} less than dime and MSO added \$4 ha^{-1} to either herbicide mixture. Because herbicide mixtures did not affect yield, gross margin was compared only between CC conditions; among herbicide mixtures, it would only reflect their differences in cost.

2.4 Conclusion

Palmer amaranth control was driven by the active ingredient in the residual herbicide rather than by the CC condition. Flumioxazin reduced Palmer amaranth emergence, density, and biomass across both CC conditions or no CC, with no tradeoff due to its combined foliar + soil-residual herbicide activity on green plant tissue (H0 rejected). Including MSO did not improve either flumioxazin or dimethenamid-P herbicide effects on Palmer amaranth. Soybean yield was affected by the CC condition rather than by the herbicide mixtures. In 2025, with high CC biomass and below-average rainfall scenarios, living CC reduced soybean yield and gross margin, whereas in 2026, with low CC biomass and normal rainfall, terminating rye before

planting only increased the cost. Flumioxazin-containing mixtures yielded similarly to dimethenamid-P-containing mixtures at a lower cost. Evaluating POST efficacy and including weed-free and weedy checks help to quantify the economic impact of Palmer amaranth and of integrated weed management strategies when combining CC and soil-residual herbicides.

Disclaimer: Claude (Anthropic), an artificial intelligence assistant, was used to support data organization, grammar editing, and coding in R software. The author reviewed and verified all outputs and is responsible for the content of this chapter.

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Figures

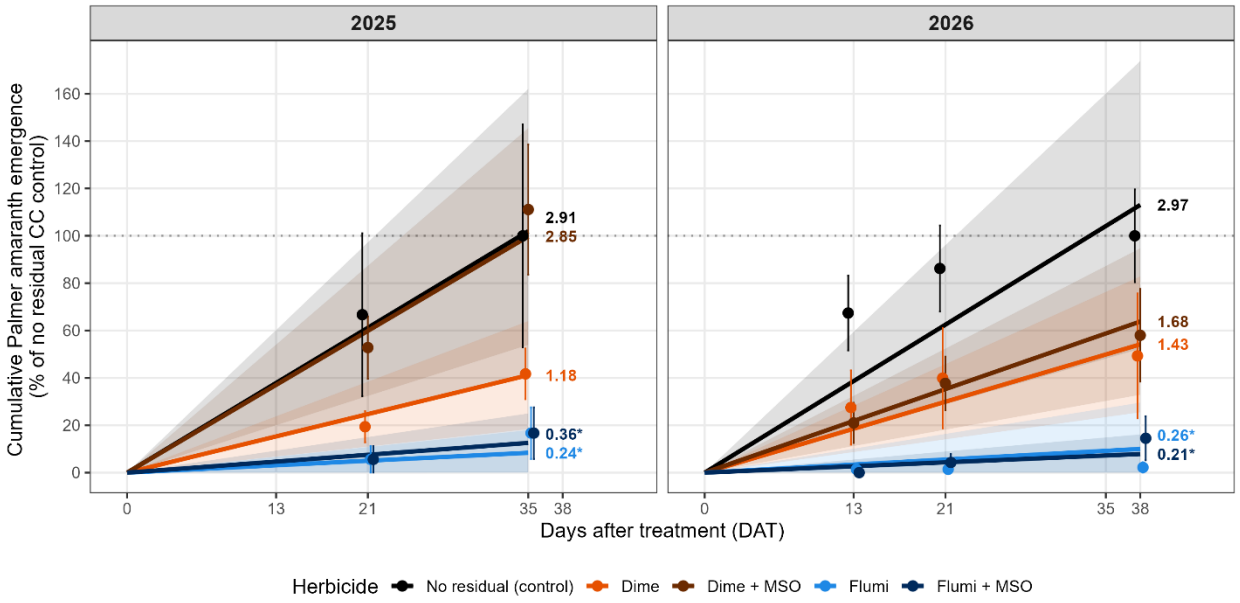


Figure 2.1. Cumulative Palmer amaranth emergence averaged across dead and living CC as a percentage of the no residual herbicide (control) by days after herbicide mixture treatment (DAT). Treatments were applied on June 2, 2025, and May 13, 2026. Lines and shaded bands are model estimates (slope × DAT) and their 95% confidence intervals; points are observed means ± SE. Values at the end of each line are slopes (% of control per day); * indicates a slope different from the control (Dunnett, $P < 0.05$).

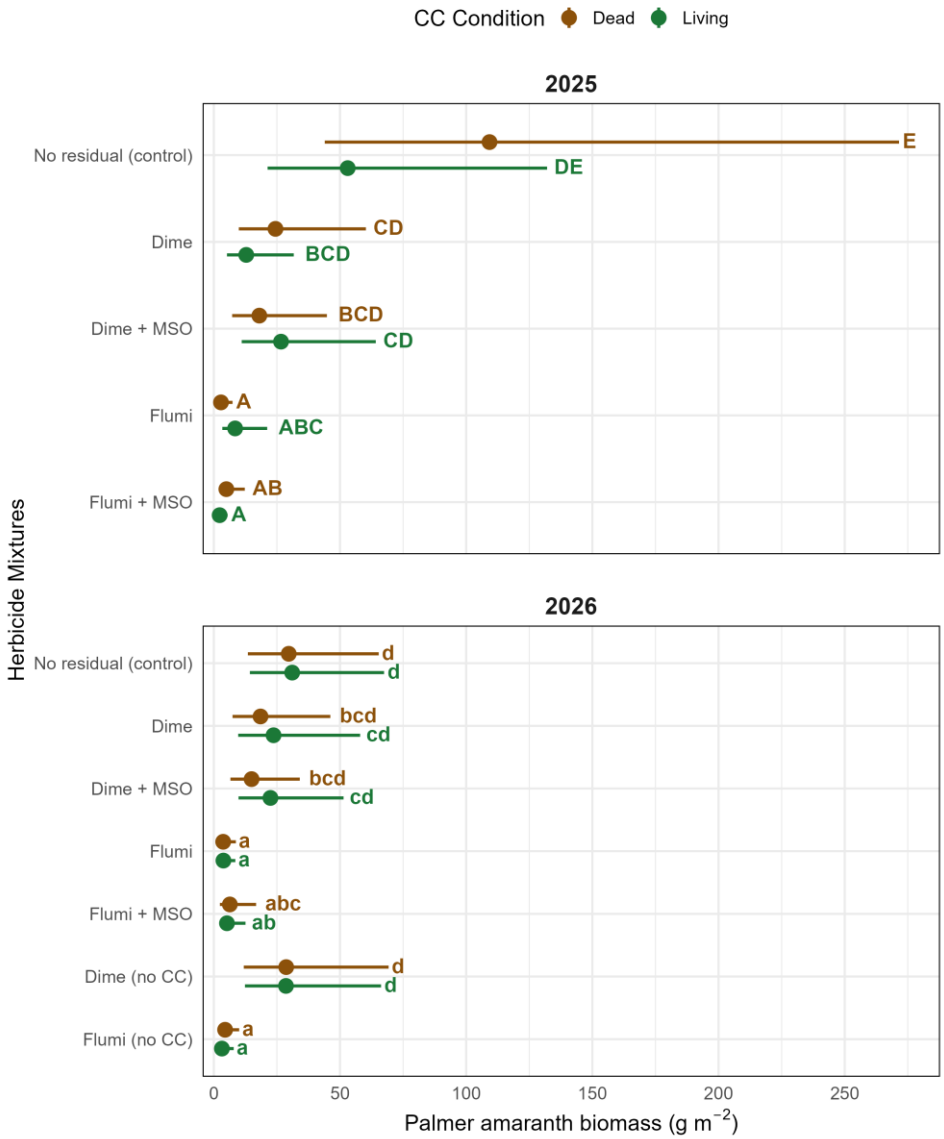


Figure 2.2. Palmer amaranth biomass (g m^{-2}) at soybean canopy closure for each herbicide mixture and CC condition combination in 2025 and 2026. Points are means back-transformed from the log scale, and bars are 95% confidence intervals. Within a year, means followed by the same letter do not differ (Tukey, $P < 0.05$); uppercase letters compare means within 2025 and lowercase letters within 2026. Dime and flumi with no CC were included in 2026 only; for these, dead and living indicate the timing of the foliar termination program.

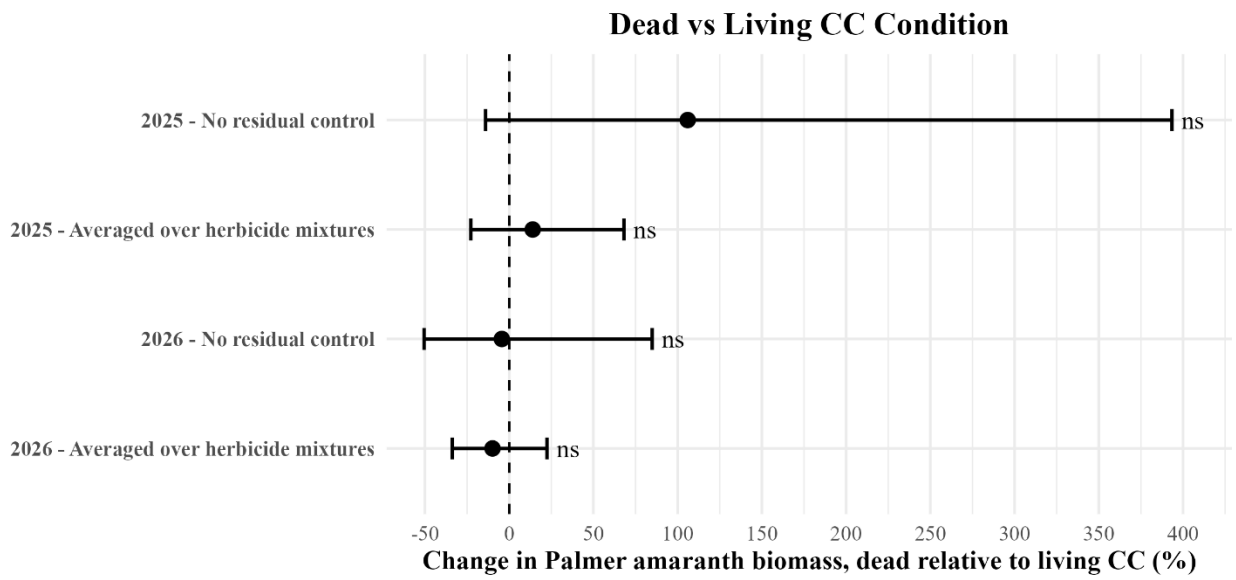


Figure 2.3. Percent change in Palmer amaranth biomass at soybean canopy closure for the dead relative to the living CC condition, within the no residual herbicide (control) and averaged over herbicide mixtures, in 2025 and 2026. Bars are 95% confidence intervals; ns, not significant ($P > 0.05$).

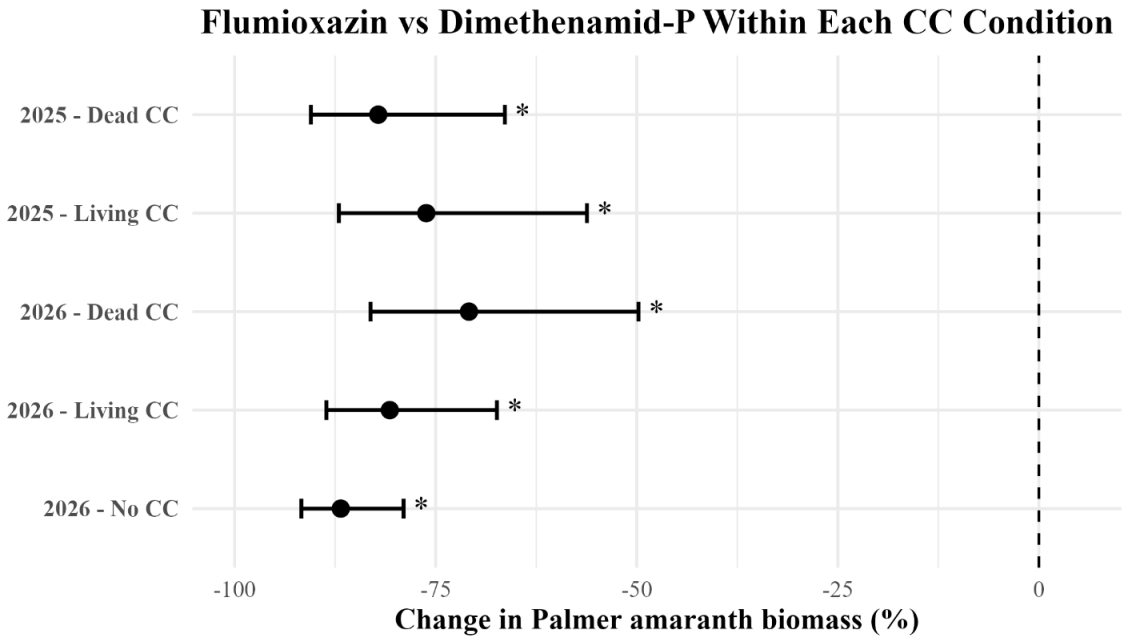


Figure 2.4. Percent change in Palmer amaranth biomass at soybean canopy closure for flumioxazin relative to dimethenamid-P within each CC condition and year, averaged over MSO inclusion (no CC in 2026 only, without MSO). Bars are 95% confidence intervals; negative values indicate less biomass with flumioxazin; * $P < 0.05$.

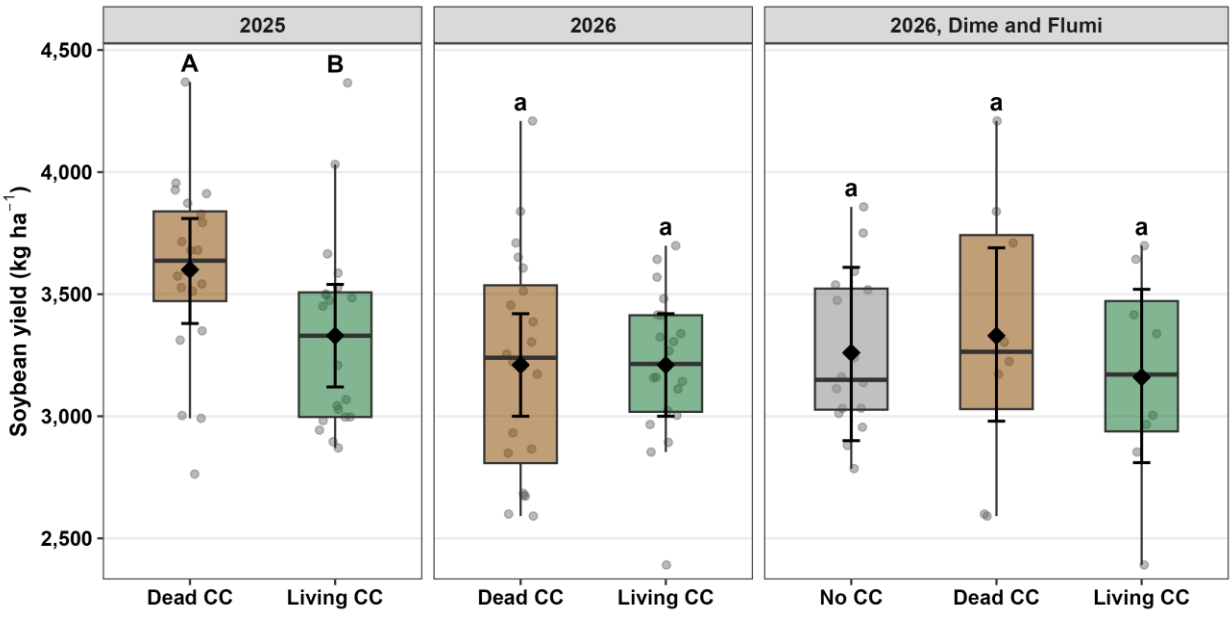


Figure 2.5. Soybean yield by CC condition in 2025 and 2026. In the 2025 and 2026 panels, dead and living CC are averaged over the five herbicide mixtures; in the third panel (2026, Dime and Flumi), no CC is compared with dead and living CC averaged over Dime and Flumi only (without MSO), the herbicides applied in the no-CC plots. Points are subplot yields adjusted for the west–east field gradient, boxes show their distribution, and diamonds and bars are model means and 95% confidence intervals. Within a panel, means followed by the same letter do not differ (Tukey, $P < 0.05$); uppercase letters compare means within 2025 and lowercase letters within 2026.

Tables

Table 2.1. Cover crop termination dates for each condition, foliar herbicides applied, and rates used in 2025 and 2026.

Cover crop condition	Termination Dates	Foliar herbicides	Rate
Dead	May 23, 2025	Glyphosate +	1040 g ha^{-1}
	May 2, 2026	Glufosinate-ammonium +	626 g ha^{-1}
		AMS 2%	2.8 kg ha^{-1}
Living	June 2, 2025	Glyphosate +	1040 g ha^{-1}
	May 13, 2026	2,4-D +	770 g ha^{-1}
		AMS 1%	1.4 kg ha^{-1}

Table 2.2. Monthly mean temperature (°C) and precipitation (mm) received during the 2024–2025 and 2025–2026 growing seasons compared with the 30-yr average (1991–2020) at Oak Hill, KS.

	Mean temperature (°C)			Precipitation (mm)		
Month	2025	2026	30-yr	2025	2026	30-yr
October	16.5	16.7	13.3	64	48	57
November	8.0	7.8	5.6	23	77	38
December	1.8	1.4	−0.3	24	14	29
January	−5.9	−2.0	−2.1	24	39	18
February	−3.5	3.6	0.3	22	8	28
March	9.5	10.1	6.2	24	11	49
April	12.8	15.2	11.9	155	92	72
May	17.2	18.3	18.1	63	177	124
June	24.0	23.8	23.8	122	180	114
July	26.5	26.9	26.6	69	46	101
August	24.4	26.2	25.1	52	51	105
September	21.3	25.2	20.5	56	117	73

Temperature and snow (liquid equivalent): NOAA NCEI, Clay Center, KS (USC00141559), about 17 km from the site. Precipitation: on-farm rain gauge. 30-yr: NOAA 1991–2020 normals, Clay Center, KS. 2025 = October 2024 to September 2025; 2026 = October 2025 to September 2026.

Table 2.3. Cost ($ ha^{-1}) of the burndown programs, residual herbicides, adjuvant, and spraying pass used to calculate direct costs.

Item	Cost ($ ha^{-1})
Burndown program at CC termination (herbicides, AMS, spray pass)	
Dead CC: glyphosate + glufosinate-ammonium + AMS, two passes	86.88
Living CC: glyphosate + 2,4-D + AMS, one pass	42.50
Residual herbicides and adjuvant	
Dimethenamid-P	27.68
Flumioxazin	6.89
MSO	3.87
Field operation, custom rate per sprayer pass	
Herbicide application, ground rig (included in the burndown programs)	26.00

Spraying pass: Northeast district custom rate (Kansas Department of Agriculture and Kansas State University Land Use Survey Office 2026). Burndown program costs include the spraying passes: dead CC, $34.88 for herbicides and AMS plus $52.00 for two passes; living CC, $16.50 plus $26.00 for one pass. Direct cost of each combination (Table 2.6) = burndown program + residual herbicide + MSO. AMS, ammonium sulfate; MSO, methylated seed oil.

Table 2.4. Palmer amaranth density (plants m^{-2} ± SE) at soybean canopy closure for main effects of CC condition across herbicide mixtures or for main effect of herbicide mixture across CC conditions in 2025 and 2026.

Main effect	Treatment	Palmer amaranth density			
		2025		2026	
		Plants m^{-2}			
CC condition	Dead	1.2 (0.3)	A	1.8 (0.4)	a
	Living	0.9 (0.2)	A	2.9 (0.7)	a
	No CC	–		3.0 (0.9)	a
Herbicide mixture	No residual herbicide (control)	3.0 (0.8)	B	6.7 (1.9)	b
	Dime	1.5 (0.4)	B	3.4 (0.9)	b
	Dime + MSO	1.5 (0.4)	B	3.3 (0.9)	b
	Flumi	0.4 (0.1)	A	1.0 (0.3)	a
	Flumi + MSO	0.4 (0.1)	A	0.9 (0.3)	a

Values are means (±SE) back-transformed from the log scale. Within each main effect and year, means followed by the same letter do not differ (Tukey, $P < 0.05$); uppercase letters compare means within 2025 and lowercase letters within 2026.

Table 2.5. Soybean yield (kg ha^{-1}) for each cover crop (CC) condition, averaged over herbicide mixtures, in 2025 and 2026.

Cover crop condition	Soybean yield			
	2025		2026	
	---------- kg ha^{-1} ----------			
Dead	3,600 (90)	A	3,210 (90)	a
Living	3,330 (90)	B	3,210 (90)	a
No CC†	–		3,260 (150)	a

Values are model means (SE) averaged over herbicide mixtures. Within a year, means followed by the same letter do not differ (Tukey, $P < 0.05$); uppercase letters compare means within 2025 ($P = 0.046$) and lowercase letters within 2026 ($P = 0.988$). † No-CC plots (2026 only) received dime or flumi without MSO; therefore, no CC was compared with the dead and living CC conditions averaged over the same herbicides.

Table 2.6. Direct cost ($ ha^{-1}) of each cover crop (CC) condition and herbicide mixture combination, and gross margin ($ ha^{-1}) of each CC condition in 2025 and 2026.

	Dead CC	Living CC
	$ ha^{-1}	
Direct cost		
No residual herbicide (control)	87	43
Dime	115	70
Dime + MSO	118	74
Flumi	94	49
Flumi + MSO	98	53
Gross margin†		
2025	1,463	1,393
2026	NC	NC

Direct cost includes foliar herbicides and adjuvants for CC termination, soil-residual herbicide, MSO, and spraying passes (Table 2.3); the dead CC condition received one additional spraying pass. Cereal rye seed and drilling, soybean seed and planting, and other production costs were the same for all treatments and were not included. † Gross margin = income − direct cost, with income from a soybean price of $0.435 kg^{-1} and the model mean yield of each CC condition, and the mean direct cost of each CC condition across herbicide mixtures, because herbicide mixtures did not affect yield. NC, not calculated, because soybean yield did not differ between CC conditions in 2026.

Chapter 3 - Integrating Cover Crop Mixtures and Residual Herbicides for Weed Control Before Late-Planted Corn

Abstract

Cereal rye (*Secale cereale* L.) cover crop (rye CC) suppresses weeds but can reduce corn (*Zea mays* L.) yield when planted immediately afterwards. Cover crop mixtures that combine a cereal with a legume, such as triticale (*Triticosecale* Wittm. ex A. Camus) and hairy vetch (*Vicia villosa* Roth), may mitigate this disadvantage but provide less weed suppression. Integrating CC with herbicide programs may be a synergistic alternative. The objective was to evaluate the integration of CC treatments and herbicide programs for weed suppression, late-planted corn yield, and economic returns, compared with traditional chemical fallow and rye CC. An on-farm study in 2025 and 2026 at Oak Hill, KS, evaluated rye CC and three blends of hairy vetch (HV) and triticale (Tr), each terminated with glyphosate + 2,4-D alone (burndown only) or with flumioxazin (burndown + residual), plus chemical fallow, before late-planted corn. Rye CC produced the most biomass in 2025 but the least in 2026, when a warm spring required early termination, whereas the triticale-HV CC treatments produced similar biomass across blends and years. Winter weed suppression increased with the cereal portion of the CC, but no CC treatment suppressed cheatgrass (*Bromus tectorum* L.). Summer weed suppression at corn planting depended on weather, CC biomass, and the dominant weed species. Adding the residual herbicide reduced summer weed infestation relative to burndown only, but its effect varied with the amount of rainfall received for activation and the target weed species. In 2025 with a drier spring, the dominant weed was velvetleaf (*Abutilon theophrasti* Medik.) and all CC treatment and herbicide program combinations reduced summer weed biomass by 97% and reduced

percent weed cover by more than 99% on average relative to chemical fallow. In 2026 which was a wetter spring, the dominant weed was Palmer amaranth (*Amaranthus palmeri* S. Watson) and only the triticale-HV CC treatments integrated with burndown + residual, which was activated soon after application, consistently reduced both weed cover and summer weed biomass (62 to 95%) relative to chemical fallow, whereas rye CC did not differ from chemical fallow. In 2025, all CC treatments corn yielded 25 to 35% less than chemical fallow (7,600 kg ha^{-1}), regardless of herbicide program. In 2026, a dry July reduced corn yield in all treatments (1,000 to 2,500 kg ha^{-1}); the triticale-HV CC treatments yielded 900 kg ha^{-1} more than rye CC and 500 kg ha^{-1} more than chemical fallow, whereas rye CC did not differ from chemical fallow. The CC treatments had \$107 to \$192 ha^{-1} greater direct costs than chemical fallow, and their gross margin was \$467 to \$649 ha^{-1} less than that of chemical fallow in 2025 (\$1,389 ha^{-1}) and \$27 to \$181 ha^{-1} less in 2026 (\$234 ha^{-1}). Integrating triticale-HV CC treatments with a residual herbicide provided the most consistent summer weed suppression across years, but before late-planted corn this benefit came with a yield and economic cost relative to chemical fallow in 2025 and, in 2026, a yield gain that did not offset the greater direct costs.

Keywords: cereal rye; chemical fallow; flumioxazin; hairy vetch; triticale; weed suppression.

3.1 Introduction

No-till production systems in North America have contributed to increased crop productivity and reduced soil erosion, largely relying on genetically modified crops (GMOs) and herbicide-based weed management. In these systems, weed control often involves chemical fallow periods of no crop, where weeds are managed exclusively with soil-applied residual and

foliar-applied herbicides (Triplett and Dick 2008; Vencill et al. 2012). Repeated use of herbicides with the same sites of action (SOA), combined with improper application practices, has accelerated the evolution of herbicide-resistant weed populations and raised environmental concerns such as groundwater contamination and herbicide drift (Almberg et al. 2018; Délye et al. 2015; Heap 2026; Oseland et al. 2024). Small-seeded weed species are better adapted to no-till production systems, and many have developed resistance to commonly used herbicides (Norsworthy et al. 2012; Osipitan et al. 2019). Among them, *Amaranthus* species stand out due to their competitiveness, high seed production capacities, and ability to evolve herbicide resistance (Bravo et al. 2018; Jha 2008). Palmer amaranth (*Amaranthus palmeri* S. Watson) is especially problematic in the US Midwest region, by outcompeting other *Amaranthus* species and by reducing crop yields (Beckett et al. 1988; Massinga et al. 2001; Roberts and Florentine 2022). Bensch et al. (2003) documented that Palmer amaranth produced the greatest biomass and reduced soybean yield the most (78%) in comparison to waterhemp [*A. tuberculatus* (Moq.) Sauer] (-56%) and redroot pigweed (*A. retroflexus* L.) in a northeastern KS field study. In corn, Palmer amaranth densities of 0.5 to 8 plants m^{-1} of row reduced grain yield by 11 to 91% (Massinga et al. 2001), and estimated yield loss reached 100% in dryland compared with 62.5% in irrigated corn at a high nitrogen rate in one year (Ruf-Pachta et al. 2013). Palmer amaranth plants that escaped a preemergence herbicide caused less corn yield loss than those in untreated corn but produced similar amounts of seed (Liphadzi and Dille 2006). Recently, a Palmer amaranth population in this area was identified to have resistance to six SOAs (Shyam et al. 2021). This highlights the need for alternative approaches for Palmer amaranth management in the region (Arsenijevic et al. 2022; Norsworthy et al. 2012; Oliveira et al. 2020).

Cover crops (CC) are non-cash crops normally grown between cash crops in the US Midwest for soil health and weed-suppressing benefits (Blanco-Canqui and Ruis 2020; Osipitan et al. 2018). This practice stands out due to its ability to suppress emergence of small-seeded weed species by modifying temperature, shifting light conditions, acting as a physical impediment, and by releasing allelopathic compounds (Creamer et al. 1996; Osipitan et al. 2019; Rice et al. 2022). Cover crops are generally less effective at suppressing large-seeded weed species, but species-specific ecological responses are variable (Mohler and Teasdale 1993). Weed suppression is largely driven by the amount of CC biomass and persistence of residue on the soil surface (Creamer et al. 1996; Nichols et al. 2020; Teasdale and Mohler 2000). Among CC options, a monoculture of a grass crop such as cereal rye (*Secale cereale* L., rye CC) or triticale (*Triticosecale* Wittm. ex A. Camus) for a given area normally outperforms species mixtures of cereals and broadleaves in biomass production and consequently, provides greater weed suppression (Baraibar et al. 2018; MacLaren et al. 2019). Smith et al. (2020) observed that in the Northeast US, winter annual weed biomass was suppressed most with monoculture cereal CC (83 to 100%) compared to diverse CC mixtures (66 to 99%) that included 5 to 14 different species of legumes, brassicas, and grasses.

Cereal rye has been widely adopted due to winter hardiness, water-use efficiency, high biomass, and potential production of allelopathic compounds (Chudzik et al. 2024; Oliveira et al. 2019; Rice et al. 2022). Potential reductions in *Amaranthus* species recruitment of up to 50% or more have been observed when sufficient CC biomass was present (Nunes et al. 2024a; Weisberger et al. 2023). Several studies agree that CC alone was not enough for sufficient weed control, and other methods of weed control were required such as herbicides (Nichols et al. 2020; Osipitan et al. 2018; Weisberger et al. 2023). Cover crops with soil-applied residual herbicides

prior to crop planting can extend weed-free period for crops and reduce the reliance on foliar-applied herbicides (Loux et al. 2017; Norsworthy et al. 2012; Nunes et al. 2024b).

Some limitations to adoption of monoculture rye CC within crop and livestock systems include hosting insect pests, immobilizing nutrients, and becoming a weed itself and causing crop yield losses (Bakker et al. 2016; Barman et al. 2026; Bergtold et al. 2019; Nielsen et al. 2015; Roesch-McNally et al. 2018). For example, Quinn et al. (2023) observed corn yield loss by up to 20% following a rye CC when no nitrogen was added. In integrated crop–livestock systems, rye CC provides limited forage quality and reduced grazing windows due to rapid anthesis in the spring compared to other CC species in the southern Midwest US (Carr et al. 2004; Glaze-Corcoran et al. 2023).

Benefits of diverse CC mixtures include improved nitrogen cycling and increased forage value (Farney et al. 2018; Gannett et al. 2024; Martin et al. 2016). However, CC mixtures with lower carbon to nitrogen ratios (C:N, e.g. 20:1 to 10:1), such as hairy vetch (*Vicia villosa* Roth) or clovers (*Trifolium* spp.), have less persistent residue and provide a shorter window of weed suppression unless more biomass was produced in comparison to CC with greater C:N (80:1 to 45:1), such as rye or triticale (Johnson et al. 2007; Palhano et al. 2018; Teasdale and Mohler 2000). Pittman et al. (2020) observed that CC with a C:N of 9:1 were able to suppress redroot pigweed by 50% at 4 weeks after CC termination (WAT), whereas to maintain the same level of suppression at 6 and 8 WAT, C:N ratios of 16:1 to 20:1 were needed.

Diverse CC mixtures have gained popularity despite limited levels of weed suppression, likely due to their ability to increase plant biodiversity, have roots that explore different soil depths, promotion of soil biological activity, and enhancing cropping system resilience (Blanco-Canqui 2024; Chu et al. 2017). In Kansas, few studies have evaluated whether integrating CC

mixtures with other weed management tools, such as residual herbicides, can overcome the limitations of monoculture cereal CC while keeping weeds below economic thresholds. Dhanda et al. (2024) found that a fall-planted CC mixture terminated with glyphosate plus a residual herbicide reduced glyphosate-resistant Palmer amaranth emergence by 42 to 56% compared with chemical fallow. Petrosino et al. (2015) observed that fall-sown triticale alone or mixed with legumes reduced kochia [*Bassia scoparia* (L.) A.J. Scott] density by 78 to 94% compared with chemical fallow in wheat-fallow production systems. However, the effects of integrating CC mixtures with residual herbicides on the yield and economics of a subsequent corn crop are not known. Therefore, the goal of this on-farm research study was to provide local insights for northcentral Kansas farmers about combinations of CC and herbicide use, while maintaining weed control levels. The objective was to compare triticale–hairy vetch mixtures and rye CC, each terminated with burndown only or burndown + residual herbicides, with chemical fallow for CC biomass, weed suppression, and late-planted corn yield in north-central Kansas. We hypothesized that (1) rye CC will provide the best weed suppression; (2) triticale-HV CC treatments will not provide weed suppression but produce more corn yield; and (3) chemical fallow will have the least weed suppression while producing the most corn yield.

3.2 Materials and Methods

3.2.1 Study Design and Treatments

On-farm experiments were established in the fall of 2024 and 2025 in fields located at Oak Hill, KS (39° 13’52.04” N; 97°12’19.55” W). Hereafter, the 2024–2025 and 2025–2026 growing seasons are referred to as 2025 and 2026, the years in which corn was grown. Field sites differed each year because the experiment was established following winter wheat grain harvest

and summer forage CC production. Both field sites were located on a Crete silty clay loam (fine, smectic, mesic Pachic Arguistolls) with 1 to 3% slopes (USDA-NRCS 2026).

Experiments were laid out in a strip-plot design with three replicates. One set of strips were four CC treatments: three blends of hairy vetch (HV) and triticale (Tr) at different seeding rates (Low HV + High Tr, Medium HV + Low Tr, and High HV + Low Tr) and rye CC (Table 3.1). The second set of strips were two herbicide programs applied at CC termination: burndown only treatment with glyphosate (1040 g ae ha^{-1}) + 2,4-D (770 g ae ha^{-1}) and burndown plus residual herbicide treatment with glyphosate + 2,4-D and flumioxazin (71 g ai ha^{-1}; Table 3.2). An additional chemical fallow strip completed the herbicide program as a control with glyphosate + 2,4-D and a higher flumioxazin rate (107 g ai ha^{-1}; Table 3.2). These factors were combined into nine treatments (four CC treatments × two herbicide programs, plus chemical fallow). Strips for the CC treatments were 12 m by 165 m and herbicide program strips were 18 m by 146 m, resulting in intersection plots (CC treatment × herbicide program) of 12 m by 18 m, except for chemical fallow, which had no CC.

One week prior to CC seeding in the fall, a tank mix of glyphosate (1040 g ae ha^{-1}) + 2,4-D (770 g ae ha^{-1}) was applied as a fall clean-up pass (Tables 3.2 and 3.3). Cover crop treatments were drilled in rows spaced 19-cm apart using a John Deere Air 1890 seeder with 1910 cart (Deere & Company, Moline, IL). The chemical fallow program was applied in the early spring to prevent CC biomass accumulation and to control winter annual weeds, replicating the timing of a common farmer practice. The herbicide programs applied at CC termination were based on when the different cereal species reached anthesis stage: rye CC was terminated about 3 wk before the triticale-HV CC treatments (Table 3.3). All herbicide applications included ammonium sulfate

(AMS) at 1% w/v (1 kg ha^{-1}), non-ionic surfactant at 115 mL ha^{-1}, and MSO at 465 mL ha^{-1} (Table 3.2).

Corn (O 23-98 TRE RIB, Ohlde Seed Farms, Palmer, KS) was planted on June 23, 2025, and July 7, 2026, in rows spaced 76-cm apart using a John Deere 1750 Max Emerge XP planter at a rate of 50,000 seeds ha^{-1}. Immediately after corn planting, the farmer applied a preemergence herbicide program of glyphosate (1040 g ae ha^{-1}), 2,4-D (770 g ae ha^{-1}), saflufenacil (25 g ai ha^{-1}), atrazine (550 g ai ha^{-1}), dimethenamid-P + topramezone (922 + 17 g ai ha^{-1}), AMS (1% w/v, 1 kg ha^{-1}), and MSO (465 mL ha^{-1}) (Table 3.2). In 2026, after the last experimental assessment, the farmer also made an additional clean-up postemergence application of dicamba + diflufenzopyr (140 g ae + 56 g ai ha^{-1}) and atrazine (550 g ai ha^{-1}) with AMS (1% w/v, 1 kg ha^{-1}) to control weed escapes (Table 3.2). All herbicides were applied using a Case IH Patriot 3340 ground rig sprayer (CNH Industrial, Racine, WI) equipped with a pulse width modulation system and MR 11004 nozzles (Wilger Industries Ltd., Saskatoon, SK, Canada) spaced 52 cm apart on the 18 m long boom. The sprayer was set to deliver 93 L ha^{-1} while traveling at 11 km h^{-1} and operating at 310 kPa and approximately 50% of the duty cycle.

3.2.2 Data Collection

Prior to CC termination, aboveground biomass of total and individual winter annual weed species and CCs were collected from one 0.30-m^2 area per plot (three CC rows by 0.5 m long). Plants were cut at the soil surface, separated by species, placed in paper bags, and oven-dried at 58°C to constant mass. Hairy vetch density was also recorded. Likewise, before corn planting, aboveground biomass of summer annual weeds was measured within a permanently marked 1-

m² frame systematically placed in the middle of each plot; 0.75 m² of the frame was used for summer weed biomass, and 0.25 m² for weed density counts.

Weed emergence and weed community composition were assessed by counting and removing plants by species within the 0.25-m² section of frame in each plot. Counts began with the first noticeable weed flush in the chemical fallow (May 21, 2025, and May 27, 2026) and in the CC treatments with the first flush after termination (10 to 25 d); subsequent counts were made when a new flush was observed, usually after a rainfall event. A final count was made 25 and 28 d after corn planting in 2025 and 2026, respectively. Because weeds were removed at each count, density in each plot was calculated as the sum of all counts made from the time of herbicide application until corn planting (pre-plant), and the count after corn planting (post-plant) was summarized separately. Cumulative pre-plant density was used as a measure of weed recruitment, that is, the weed infestation each treatment allowed before corn planting, rather than of the plants that produced the summer weed biomass. Weed community composition was described for each treatment within each year using the relative abundance of each species (Thomas 1985):

Relative abundance (%) = (Relative density + Relative frequency) / 2 [Eq. 1]

where relative density is the plant number 0.25 m^{-2} of a species as a percentage of the total density of all species and relative frequency is the proportion of plots in which a species was present as a percentage of the sum of the frequencies of all species. These data were summarized descriptively and were not subjected to statistical analysis.

Percent weed cover was estimated from aerial multispectral imagery acquired on June 23, 2025, and June 29, 2026, before corn planting. In 2025, images were captured with an Altum-PT sensor (MicaSense, AgEagle Aerial Systems Inc., Wichita, KS) mounted on a DJI Matrice 350

RTK unmanned aerial vehicle (DJI, Shenzhen, China), and in 2026 with a 6X Thermal Pro sensor (Sentera Inc., St. Paul, MN) mounted on an Astro unmanned aerial vehicle (Freefly Systems, Woodinville, WA), both flown at 50 m above ground level with 80% overlap between consecutive images, giving a ground sampling distance of 2.9 cm per pixel in 2025 and 2.2 cm per pixel in 2026. Images were processed in Pix4Dmapper (Pix4D S.A., Prilly, Switzerland) to generate an orthomosaic and a normalized difference vegetation index (NDVI) map. The NDVI map was clipped to the experimental area, and the 108 plots were overlaid as a georeferenced grid using GDAL (OSGeo Foundation) in QGIS 3.34 (QGIS Development Team, Open-Source Geospatial Foundation). To limit edge effects between adjacent treatments, a 3-m border was excluded from each side of every plot, leaving a central 6.1- by 12.2-m area for analysis. Pixels with NDVI greater than the threshold obtained with Otsu's method (Otsu 1979) for each flight, 0.29 in 2025 and 0.28 in 2026, were classified as live green vegetation, and weed cover was expressed as the percentage of pixels in the central area exceeding this threshold. Pixel values within the central area of each plot were extracted with the terra package (Hijmans 2026) in R to calculate this percentage for each plot.

Corn grain was harvested from the center eight rows of each plot (one sample of 93 m^2 per plot) using a John Deere S780 combine (Deere & Company, Moline, IL). A single yield and grain moisture value was obtained per plot, and grain yield was corrected to 15.5% moisture. Daily precipitation was recorded with an on-site rain gauge, and 2025–2026 snowfall was added as liquid equivalent. Daily air temperature and snow depth were obtained from the NOAA NCEI Clay Center station (USC00141559), about 17 km from the study site, and 1991–2020 monthly normals from the same station were used for comparison (NOAA NCEI 2021; Table

3.4). Normals were prorated by day for periods covering parts of a month for CC treatments, herbicide program application until corn planting, and corn growing seasons.

3.2.3 Economic Analysis

Direct costs were calculated for each CC treatment and herbicide program combination. Gross margin was calculated as income less direct costs and was compared only for factors that significantly affected corn yield; thus, differences in gross margin reflect differences in direct costs. Income was based on the corn grain yield of each year and the corn grain price:

$$\text{Income (\$ ha}^{-1}\text{)} = \text{yield (kg ha}^{-1}\text{)} \times \text{price (\$ kg}^{-1}\text{)} \quad \text{[Eq. 2]}$$

Direct costs included CC treatment establishment and the herbicide programs:

$$\text{Direct cost (\$ ha}^{-1}\text{)} = \text{CC seed + drilling pass + herbicide program} \quad \text{[Eq. 3]}$$

Cover crop establishment included the seed of each CC treatment at its seeding rate (Table 3.1) and one no-till drilling pass; chemical fallow had no establishment cost. The herbicide program was the CC termination program in the CC treatments, burndown + residual or burndown only, and the herbicide application in chemical fallow (Table 3.5). It included the burndown herbicides and flumioxazin when applied, the adjuvants, and one spraying pass. The fall clean-up application before CC seeding was not included because it was considered a normal practice that the farmer would do after the summer use of the field, regardless of the CC treatment. All other production costs, such as corn seed and planting, and the farmer's herbicide applications after corn planting, were the same for all treatments and were not included. Herbicide, adjuvant, and corn prices were provided by the cooperating farmer and represented 2026 cropping season costs near Clay Center, KS; the corn price was \$0.191 kg^{-1}. Cover crop seed prices were list prices from the seed supplier, Green Cover (Bladen, NE), accessed on October 31, 2026. The cost of

each drilling and spraying pass was obtained from the Northeast district of the Kansas custom rates survey (Kansas Department of Agriculture and Kansas State University Land Use Survey Office 2026).

3.2.4 Statistical Analysis

All responses analyzed inferentially were described with generalized linear mixed models (GLMMs): total CC biomass with a gamma distribution, weed cover with an ordered beta distribution, and CC biomass by species, winter and summer weed biomass, and corn grain yield with a Gaussian distribution, with biomass responses log-transformed. Hairy vetch density, weed density (sum of all counts), and weed community composition were summarized descriptively as mean ± SE across plots. Variables with a high occurrence of zero values, hairy vetch density and winter weeds in 2026, were reported descriptively, whereas hairy vetch biomass and winter weed biomass in 2025 were analyzed only in the plots where they were present. Fixed effects were CC treatment or the CC treatment and herbicide program combination, year, and their interaction when estimable. Random effects corresponded to the strip-plot structure within each year: block, CC strip within block, herbicide program strip within block, and plot when more than one subsample per plot was collected. Models with different interactions and residual variance allowed to differ among fixed effects were fitted and evaluated based on residual diagnosis and on AIC. Significance was considered at $P < 0.05$.

Total CC biomass was described with a gamma distribution with a log link function, and the linear predictor included CC treatment, year, and their interaction as fixed effects, and block within year, CC strip within block and year, and plot within year as random effects (Appendix B, Eq. B.1). The dispersion parameter was allowed to vary by CC treatment × year, so the

parameter phi described the variability among subsamples within plots for each CC treatment and year, which was used as a proxy for stand patchiness.

CC biomass by species in the HV-triticale CC treatments were analyzed together with CC treatment, species, year, and their interactions as fixed effects, and block within year, CC strip within block and year, herbicide program strip within block and year, plot within year, and subsample as random effects, with residual variance differing by species × year (Appendix B, Eq. B.2).

Winter weed biomass was analyzed only in 2025, for the CC treatments with plots where winter weeds were recorded. Total winter weed biomass was described with a Gaussian distribution with a log-transformed response, and the linear predictor included CC treatments, whereas CC treatment block and CC strip within block were random effects and residual variance was allowed to differ by CC treatment (Appendix B, Eq. B.3). Biomass of winter weed species (species) followed the same distribution and log-transformation and was described as a function of CC treatment, species, and their interaction, in the plots where each species was present, with block, CC strip within block, and plot as random effects and residual variance differing by species (Appendix B, Eq. B.4). Summer weed biomass at corn planting was described with a Gaussian distribution with log transformation performed, and was described as a function of treatment, year, and their interaction, with CC block and herbicide program block within year, CC strip within block and year, and herbicide program strip within block and year as random effects, and residual variance differing by herbicide program × year and by CC treatment × year (Appendix B, Eq. B.5).

Weed cover was analyzed as a proportion with an ordered beta GLMM with a logit link function (Kubinec 2023), fitted with the ordbeta family of the glmmTMB package, which

accommodates the exact zeros observed in the CC plots in 2025. Fixed and random effects were the same as for summer weed biomass, and the precision parameter varied by herbicide program × year (Appendix B, Eq. B.6). In 2026, 11 plots under cloud shadow interference were excluded.

Corn grain yield was described with a Gaussian distribution, and the linear predictor included treatment (the eight CC treatment and herbicide program combinations plus chemical fallow), year, and their interaction as fixed effects, and CC block and herbicide program block within year, CC strip within block and year, and herbicide program strip within block and year as random effects, with residual variance differing by CC treatment × year (Appendix B, Eq. B.7). Because chemical fallow was not part of the CC treatment × herbicide program factorial, the main effects of CC treatment and herbicide program and their interaction were tested with joint Wald tests of contrasts among the eight CC treatment and herbicide program combinations within each year.

All analyses were done in R v. 4.4.2 (R Core Team 2026), and models were fitted with the glmmTMB package (Brooks et al. 2017) using restricted maximum likelihood. Model assumptions were checked with simulated quantile residuals using the DHARMa package (Hartig 2024), and competing models were compared with AIC. Fixed effects were tested with Type II Wald chi-square tests using the car package (Fox and Weisberg 2019). Estimated marginal means were obtained with the emmeans package (Lenth and Piaskowski 2026) and compared within year with Tukey-adjusted pairwise comparisons and compact letter displays from the multcomp package (Hothorn et al. 2008). Estimates from models with log-transformed responses were back-transformed to the original scale. Planned contrasts were evaluated within year to compare all CC treatment and herbicide program combinations with chemical fallow; burndown + residual with burndown only, across all CC treatments and across the triticale-HV

CC treatments; the triticale-HV CC treatments and Low HV + High Tr with rye CC within each herbicide program; and Low HV + High Tr with Medium and High HV + Low Tr within each herbicide program. Contrasts were estimated on the log scale, back-transformed to ratios, and expressed as percent difference [(ratio − 1) × 100] ± SE with 95% confidence intervals. For weed cover, the estimated means were transformed to the log scale before computing the contrasts. For corn yield, planned contrasts compared all CC treatments, the triticale-HV CC treatments together, and each CC treatment, averaged over herbicide programs, with chemical fallow, and the triticale-HV CC treatments, together and individually, with rye CC, and burndown + residual with burndown only across CC treatments; these contrasts were estimated as differences in kg ha^{-1}. *P* values of planned contrasts were not adjusted for multiplicity. Figures were made with the ggplot2 package (Wickham 2016).

3.3 Results and Discussion

3.3.1 Weather

Precipitation from time of CC establishment, defined as the first rain after CC planting that triggered emergence (Table 3.3), to time of CC termination was 382 and 420 mm for rye CC and the triticale-HV CC treatments in 2025, respectively, and were similar to the 30-yr averages of 322 and 400 mm, respectively. In 2026, 290 and 390 mm of precipitation were received for rye CC and triticale-HV CC treatments, respectively, and were similar to the 30-yr averages of 292 and 384 mm, respectively (Table 3.4). The key difference was delayed CC establishment in 2025, when the plots received no rain until 56 d after planting, whereas in 2026 plots received 25 mm the day after CC planting (Table 3.3). Precipitation received during the corn growing season

was below average in both years with only 253 mm in 2025 and 193 mm in 2026 compared to the 30-yr averages of 306 and 256 mm, respectively.

In 2026, from February to April, temperatures were 3.3 to 3.9 °C above the 30-yr average, and precipitation was below the 30-yr average (Table 3.4). These conditions advanced anthesis in 2026, so termination of rye CC was 19 d earlier and termination of triticale-HV CC treatments was 16 d earlier than in 2025 (Table 3.3). Overall, the triticale-HV CC treatments grew 23 d longer than rye CC in 2026 and received 100 mm of rain during that period, compared with growing for 20 d longer than rye CC but only receiving 38 mm of rain in 2025. Winter conditions also differed between years. In 2025, all hard freezes (≤ −15 °C) occurred with snow cover, whereas in 2026, the temperature dropped on January 23 from 6.1 °C to −15.6 °C on bare ground. More frequent warm–freeze cycles occurred in 2026, with 9 d of freezing conditions (≤ −5 °C) within 3 d after a warm day (≥ 15 °C), compared with only 3 d in 2025. These differences affected mainly the length of the CC growing cycle and HV winter survival.

3.3.2 Total Cover Crop Biomass

In 2025, rye CC produced the greatest biomass, 11,630 (± 680) kg ha^{-1} and it was 2.9 to 3.6 times more than the CC biomass produced by triticale-HV CC treatments (3,250 to 4,060 kg ha^{-1}), which did not differ from each other (Table 3.6). In 2026, the order was reversed: the triticale-HV CC treatments were not different from each other, produced the greatest biomass (2,850 to 2,910 kg ha^{-1}), and were 1.5 to 1.6 times more than rye CC. Greater variability in CC biomass between years was observed for rye CC, which produced 6.3 times more biomass in 2025 than in 2026, whereas the triticale-HV CC treatments produced consistent biomass amount in both years. Typically, rye CC produces the most biomass among CC (Duiker 2014; Ruis et al.

2019). Rye tends to develop faster than triticale (Glaze-Corcoran et al. 2023) and the warm spring conditions in 2026 advanced its time to anthesis, so rye CC was terminated before the May rains, whereas the triticale-HV CC treatments grew longer receiving more rain during that period (Table 3.3). This corresponds to CC biomass production that depends on the length of the growing season and on available water (Nielsen et al. 2015; Ruis et al. 2019).

In the on-farm study, the variability in biomass among samples of the same CC treatment was described by the dispersion parameter φ of the gamma model (Table 3.6); a greater φ indicates a patchier CC stand across the field site. In 2025, the triticale-HV CC treatments had patchier stands than rye CC (φ = 0.17 to 0.75 vs. 0.01), whereas in 2026, all CC treatments had similarly even stands (φ = 0.04 to 0.09). This difference between years was likely attributed to the weather and the different field site of each year, as no other variable observed in this study helped to explain it.

3.3.3 Impact of Triticale-HV CC Treatments

Triticale was the dominant component of the three CC mixtures in both years, and its biomass did not differ among triticale-HV CC treatments. In 2025, triticale biomass ranged from 2,260 to 2,950 kg ha^{-1}, and in 2026 from 2,450 to 2,920 kg ha^{-1} across the mixtures.

Hairy vetch produced measurable biomass by the time of termination in 91% of the plots in 2025, but in only 43% of the plots in 2026. Hairy vetch biomass increased with HV seeding rate in both years but differed among the triticale-HV CC treatments only in 2025 (Figure 3.1). In 2025, High HV + Low Tr produced 2.1 times more HV biomass than Medium HV + Low Tr and 5.3 times more than Low HV + High Tr. Similarly in 2026, High HV + Low Tr produced 1.2 times more HV biomass than Medium HV + Low Tr and 2.4 times more than Low HV + High

Tr. Hairy vetch density at time of termination was 42 to 56% lower in 2026 than in 2025 in all Triticale-HV CC treatments. From 2025 to 2026, density decreased from 27 (± 2) to 12 (± 2) HV plants m^{-2} in High HV + Low Tr, from 12 (± 1) to 7 (± 1) HV plants m^{-2} in Medium HV + Low Tr, and from 10 (± 1) to 4 (± 1) HV plants m^{-2} in Low HV + High Tr.

Overwinter conditions such as a hard freeze with no snow cover likely resulted in less density and biomass of HV in 2026. Hairy vetch has lower cold tolerance than winter cereals (Chintala et al. 2023; Clark 2007) and its winter survival decreases as freezing temperatures without snow cover accumulate (Kucek et al. 2024). Warm periods during the winter can cause plants to lose part of their acquired cold hardiness making them more sensitive to subsequent freezes (Kalberer et al. 2006). Several HV plants were winter killed, reducing the number of HV plants by termination, resulting in less biomass, reduced occurrence in plots, and differences among triticale-HV CC treatments.

3.3.4 Cover Crop Effects on Biomass of Winter Annual Weeds

Winter annual weeds were observed in 47 of the 108 plots (44%) in 2025 but in only 8 plots (7%) in 2026, and never in chemical fallow; therefore, only the CC treatments in 2025 were analyzed. Total winter weed biomass was affected by CC treatment ($P < 0.001$), and individual species biomass was affected by the interaction of CC treatment and weed species ($P = 0.013$) (Table 3.7). Dominant winter annual weeds were mustard species, mainly pinnate tansymustard [*Descurainia pinnata* (Walt.) Britt.], shepherdspurse [*Capsella bursa-pastoris* (L.) Medik.] and field pennycress (*Thlaspi arvense* L.), and cheatgrass (*Bromus tectorum* L.), which are common in the US Midwest region (Werle et al. 2014). Other winter broadleaf weeds occurred less frequently, such as prickly lettuce (*Lactuca serriola* L.), henbit (*Lamium amplexicaule* L.), and

horseweed (*Erigeron canadensis* L.); they were 6% of the total biomass but not analyzed as separate species.

Winter weed biomass produced in rye and Low HV + High Tr CC treatments did not differ from each other but had 71 and 88% less winter weed biomass, respectively, than High HV + Low Tr (Table 3.7). The rye CC produced about three times more biomass than the Low HV + High Tr mixture but resulted in similar levels of winter weed biomass suppression. Cover crop biomass is usually the main driver (Osipitan et al. 2018; MacLaren et al. 2019), but here suppression followed the cereal seeding rate more closely than final CC biomass. This agrees with Osipitan et al. (2019), who reported greater weed suppression at higher CC seeding rates and with grass rather than broadleaf CC species. Similarly, Baraibar et al. (2018) found grass CC to be the most, and legume CC the least, weed suppressive group of species among fall-seeded CCs.

Rye CC reduced mustard species biomass the most, with 85% and 76% less biomass than High HV + Low Tr and Medium HV + Low Tr, respectively (7.8 vs. 53.3 and 32.3 g m^{-2}), which did not differ from each other (Table 3.7). Low HV + High Tr was intermediate (11.5 g m^{-2}) and did not differ from any CC treatment. Mustard biomass therefore decreased as the cereal component and total biomass of the CC increased. This response may be related to the biology of mustard species, such as their timing of emergence (Werle et al. 2014), and to CC competition for resources such as nitrogen (Kumar et al. 2008; Glaze-Corcoran et al. 2023) and early light capture (MacLaren et al. 2019), which strongly affect mustard growth but were beyond the scope of this study's assessments.

Cheatgrass biomass was not suppressed by any CC treatment (Table 3.7). Cheatgrass is among the first winter annuals to emerge in the fall and has a life cycle like winter cereals (Thill

et al. 1984; Werle et al. 2014). Its establishment is favored by disturbance and little early competition (Morrow and Stahlman 1984; Chambers et al. 2007), and once established, it tolerates competition from winter cereals (Thill et al. 1984; Wicks 1984). Both conditions occurred in 2025. The pre-plant burndown was applied before cheatgrass emerged, and no rain was received until 56 d after CC planting (Table 3.3), so cheatgrass and CC treatments emerged together and could not suppress it. If cheatgrass is present in the field, it requires integrated management, such as controlling the first flush before or shortly after CC planting (Wicks 1984).

In 2026, winter weeds emerged before CC planting and were controlled by the pre-plant burndown. The experiment received rain the day after seeding (Table 3.3) and allowed the CC treatments to establish quickly, leaving little opportunity for later winter weed emergence.

3.3.5 Summer Annual Weed Levels at Corn Planting

In 2025, the pre-plant period, from herbicide application to corn planting, was 69 d for chemical fallow, 33 d for rye CC, and 13 d for the triticale-HV CC treatments, receiving 150, 63, and 25 mm of rainfall, respectively. In 2026, the pre-plant period was longer and wetter, with 109, 66, and 43 d for chemical fallow, rye CC, and triticale-HV CC treatments, receiving 470, 377, and 277 mm of rainfall, respectively. Resulting percent weed cover at corn planting, which was estimated from drone imagery as the percentage of each plot covered by green vegetation, was affected by the interaction of the combination of CC treatment by herbicide program and years ($P < 0.001$).

In 2025, weed cover in all the combinations of CC treatment and herbicide program was very low, resulting in less than 0.5%, whereas chemical fallow had the greatest weed cover at 22.0% (± 6.9) (Table 3.8). Based on the contrast, all CC by herbicide program treatment

combinations resulted in a 99.6% reduction in weed cover relative to chemical fallow ($P < 0.001$; Figure 3.2). For example, no green vegetation was detected in 26 of the 36 CC plots with burndown + residual and in 17 of the 36 plots with burndown only. Overall, burndown + residual decreased weed cover by 77% (± 8.9) compared with burndown only across all CC treatments ($P < 0.001$; Figure 3.2). In 2026, weed cover was low (2.4% to 3.8%) in the triticale-HV CC treatments with burndown + residual, whereas chemical fallow had the greatest weed cover at 44.9% (± 10.3) (Table 3.8). This represented a 91 to 95% reduction in weed cover relative to chemical fallow. The other CC treatment and herbicide program combinations, rye CC with either herbicide program and the triticale-HV CC treatments with burndown only, had 18.8 to 35.0% weed cover and did not differ from chemical fallow. Thus, the triticale-HV CC treatments with burndown + residual reduced weed cover by 84 to 93% relative to rye CC with either herbicide program or by 80 to 88% relative to burndown only within each triticale-HV CC treatment.

In 2026, the planned contrasts showed that, on average, the combinations of CC treatment and herbicide program resulted in a 76% reduction in weed cover relative to chemical fallow ($P < 0.001$; Figure 3.2). The burndown + residual herbicide program resulted in a 79% (± 4.7) reduction in weed cover relative to burndown only across CC treatments ($P < 0.001$). With burndown + residual, the triticale-HV CC treatments reduced weed cover by 88% (± 4.2) relative to rye CC ($P < 0.001$), whereas with burndown only there was no strong evidence of a difference from rye CC ($P = 0.087$). The triticale-HV CC treatments did not differ from each other with either herbicide program.

Because weed cover integrates a large area of each plot, it reduced the effect of weed patchiness and showed the overall level of control at corn planting. Low weed cover was also

what targeted spraying technologies exploit to reduce herbicide use without compromising weed control (Avent et al. 2024; Dodde et al. 2026). In Kansas, targeted spraying reduced herbicide costs by 19 to 71% compared with broadcast applications in programs that included a soil-residual herbicide (Barnhart et al. 2025), but most savings were lost once weed cover exceeded about 20%, when more than 90% of the area was sprayed (Dodde et al. 2026). In our study, all CC treatment and herbicide program combinations were far below this threshold in 2025, with almost no weed cover. In 2026, the threshold was exceeded in chemical fallow, rye CC, and High HV + Low Tr with burndown only, and only the triticale-HV CC treatments with burndown + residual kept weed cover low enough to benefit from targeted spraying. However, weed cover describes the area occupied by weeds but not their size, which is key for herbicide efficacy.

Weed cover was represented by summer weed biomass at corn planting (Table 3.8). Summer weeds were present in all plots at corn planting. In 2025, summer weed biomass was mainly composed of velvetleaf (*Abutilon theophrasti* Medik. 44%), Palmer amaranth (20%), spurge (*Euphorbia* spp.; 8%), and other species (28%) that included summer broadleaves such as buffalobur (*Solanum rostratum* Dunal) and prickly sida (*Sida spinosa* L.), whereas in 2026, Palmer amaranth was the dominant species and the only weed in the summer weed biomass samples (volunteer CC excluded), although carpetweed was also present at lower density (Table 3.10). In 2025, six of the eight combinations of CC treatment and herbicide program had less summer weed biomass than chemical fallow, ranging from 0.2 g m^{-2} in Low HV + High Tr with burndown only, to 1.9 g m^{-2} in Low HV + High Tr with burndown + residual, whereas chemical fallow had the greatest summer annual weed biomass 16.2 (± 4.6) g m^{-2} (Table 3.8). Combinations represented an 88 to 99% reduction in summer weed biomass relative to chemical

fallow (97% on average; $P < 0.001$; Figure 3.3). Medium and High HV + Low Tr with burndown + residual (1.2 and 0.3 g m^{-2}) did not differ from chemical fallow or from the other combinations, because of the high variability in summer weed biomass among their plots.

Burndown + residual did not reduce summer weed biomass relative to burndown only when averaged across CC treatments ($P = 0.697$; Figure 3.3). With burndown only, the triticale-HV CC treatments had 54% less biomass than rye CC ($P = 0.047$), and Low HV + High Tr had 80% less than rye CC ($P < 0.001$) and 71% less than Medium and High HV + Low Tr ($P = 0.025$). With burndown + residual, however, Low HV + High Tr had more biomass than rye CC (1.9 vs 0.3 g m^{-2}; $P = 0.013$). These differences were again related to the dominant weed patchiness pattern in the field.

In 2026, the triticale-HV CC treatments with burndown + residual and Medium HV + Low Tr with burndown only had the lowest summer weed biomass, ranging from 3.5 g m^{-2} to 5.3 g m^{-2}, whereas rye CC with burndown only had the greatest weed biomass 17.4 (± 4.6) g m^{-2}, along with its combination with burndown + residual and chemical fallow (Table 3.8). This greater suppression by the triticale-HV CC treatments with their respective herbicide programs represented a 53 to 69% reduction relative to chemical fallow (11.2 g m^{-2}; 41% on average across all combinations; $P < 0.001$; Figure 3.3) and a 51 to 80% reduction relative to rye CC with burndown + residual and burndown only. Across CC treatments, burndown + residual reduced summer weed biomass by 38% relative to burndown only ($P < 0.001$; Figure 3.3). The triticale-HV CC treatments had 63% less biomass than rye CC with either herbicide program ($P < 0.001$), whereas the high and low triticale seeding rates did not differ ($P \geq 0.063$).

Pre-plant weed density, the weeds recruited from the soil seedbank from herbicide program application to corn planting, was summarized descriptively and used to calculate the

relative abundance of each species (Tables 3.9 and 3.10). In 2025, density was low in the CC treatments, from 1.3 to 17.8 plants m^{-2}, and 27.8 plants m^{-2} in chemical fallow. In 2026, density was greater in all treatments, from 7.6 to 8.9 plants m^{-2} in the triticale-HV CC treatments with burndown + residual to 443 plants m^{-2} in rye CC with burndown only, and 84.7 plants m^{-2} in chemical fallow.

Relative abundance showed that weed density was distributed among more species in 2025 than in 2026 (Tables 3.9 and 3.10). In 2025, velvetleaf and Palmer amaranth were present in nine and seven of the nine treatments, respectively, and dominated the triticale-HV CC treatments. Rye CC was the only CC treatment with low velvetleaf relative abundance (5 to 22%), and its weed community was dominated by spurge species with burndown + residual (68%) and by other species, such as buffalobur and yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.], with burndown only (38%). In 2026, Palmer amaranth dominated all treatments (58 to 100%), followed by carpetweed (*Mollugo verticillata* L.) and volunteer CC buckwheat (*Fagopyrum esculentum* Moench), mainly in chemical fallow, rye CC, and the triticale-HV CC treatments with burndown only; Palmer amaranth was the only species in Low HV + High Tr and High HV + Low Tr with burndown + residual. This shift matters for management because Palmer amaranth is highly competitive in corn (Massinga et al. 2001), emerges over an extended period and grows rapidly (Ward et al. 2013), and has evolved resistance to multiple herbicide sites of action in Kansas (Shyam et al. 2021); in fact, the farmer made an additional postemergence clean-up application in 2026 to control missed plants (Table 3.2).

The reduced weed recruitment and biomass in the triticale-HV CC treatments compared to rye CC was mainly driven by termination timing. Rye CC was terminated 20 to 23 d earlier (Table 3.3), so weeds that emerged after burndown had more time to establish and grow before

corn planting, whereas in the triticale-HV CC treatments, weeds emerged within the CC canopy were controlled by the later termination timing, and subsequent flushes had less time to grow.

The residual herbicide effect depended on the weed species and on rainfall. In 2025, it had little effect because velvetleaf emerges from deeper soil (Xiong et al. 2018) than the top 1 to 2 cm where flumioxazin is most effective (Shaner 2014), and the short, dry pre-plant period limited emergence. In 2026, Palmer amaranth, a small-seeded species that emerges from near the soil surface after each rain (Jha 2008; Ward et al. 2013), was controlled where flumioxazin was activated soon after application, as in the triticale-HV CC treatments, which received 25 mm within 3 d after termination. In rye CC, the 4 to 5mm that fell after termination were below the amount needed for flumioxazin activation (Norsworthy et al. 2010) but enough for Palmer amaranth to emerge. A subsequent activating rainfall did not occur until 16 d later (Table 3.3). Moreover, corn was planted 40 to 73 d after the first activating rain, far beyond the 12- to 18-d field half-life of flumioxazin (Shaner 2014), so later flushes escaped the residual herbicide and were larger at corn planting, which explains why the residual herbicide reduced density more than biomass.

Cover crop biomass also influenced suppression. In 2025, all CC treatments produced high biomass and reduced weed density and biomass relative to chemical fallow. Velvetleaf, a large-seeded species that requires more residue to be suppressed (Teasdale and Mohler 2000), was common in all treatments except rye CC which had the greatest biomass. The high triticale seeding rate, which also had the least winter weed biomass (Table 3.7), had less summer weed biomass with burndown only. In 2026, rye CC produced the least biomass and had greater weed density than chemical fallow, likely because its thin residue was able to conserve soil moisture that favored Palmer amaranth emergence rather than suppressing it (Nunes et al. 2024a). The

triticale-HV CC treatments produced sufficient biomass that was close to the recommended residue level needed to reduce waterhemp [Amaranthus tuberculatus (Moq.) Sauer] biomass by 50% (Nunes et al. 2024a). But with burndown only, the CC treatments alone did not reduce Palmer amaranth density relative to chemical fallow in that year. The greater summer weed biomass in 2025 with the Low HV + High Tr compared to rye CC that integrated burndown + residual likely reflects isolated velvetleaf clumps within the small sampling areas, as weed cover showed no such difference.

Across weed cover, biomass, and density, the triticale-HV CC treatments suppressed summer weeds more consistently than rye CC, and when integrated with the residual herbicide, they were the most suppressive combinations in both years but more noticeable in the weedier 2026 season. The residual herbicide was most effective on small-seeded species when rainfall activated it soon after application. Rye CC suppressed weeds only when it produced high biomass, and chemical fallow did not prevent weed infestation before corn planting. Therefore, a later-terminated, triticale-based CC combined with residual herbicide was the most reliable strategy to reduce summer weed infestation for late-planted corn.

3.3.6 Corn Grain Yield

Corn grain yield was affected by the interaction of treatment (CC treatment and herbicide program combinations) and year ($P < 0.001$); therefore, years are presented separately (Table 3.11). In 2025, chemical fallow had the greatest corn yield, 7,560 (± 350) kg ha^{-1}, whereas the CC treatment and herbicide program combinations yielded 4,730 to 5,750 kg ha^{-1} and did not differ from each other. Averaged over herbicide programs, each CC treatment yielded 25 to 35% less than chemical fallow ($P < 0.001$; Figure 3.4), and the triticale-HV CC treatments did not differ from rye CC ($P = 0.245$). In 2026, yield was low in all treatments and ranged from 950 to

2,490 kg ha^{-1}. Averaged over CC treatments, the CC treatment and herbicide program combinations did not differ from chemical fallow (1,510 ± 310 kg ha^{-1}; $P = 0.133$).

The farmer's preemergence herbicide program applied immediately after corn planting controlled the weeds present in all plots, diminishing the effect of summer annual weeds present at time of planting on yield. Instead, the CC treatments likely reduced corn yield through soil water use (Holman et al. 2018, 2021) and/or nitrogen immobilization by cereal-dominated residue shortly before late-planted corn. Quinn et al. (2023) observed corn yield losses of up to 20% following rye CC when no nitrogen was added. Soil water and nitrogen were not measured in this study, so these causes could not be confirmed.

Yield in 2026 was limited mainly by water stress that extended from the vegetative stages of corn into the beginning of the reproductive stages. Only 25 mm of rain fell from time of corn planting on July 7 to August 11, 2026, when corn was at the late vegetative to tasseling stages, and both July and August received about half of the 30-yr average precipitation (46 and 51 mm vs. 101 and 105 mm; Table 3.4). Water stress during the vegetative stages reduces plant growth and leaf area, and when it continues through tasseling, silking, and ear formation, it reduces the number of kernels per ear, which is among the most detrimental effects on corn yield (Çakir 2004). In 2025, water stress occurred mainly at the end of grain filling, when it had a smaller effect on yield. In 2026, the lowest yields occurred in the CC treatment and herbicide program combinations with the greatest summer weed infestation at corn planting. Rye CC and chemical fallow had the greatest weed cover (24 to 45%), summer weed biomass (10.8 to 17.4 g m^{-2}), and pre-plant density (85 to 443 plants m^{-2}) consisting of Palmer amaranth (Tables 3.8 and 3.10), whose presence required an additional postemergence clean-up application in corn (Table 3.2).

Palmer amaranth is highly competitive in corn (Massinga et al. 2001), so competition from these plants likely added to the water stress during the vegetative stages. The triticale-HV CC treatments, which had less summer weed infestation, particularly with burndown + residual, yielded 1,700 to 2,300 kg ha^{-1} averaged over herbicide programs (Table 3.11). Thus, the triticale-HV CC treatments did not reduce yield relative to rye CC in 2025 and increased it in 2026, when they also yielded more than chemical fallow; however, this yield gain occurred only in the low-yielding 2026 season, and in 2025 all CC treatments yielded less than chemical fallow.

3.3.7 Economics

Direct costs ranged from a low of \$54 ha^{-1} for chemical fallow to a high of \$246 ha^{-1} for High HV + Low Tr with burndown + residual (Table 3.12). Direct cost of cover crop establishment differed among treatments (seed and drilling pass; Tables 3.1 and 3.5): \$114 ha^{-1} for rye CC, \$136 and \$143 ha^{-1} for Medium HV + Low Tr and Low HV + High Tr, respectively, and \$194 ha^{-1} for High HV + Low Tr, because HV seed cost 5.7 to 6.7 times more per kilogram than triticale or rye seed. Adding flumioxazin to the burndown increased the cost of the herbicide program by \$5 ha^{-1}. Compared with chemical fallow, the CC treatment and herbicide program combinations cost \$107 to \$192 ha^{-1} more; this cost would be recovered with 600 to 1,000 kg ha^{-1} of additional corn yield.

In 2025, the CC treatments yielded 2,200 kg ha^{-1} less than chemical fallow, which reduced income by \$422 ha^{-1}. Together with their greater direct costs, the CC treatment and herbicide program combinations had a gross margin of \$740 to \$922 ha^{-1}, which was \$467 to \$649 ha^{-1} less than chemical fallow (\$1,389 ha^{-1}; Table 3.12). Because CC treatment, but not herbicide program, affected yield in 2025, gross margin was calculated from the mean yield of

each CC treatment averaged over herbicide programs. The additional corn yield needed to recover the greater direct costs of the CC treatments (600 to 1,000 kg ha^{-1}) was not achieved.

In 2026, the low yields resulted in small gross margins in all treatments (Table 3.12). Because CC treatment, but not herbicide program, affected yield, gross margin was calculated from the mean yield of each CC treatment averaged over herbicide programs. Chemical fallow had a gross margin of \$234 ha^{-1}, whereas the CC treatments ranged from \$53 to \$57 ha^{-1} in rye CC to \$195 to \$207 ha^{-1} in High HV + Low Tr and Low HV + High Tr. Although Low HV + High Tr and High HV + Low Tr yielded 600 and 800 kg ha^{-1} more than chemical fallow (P = 0.047 and P = 0.015), these yield gains did not recover their greater direct costs; therefore, they had \$27 to \$39 ha^{-1} less gross margin than chemical fallow, and rye CC had \$177 to \$181 ha^{-1} less.

The residual herbicide added \$5 ha^{-1} to the herbicide program without a yield benefit in either year; therefore, burndown + residual had \$5 ha^{-1} less gross margin than burndown only. However, the residual herbicide provided the most consistent summer weed suppression with the triticale-HV CC treatments, which may reduce weed seedbank additions and future weed management costs that were not accounted for in this single-season analysis.

3.4 Conclusion

Integrating the triticale-HV CC treatments with burndown + residual provided the most consistent summer weed suppression across two years with contrasting weather. This provides evidence that integrating CCs with residual herbicides can buffer weather effects and stabilize weed control (Hand et al. 2021; Norsworthy et al. 2012; Whalen et al. 2020). The longer growth cycle of the triticale-HV CC treatments shortened the period between CC termination and late-

planted corn, which allowed better integration with the residual herbicide to control spring emerging small- and large-seeded species. The residual herbicide added weed suppression under both contrasting weather and dominant weed species scenarios. In the drier, shorter pre-plant period dominated by large-seeded species in 2025, there was little added suppression, whereas in the wetter, longer pre-plant period dominated by small-seeded Palmer amaranth in 2026, it was crucial to reduce weed infestation before late-planted corn. When the CC did not produce enough biomass and the residual herbicide was not activated soon after application, as in rye CC in 2026, greater Palmer amaranth infestations can be expected.

Neither the CC treatment nor the herbicide program alone suppressed weeds consistently across years because responses depended on the dominant weed species in the field, amount of CC biomass produced, and weather. The triticale-HV CC treatments produced similar biomass across seeding rates and years, whereas rye CC produced the most biomass in 2025 but the least in 2026. Chemical fallow had no winter annual weed species in 2026. Among the CC treatments, those with more cereal, that is, rye CC and Low HV + High Tr, suppressed winter annual broadleaf weeds the most, but none suppressed cheatgrass, and in 2026 the farmer's fall clean-up application alone controlled winter annual weeds.

In the short term, weed suppression provided by the CC treatments did not offset their yield and economic costs before late-planted corn. All CC treatments yielded less than chemical fallow in 2025, and in 2026, when water stress limited yield in all treatments, the triticale-HV CC treatments yielded more than rye CC and chemical fallow. The gain in yields did not recover their greater direct costs and the added cost of residual herbicide did not provide a yield benefit. Integrated weed management practices often have short-term costs, whereas medium to long-term benefits, such as a smaller weed seedbank, delayed herbicide resistance (Norsworthy et al.

2012), and improved soil health (Bergtold et al. 2019) take longer to occur. In the semiarid Great Plains, CC grown in place of fallow often reduced soil water and yield of the following crop (Holman et al. 2018, 2021; Obour et al. 2022) and reduced net returns when used only as a cover. However, using CC as supplementary forage crop improved profitability (Holman et al. 2018, 2022, 2023; Obour et al. 2022). Thus, studies that evaluate CC integration across multiple dimensions are needed to identify uses that help producers offset greater management complexity of using CC and higher short-term costs.

Disclaimer: Claude (Anthropic), an artificial intelligence assistant, was used to support data organization, grammar editing, and coding in R software. The author reviewed and verified all outputs and is responsible for the content of this chapter.

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Figures

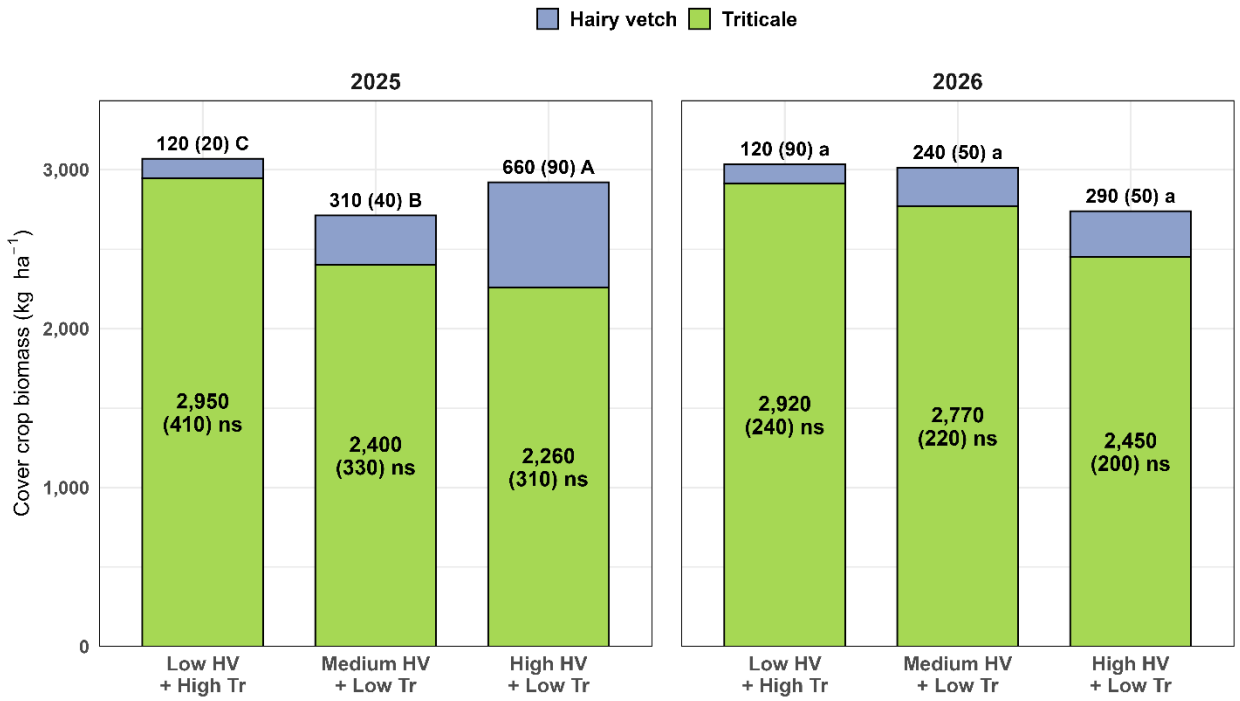


Figure 3.1. Triticale (Tr) and hairy vetch (HV) biomass (kg ha^{-1}) at cover crop (CC) termination in the triticale-HV CC treatments in 2025 and 2026. Values inside and above the bars are triticale and HV biomass, respectively, back-transformed from the log scale, with SE in parentheses. Within a year, HV values followed by the same letter do not differ (Tukey, $P < 0.05$); ns, not significant.

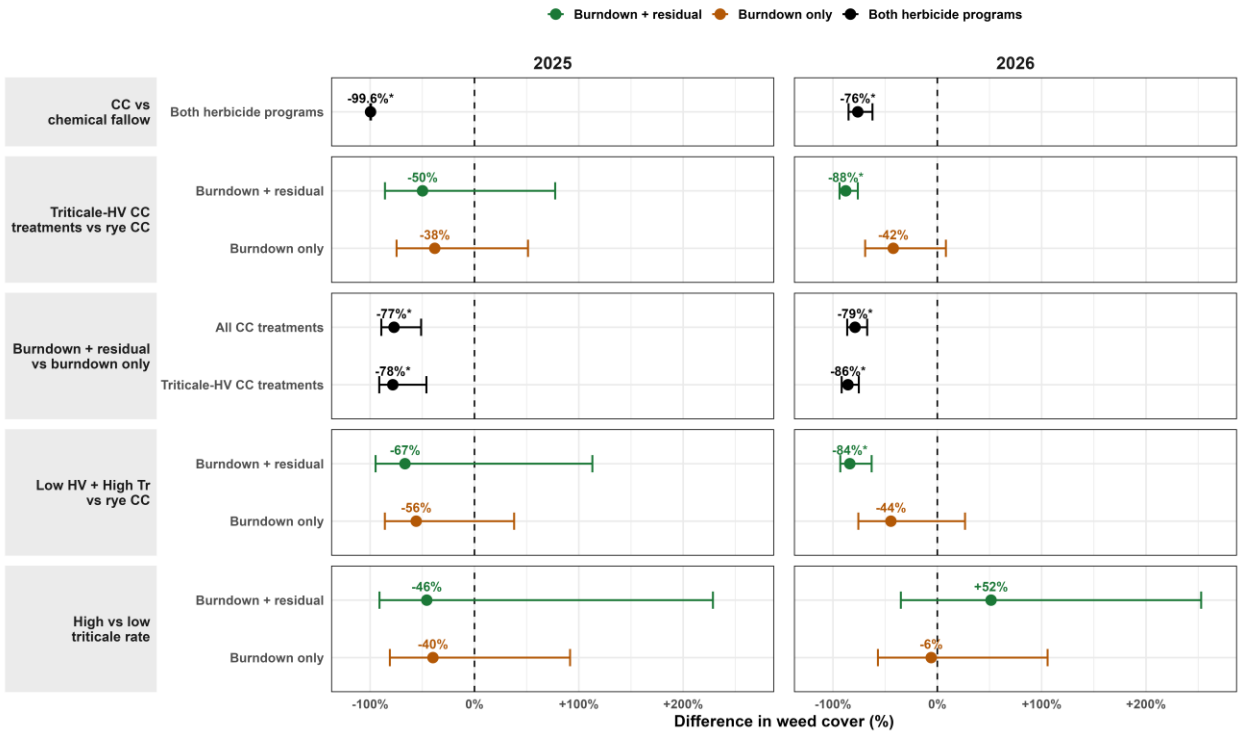


Figure 3.2. Percent difference in weed cover at corn planting for the planned contrasts, within year. Points are % differences between the first and second group, and bars are 95% confidence intervals; negative values indicate less weed cover in the first group. Rows indicate the herbicide program within which each comparison was made. *, $P < 0.05$. High vs low triticale rate = Low HV + High Tr vs Medium and High HV + Low Tr.

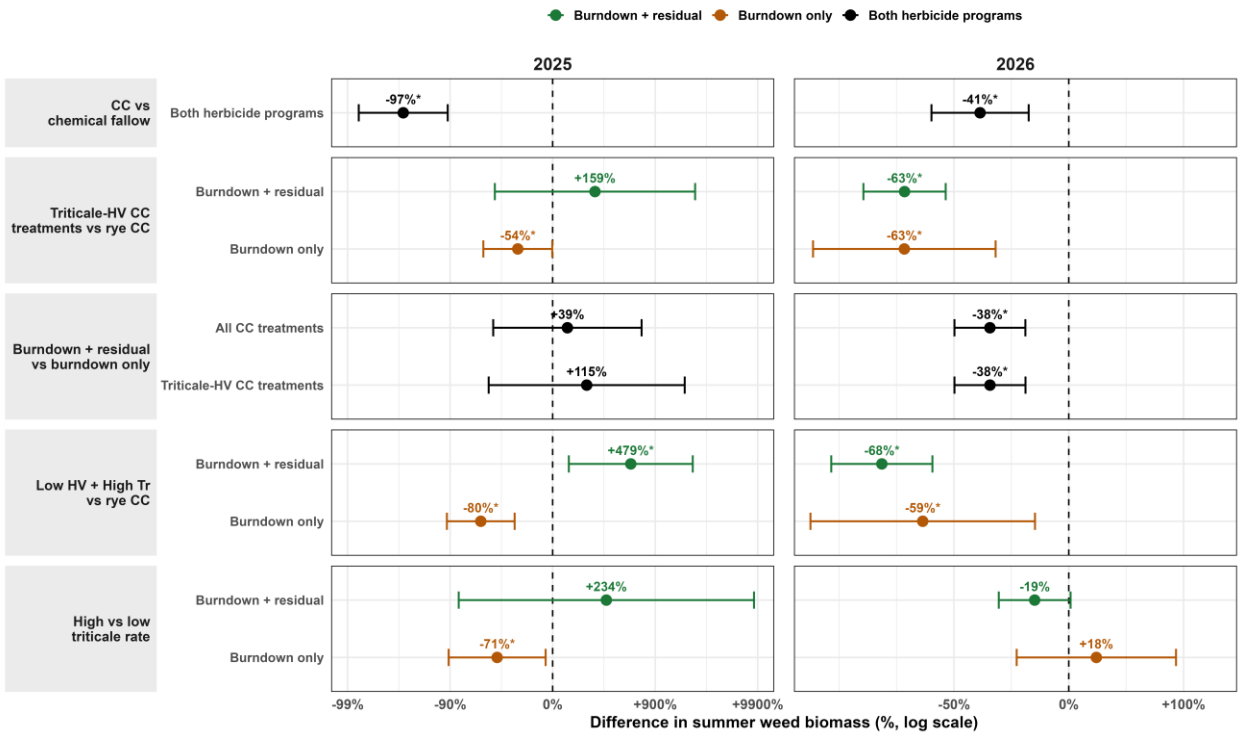


Figure 3.3. Results of planned contrasts measured as percent difference in summer annual weed biomass at corn planting for each year. *, $P < 0.05$. High vs low triticale rate = Low HV + High Tr vs Medium and High HV + Low Tr. Negative values indicated less summer weed biomass in the first group of the contrast.

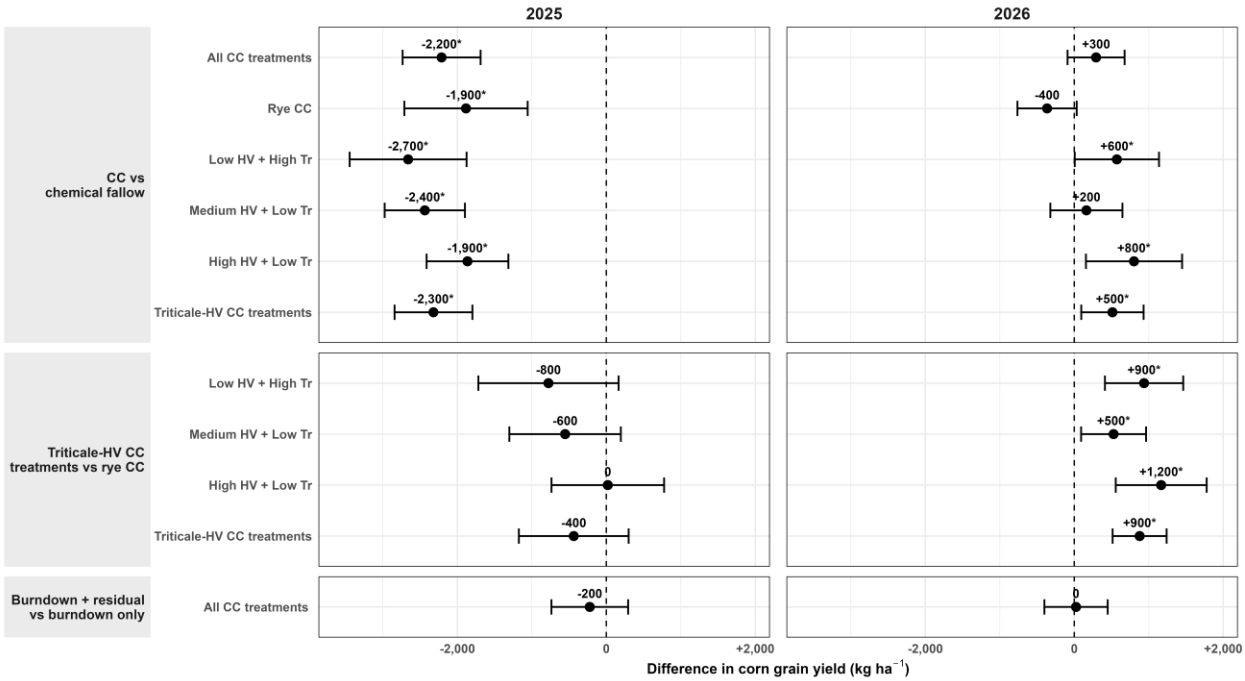


Figure 3.4. Difference in corn grain yield (kg ha^{-1}) for the planned contrasts, within year. Points are differences between the first and second group, with cover crop (CC) treatments averaged across herbicide programs, and bars are 95% confidence intervals; negative values indicate less yield in the first group. *, $P < 0.05$; differences are labeled to the nearest 100 kg ha^{-1}. HV, hairy vetch; Tr, triticale.

Tables

Table 3.1. Cover crop species and seeding rates drilled in the fall of 2024 and 2025 in the on-farm study at Oak Hill, KS.

Cover crop species	Cover crop treatment	Seeding rate	Seed cost
		kg ha^{-1}	$ ha^{-1}
Hairy vetch (HV) + Triticale (Tr)	Low HV + High Tr	4.5 + 73	91
	Medium HV + Low Tr	11 + 28	84
	High HV + Low Tr	22 + 28	142
Cereal rye	Rye CC	78	62

Seed cost was calculated with Green Cover (Bladen, NE) list prices (October 31, 2026): hairy vetch \$5.29, triticale \$0.93, and cereal rye \$0.79 kg^{-1}.

Table 3.2. Active ingredients, trade names, and sources of herbicides and adjuvants applied in burndown or burndown + residual in the experiment or by the farmer after corn planting, 2025 and 2026.

Active ingredient	Trade name	Source
Glyphosate	Willowood Glypho 5	Willowood, Henderson, NV
2,4-D	2,4-D LV6®	Winfield Solutions, St. Paul, MN
Flumioxazin	Flumioxazin 51% WDG	RedEagle International LLC, Lakeland, FL
Saflufenacil	Sharpen®	BASF Corporation, Research Triangle Park, NC
Atrazine	Atrazine 4L	WinField United, Arden Hills, MN
Dimethenamid-P + topramezone	Armezon PRO®	BASF Corporation, Research Triangle Park, NC
Dicamba + diflufenzopyr[a]	Status®	BASF Corporation, Research Triangle Park, NC
Methylated seed oil (MSO)	Fire Zone®	Helena Agri-Enterprises, Collierville, TN
Non-ionic surfactant	Brandt Super Wetter	Brandt Consolidated, Inc., Springfield, IL

[a] Applied in 2026 only, as a clean-up postemergence application. Ammonium sulfate (AMS) spray-grade was also included in both applications.

Table 3.3. Dates of cover crop (CC) planting, herbicide program application, and the date and amount (mm) from on-site rain gauge of the first rain after event in 2025 and 2026 in the on-farm study at Oak Hill, KS.

Year	Treatment	CC planting	First rain after CC planting (mm)	Herbicide application	First rain after herbicide application (mm)
2025	Chemical fallow	—	—	4/15/25	4/17/25 (31)
	Rye CC	9/4/24	10/30/24 (64)	5/21/25	5/24/25 (18)
	Triticale-hairy vetch mixtures	9/4/24	10/30/24 (64)	6/10/25	6/17/25 (25)
2026	Chemical fallow	—	—	3/20/26	4/25/26 (20.3)
	Rye CC	10/4/25	10/5/25 (25)	5/2/26	5/18/26 (76)
	Triticale-hairy vetch mixtures	10/4/25	10/5/25 (25)	5/25/26	5/28/26 (25)

Table 3.4. Monthly air temperature (°C) and precipitation (mm) in the 2025 and 2026 seasons and the 30-yr average (1991–2020) at Oak Hill, KS.

	Maximum (°C)			Minimum (°C)			Mean (°C)			Precipitation (mm)		
Month	2025	2026	30-yr	2025	2026	30-yr	2025	2026	30-yr	2025	2026	30-yr
October	25.2	22.6	20.1	7.8	10.7	6.4	16.5	16.7	13.3	64	48	57
November	13.6	14.9	11.9	2.4	0.7	−0.6	8.0	7.8	5.6	23	77	38
December	8.0	7.8	5.3	−4.4	−5.2	−5.9	1.8	1.4	−0.3	24	14	29
January	−0.2	4.7	3.7	−11.6	−8.7	−7.9	−5.9	−2.0	−2.1	24	39	18
February	2.5	10.9	6.5	−9.4	−3.7	−5.9	−3.5	3.6	0.3	22	8	28
March	18.4	18.8	12.9	0.6	1.3	−0.7	9.5	10.1	6.2	24	11	49
April	19.6	22.8	18.7	6.1	7.7	5.1	12.8	15.2	11.9	155	92	72
May	24.2	25.6	24.3	10.1	10.9	11.9	17.2	18.3	18.1	63	177	124
June	30.4	29.2	30.0	17.6	18.3	17.6	24.0	23.8	23.8	122	180	114
July	32.6	32.6	32.8	20.5	21.3	20.2	26.5	26.9	26.6	69	46	101
August	30.4	32.3	31.4	18.3	20.1	18.8	24.4	26.2	25.1	52	51	105
September	27.6	30.9	27.1	15.0	19.4	13.8	21.3	25.2	20.5	56	117	73

Temperature and snow (liquid equivalent): NOAA NCEI, Clay Center, KS (USC00141559), about 17 km from the site. Precipitation: on-farm rain gauge. 30-yr: NOAA 1991–2020 normals, Clay Center, KS. Temperatures are monthly means of daily values. 2025 = October 2024 to September 2025; 2026 = October 2025 to September 2026.

Table 3.5. Cost ($ ha^{-1}) of the herbicides, adjuvants, and field operations used to calculate direct costs.

Item	Cost ($ ha^{-1})
Herbicides and adjuvants, per application	
Glyphosate	7.45
2,4-D	8.10
Flumioxazin, B + RE	4.59
Flumioxazin, chemical fallow	6.91
Ammonium sulfate	0.64
Non-ionic surfactant	2.43
Methylated seed oil	2.58
Field operations, custom rates per pass	
No-till drilling	51.69
Herbicide application, ground rig	26.00

Herbicide and adjuvant prices were provided by the cooperating farmer and converted to metric units of formulated product. Field operations are Northeast district custom rates (Kansas Department of Agriculture and Kansas State University Land Use Survey Office 2026). B + RE, burndown + residual.

Table 3.6. Total cover crop (CC) biomass at termination and dispersion parameter (φ) for each CC treatment in 2025 and 2026. Biomass was sampled at termination: May 21, 2025, and May 2, 2026, for rye CC, and June 10, 2025, and May 25, 2026, for the triticale-HV CC treatments.

Year	CC treatment	Total CC biomass (kg ha^{-1})	Phi φ
2025	Rye CC	11,630 (680) A	0.01
	Low HV + High Tr	4,060 (650) B	0.75
	Medium HV + Low Tr	3,250 (310) B	0.22
	High HV + Low Tr	3,490 (310) B	0.17
2026	Rye CC	1,850 (130) b	0.08
	Low HV + High Tr	2,910 (190) a	0.04
	Medium HV + Low Tr	2,850 (190) a	0.04
	High HV + Low Tr	2,850 (210) a	0.09

Biomass values are means (±SE) from a gamma generalized linear mixed model (Eq. B.1). Within a year, means followed by the same letter do not differ (Tukey, $P < 0.05$); uppercase letters compare means within 2025 and lowercase letters within 2026. φ, dispersion parameter of the gamma distribution. HV, hairy vetch; Tr, triticale.

Table 3.7. Total winter annual weed biomass and biomass of mustard species and cheatgrass at cover crop (CC) termination for each CC treatment in 2025.

CC treatment	Total winter weeds	Mustard species	Cheatgrass
	---------- g m^{-2} ----------		
Rye CC	14.8 (3.9) BC	7.8 (3.5) B	13.9 (6.5) A
Low HV + High Tr	6.0 (2.5) C	11.5 (6.1) AB	8.1 (4.7) A
Medium HV + Low Tr	33.4 (8.6) AB	32.3 (14.1) A	15.2 (6.4) A
High HV + Low Tr	51.9 (15.5) A	53.3 (26.7) A	20.3 (10.2) A

Biomass values are means (±SE) back-transformed from the log scale, for plots where winter weeds were present. Within a column, means followed by the same uppercase letter do not differ (Tukey, $P < 0.05$). Mustard species: pinnate tansymustard [*Descurainia pinnata* (Walt.) Britt.], shepherdspurse [*Capsella bursa-pastoris* (L.) Medik.], and field pennycress (*Thlaspi arvense* L.); cheatgrass *(Bromus tectorum* L.). Total winter weeds biomass also includes other broadleaf weed species: prickly lettuce (*Lactuca serriola* L.), henbit (*Lamium amplexicaule* L.), and horseweed (*Erigeron canadensis* L.). Chemical fallow plots had no winter weeds. HV, hairy vetch; Tr, triticale.

Table 3.8. Weed cover (%) and summer annual weed biomass (g m^{-2}) at corn planting for each treatment in 2025 and 2026.

Year	Cover crop treatment	Herbicide program	Weed cover (%)	Summer weed biomass (g m^{-2})
2025	No CC	Chemical fallow	22.0 (6.9) A	16.2 A
	Rye CC	B + RE	0.07 (0.04) BC	0.3 BC
		B only	0.27 (0.13) BC	0.9 B
	Low HV + High Tr	B + RE	0.02 (0.02) BC	1.9 B
		B only	0.12 (0.07) BC	0.2 C
	Medium HV + Low Tr	B + RE	0.03 (0.02) BC	1.2 ABC
		B only	0.09 (0.06) BC	0.4 BC
	High HV + Low Tr	B + RE	0.08 (0.04) C	0.3 ABC
		B only	0.44 (0.23) B	1.0 BC
2026	No CC	Chemical fallow	44.9 (10.3) a	11.2 a
	Rye CC	B + RE	23.8 (7.7) a	10.8 a
		B only	35.0 (11.2) a	17.4 a
	Low HV + High Tr	B + RE	3.8 (1.8) b	3.5 c
		B only	19.4 (8.0) a	7.2 ab
	Medium HV + Low Tr	B + RE	2.4 (1.2) b	4.3 bc
		B only	18.8 (7.5) a	5.3 b
	High HV + Low Tr	B + RE	2.6 (1.3) b	4.3 bc
		B only	22.7 (9.1) a	7.0 ab

Weed cover: model mean (±SE) from the ordered beta model (Eq. B.6). Summer weed biomass: mean back-transformed from the log scale (Eq. B.5). Within a year and column, means followed by the same letter do not differ (Tukey, $P < 0.05$); uppercase letters compare means within 2025 and lowercase letters within 2026. B + RE, burndown + residual; B only, burndown only; HV, hairy vetch; Tr, triticale.

Table 3.9. Weed density and relative abundance of weed species from herbicide application to corn planting (pre-plant) in 2025.

CC treatment	Herbicide program	Density (plants m^{-2})	Relative abundance (%)			
			Palmer amaranth	Velvetleaf	Spurge	Others†
No CC	Chemical fallow	27.8 (4.0)	22	33	21	23
Rye CC	B + RE	8.4 (2.6)	–	22	68	10
	B only	17.8 (5.3)	41	5	16	38
Low HV + High Tr	B + RE	2.2 (1.4)	53	47	–	–
	B only	4.9 (2.0)	26	48	13	13
Medium HV + Low Tr	B + RE	2.2 (1.2)	37	63	–	–
	B only	2.2 (0.7)	40	40	–	20
High HV + Low Tr	B + RE	1.3 (1.3)	–	100	–	–
	B only	1.8 (1.4)	38	62	–	–

Density: mean (SE) of the sum of pre-plant counts per plot (three in chemical fallow, two in rye CC, and one in the triticale-HV CC treatments). Relative abundance: Eq. 1. Spurge, Euphorbia spp. † Other species: buffalobur (Solanum rostratum Dunal), yellow foxtail [Setaria pumila (Poir.) Roem. & Schult.], prickly sida (Sida spinosa L.), yellow nutsedge (Cyperus esculentus L.), woodsorrel (Oxalis spp.), horseweed (Erigeron canadensis L.), common chickweed [Stellaria media (L.) Vill.], cocklebur (Xanthium strumarium L.), and field bindweed (Convolvulus arvensis L.). B + RE, burndown + residual; B only, burndown only; HV, hairy vetch; Tr, triticale.

Table 3.10. Weed density and relative abundance of weed species from herbicide application to corn planting (pre-plant) in 2026.

CC treatment	Herbicide program	Density (plants m^{-2})	Relative abundance (%)			
			Palmer amaranth	Velvetleaf	Carpetweed	Volunteer buckwheat
No CC	Chemical fallow	84.7 (8.7)	62	–	8	30
Rye CC	B + RE	153.3 (58.7)	58	–	28	14
	B only	443.1 (97.7)	60	–	21	18
Low HV + High Tr	B + RE	7.6 (1.4)	100	–	–	–
	B only	96.9 (21.2)	83	–	13	4
Medium HV + Low Tr	B + RE	8.4 (4.5)	91	–	9	–
	B only	47.6 (15.5)	95	5	–	–
High HV + Low Tr	B + RE	8.9 (3.6)	100	–	–	–
	B only	140.4 (52.0)	82	–	18	–

Density: mean (SE) of the sum of pre-plant counts per plot (four in chemical fallow and rye CC, and two in the triticale-HV CC treatments). Relative abundance: Eq. 1; –, not present. Carpetweed, Mollugo verticillata L.; volunteer buckwheat, volunteer CC buckwheat (Fagopyrum esculentum Moench). B + RE, burndown + residual; B only, burndown only; HV, hairy vetch; Tr, triticale.

Table 3.11. Corn grain yield (kg ha^{-1}), adjusted to 15.5% moisture, for each cover crop (CC) treatment and herbicide program combination and chemical fallow in 2025 and 2026.

Year	Cover crop treatment	Herbicide program	Corn grain yield (kg ha^{-1})
2025	No CC	Chemical fallow	7,560 (350) A
	Rye CC	B + RE	5,600 (570) B
		B only	5,740 (570) B
	Low HV + High Tr	B + RE	4,730 (530) B
		B only	5,060 (530) B
	Medium HV + Low Tr	B + RE	4,970 (340) B
		B only	5,270 (340) B
	High HV + Low Tr	B + RE	5,630 (340) B
		B only	5,750 (340) B
2026	No CC	Chemical fallow	1,510 (310) ab
	Rye CC	B + RE	950 (320) b
		B only	1,330 (310) ab
	Low HV + High Tr	B + RE	1,860 (430) ab
		B only	2,300 (430) a
	Medium HV + Low Tr	B + RE	1,940 (380) ab
		B only	1,400 (370) ab
	High HV + Low Tr	B + RE	2,490 (480) a
		B only	2,130 (480) ab

Values are model means (SE) from a Gaussian generalized linear mixed model (Appendix B, Eq. B.7). Within a year, means followed by the same letter do not differ (Tukey, $P < 0.05$); uppercase letters compare means within 2025 and lowercase letters within 2026. B + RE, burndown + residual; B only, burndown only; HV, hairy vetch; Tr, triticale.

Table 3.12. Direct cost and gross margin ($ ha^{-1}) of each cover crop (CC) treatment and herbicide program combination in 2025 and 2026.

Cover crop treatment	Herbicide program	Direct cost	Gross margin	
			2025	2026
		---------- $ ha^{-1} ----------		
No CC	Chemical fallow	54	1,389	234
Rye CC	B + RE	165	918	53
	B only	161	922	57
Low HV + High Tr	B + RE	195	740	202
	B only	190	745	207
Medium HV + Low Tr	B + RE	188	790	131
	B only	183	795	136
High HV + Low Tr	B + RE	246	841	195
	B only	241	846	200

Direct cost includes CC seed and drilling, and the herbicide program: burndown herbicides, flumioxazin in B + RE and chemical fallow, adjuvants, and one spraying pass. Costs of each item are given in Tables 3.1 and 3.5. Gross margin = income − direct cost; income was calculated with a corn price of $0.191 kg^{-1} from the model mean corn yield of chemical fallow (7,600 and 1,500 kg ha^{-1} in 2025 and 2026); for the CC treatments, from the mean of each CC treatment averaged over herbicide programs (4,900 to 5,700 kg ha^{-1} in 2025 and 1,100 to 2,300 kg ha^{-1} in 2026), because herbicide programs did not affect yield. B + RE, burndown + residual; B only, burndown only; HV, hairy vetch; Tr, triticale.

Appendix A - Supplementary Material for Chapter 2

Model equations for statistical analyses

Indices: i = CC condition (dead or living; no CC in Eq. A.5 and A.6); l = herbicide mixture (HERB); j = year; k = block; m = whole plot; n = subplot (sub-subplot in the 2026 no-CC plots); o = observation within subplot (card, quadrat, or sample). All random effects follow a Gaussian distribution with mean zero, and log = natural logarithm.

Equation A.1. Cover crop biomass

CC biomass was described with a gamma generalized linear mixed model with a log link:

$$CCBio_{ijkm} \sim Gamma(\lambda_{ijkm}, \varphi)$$

$$log(\lambda_{ijkm}) = \mu_0 + CC_i + Year_j + Block_{jk} + WP_{jkm} \quad (A1)$$

$$Block_{jk} \sim N(0, \sigma_B lock^2)$$

$$WP_{jkm} \sim N(0, \sigma_W P^2)$$

where CCBioijkm is the CC biomass (kg ha^{-1}) of the subplot with the ith CC condition in the mth whole plot, which follows a gamma distribution with mean λijkm and dispersion φ; log(λijkm) is the sum of the overall expected mean μ0, the effect of the ith CC condition, the effect of the jth year, the random effect of the kth block within the jth year, and the random effect of the mth whole plot within the kth block and jth year. One sample was collected per subplot, so the subplot was the residual unit.

Equation A.2. Spray interception

Spray interception was described with a beta generalized linear mixed model with a logit link:

$$SI_{iljkmno} \sim Beta(\pi_{iljkmn}, \varphi)$$

$$logit(\pi_{iljkmn}) = \mu_0 + HERB_l + CC_i + Year_j + (HERB \times CC)_{li} + (HERB \times Year)_{lj} + (CC \times Year)_{ij} + (HERB \times CC \times Year)_{lij} + Block_{jk} + WP_{jkm} + SP_{jkmn} \quad (A2)$$

$$Block_{jk} \sim N(0, \sigma_B lock^2)$$

$$WP_{jkm} \sim N(0, \sigma_W P^2)$$

$$SP_{jkmn} \sim N(0, \sigma_S P^2)$$

where SIiljkmno is the proportion of spray intercepted on the oth card pair of the nth subplot, calculated as (coverage above − coverage below) / coverage above, which follows a beta distribution with mean πiljkmn and precision φ; logit(πiljkmn) is the sum of the overall expected mean μ0, the effect of the lth herbicide mixture, the effect of the ith CC condition, the effect of the jth year, their two- and three-way interactions, the random effect of the kth block within the jth year, the random effect of the mth whole plot within the kth block and jth year, and the random effect of the nth subplot within the mth whole plot, kth block, and jth year.

Equation A.3. Palmer amaranth early-season cumulative density (35 DAT in 2025; 38 DAT in 2026)

Cumulative counts were described with a negative binomial generalized linear mixed model with a log link:

$$log(\lambda_{iljkmn}) = log(A) + \mu_0 + CC_i + HERB_l + (CC \times HERB)_{il} + Year_j + Block_{jk} + WP_{jkm} + SP_{jkmn} \quad (A3)$$

$$Block_{jk} \sim N(0, \sigma_B lock^2)$$

$$WP_{jkm} \sim N(0, \sigma_W P^2)$$

$$SP_{jkmn} \sim N(0, \sigma_S P^2)$$

where Yiljkmno is the cumulative number of Palmer amaranth plants in the oth 0.25-m² quadrat of the nth subplot, which follows a negative binomial distribution with mean λiljkmn and dispersion θ; log(λiljkmn) is the sum of the offset log(A), where A is the quadrat area (0.25 m²) used to express estimates as plants m⁻², the overall expected mean μ0, the effect of the ith CC condition, the effect of the lth herbicide mixture, their interaction, the effect of the jth year, the random effect of the kth block within the jth year, the random effect of the mth whole plot within the kth block and jth year, and the random effect of the nth subplot within the mth whole plot, kth block, and jth year. Only the ten treatment combinations present in both years were included.

Equation A.4. Palmer amaranth early-season emergence

Early-season emergence was described with a hurdle gamma generalized linear mixed model with a log link:

$$ER_{iljkm} = \begin{cases} 0, \text{ with probability } p_l \\ \sim Gamma(\lambda_{iljkm}, \varphi), \text{ with probability } 1 - p_l \end{cases}$$

$$logit(p_l) = \gamma_0 + \gamma_l$$

$$log(\lambda_{iljkm}) = \mu_0 + HERB_l + Year_j + CC_i + (HERB \times Year)_{lj} + (HERB \times CC)_{li} + Block_{jk} + WP_{jkm} \quad (A4)$$

$$Block_{jk} \sim N(0, \sigma_B lock^2)$$

$$WP_{jkm} \sim N(0, \sigma_W P^2)$$

where ERiljkm is the Palmer amaranth early-season emergence, expressed as the slope (% of the no residual herbicide (control) cumulative emergence per day) of the subplot with the ith CC condition in the mth whole plot, calculated as the slope through the origin of cumulative emergence against DAT; pl is the probability of no emergence for the lth herbicide mixture, modeled with intercept γ0 and herbicide effect γl; when emergence occurred, the slope followed a gamma distribution with mean λiljkm and dispersion φ; log(λiljkm) is the sum of the overall expected mean μ0, the effect of the lth herbicide mixture, the effect of the jth year, the effect of the ith CC condition, the herbicide mixture × year and herbicide mixture × CC condition interactions, the random effect of the kth block within the jth year, and the random effect of the mth whole plot within the kth block and jth year. Each subplot had one slope, so the subplot was the residual unit. Estimated means combine both parts: (1 − pl) × λiljkm.

Equation A.5. Palmer amaranth final density at canopy closure

Palmer amaranth counts at canopy closure were described with a negative binomial generalized linear mixed model with a log link:

$$Y_{iljkmno} \sim NegBin(\lambda_{iljkmn}, \theta)$$

$$log(\lambda_{iljkmn}) = log(A_j) + \mu_0 + HERB_l + CC_i + Year_j + (CC \times Year)_{ij} + Block_{jk} + WP_{jkm} + SP_{jkmn} \quad (A5)$$

$$Block_{jk} \sim N(0, \sigma_B lock^2)$$

$$WP_{jkm} \sim N(0, \sigma_W P^2)$$

$$SP_{jkmn} \sim N(0, \sigma_S P^2)$$

where Yiljkmno is the number of Palmer amaranth plants in the oth sample of the nth subplot, which follows a negative binomial distribution with mean λiljkmn and dispersion θ; log(λiljkmn) is the sum of the offset log(Aj), where Aj is the sampled area in the jth year (5.81 m² in 2025 and 2.14 m² in 2026), the overall expected mean μ0, the effect of the lth herbicide mixture, the effect of the ith CC condition (no CC, dead, or living; no CC only in 2026), the effect of the jth year, the interaction between the ith CC condition and jth year, the random effect of the kth block within the jth year, the random effect of the mth whole plot within the kth block and jth year, and the random effect of the nth subplot (sub-subplot in no-CC plots) within the mth whole plot, kth block, and jth year.

Equation A.6. Palmer amaranth biomass at canopy closure

Palmer amaranth biomass was described with a gamma generalized additive mixed model with a log link:

$$PABio_{iljkmno} \sim Gamma\left(\lambda_{iljkmn}, \varphi\right)$$

$$\begin{aligned} log\left(\lambda_{iljkmn}\right) = \mu_0 + HERB_l + CC_i + Year_j + (HERB \times CC)_{li} + (HERB \times Year)_{lj} \\ + (CC \times Year)_{ij} + (HERB \times CC \times Year)_{lij} + Block_{jk} + WP_{jkm} + SP_{jkmn} \\ + f_j(range, pass) \quad (A6) \end{aligned}$$

$$Block_{jk} \sim N\left(0, \sigma^2_{Block,j}\right)$$

$$WP_{jkm} \sim N\left(0, \sigma^2_{WP,j}\right)$$

$$SP_{jkmn} \sim N\left(0, \sigma^2_{SP,j}\right)$$

where PABioiljkmno is the Palmer amaranth biomass (g m^{-2}) of the oth sample of the nth subplot, which follows a gamma distribution with mean λiljkmn and dispersion φ; log(λiljkmn) is the sum of the overall expected mean μ0, the effect of the lth herbicide mixture, the effect of the ith CC condition, the effect of the jth year, their two- and three-way interactions, the random effects of the kth block, the mth whole plot, and the nth subplot (sub-subplot in no-CC plots), with variances that differed by year, and fj(range, pass), a two-dimensional thin-plate regression spline (basis dimension 10) of block row (range) and plot column (pass) estimated for the jth year. In 2026, the no-CC plots were included as two additional herbicide levels (dime and flumi with no CC), and in these plots the CC term identified the foliar program received.

Equation A.7. Soybean grain yield

Soybean yield was described with a Gaussian generalized linear mixed model:

$$Y_{iljkm} \sim N\left(\mu_{iljkm}, \sigma^2\right)$$

$$\mu_{iljkm} = \mu_0 + HERB_l + CC_i + Year_j + HERB \times CC_{li} + HERB \times Year_{lj} + CC \times Year_{ij}$$

$$+ HERB \times CC \times Year_{lij} + \beta_j P_m + WP_{jkm} + SP_{ijkm} \quad (A7)$$

$$WP_{jkm} \sim N(0, \sigma^2_{WP})$$

$$SP_{ijkm} \sim N(0, \sigma^2_{SP})$$

where Y_{iljkm} is the soybean yield (kg ha^{-1}) of the subplot with the ith CC condition in the mth whole plot, which follows a Gaussian distribution with mean μ_{iljkm} *and variance* σ^2; μ_{iljkm} is the sum of the overall expected mean μ_0, the effect of the lth herbicide mixture, the effect of the ith CC condition, the effect of the jth year, their two- and three-way interactions, a linear trend along the harvest direction with year-specific slope β_j, where P_m is the harvest pass of the mth whole plot, the random effect of the mth whole plot within the kth block and jth year, and the

random effect of the subplot with the ith CC condition within the mth whole plot, kth block, and jth year. In 2026, the no-CC plots were included as two additional herbicide levels (dime and flumi with no CC). The block variance was estimated as zero and was removed.

Palmer amaranth cumulative density

Palmer amaranth cumulative density by 35 DAT in 2025 and 38 DAT in 2026 was affected by herbicide mixture ($P < 0.001$) and year ($P = 0.004$), but not by CC condition ($P = 0.669$) or the herbicide mixture × CC condition interaction ($P = 0.086$). Density was about 2.4 times greater in 2026 than in 2025. Because year was included as an additive effect, treatment differences and percent reductions were the same in both years (Table A.1). Flumi with either CC condition and flumi + MSO with the dead CC condition had the lowest densities, reducing Palmer amaranth density by 94 to 99% relative to the no residual herbicide (control) with the dead CC condition, whereas dime + MSO reduced density by only 30 to 44% and did not differ from the no residual herbicide (control) treatments.

Table A.1. Palmer amaranth cumulative density at 35 DAT (2025) and 38 DAT (2026) for each herbicide mixture and CC condition combination, within year.

Herbicide mixture	CC condition	2025		2026	
		Density (plants m^{-2})	Group	Density (plants m^{-2})	Group
No residual herbicide (control)	Dead	7.8 (3.2)	B	19.0 (7.7)	b
	Living	4.4 (1.9)	B	10.7 (4.5)	b
Dime	Dead	2.1 (0.9)	AB	5.0 (2.3)	ab
	Living	2.9 (1.3)	AB	7.0 (3.1)	ab
Dime + MSO	Dead	4.4 (1.9)	B	10.7 (4.4)	b
	Living	5.5 (2.3)	B	13.3 (5.5)	b
Flumi	Dead	0.4 (0.3)	A	1.0 (0.7)	a
	Living	0.3 (0.2)	A	0.8 (0.5)	a
Flumi + MSO	Dead	0.1 (0.1)	A	0.2 (0.3)	a
	Living	1.7 (0.8)	AB	4.1 (1.9)	ab

Values are means (±SE) back-transformed from the log scale. The herbicide mixture × CC condition interaction was not significant ($P = 0.086$); combinations are shown to describe how means varied between the dead and living CC conditions. Year was an additive effect, so treatment separation is the same in both years. Within a year, means followed by the same letter do not differ (Tukey, $P < 0.05$); uppercase letters compare means within 2025 and lowercase letters within 2026. No-CC plots (2026 only) excluded. DAT, days after herbicide mixture application.

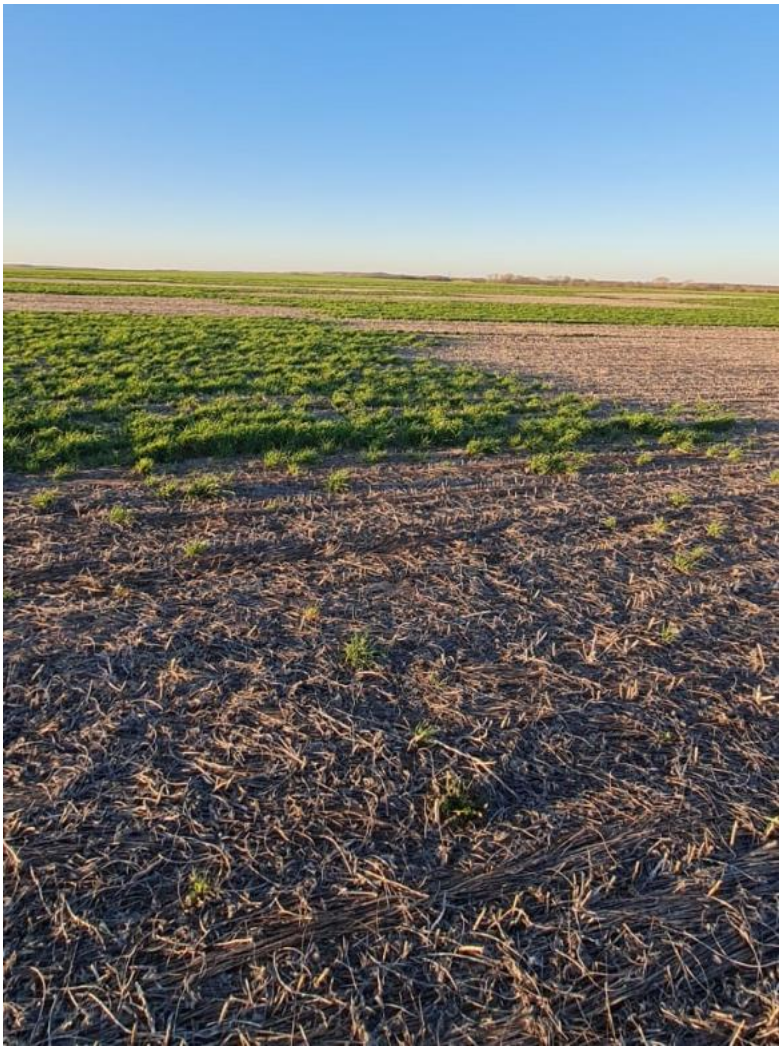


Figure A.1. Cover crop dead condition (bottom bare ground) and living condition (top volunteer rye) after soybean harvest.

Appendix B - Supplementary Material for Chapter 3

Model equations for statistical analyses

Indices: i = cover crop (CC) treatment; l = herbicide program (HERBP); t = treatment (CC treatment × HERBP combination, or chemical fallow); s = species; j = year; k = CC block; h = HERBP block; m = plot; r = herbicide program strip (CC biomass by species); n = subsample. All random effects follow a Gaussian distribution with mean zero, and log = natural logarithm.

Equation B.1. Total cover crop biomass

Total CC biomass was described with a gamma generalized linear mixed model with a log link:

$$TCCBio_{ijkmn} \sim \text{Gamma}(\lambda_{ijkm}, \varphi_{ij})$$

$$\log(\lambda_{ijkm}) = \mu_0 + CC_i + Year_j + (CC \times Year)_{ij} + CCblock_{jk} + CCstrip_{ijk} + Plot_{jm} \quad (B.1)$$

$$CCblock_{jk} \sim \text{N}(0, \sigma^2_{CCblock})$$

$$CCstrip_{ijk} \sim \text{N}(0, \sigma^2_{CCstrip})$$

$$Plot_{jm} \sim \text{N}(0, \sigma^2_{Plot})$$

$$\log(\varphi_{ij}) = \delta_0 + \delta_i + \delta_j + \delta_{ij}$$

where $TCCBio_{ijkmn}$ is the total CC biomass (kg ha^{-1}) of the nth subsample in the mth plot, which follows a gamma distribution with mean λ_{ijkm} and dispersion φ_{ij}; $\log(\lambda_{ijkm})$ is the sum of the overall expected mean μ_0, the effect of the ith CC, the effect of the jth year, the interaction between the ith CC and jth year, the random effect of the kth CC block within the jth year, the random effect of the ith CC strip within the kth CC block and jth year, and the random effect of the mth plot within the jth year. The dispersion φ_{ij} was allowed to vary by CC × year, and the residual coefficient of variation among subsamples within plots was computed as CV = $\sqrt{\varphi_{ij}}$.

Equation B.2. Cover crop biomass by species in the triticale-hairy vetch CC treatments

Triticale and hairy vetch biomass were log-transformed and described with a Gaussian generalized linear mixed model:

$$\log(CCBio_{isjkrmn})$$

$$= \mu_0 + CC_i + Sp_s + Year_j + (CC \times Sp)_{is} + (CC \times Year)_{ij}$$

$$+ (Sp \times Year)_{sj} + (CC \times Sp \times Year)_{isj} + CCblock_{jk} + CCstrip_{ijk}$$

$$+ HERBPstrip_{jkr} + Plot_{jm} + Sub_n + \epsilon_{isjkrmn} \qquad (A2)$$

$$CCblock_{jk} \sim \mathrm{N}(0, \sigma^2_{CCblock})$$

$$CCstrip_{ijk} \sim \mathrm{N}(0, \sigma^2_{CCstrip})$$

$$HERBPstrip_{jkr} \sim \mathrm{N}(0, \sigma^2_{HERBPstrip})$$

$$Plot_{jm} \sim \mathrm{N}(0, \sigma^2_{Plot})$$

$$Sub_n \sim \mathrm{N}(0, \sigma^2_{Sub})$$

$$\epsilon_{isjkrmn} \sim \mathrm{N}(0, \sigma^2_{sj})$$

where $CCBio_{isjkrmn}$ is the biomass (kg ha^{-1}) of the sth CC species (triticale or hairy vetch) in the nth subsample, log-transformed, that is the sum of the overall expected mean μ_0, the effect of the ith CC, the effect of the sth species, the effect of the jth year, their two- and three-way interactions, the random effect of the kth CC block within the jth year, the random effect of the ith CC strip within the kth CC block and jth year, the random effect of the rth herbicide program strip within the kth CC block and jth year, the random effect of the mth plot within the jth year, the random effect of the nth subsample (shared by both species), and the residual $\epsilon_{isjkrmn}$, whose variance σ_{sj}^2 was allowed to vary by species × year. Only samples in which the species was present were included.

Equation B.3. Total winter weed biomass, 2025

Total winter weed biomass was log-transformed and described with a Gaussian generalized linear mixed model:

$$\log(TWWBio_{ikm}) = \mu_0 + CC_i + CCblock_k + CCstrip_{ik} + \epsilon_{ikm} \qquad (B.3)$$

$$CCblock_k \sim \mathrm{N}(0, \sigma^2_{CCblock})$$

$$CCstrip_{ik} \sim \mathrm{N}(0, \sigma^2_{CCstrip})$$

$$\epsilon_{ikm} \sim \mathrm{N}(0, \sigma^2_i)$$

where TWWBio_{ikm} is the total winter weed biomass (g m^{-2}) in the mth plot (mean of its subsamples), log-transformed, that is the sum of the overall expected mean μ_0, the effect of the ith CC, the random effect of the kth CC block, the random effect of the ith CC strip within the kth CC block, and the residual ϵ_{ikm}, whose variance σ_i^2 was allowed to vary by CC. Plots with zero biomass were assigned half of the smallest observed value before log transformation.

Equation B.4. Winter weed biomass by species, 2025

Biomass of mustard species and cheatgrass was log-transformed and described with a Gaussian generalized linear mixed model:

$$\log(WWBio_{iskm}) = \mu_0 + CC_i + WSp_s + (CC \times WSp)_{is} + CCblock_k + CCstrip_{ik} + Plot_{ikm} + \epsilon_{iskm} \qquad (A4)$$

$$CCblock_k \sim \mathrm{N}(0, \sigma^2_{CCblock})$$

$$CCstrip_{ik} \sim \mathrm{N}(0, \sigma^2_{CCstrip})$$

$$Plot_{ikm} \sim \mathrm{N}(0, \sigma^2_{Plot})$$

$$\epsilon_{iskm} \sim \mathrm{N}(0, \sigma^2_s)$$

where WWBio_{iskm} is the biomass (g m^{-2}) of the sth winter weed species (mustard species or cheatgrass) in the mth plot, log-transformed, that is the sum of the overall expected mean μ_0, the effect of the ith CC, the effect of the sth winter weed species, the interaction between the ith CC and sth winter weed species, the random effect of the kth CC block, the random effect of the ith

CC strip within the kth CC block, the random effect of the mth plot, and the residual ϵ_{iskm}, whose variance σ_s^2 was allowed to vary by species. Only plots in which the species was present were included.

Equation B.5. Total summer weed biomass

Total summer weed biomass was log-transformed and described with a Gaussian generalized linear mixed model:

$$\log(TSWBio_{tjkhm}) = \mu_0 + Trt_t + Year_j + (Trt \times Year)_{tj} + CCstrip_{ijk} + HERBPstrip_{ljh} + \epsilon_{tjkhm} \quad (A5)$$

$$CCblock_{kj} \sim \mathrm{N}(0, \sigma^2_{CCblock})$$

$$HERBPblock_{hj} \sim \mathrm{N}(0, \sigma^2_{HERBPblock})$$

$$CCstrip_{ijk} \sim \mathrm{N}(0, \sigma^2_{CCstrip})$$

$$HERBPstrip_{ljh} \sim \mathrm{N}(0, \sigma^2_{HERBPstrip})$$

$$\epsilon_{tjkhm} \sim \mathrm{N}(0, \sigma^2_{lij})$$

$$\log(\sigma_{lij}) = \delta_0 + \delta_l + \delta_j + \delta_{lj} + \delta_{ij}$$

where $TSWBio_{tjkhm}$ is the total summer weed biomass (g m^{-2}; volunteer CC excluded) in the mth plot, log-transformed, that is the sum of the overall expected mean μ_0, the effect of the tth treatment (combination of the ith CC and lth HERBP, or chemical fallow), the effect of the jth year, the interaction between the tth treatment and jth year, the random effect of the kth CC block within the jth year, the random effect of the hth HERBP block within the jth year, the random effect of the ith CC strip within the kth CC block and jth year, the random effect of the lth HERBP strip within the hth HERBP block and jth year, and the residual ϵ_{tjkhm}, whose

standard deviation σ_{lij} was allowed to vary by HERBP × year and by CC × year. Plots with zero biomass were assigned half of the smallest observed value before log transformation.

Equation B.6. Weed cover

Weed cover was described with an ordered beta generalized linear mixed model with a logit link (Kubinec, 2023):

$$WC_{tjkhm} \sim \text{OrdBeta}(\pi_{tjkhm}, \varphi_{lj}, \kappa_1, \kappa_2)$$

$$\text{logit}(\pi_{tjkhm}) = \mu_0 + Trt_t + Year_j + (Trt \times Year)_{tj} + CCstrip_{ijk} + HERBPstrip_{ljh} \quad (A6)$$

$$CCblock_{kj} \sim \text{N}(0, \sigma^2_{CCblock})$$

$$HERBPblock_{hj} \sim \text{N}(0, \sigma^2_{HERBPblock})$$

$$CCstrip_{ijk} \sim \text{N}(0, \sigma^2_{CCstrip})$$

$$HERBPstrip_{ljh} \sim \text{N}(0, \sigma^2_{HERBPstrip})$$

$$\log(\varphi_{lj}) = \delta_0 + \delta_l + \delta_j + \delta_{lj}$$

where WC_{tjkhm} is the weed cover in the mth plot, expressed as the proportion of pixels in the plot center with NDVI above the Otsu threshold, which follows an ordered beta distribution with mean π_{tjkhm}, precision φ_{lj}, and cutpoints κ_1 and κ_2 that separate exact zeros, values between 0 and 1, and exact ones; $\text{logit}(\pi_{tjkhm})$ is the sum of the overall expected mean μ_0, the effect of the tth treatment, the effect of the jth year, the interaction between the tth treatment and jth year, the random effect of the kth CC block within the jth year, the random effect of the hth HERBP block within the jth year, the random effect of the ith CC strip within the kth CC block and jth year, and the random effect of the lth HERBP strip within the hth HERBP block and jth year. The precision φ_{lj} was allowed to vary by HERBP × year.

Equation B.7. Corn grain yield

Corn grain yield was described with a Gaussian generalized linear mixed model with residual variance differing by CC treatment × year:

$$CY_{tjkh} = \mu_0 + Trt_t + Year_j + (Trt \times Year)_{tj} + CCblock_{kj} + HERBPblock_{hj} + CCstrip_{ijk} + HERBPstrip_{ljh} + \epsilon_{tjkh} \qquad (A7)$$

$$CCblock_{kj} \sim \mathrm{N}(0, \sigma^2_{CCblock})$$

$$HERBPblock_{hj} \sim \mathrm{N}(0, \sigma^2_{HERBPblock})$$

$$CCstrip_{ijk} \sim \mathrm{N}(0, \sigma^2_{CCstrip})$$

$$HERBPstrip_{ljh} \sim \mathrm{N}(0, \sigma^2_{HERBPstrip})$$

$$\epsilon_{tjkh} \sim \mathrm{N}(0, \sigma^2_{ij})$$

$$\log(\sigma_{ij}) = \delta_0 + \delta_i + \delta_j + \delta_{ij}$$

where CY_{tjkh} is the corn grain yield (Mg ha^{-1}, adjusted to 15.5% moisture), that is the sum of the overall expected mean μ_0, the effect of the tth treatment (combination of the ith CC and lth HERBP, or chemical fallow), the effect of the jth year, the interaction between the tth treatment and jth year, the random effect of the kth CC block within the jth year, the random effect of the hth HERBP block within the jth year, the random effect of the ith CC strip within the kth CC block and jth year, the random effect of the lth HERBP strip within the hth HERBP block and jth year, and the residual ϵ_{tjkh}. The residual standard deviation σ_{ij} was estimated separately for each CC treatment, including chemical fallow, and year.

Post-plant weed density

Post-plant weed density was assessed once, 25 and 28 d after corn planting in 2025 and 2026, respectively, to evaluate the carryover effect of the CC treatments and herbicide programs (Table B.1). However, the farmer's preemergence herbicide program, applied to all plots immediately after corn planting, was strong and kept post-plant density low in both years (≤ 12.4 plants m^{-2}), and in 2026 the additional postemergence clean-up application added further noise to any carryover effect; therefore, post-plant density is presented descriptively only. Palmer amaranth prevailed in both years, particularly in 2026 (83 to 100% relative abundance), when its escapes required the clean-up application (Table 3.2).

Table B.1. Post-plant weed density and relative abundance of weed species in 2025 and 2026.

CC treatment	Herbicide program	2025					2026		
		Density (plants m^{-2})	Palmer amaranth	Velvetleaf	Spurge	Others†	Density (plants m^{-2})	Palmer amaranth	Carpetweed
No CC	Chemical fallow	5.0 (1.1)	48	43	–	9	6.0 (1.1)	83	17
Rye CC	B + RE	1.8 (1.0)	29	71	–	–	5.3 (1.5)	90	10
	B only	0.0 (0.0)	–	–	–	–	12.4 (2.7)	100	–
Low HV + High Tr	B + RE	0.9 (0.6)	50	50	–	–	3.6 (1.2)	85	15
	B only	0.0 (0.0)	–	–	–	–	9.8 (1.8)	100	–
Medium HV + Low Tr	B + RE	1.3 (0.7)	67	33	–	–	4.9 (2.0)	87	13
	B only	3.1 (2.6)	68	32	–	–	7.6 (4.1)	100	–
High HV + Low Tr	B + RE	1.8 (1.8)	38	62	–	–	3.1 (1.5)	100	–
	B only	0.0 (0.0)	–	–	–	–	7.6 (1.7)	100	–

Density: mean (SE) of one count 25 (2025) and 28 (2026) d after corn planting. Species columns are relative abundance (%; Eq. 1); –, not present. Spurge, Euphorbia spp.; carpetweed, Mollugo verticillata L. † Other species, as in Table 3.9. B + RE, burndown + residual; B only, burndown only; HV, hairy vetch; Tr, triticale.