CEREAL RYE TERMINATION METHOD EFFECTS ON HORSEWEED SUPPRESSION AND HERBICIDE EFFECTS ON COVER CROP ESTABLISHMENT

By

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ABSTRACT

Field experiments were conducted from 2021-2023 to evaluate how mechanical rolling methods and termination timing of cereal rye affects horseweed (*Conyza canadensis* L.) suppression and soybean yield. At the time of postemergence (POST) herbicide application, cereal rye terminated prior to soybean planting provided less ground cover, which led to more horseweed than the delayed terminations. Horseweed suppression was not influenced by flattening cereal rye with a roller, roller-crimper, or cultipacker. At soybean harvest, cereal rye reduced horseweed biomass 44 to 91%. Applying an effective POST herbicide after these treatments further improved horseweed control. Delaying cereal rye termination until unifoliate soybean, regardless of termination method, hindered soybean growth and development, leading to an 18 to 93% reduction in yield. Cereal rye termination time more than method affected horseweed suppression and soybean yield. Separate field experiments were also conducted to determine cover crop sensitivity to carryover from spring-applied winter wheat herbicides (8 site-years) and cover crop establishment from postharvest herbicide applications (5 site-years). From 8 site-years, all nine cover crop species were safe to plant following spring applications of eight commonly used winter wheat herbicides. All cover crops were also safe to plant following postharvest glyphosate and glufosinate applications. Annual ryegrass, cereal rye, and oat were safe to plant following postharvest saflufenacil and 2,4-D. However, saflufenacil should not be applied before crimson clover, red clover, mustard, oilseed radish, or dwarf Essex rapeseed. Do not apply 2,4-D prior to seeding Austrian winter pea, crimson clover, or red clover.

Dedicated to my family and friends that provided me depthless love and encouragement.
And for young girls who dream of being scientists, it may not always be easy, but it’s worth it.

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CHAPTER 1: LITERATURE REVIEW

Introduction

One of the most economically important crops in the United States, and across the world, is soybean (*Glycine max* L.). In the last ten years, Michigan soybeans generated an average of \$1.1 billion on the 920,000 hectares harvested each year, with an average yield of 3,246 kg ha^{-1}, just under the national 10-year average of 3,943 kg ha^{-1} (USDA NASS 2023). The uses of soybean are vast and are generally split into consumable and non-consumable products (USB 2020). Consumable products range from vegetable oil for cooking to meal used in livestock feed. Non-food products include tire production, lubricants, and biodiesel. Nearly half of the raw material used in biodiesel production comes from soybean oil.

A main challenge in soybean production is weed management. Uncontrolled weed interference in soybean can decrease yield by 52% and cause an annual loss of \$16 billion in the U.S. (Soltani et al. 2017). Previous research found that poor late season weed control in soybean reduced yields by 9-21%, depending on annual precipitation (Landau et al. 2022). Since the introduction of glyphosate resistant soybeans in 1996, 59 weed species have developed resistance to glyphosate (Heap 2024), 21 within the last seven years. Glyphosate resistance occurs through target site resistance (TSR) mechanisms in the EPSPS gene or non-target site resistance (NTSR) (Heap and Duke 2018). Within TSR mutations, amino acid substitution of Pro-106 in the EPSPS gene is the most reported mechanism (Gaines et al. 2020).

Glyphosate-resistant (GR) horseweed (*Conyza canadensis* L.) is a challenge for Michigan soybean growers, especially on no-till acres. In a survey in the last five years, horseweed was the number one weed control challenge for Michigan row crop farmers (Burns and Sprague, Michigan State University, personal communication, 2023). The spread of horseweed resistant to glyphosate and ALS inhibitors ultimately reduces herbicide options, generating the need for alternative and integrated weed management approaches. Economical and integrated solutions are essential for horseweed management in soybean.

In Michigan, wheat is the third most planted crop behind corn and soybean, with 186,155 hectares in 2022 (USDA NASS 2023). Winter wheat production was valued at $299 million in 2023, up from a 10-year average of $244 million. Most of the wheat produced in Michigan is milled by global and regional companies and turned into products sold in the Great Lakes region for human consumption (Michigan Wheat Program, 2023). Winter wheat harvest occurs from mid-July to early August; this creates an ideal window for growers to plant cover crops. Planting cover crops after wheat harvest provides an opportunity for weed suppression in the following spring, to better manage herbicide-resistant weeds (Fisher and Sprague 2022; Ghimire et al. 2019; Noland et al. 2018; Schramski et al. 2021b; Wallace et al. 2019).

Horseweed

Growth Habit. Horseweed seeds can germinate after they are shed from the mother plant. Therefore, horseweed may not be a true winter annual, rather developing the rosette to survive cold winter conditions (Buhler and Owen 1997; Schramski et al. 2021a). In Indiana and Michigan, horseweed has shifted more toward a summer annual lifecycle with more emergence in the spring than the fall (Davis and Johnson 2008; Schramski et al. 2021a). As Schramski et al. (2021b) noted more horseweed plants in Michigan emerge in late April through mid-May as an upright biotype, indicating that the rosette biotypes developed to survive cold winter temperatures. As the plant matures, the stem elongates or bolts during early summer, then in mid-late August plants develop small, white pistillate flowers accompanied by yellow disk flowers at the apex, supported by bracts (Loux et al. 2006; Weaver 2001). At maturity in late summer, the florets transform into a fluffy, white/tan pappus, with a 1 mm-long seed, and up 200,000 seeds per plant (Loux et al. 2006; Weaver 2001). Horseweed seed production is directly influenced by plant height, as taller plants produce more seeds (Regehr and Bazzaz 1979). These seeds are located at the plant's highest point, facilitating effortless wind dispersal, which provides an advantage for taller plants with more seeds. Due to their minute size and the fluffy pappus, the wind carries these seeds over considerable distances, reaching up to 500 km away from their origin (Shields et al. 2006).

Herbicide Resistance. Herbicide resistance is problematic as growers struggle to control weeds in an economical manner. Herbicide resistance is a consistent problem when growers rely on limited methods to control weeds. Using one mode or site of action repeatedly selects for herbicide resistance if plants survive and reproduce. Horseweed is resistant to Weed Science Society of America (WSSA) Herbicide Groups 2 (acetolactate synthase (ALS) inhibitors), 5 (photosystem II inhibitors), 9 (inhibition of EPSP synthase), and 22 (photosystem I electron diversion), and some populations have multiple resistance (Heap 2024). In Michigan, horseweed is commonly resistant to Groups 2 (ALS-inhibiting herbicides) and 9 (glyphosate) (Hill 2024).

Horseweed has developed both target-site resistance (TSR) and non-target site resistance (NTSR) mechanisms against glyphosate. (Beres et al. 2020; Ge et al. 2010, 2014; Moretti and Hanson 2017; Page et al. 2018). The most common mechanism of NTSR resistance in horseweed is vacuolar sequestration which results in reduced translocation of glyphosate (Dinelli et al. 2006; Ge et al. 2010; Moretti and Hanson 2017). Page et al. (2018) first documented TSR in horseweed populations across Canada, where they found a Pro-106 mutation, with proline substituted for serine. More recently Beres et al. (2020) discovered populations in Ohio and Iowa with the same TSR mechanism, demonstrating a 20- to 40-fold level of resistance to the field-rate of glyphosate. There are no observable effects on seed production, plant height, or leaf area index following an application of glyphosate on glyphosate-resistant horseweed, indicating that glyphosate-resistant horseweed has no obvious fitness trade-off (Davis et al. 2009).

NTSR resistant types at the rosette stage are approximately three times more resistant than the susceptible plant (Dinelli et al. 2006). Horseweed biotypes of either rosette or upright plants show different levels of resistance, including different mechanisms (Fisher et al. 2023; Schramski et al. 2021a). Schramski et al. (2021a) found that horseweed biotypes from the same parent plants differed in glyphosate sensitivity. They found that horseweed plants with a rosette biotype were 3-4 times less resistant than the upright biotypes. Fisher et al. (2023) continued this research using seeds from the same population and discovered that rosette biotypes of horseweed had reduced translocation due to rapid vacuolar sequestration. However, upright biotypes of horseweed did not show reduced translocation, leading Fisher et al. (2023) to speculate that the resistance mechanism changed between biotypes.

Horseweed Management. Due to the growth capability of horseweed and its growth rate, horseweed reduces soybean yield. Horseweed's relative growth rate is 0.16 g g^{-1} day^{-1}, while the relative growth rate of soybean is 0.155 g g^{-1} day^{-1} which makes horseweed competitive with soybean (Levang-Brilz and Biondini 2002; Loux et al. 2006; Seibert and Pearce 1993). Horseweed caused a 35-42% soybean yield reduction when it was not controlled with an effective herbicide (Byker et al. 2013). Glufosinate applied as a preplant burndown can control up to 88% of horseweed in soybean (Eubank et al. 2008). The uncontrolled horseweed in glufosinate treatments had no effect on yield, and all glufosinate based programs had at least 60% higher yield compared with the nontreated control. However, there is still a need for subsequent control measures following a preplant or preemergence herbicide application, regardless of the herbicide used (Bruce and Kells 1990; Byker et al. 2013). It is important to make the subsequent postemergence herbicide application when horseweed is small. Postemergence herbicide applications when horseweed was less than 35 cm saved 37-40% of soybean yield (Moseley and Hagood 1990). However, a herbicide application when horseweed was ≤5 cm can provide 99% control up to 6 weeks after the herbicide application (Budd et al. 2017).

Cereal Rye

Cereal rye, when used as a cover crop, plays a crucial role in disrupting the fitness advantage that larger weeds could have during herbicide applications. Cereal rye reduces this advantage by out-competing weeds through high resource acquisition, so weeds are less likely to survive preplant herbicide application (Wallace et al. 2019). Fall-planted cereal rye starts growing when it is planted, is dormant during the winter, and continues to grow rapidly in the spring as growing degree days accumulate. Cereal rye or a cereal rye mixture with higher ground cover in late fall significantly reduced horseweed density in the spring (Wallace et al. 2019). This reduction is directly tied to the cover crop's capacity for growth, with ground cover and biomass increasing proportional to the time allowed for growth. Cereal rye's capacity for spring growth has consistently shown weed suppression in early spring (Baraibar et al. 2018; Fisher and Sprague 2022; Hayden et al. 2012; Hodgskiss et al. 2021; Schramski et al. 2021b). Cereal rye effectively suppresses horseweed before planting no-till soybeans, but this does not eliminate the need for postemergence herbicides (Essman et al. 2020, 2023). Schramski et al. (2021) found that delaying cover crop termination one week after soybean planting further increased horseweed suppression.

C: N. The C: N is the ratio of grams of carbon for each gram of nitrogen (Flavel and Murphy 2006), therefore, a ratio of 25 means there is 25 g carbon for each g of nitrogen in the organic matter. Rapid mineralization and release of N occur when the C:N ratio is between 1 and 15 (Brust 2019). A C:N ratio greater than 35, out of the equilibrium of 20-30, results in nitrogen immobilization by soil microorganisms. The organic matter with a lower C:N ratio is mineralized quicker which returns nitrogen for immediate plant use (Watson et al. 2002). A cover crop's C:N ratio is a predictor of N retention rates and main crop yields (Finney et al. 2016). If the cover crops C:N ratio is high, the main crop yield is likely to suffer.

Weed Suppression. Growers generally rely on chemical and cultural practices that have lasting impacts on the agroecosystem. Reliance on herbicides to control weeds risks herbicide resistance evolution, decreasing the effectiveness of existing herbicides. Relying on cultivation for weed control is difficult in-season and using intense fall/spring tillage increases the likelihood of both soil erosion and field compaction. Integrating cover crops into a crop rotation gives an additional method of weed control that can be implemented with other control options. Fall-planted cover crops that overwinter can decrease winter and spring annual weeds.

Managing weeds with cover crops disrupts the weed's lifecycle and prevents seed production, lowering the number of seeds present in the seed bank (Ruffo et al. 2004). The residue left by the terminated cover crop acts as a natural mulch that shades out emerging weeds (Teasdale and Mohler 1993). As seedlings attempt to penetrate a physical layer of residue, they are shaded which impedes their growth or successful establishment (Mirsky et al. 2013). Seedlings exhaust their nutrient reserves and die before reaching adequate light conditions for growth and establishment. At the time of a postemergence herbicide application, Fisher and Sprague (2022) reported horseweed biomass was 71-91% lower in cereal rye cover than in than no-cover. Similarly, Schramski et al. (2021b) had 46% to 93% lower horseweed biomass in treatments that were planted green, although horseweed density was similar. Wallace et al. (2019) found that cereal rye or a mixture containing cereal rye equalized horseweed plant sizes within the population. Variations in weed size may result in more inconsistent control of plants by a field rate of an herbicide. Cereal rye alone or in a mixture can provide weed suppression, however, termination method and timing might further impact the effectiveness and subsequent crop yield.

Termination Method and Timing Effects on Soybean Yield. Several methods exist for mechanical cereal rye termination, including mowing or rolling with a roller or roller-crimper (Creamer and Dabney 2002; Davis 2010; Mirsky et al. 2009). Mowing can be a difficult, since mower height needs to be low, and this may be hard to achieve on uneven ground (Creamer and Dabney 2002). Further, mowing distributes the residues in clumps, which creates uneven weed suppression, and may create challenges for planting a main crop. Cover crops terminated with a roller-crimper can suppress weed growth greater than chemical termination alone (Davis 2010). Using a roller-crimper for cereal rye termination has the best results when cereal rye reaches anthesis (Feekes 10.5.1-10.5.3) (Mirsky et al. 2009). Roller-crimpers maximize cover crop ground contact and lay down cereal rye the same direction that a field will be planted, this reduces chances of clogging planting parts or displacing seed (Creamer and Dabney 2002; Mischler et al. 2010). Previous research showed that rolling soybeans up to V4 has no effect on soybean yield (Boyers et al. 2020), therefore, rolling cereal rye at anthesis after soybeans have emerged should not impact yield.

Determining the optimal termination time for cereal rye is essential to increase weed control while not sacrificing soybean yield. Previous research found that cereal rye terminated at the time of soybean planting, had higher biomass than terminating before planting, but there were no differences in soybean population or yield (Pittman et al. 2019; Reed et al. 2019; Ruffo et al. 2004). In two of three years, cereal rye terminated two weeks prior to or at soybean planting improved soybean yields when compared to no cover (Pinnamaneni et al. 2022). Soybeans grown after cereal rye had higher yield, more pods per plant, and higher stand count than soybean grown in a no cover control. Cereal rye terminated after soybean planting resulted in higher cover crop biomass and weed control compared with termination prior to or at soybean planting in April and May (Essman et al. 2023; Fisher and Sprague 2022; Hodgskiss et al. 2021; Schramski et al. 2021b). This resulted in higher yields when Schramski et al. (2021b) terminated cereal rye one week after soybean planting.

Previous research has shown positive results when cereal rye was included in weed management, where soybean yield varied depending on termination time. The difference in termination time after soybean planting resulted in differences in soybean yield across the previous research (Essman et al. 2023; Fisher and Sprague 2022; Schramski et al. 2021b). Both (Fisher and Sprague 2022) and Schramski et al. (2021b) observed higher soybean yields following an effective postemergence herbicide across all cereal rye treatments. Essman et al. (2023), also found cereal rye did not provide season-long weed control and the postemergence herbicide was necessary for higher soybean yield. Cereal rye terminated 21 d after planting led to lower soybean stands and yield compared with termination before or at soybean planting, in one of two years. Fisher and Sprague (2022) observed when a postemergence herbicide was applied, soybean yields with cereal rye terminated early were higher than cereal rye terminated after planting. The time until delayed cereal rye termination between Essman et al. (2023) and (Fisher and Sprague 2022) and Schramski et al. (2021b) explains why soybean yield was affected differently.

When cover crop mixtures had exceptionally high biomass, above 6,800 kg ha^{-1}, soybean yield was reduced since early-season growth was restricted by the cover crop biomass (Osipitan et al. 2018). Snyder et al. (2016) found that cereal rye in no-till soybeans had lower yield due to high rye biomass. Cereal rye biomass as high as 7,876 kg ha^{-1} interfered with planting and led to lower soybean populations (Snyder et al. 2016). Cover crops grown before a cash crop that are not properly managed can create nutrient and/or water deficiencies in the soil. Yield may be lower when soybeans are planted following cereal rye terminated under dry conditions (Osipitan et al., 2018, Wells et al., 2016). Reed et al. (2019) found that soil moisture was higher when cereal rye terminated before soybean planting compared with cereal rye terminated after planting. Cereal rye left standing after termination had lower soil moisture compared with cereal rye flattened by rolling, up to three weeks after rolling (Kornecki et al. 2009). Rolled treatments created a cereal rye mulch layer which limited evaporation. Growers may implement a rolling method to terminate cereal rye with or without chemicals to maintain soil moisture.

Cover Crops

A cover crop is a crop grown for seasonal or long-term benefits, such as improving soil health, increasing water quality, or providing habitat for bees (USDA 2014). Integrating cover crops into crop rotations can provide ecosystem services such as decreasing wind and water soil erosion, decreasing weed abundance, increasing soil organic matter, and protecting crop yield (Chen et al. 2022; Langdale et al. 1991; Reicosky and Forcella 1998; Shackelford et al. 2019). The use of cover crops in the United States has increased 27% over the last five years and is projected to continue to climb (SARE, 2024).

Cover crops can be integrated into systems in several ways, and different species provide varying ecosystem services. Grasses such as annual ryegrass and cereal rye provide fall and spring weed suppression (Hodgdon et al. 2016; Madsen et al. 2016; Wallace et al. 2019). Cereal rye and oat have high biomass and are an effective weed suppression tool alone, or when mixed with radish (Ghimire et al. 2019; Noland et al. 2018; Wallace et al. 2019). Red clover and crimson clover are commonly seeded into corn or winter wheat, as a living cover (Gaudin et al. 2014; Noland et al. 2018; Ott and Hargrove 1989). Clover as well as Austrian winter pea are utilized as winter cover crops and contribute to erosion prevention and nitrogen recycling (Ashworth et al. 2020; Baraibar et al. 2018; Hoyt and Hargrove 1986). Brassica cover crops, such as radish and mustard, produce glucosinolate residues that break nematode and disease cycles, while maintaining weed suppression in the fall (Hodgdon et al. 2016; Norsworthy et al. 2005; Snapp et al. 2005). Radishes exhibit competitive fall growth which slows winter weed annual growth and development (Lawley et al. 2012). They also have the potential to decrease nitrogen leaching after a main crop of barley and pea (Norberg and Aronsson 2020).

Ecosystem Services. Daryanto et al. (2018) summarized cover crop impacts on ecosystems services, which included increased soil organic matter, nutrient scavenging, decomposition and mineralization, and microbial activity. Services outside of the soil include an increase in crop yield, higher biodiversity, and potential allelopathy depending on the cover crop species. Ecosystem disservices caused by cover crops include loss of mobile nutrients such as phosphorus, weediness if not terminated, and possible interactions as alternate hosts to crop-specific pests. Keeping soil surfaces protected from wind and water erosion is extremely important to maintain topsoil on a field, where most nutrients are recycled. Cover crop biomass covers the soil and protects it from both wind and water erosion (Langdale et al., 1991; Reicosky

& Forcella, 1998). This is accomplished with increasing soil organic matter and soil aggregate size through the consistent use of cover crops in a rotation. Soil organic carbon increases soil aggregation and water retention (Blanco-Canqui and Ruis 2020). Blanco-Canqui and Ruis (2020) also found that cover crops reduce extreme soil temperature fluctuations, keeping winter soils warmer and summer soils cooler. The effect of cover crops on soil temperature may cause spring soils to be cooler, possibly affecting seed germination of cash crops such as corn and soybean. Cooler soils in the spring may, however, be a trade-off with the increase of soil organic carbon and soil aggregation.

Nitrogen is important for all crops to grow, and the addition of cover crops may reduce N leaching potential while also adding N back to the soil. Cover crop mixtures with high legume seeding rates can reduce NO_3^- leaching, while including non-leguminous, over-wintering cover crops increase N retention (White et al. 2017). When cover crop biomass is incorporated into the soil, organic carbon will also increase plant available nitrogen and help soil aggregates form. Cereal rye also reduced NO_3-N leaching when planted following corn harvest (Ruffo et al. 2004; Villamil et al. 2006). Cereal rye traps soil phosphorus in a no-till corn/soybean rotation, (Villamil et al. 2006), retaining nutrients within the soil.

Cover Crop Establishment

Winter wheat is harvested from July to August in mid-Michigan, creating a window for cover crop establishment. Summer temperatures help cover crops emerge and thrive until a hard frost in October-November. Currently, in the U.S. weed control practices after wheat harvest consists of chemical, cultural, and mechanical methods. Chemical postharvest weed control is important to kill herbicide-resistant weeds that emerge after wheat harvest. In the Central Great Plains several combinations of herbicides including paraquat, dicamba, and 2,4-D effectively controlled Palmer amaranth that emerged after wheat harvest (Kumar et al. 2021). In the Pacific Northwest, downy brome is controlled by tillage with a sweep plow or disk after wheat harvest (Young et al. 2014). Italian ryegrass, a weed that has resistance to six herbicide sites of action, has been found to be best managed with a combination of several in-season herbicides and narrow-windrow burning after wheat harvest (Maity et al. 2022). Cover crops interseeded with wheat have also been evaluated, red clover can reduce weed biomass of downy brome and volunteer wheat up to 99% (Anderson 2016). Previous research has found planting cover crops after wheat harvest provided strong competition for the and the cover crops suppressed both fall and spring emerging weeds (Baraibar et al. 2018). Cover crops have the potential to suppress herbicide-resistant weeds that emerge after wheat harvest.

Cover Crop Sensitivity to Herbicides. Not all herbicide labels provide information about cover crop rotation restrictions. This lack of knowledge creates uncertainty for growers who want to integrate cover crops into their crop rotations. Existing studies on herbicide effects on cover crops primarily focus on corn and soybean trials, leaving wheat herbicides largely unexplored.

The persistence of herbicides in soil is influenced by soil organic matter and content, and environmental conditions such as precipitation and temperature (Braschi et al. 2011). The impact of herbicides on cover crops varies depending on soil texture. For example, Group 14 herbicides like flumioxazin injured crimson clover on coarse textured soils, but not on finer textured soils (Rector et al. 2020). Previous research also found that annual ryegrass was sensitive to several herbicides when planted too close to the herbicide application, even 40 days after the application there was a high injury rating from metolachlor and pendimethalin (Tharp and Kells 2000).

Differences in cover crop sensitivity to herbicides is dependent on the species and can cause a wide range of injury and biomass production. Despite visible injury symptoms, cover crop biomass was not reduced by postemergence herbicides applied ten weeks preceding planting (Rector et al. 2020). Some residual herbicides can affect cover crop establishment following the cash crop season, but in most cases, injury is within commercially acceptable expectations (Rector et al. 2020). Certain Brassica species and cover crops with larger seeds, such as winter cereals and Austrian winter peas, exhibit higher tolerance to preemergence herbicides like dimethenamid and acetochlor (Wallace 2023). Austrian winter pea and crimson clover are both legumes but can have different responses to the same herbicide. Clopyralid, when used within rotational restrictions, reduced stands of crimson clover and Austrian winter pea (Cornelius and Bradley 2017). In a comprehensive analysis by Cornelius and Bradley (2017), oilseed radish and crimson clover exhibited higher injury levels across 29 herbicides, where cereal rye only had injury to five herbicides. Within the study, pyroxasulfone, prosulfuron, isoxaflutole, fluometuron, and cloransulam-methyl caused $\leq$20% injury to cereal rye which did not impact final biomass. More recently, corn herbicides of dimethenamid-P, dimethenamid-P + saflufenacil, and acetochlor + clopyralid + mesotrione that were applied preemergence, did not impact cereal rye biomass (Ley et al. 2023). These observations emphasize the varying sensitivity of cover crops to herbicides, creating the need for careful consideration when selecting herbicides for weed control in wheat and the following cover crop species.

Wheat Herbicides

Common winter wheat herbicides include chemistries from WSSA Groups 1, 2, 4, 6, and 27. Pinoxaden + fenoxaprop as Axial Bold are both a Group 1 herbicide active ingredients that control winter annual grasses often found in winter wheat (Anonymous 2022a). Thifensulfuron + tribenuron as Affinity Broadspec are both Group 2 herbicide active ingredients that control winter annual broadleaf weed species, such as common chickweed (*Stellaria media* L.), henbit

(*Lamium amplexicaule* L.), purple deadnettle (*Lamium purpureum* L.), field pennycress (*Thlaspi arvense* L), mustards (*Brassica* spp), shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.], and mayweed chamomile (*Anthemis cotula* L.) (Anonymous 2019a). Affinity Broadspec will also control summer annual weeds, like common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), and pigweeds (*Amaranthus* spp). Osprey and Osprey Xtra are also Group 2 herbicides, that contain the herbicide active ingredients mesosulfuron and mesosulfuron + thiencarbazone, respectively (Anonymous 2020b; Anonymous 2020c). Osprey controls grasses, especially annual bluegrass (*Poa annua* L.), windgrass (*Apera spica-venti* L.), and roughstalk bluegrass (*Poa trivialis* L.). Osprey Xtra provides control of the same species as Osprey, with greater control of cheat (*Bromus tectorum* L.) and brome (*Bromus* spp) species. PowerFlex HL, as pyroxsulam, is another Group 2 herbicide that demonstrates control of most grass species and some broadleaves such as common chickweed, shepherd's-purse, field pennycress, mustard species, common lambsquarters, and pigweed species (Anonymous 2022b). Quelex is a herbicide premixture that contains halauxifen (Group 4) + florasulam (Group 2) (Anonymous 2018). Quelex provides control of most winter annual broadleaf weeds, including horseweed (*Conyza canadensis* L.), as well as common lambsquarters and pigweed species. A Group 4 herbicide, clopyralid, also known as Stinger, controls annual and perennial broadleaf weeds including horseweed, mayweed chamomile, common and giant ragweed (*Ambrosia trifida* L)., and Canada thistle ([*Cirsium arvense* (L.) Scop.] (Anonymous 2019b). Huskie is a premixture of pyrasulfotole (Group 27) and bromoxynil (Group 6) (Anonymous 2022a). Huskie provides control for most winter annual and summer annual broadleaf weeds. Talinor also contains the Group 6 and 27 herbicide active ingredients of bromoxynil and bicyclopyrone, respectively (Anonymous 2016). Talinor provides weed control similar to Huskie with most winter annual and summer annual broadleaf weeds.

Grower interest of integrated weed management to combat herbicide resistance, along with the shift of the horseweed lifecycle to a summer annual in Michigan has created a need for understanding cereal rye management in soybean production systems. As cover cropping increases, the area of cover crop sensitivity to herbicides also needs to be explored in order to allow growers to make informed decisions based on research relevant to their cropping systems. Questions that remain to be answered:

1. Is there a difference between a land roller, roller-crimper, or cultipacker when terminating cereal rye on ground cover and horseweed suppression?
2. Is there a difference in horseweed suppression when cereal rye is terminated before planting, at-planting, or at unifoliate soybean?
3. Will effective horseweed suppression with cereal rye lead to higher soybean yields?
4. Are cover crops planted after winter wheat harvest injured following winter wheat herbicides applied in the spring?
5. Do postharvest/burndown herbicides after wheat harvest injure fall-planted cover crops?

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CHAPTER 2: CEREAL RYE TERMINATION METHOD EFFECTS ON HORSEWEED SUPPRESSION AND SOYBEAN YIELD

Abstract

Cereal rye terminated close to or soon after no-till soybean planting has been an effective early-season management strategy for herbicide-resistant horseweed (*Conyza canadensis* L.). However, standing terminated cereal rye can interfere with soybean growth, harvest, and yield. Therefore, field experiments were conducted in 2021, 2022, and 2023 to evaluate various cereal rye termination methods and termination timings on horseweed suppression and soybean yield and to determine how these methods can be integrated into an overall horseweed management program. Cereal rye terminated before soybean planting provided less cover than the other termination timings, which resulted in less effective horseweed suppression at the time of the postemergence (POST) herbicide application. In two out of three years, horseweed density at POST was equally suppressed by all cereal rye termination methods in the at-plant and soybean unifoliate terminations (1-2 plants ha^{-1}). At the time of the POST herbicide application, horseweed biomass was lowest all three years when cereal rye was terminated at or after soybean planting, with no differences between rolled and standing rye. The reduction in horseweed biomass at soybean harvest was 95% lower with an effective POST herbicide, but even with a non-effective POST the cereal rye was able to provide 63% suppression, demonstrating a potential for season-long suppression. In all three years, delaying cereal rye termination until soybean unifoliate, regardless of termination method, decreased soybean yield by 18-93%, compared to the highest yielding treatment. While delaying cereal rye termination until unifoliate can help with horseweed suppression, significant reductions in soybean yield can occur, particularly when cereal rye is terminated in dry spring conditions.

Introduction

Horseweed, (*Conyza canadensis* L.), is a facultative winter annual that has shifted from fall to primarily spring and early summer emergence in soybean cropping systems in the U.S. (Davis and Johnson 2008; Schramski et al. 2021b). In Michigan under adequate soil moisture, peak horseweed emergence (>80%) occurs in April and May when 50 to 100 GDDs (base 10 C) accumulate (Schramski et al. (2021b). Otherwise, horseweed emergence is dependent on rainfall events throughout the growing season. Horseweed has been the number one weed management challenge for Michigan row crop farmers over the past five years (E Burns and C Sprague, Michigan State University, personal communication, 2023). Uncontrolled horseweed competes with soybeans and can reduce soybeans yield 65% to 98% (Byker et al. 2013; Eubank et al. 2008; Pittman et al. 2019). Herbicide applications to control horseweed can be difficult to time, due to varying emergence throughout the summer, which may lead to horseweed escapes and ultimately a yield loss.

The evolution of herbicide-resistant biotypes has made horseweed management more difficult. Currently, horseweed biotypes in Michigan are resistant to four different herbicide sites of action: acetolactate synthase (ALS) inhibitors (WSSA Group 2); photosystem II inhibitors (WSSA Group 5), glyphosate, the 5-enolypyruvate-shikimate-3-phosphate inhibitor (EPSP; WSSA Group 9); and paraquat, a photosystem I electron diverter (WSSA Group 22) (Heap 2024). Compounding this issue, the majority of Michigan's horseweed populations are resistant to both the ALS-inhibiting herbicides and glyphosate (Hill 2024), limiting potential herbicide options for control.

Cover crops have been useful in suppressing weeds early in the season (Baraibar et al. 2018; Fisher and Sprague 2022; Hayden et al. 2012; Hodgskiss et al. 2021; Schramski et al.

2021b). The residue of terminated cover crops acts as a natural mulch that shades out and disrupts weeds by inhibiting their emergence and preventing seed production (Ruffo et al. 2004; Teasdale and Mohler 1993). Cereal rye, (*Secale cereale* L.), or a cereal rye mixture with high areas of ground covered by the cover crop in late fall reduces horseweed density in the spring and decreases plant size inequalities (Wallace et al. 2019). Starting the season with a lower horseweed density and plants of the same size increases the effectiveness of chemical weed control. Terminating cereal rye 7 or 21 days after soybean planting has shown increases in cereal rye biomass and ground cover which led to higher weed suppression (Essman et al. 2023; Fisher and Sprague 2022; Schramski et al. 2021b). While a cereal rye cover can suppress horseweed in the spring, it does not eliminate the need for postemergence (POST) herbicides (Essman et al. 2023; Fisher and Sprague 2022; Schramski et al. 2021b). These findings suggest that using cereal rye as a cover crop is an effective strategy for suppressing horseweed early in the soybean growing season. Extending the effectiveness of cereal rye may depend on biomass accumulated at termination and increased ground cover and soil contact.

Cereal rye that is chemically terminated and left standing may have less ground cover and interfere with soybean harvest. Several mechanical methods may be employed to increase cereal rye ground cover. A roller or roller crimper lays down cereal rye in one direction, making it easier to plant the cash crop (Creamer and Dabney 2002; Mischler et al. 2010). Delaying cereal rye termination and rolling after soybean emergence should not impact soybean yield; previous research showed that rolling soybean up to the V4 growth stage had no effect on yield (Boyers et al. 2020). Mirsky et al. (2011) found that cover crops terminated with an herbicide, followed by a roller-crimper, suppressed annual weeds. As cover crop termination was delayed, cover crop biomass increased and weed densities decreased. Similarly, Pinnamaneni et al. (2022)

determined that plots with cereal rye terminated at or after soybean planting had 72% lower weed biomass eight weeks after planting, compared with a no cover control. Delaying cereal rye termination can lead to increased weed control but may impact crop germination under dry conditions. Cereal rye terminated at or up to five days after soybean planting in low soil moisture can lead to poor soybean yield (Reed et al. 2019; Wells et al. 2016).

Although cereal rye can provide excellent weed control, there is a potential trade off with soybean yield. Cover crop termination that was delayed approximately 5 days after soybean planting had no effect on soybean yield (Reed et al. 2019). Schramski et al. (2021b) found that cover crop biomass increased 200% between the time of terminating cover crops one week before and one week after soybean planting, which improved horseweed suppression. Despite greater horseweed control, the cover crop termination timing had no effect on soybean yield. Similarly, Pittman et al. (2019) and Tyler (2021) observed no difference in yield when cereal rye was terminated before or at planting in no-till fields. Further, Fisher and Sprague (2022) did not observe soybean yield differences when cereal rye was terminated 7 days before or 7 days after planting in three of four site-years. Delaying cereal rye termination in the fourth site-year, resulted in a 10% reduction in yield due to an increased incidence of white mold. Furthermore, Hodgskiss et al. (2021) found that delaying cover crop termination until 12 days after soybean planting reduced soybean yield up to 31%, compared with the early termination, when all treatments received a POST application. Delaying cereal rye termination until 21 days after planting in dry conditions decreased soybean yield up to 8% (Essman et al. 2023).

Cereal rye may provide early-season horseweed control, and when partnered with an effective POST herbicide, provide full-season horseweed control and higher soybean yields. Cereal rye terminated 14 days before soybean planting, at soybean planting, and at unifoliate soybean may influence horseweed suppression. Further, mechanical methods following chemically terminated cereal rye might increase ground cover which would effectively reduce horseweed presence. The objectives of this research were to 1) evaluate the effectiveness of a roller, roller-crimper, and cultipacker on cereal rye ground cover for improved horseweed suppression, 2) determine if cereal rye terminated before, at, or after soybean planting provides season long horseweed suppression without a postemergence herbicide application, and 3) compare soybean yield across cereal rye treatments with and without an effective POST herbicide.

Materials and Methods

Field experiments were conducted at the Michigan State University Agronomy Farm in Lansing, MI in 2021 (42.688917° N, -84.490833° W), 2022 (42.707° N, -84.472806° W), and 2023 (42.686222° N, -84.49075° W). Fields were selected based on the presence of glyphosate-resistant horseweed the previous year. The soil type in 2021, 2022, and 2023 was a Conover loam (fine-loamy, mixed, active, mesic Aquic Hapludalfs) with pH 6.2, 7.2 and 5.9, and 3.2%, 2.9% and 2.7% organic matter, respectively.

The experiment was arranged in a split-plot randomized complete block design with four replications. Cereal rye treatments were the main plot factor and POST herbicide treatment was the sub-plot factor. Individual plots measured 3 m wide by 11 m long. Cereal rye treatments consisted of three termination timings: early (two weeks before planting), at soybean planting, and delayed until soybean reached the unifoliate stage. A no cereal rye cover and a no cover plus residual herbicide program (2022 and 2023) were established as controls. Termination was done with one to four different methods within each termination timing. All cereal rye termination methods started with an application of glyphosate (Roundup PowerMAX 3; Bayer CropScience, St. Louis, MO) at 1.26 kg ae ha^{-1} plus ammonium sulfate (AMS) (Actamaster; Loveland Products, Inc., Greeley, CO) at 2% w w^{-1}. Cereal rye was then left standing (standing) or rolled flat with a land-roller (+ roller), a roller-crimper (+ crimper) , or cultipacker (+ cultipacker) 2 to 4 h after glyphosate application. A complete listing of early season main plot treatments can be found in Table 2.1.

The subplot factor included two POST herbicide strategies: a non-effective POST to control all weeds, except GR horseweed, and an effective POST to control all weeds, including GR horseweed. The non-effective POST consisted of glyphosate at 1.26 kg ae ha^{-1} plus AMS at 2% w w^{-1}. The effective POST was glufosinate (Liberty; BASF Corporation, Research Triangle Park, NC) at 0.66 kg ha^{-1} plus 2,4-D choline (Enlist One; Corteva Agriscience, Indianapolis, IN) at 1.1 kg ha^{-1} plus AMS at 2% w w^{-1}, respectively (Table 2.1).

The fall prior to each experiment, 'Wheeler' cereal rye was drilled in 19 cm rows at 67 kg ha^{-1} with a John Deere 1560 no-till small grain drill (John Deere, Moline, IL). The following spring, cereal rye was terminated, and early season main plot treatments were established. In May, glyphosate, glufosinate, and 2,4-D choline-resistant varieties of 'P25A16E' or 'P24T35E' varieties were planted in 76 cm with a four-row John Deere MaxEmerge2 vacuum planter (John-Deere, Moline, IL) at 370,500 seeds ha^{-1}. POST herbicide applications were made when horseweed was approximately 10 cm tall in the no-cover plots. Herbicide applications were made with a tractor-mounted, compressed air sprayer calibrated to deliver 178 L ha^{-1} at 207 kPa of pressure through 11003 AIXR nozzles (TeeJet, Spraying Systems CO., Wheaton, IL 60187). Dates for all field operations are listed in Table 2.2.

Air temperature and precipitation data were collected throughout the growing season using the nearest weather station on the Enviro-weather Automated Weather Station Network (https://mawn.geo.msu.edu, Michigan State University, East Lansing, MI) (Table 2.3). Air temperature data was used to calculate growing degrees days, using base 10 C for horseweed and base 4.4 C for cereal rye (Steinmaus et al. 2000). Thirty-year precipitation data averages were collected from the National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/cdo-web/datatools/normals).

Data Collection. Aboveground cereal rye biomass, and GR horseweed density and biomass were collected from two randomly placed 0.25 m^2 subsamples per plot at each termination time. Cereal rye and horseweed biomass were dried for approximately 7 days at 65 C and weighed. In 2022 and 2023, subsamples of cereal rye biomass were sent to A&L Great Lakes Laboratories, Inc. (Fort Wayne, IN) to be analyzed for C:N ratios using a TruMax CNS Macro Analyzer (LECO Corporation, St. Joseph, MI).

In 2022 and 2023, soil moisture was measured at the time of soybean planting by taking 5 measurements per plot at a depth of 7.6 cm using a Field Scout TDR 300 Soil Moisture Meter (FieldScout, Spectrum Technologies, Aurora, IL). When soybean reached the V1-V2 growth stage, soybean stand was assessed by counting the number of emerged plants in 6 m of row.

Prior to POST herbicide application, 5 to 7 wk after planting, percent ground cover was assessed using a line-transect (Laflen et al. 1981). An 11 m line-transect was laid diagonally across each plot and the presence of cereal rye, GR horseweed, soybean, other weeds, or no vegetation was recorded every 30 cm and converted into a percentage of the total plot. At the time of POST herbicide application, horseweed density and biomass were collected in, two randomly placed 0.25 m^2 subsamples, then dry biomass was weighed.

Soybean canopy closure for each termination method was measured beginning 5 wk after planting and continued approximately every 7-10 d until the majority of the plots reached full canopy closure, 90% or higher. Three photos per plot were taken using a smartphone (iPhone 11, Apple®) 1.1 meters above the soil surface. The photos were uploaded to the web application Foliage (https://andres-patrignani.github.io/foliage/) for analyzing green canopy cover (Patrignani 2020). Soybean growth and development was evaluated bi-weekly (Pedersen 2009).

Prior to soybean harvest, GR horseweed density and biomass was once again collected from two randomly placed 0.25 m^2 subsamples per plot. Biomass was dried and weighed. Soybean was harvested from the center two-rows using a small-plot research combine (Massey-Ferguson 8XP, AGCO, Duluth, GA) when soybean reached full maturity. Yields were adjusted to 13% moisture.

Statistical Analysis. Data was analyzed using PROC MIXED in SAS Studio 3.8 (SAS Institute 2023, Cary, NC). The statistical model for data collected prior to POST herbicide application consisted of cereal rye treatment as a fixed effect. After the POST herbicide application, fixed effects were cereal rye treatment and POST herbicide treatment. Replications were used as an error term for testing the effects of year. Replications and replication nested within year were considered random effects when data were combined over years. Data were analyzed separately by year if there was a significant year by fixed effect interaction ($p \leq 0.05$), otherwise all data was combined over years. Normality assumptions were checked by examining histogram and normal probability plots of the residuals. Unequal variance assumptions were assessed by visual inspection of the side-by-side box plots of the residuals followed by Levene's test for unequal variances. Treatment means were separated using Fisher's Protected LSD at $\alpha \leq 0.05$.

Canopy closure data were analyzed in R Studio v. 4.3.2 (R Development Core Team, 2023) using the dose-response curve (drc) package. A four-parameter log-logistic model (Equation 1) was fitted for each cereal rye termination time as selected by the drc modelFit function using the lack-of-fit test. The effective time to reach 50 and 90% canopy closure was determined using the ED function for each cereal rye termination time.

$$y = c + \frac{d-c}{1+\exp(b(\log(x)-\log(e)))} \quad [1]$$

For this equation, y is the % canopy closure; x is the time (days after planting), c and d are the lower and upper limits, respectively, b is the relative slope around e, and e is the inflection point (Ritz and Strebig 2015). Differences in days to 50 and 90% canopy closure cereal rye treatments were compared based on a t-statistic ($\alpha \leq 0.05$) using the EDcomp function.

Results and Discussion

Cereal Rye Growth and Termination. The weather (precipitation and growing degree days) between cereal rye seeding and termination time greatly influenced cereal rye growth stage, height, and biomass among the three study years. The target termination date for early-terminated cereal rye was the first week of May, with the intent to plant soybean in mid-May. This target was reached in 2021 and 2023 but delayed by one week in 2022 due to excessive precipitation in late-April and early-May (Table 2.3). Even with this delay, the cereal rye growth stage for the early termination was at Feekes stage 5 in 2021 and 2022 (Table 2.4). However, both cereal rye height and biomass was close to twice as much in 2022 than in 2021, most likely due to higher precipitation and 135 more GDDs (base 4.4 C) in 2022 between cereal rye seeding and termination (Tables 2.2 and 2.4). Cereal rye biomass in 2021 was 1,074 kg ha^{-1}, similar to what was previously reported by Fisher and Sprague (2022) with GDDs ranging from 418-561 for early terminated cereal rye. An overall milder winter in 2023 with 100 GDDs more than 2022 resulted in an advanced stage of cereal rye growth (Feekes stage 9) and more cereal rye biomass for the early termination time (Table 2.4). Cereal rye biomass for 2021, 2022, and 2023 at the early termination time was 1,074, 2,203 and 6,546 kg ha^{-1}, respectively (Table 2.4).

In the two weeks between the early cereal rye termination and soybean planting, cereal rye progressed from Feekes stage 5 to 8 in 2021 (Table 2.4). This corresponded to a 2,700 kg ha^{-1} increase in cereal rye biomass. Warmer spring temperatures in 2022 and 2023 with >1,000 GDDs between cereal rye seeding and soybean planting resulted in cereal rye reaching Feekes stages 10.2 and 10, respectively (Tables 2.2 and 2.4). Cereal rye biomass increased by 2,943 kg ha^{-1} between the early termination and soybean planting in 2022; however, there was no difference in cereal rye biomass for these termination times in 2023. This was most likely due to the advanced stage of cereal rye growth early in the season and the dense stand that contributed to higher biomass in the early termination.

Soil moisture was measured at soybean planting/at-plant termination time in 2022 and 2023. Overall, the mean volumetric soil moisture was higher in 2022 than in 2023 (Table 2.5). This was likely due to greater amounts of April and early May precipitation prior to soybean planting in 2022 (108 mm) compared with 2023 (81 mm) (Table 2.3). Cereal rye that was terminated early (2 wk prior to planting) had 2% and 6.3% higher moisture than the no cover control in 2022 and 2023, respectively (Table 2.5). In contrast, non-terminated standing cereal rye negatively impacted soil moisture with 3.8% lower soil moisture than the no cover control in 2022. Similarly, Schramski et al. (2021b) also found lower soil moisture when termination of cereal cover crops was delayed in one site-year; soil moisture was 1.8% lower for the delayed termination compared with the early termination. In 2023 soil moisture was not affected by the non-terminated cereal rye (10.7%) compared with the no cereal rye control (9.9%), likely due to below average precipitation in 2023 (Table 2.3). Fisher and Sprague (2022) also reported cereal rye did not affect soil moisture when mean volumetric soil moisture content was between 9 and 11%.

Soybean reached the unifoliate growth stage in living cereal rye 23, 14, and 17 d after planting in 2021, 2022, and 2023, respectively (Table 2.2). Cereal rye terminated at this time was at full heading (Feekes stage 10.5) in 2021 and 2022 and 50% heading (Feekes stage 10.3) in 2023 (Table 2.4). Delaying termination until unifoliate soybean resulted in 5,754, 6,444, and 10,429 kg ha^{-1} of cereal rye biomass which was an increase of 44%, 20%, and 40% compared with cereal rye terminated at planting in 2021, 2022, and 2023, respectively. This amount of biomass was substantially higher than the 4,217 to 4,791 kg ha^{-1} previously reported when cereal rye was terminated at a similar growth stage 1 wk after soybean planting (Fisher and Sprague 2022; Schramski et al. 2021b). The amount of accumulated growing degree days in these studies ranged from 548-812, while over 1,200 GDDs had accumulated between cereal rye seeding and termination at unifoliate soybean (Table 2.2).

Cereal rye biomass subsamples were analyzed for carbon-to-nitrogen (C:N) ratios in 2022 and 2023. As cereal rye growth stage and biomass increased, the C:N ratio of the plant tissue increased (Table 2.4). C:N ratios provide an estimate for potential plant residue decomposition and nitrogen mineralization/immobilization. An optimal C:N ratio for microbial decomposition is approximately 24:1; plant residues with higher C:N ratios decompose more slowly and may result in sub-optimal N availability (Jahanzad et al. 2016; Odhiambo and Bomke 2001; USDA NRCS 2011). Cereal rye terminated early and at soybean planting had C:N ratios ranging from 15:1 to 19:1 (Table 2.4). Delaying cereal rye termination until unifoliate soybean resulted in C:N ratios well above the optimal ratio, 69:1 and 48:1 in 2022 and 2023, respectively, potentially leading to cereal rye residues persisting longer and likely higher nitrogen immobilization (Brust 2019). Previous research from Fisher and Sprague (2022) reported a C:N of 42:1 for cereal rye terminated at Feekes stage 10.5.1; compared to a C:N ratio of 18:1 at Feekes stages 5 and 6.

The different termination methods were not affected by differences in cereal rye stage, height, and biomass among the three termination timings (data not shown). All methods successfully killed cereal rye within two weeks of implementation, regardless of timing. Cereal rye treated with glyphosate only remained standing. Rye treated with glyphosate followed by a roller, roller-crimper, or cultipacker within 2 to 4 h was flattened regardless of timing.

Cereal rye ground cover at the time of POST herbicide application, 5 to 8 wk after planting, was affected more by the time of termination than termination method. In two of three years, cereal rye ground cover was no different between the at-plant and unifoliate treatments (Table 2.6). In 2021, the cereal rye ground cover increased as cereal rye termination was delayed. Cereal rye ground cover was 36, 56, and 75% averaged across termination methods for the early, at-plant, and unifoliate treatments. Cereal rye termination method did not affect ground cover in 2022 or 2023 as well. In 2022, cereal rye ground cover was 20% for early termination and 71% for the at-plant and unifoliate treatments. Increased Feekes stages and high biomass in the early season caused few differences in 2023 ground cover, 73% or greater ground cover was observed. Fisher and Sprague (2022) observed a 12% increase of cereal rye ground cover from cereal rye terminated 7 d before planting and 7 d after planting. Similarly, Schramski et al. (2021b) found that cereal cover crops terminated 7 d after soybean planting provided 55% more ground cover than cereal rye terminated 7 d before soybean planting. Overall, we found that cereal rye ground cover marginally increased when cereal rye was terminated at Feekes stage 10.1 or later, regardless of termination timing or method.

Cereal Rye Effects on Horseweed Management. In 2021, at the time of the unifoliate stage of soybean, cereal rye terminated at planting, regardless or termination method, suppressed horseweed density by more than 83% compared with the no cover control and early terminated cereal rye treatments (Table 2.7). Horseweed biomass was also reduced; however, there was not a substantial amount of biomass present (<4 g ha^{-1}) since horseweed diameter/height at this termination time averaged 2 cm. This finding is consistent with previous research where cereal rye reduced horseweed density 46 to 80% and biomass 41 to 97% at the time of delayed termination (Essman et al. 2020; Fisher and Sprague 2022; Pittman et al. 2019; Schramski et al. 2021; Wallace et al. 2019). In 2022 and 2023, no suppression by rye of either horseweed density or biomass was detected at the unifoliate termination timing, likely due in part to low horseweed populations even in the no cover control (Table 2.7).

POST herbicide applications were made 5 to 8 wk after soybean planting. At this time, in 2021, horseweed density was only reduced when cereal rye was terminated at the unifoliate stage compared with the no cover control (Table 2.6). However, horseweed biomass was 61 to 88% lower than the no cover control when cereal rye was terminated at planting, regardless of whether cereal rye was left standing or flattened mechanically. Delaying termination until unifoliate soybean further reduced horseweed biomass by 99%. In 2022/2023, cereal rye terminated early reduced horseweed biomass by 75% regardless of termination method. The impact of early terminated cereal rye may partially be explained by the lower horseweed densities and substantially higher cereal rye biomass encountered in 2022 and 2023 compared with 2021 (Table 2.4). In 2022/2023, horseweed density and biomass reductions of over 85% and 98%, respectively, were present when cereal rye was terminated at planting or at the unifoliate stage (Table 2.6). Reductions of horseweed density and biomass for these termination times were similar to the no cover preemergence residual herbicide treatment, which provided 100% horseweed control. In contrast, Fisher and Sprague (2023) had greater horseweed control at the time of the POST herbicide application from the preemergence residual treatment compared with planting green, although both treatments suppressed horseweed greater than no cover in 76 cm rows.

Prior to soybean harvest, cereal rye reduced horseweed density by 36 to 86% in 2021 and 33 to 60% in 2022/2023 compared with the no cover control when a non-effective POST herbicide was applied, regardless of rye termination time or method (Table 2.8). Fisher and Sprague (2022) reported delayed termination of cereal rye reduced horseweed density by 42%. Horseweed biomass was also suppressed by all cereal rye treatments, except for cereal rye terminated at planting followed by a roller in 2021. All other cereal rye treatments provided similar horseweed suppression with reductions in biomass ranging from 64 to 91% in 2021 and 44 to 73% in 2022/2023. In 2022/2023, the only treatment that suppressed horseweed biomass similar to PRE residual herbicide treatment was the standing cereal rye terminated at unifoliate.

When the effective POST herbicide treatment of glufosinate + 2,4-D choline was applied, horseweed density and biomass was similar among all cereal rye treatments and the no cover control prior to soybean harvest (Table 2.8). These treatments provided 83 to 100% suppression of horseweed density and 92 to 100% of horseweed biomass compared with the no cover control with the non-effective POST herbicide treatment. Similarly, Schramski et al. (2021b) did not observe an effect of cereal rye on horseweed density or biomass prior to soybean harvest when an effective POST herbicide was applied. In contrast, Fisher and Sprague (2022) reported that cereal rye terminated prior to or after soybean planting helped with the overall reduction of horseweed biomass. Lower horseweed biomass was observed when an effective POST herbicide was applied compared with the no cover control. The effectiveness of the POST herbicide treatment in our research explains these differences (Table 2.8). Across previous research, applying an effective POST herbicide for horseweed control after early season suppression with cereal rye has been necessary for full-season control, since cereal rye alone does not provide season-long suppression (Essman et al. 2023; Fisher and Sprague 2022; Schramski et al. 2021b).

Cereal Rye Effects on Soybean Growth and Yield. Soybean establishment was affected by cereal rye termination time and method in 2022 and 2023. Soybean stand in the no cover controls was 67% and 51% of the seeding rate planted in 2022 and 2023, respectively (Table 2.9). The extreme drought conditions experienced in 2023 had the greatest impact on soybean emergence. Across both years soybean stand was not impacted when cereal rye was terminated early compared with the no cover control. However, cereal rye terminated at soybean planting and left standing resulted in lower soybean stands in both years. In 2023, the at-plant termination time followed by the roller and cultipacker also resulted in lower soybean stands. The greatest reduction in soybean stand occurred with the delayed termination time, especially under the drought conditions in 2023. Soybean stand was 92% and 72% lower when cereal rye was terminated at unifoliate soybean and left standing or rolled, respectively. Volumetric soil moisture at the time of planting in cereal rye that was standing was 4-6% lower than early terminated cereal rye treatments. Precipitation was less than 10 mm within the two weeks after soybean planting in both years and a 35 and 73 mm departure in precipitation from the 30-year average in 2022 and 2023, respectively (Table 2.3). Low soil moisture and lack of rainfall around planting compounded the negative effects of the unifoliate termination. Consistently, previous research showed that low precipitation near the time of cereal rye termination and soybean planting can lead to lower soybean stands in late May (Mischler et al. 2010). Soybean stands were lower when cereal rye biomass was greater than 4,000 kg ha^{-1} or when termination was 21 d after soybean planting (Essman et al. 2020, 2023). In our research, termination was 14 and 17 d after planting, and cereal rye biomass was 6,444 and 10,429 kg ha^{-1} in 2022 and 2023, respectively. However, others have shown no effect of delayed terminations on soybean populations (Reed et al. 2019; Schramski et al. 2021b).

One of the most notable differences across treatments was the reduced soybean growth in plots with cereal rye (data not shown). In 2022, cereal rye terminated at unifoliate soybean resulted in soybeans being one to two growth stages behind no cover control, the early termination, and at-plant termination times. In mid-August, the majority of soybean had reached R4, however, the delayed termination treatments were at the R3 growth stage. In early September, soybeans were at R6 for all treatments, except the unifoliate termination that were R5. Soybean reached the same growth stage at end of September. Greater differences in soybean development across cereal rye treatments were observed in 2023. In late July, the no cover and early cereal rye termination treatments were at R1, while soybean in the at-plant termination treatments were in the late vegetative stages, and treatments that were terminated at the unifoliate stage were at V2-V4. By mid-August, the no cover, early termination, and at-plant termination treatments were at the R5 growth stage, while the unifoliate termination treatments were only at R3. The lag in soybean growth continued into September. In October all treatments reached R7 with the exception of the unifoliate termination treatments. This delayed growth resulted in a four-day delay in soybean maturity. Early-season drought and high cereal rye biomass likely contributed to the delayed soybean emergence and growth.

In addition to differences in soybean development, cereal rye termination time, not method, affected soybean canopy closure in 2022 and 2023 (Figure 2.1; Figure 2.2). Cereal rye, regardless of termination time, slowed soybean canopy development. The time to 50% canopy closure was delayed by 3, 6, and 21 d for early, at-plant, and the unifoliate termination times compared with the no cover control in 2022 (Table 2.10). Days to 50% canopy closure were extended in 2023, with a 4, 14, and 65 d for early, at-plant, and the unifoliate termination times. Soybean canopy development to 90% canopy closure was similar for the early terminated and the at-plant (2022 only) terminated cereal rye compared with the no cover control. The unifoliate termination in 2022 delayed soybean canopy closure to 90% 18 d. In 2023, the at-plant termination time resulted in a 22 d delay and the unifoliate termination time never reached 90% canopy closure. Across both years, cereal rye slowed soybean growth in most treatments, and delaying cereal rye termination until after soybean planting had a larger effect than other termination times. This effect was greater in 2023 when soybeans never reached row closure, likely due to higher cereal rye biomass, poor germination, and lack of rainfall at planting. Further, the slow growth observed in 2023 was likely due to a five-week period of moderate drought had occurred from mid-June to through mid-July (Akyuz 2024). In previous research, soybean light interception 78 d after planting was reduced 30 to 43% in treatments with cereal rye compared with no cereal rye (Westgate et al. 2005). In contrast to our findings, Westgate et al. (2005) also observed soybeans had less light interception in treatments where cereal rye was terminated 14 d before planting compared with soybeans planted following cereal rye terminated close to soybean planting.

Soybean yield was affected by the cereal rye treatments averaged over the POST herbicide treatments in all three years. The standing and rolled cereal rye terminated at the unifoliate stage reduced soybean yields an average 9% and 32% in 2021 and 2022, respectively, compared with the highest yielding treatment each year (Table 2.11). The greatest reduction in soybean yield was from the unifoliate termination time in 2023 (71-93%). However, rolling cereal rye resulted in 88% more yield than the standing cereal rye at this termination time. High cereal rye biomass and dry conditions that reduced soybean stand and slowed development contributed to these extreme reductions in yield. A year with fewer precipitation events can cause a decrease in soybean yield when cereal rye is terminated 21 days after soybean planting (Essman et al. 2023). We found a large yield reduction. Cereal rye terminated at unifoliate soybean, decreased soybean yield by 938.5 to 4, 875.5 kg ha^{-1}. In 2021, cereal rye treatments that were terminated early or at soybean planting with the roller-crimper or cultipacker were the highest yielding (Table 2.11). Flattening cereal rye with the cultipacker or roller-crimper improved yield compared with leaving the cereal rye standing. Additionally, the at-plant + cultipacker treatment outyielded the no cover control, likely due to the reduction in horseweed density and biomass throughout the growing season. In 2022, soybean yield was similar for all treatments where cereal rye was terminated early or at soybean planting and compared with the no cover control. However, applying a residual herbicide without a cover provided the highest yield of 4,370 kg ha^{-1}. Due to the early dry condition in 2023, cereal rye, regardless of termination time, reduced soybean yield compared with the no cover control. However, there was no difference in termination method within the early and at-plant termination times. Previous research reported a 31% decrease in soybean yield when cereal rye was terminated 12 days after soybean planting (Hodgskiss et al. 2021). In contrast, there was no difference in soybean yield when cereal rye terminated 7 to 14 days after soybean planting (Fisher and Sprague 2022; Pittman et al. 2019; Reed et al. 2019; Schramski et al. 2021b). Differences between our findings and previous research could be attributed to higher cereal rye biomass accumulated due to warmer winters, drier planting conditions in the spring, and lower horseweed pressure early in the season for 2/3 years.

Averaged across cereal rye treatments, the addition of an effective POST herbicide application was only beneficial in 2022, improving soybean yield by 7% (Table 2.11). In 2022, horseweed plants emerged after the unifoliate termination, and the effective POST herbicide application controlled the late spring emerging horseweed, while the non-effective POST herbicide application allowed the horseweed plants to continue growing. Horseweed not controlled by the POST herbicide competed with soybeans and accumulate more biomass by the end of the season. Similarly, Fisher and Sprague (2022) had an 11% yield increase in three of four site-years across cereal rye treatments when an effective POST was applied. We had up to 15 horseweed plants m^{-2} in the no cover treatments with a non-effective POST without a large soybean yield reduction in 2 of 3 years. Previous research has found that a density of 20 to 25 plants m^{-2} of *Conyza bonariensis* L., which is a close relative to horseweed, can cause a 46% soybean yield loss (Trezzi et al. 2013).

Increases in cereal rye biomass, ground cover, and C:N ratios led to higher horseweed suppression until the POST herbicide application. Horseweed density and biomass in two of three years at the POST herbicide application was similar between at-planting and unifoliate termination methods. No differences in horseweed biomass at the POST herbicide application were observed between the cereal rye rolling methods within each timing. By the end of the growing season, there was no difference in horseweed suppression between cereal rye termination methods or timings within the respective POST herbicide treatments. An effective POST herbicide treatment lowered horseweed biomass greater than cereal rye alone. However, within the non-effective POST treatment, treatments with cereal rye had fewer horseweed plants, although not as low as the preemergence residual herbicide treatment. Plots with cereal rye terminated at unifoliate soybean had lower soybean densities, delayed soybean maturity and canopy closure, and reduced soybean yield. Soybean yields were higher when cereal rye was terminated before or at soybean planting. However, soybeans with no cover with or without a residual herbicide tended to have the highest yields in 2 of 3 years. The unifoliate termination reduced soybean yields 18 to 93% across three years. Cereal rye likely dried out the soils, but in 2023 when there was low soil moisture and less rainfall around soybean planting, the effects were exacerbated. Also, the high C:N allowed the cereal rye to persist for a long time, which caused harvesting interference in the standing unifoliate treatments. Integrating cereal rye terminated before or at soybean planting with an effective POST herbicide maximized horseweed suppression, however, cereal rye terminated at or past Feekes stage 10.1 can decrease soybean yield. The additional pass of a roller-crimper or cultipacker in one of three years increase soybean yield above the no cover, likely from increased horseweed control. However, in the other two years, the additional pass of a roller, roller-crimper, or cultipacker did not influence soybean yield, except for the roller in the unifoliate treatment in 2023

Tables

Table 2.1. Treatments evaluated for early-season horseweed and cereal rye management (main plots) and POST herbicide strategies (sub plots) in research studies conducted in 2021-2023.

Treatment	Cereal rye[a]	Timing[b]	Herbicide/termination method[c, d, e]	Rates
Early season (main plots)				kg ai or ae ha^{-1}
No cover	None	14 DBP, PRE	glyphosate, glyphosate	1.26, 1.26
No cover + residual[f]	None	PRE	glyphosate + 2,4-D choline + metribuzin + flumioxazin	1.26 + 1.1 + 0.31 + 0.07
Early standing	Yes	14 DBP	glyphosate	1.26
Early + roller[f]	Yes	14 DBP	glyphosate + roller	1.26
At-plant standing	Yes	PRE	glyphosate	1.26
At-plant + roller	Yes	PRE	glyphosate + roller	1.26
At-plant + crimper	Yes	PRE	glyphosate + roller-crimper	1.26
At-plant + cultipacker	Yes	PRE	glyphosate + cultipacker	1.26
Unifoliate standing	Yes	UNI	glyphosate	1.26
Unifoliate + roller	Yes	UNI	glyphosate + roller	1.26
POST (sub plots)	--			
Non-effective POST	--	POST	glyphosate	1.26
Effective POST	--	POST	glufosinate + 2,4-D choline	0.66 + 1.1

[a]'Wheeler' cereal rye drilled the previous fall at 67 kg ha^{-1}.
[b]DBP = days before planting; PRE = preemergence (just prior to planting); UNI = unifoliate soybean; POST = postemergence.
[c]All herbicide applications included 2% w w^{-1} of ammonium sulfate = Actamaster, Loveland Products, Inc., Greeley, CO.
[d]Glyphosate was applied 2 to 4 h prior to roller, roller-crimper, or cultipacker use.
[e]glyphosate = Roundup PowerMax 3 (Bayer CropScience, St. Louis, MO); 2,4-D choline = Enlist One (Corteva Agriscience, Indianapolis, IN); metribuzin = Dimetric DF (WinField United, St. Paul, MN); flumioxazin = Valor SX (Valent U.S.A. LLC, San Ramon, CA).
[f]These treatments were not present in 2021.

Table 2.2. Cereal rye seeding and termination dates, including precipitation and GDDs[a,b,c] from cereal rye seeding until each termination, soybean planting dates, POST herbicide application dates, total precipitation for the soybean growing season, and soybean harvest dates for the research studies conducted in 2021, 2022, and 2023 at Michigan State University.

Operation	2021	2022	2023
Cereal rye seeding	10 October 2020	18 October 2021	7 October 2022
Early termination	4 May 2021	12 May 2022	4 May 2023
Precipitation (mm)	236	316	335
GDDs (base 4.4 C)	635	770	876
GDDs (base 10 C)	239	211	146
At-plant termination/ soybean planting	18 May 2021	23 May 2022	16 May 2023
Precipitation (mm)	238	337	338
GDDs (base 4.4 C)	739	1,018	1,110
GDDs (base 10 C)	306	354	271
Unifoliate termination	10 June 2021	6 June 2022	2 June 2023
Precipitation (mm)	257	351	348
GDDs (base 4.4 C)	1,260	1,370	1,459
GDDs (base 10 C)	713	570	473
POST application	9 July 2021	28 June 2022	10 July 2023
Precipitation (mm) – soybean growing season	508	241	464
Soybean harvest	18 October 2021	23 October 2022	2 & 6 November 2023[d]

[a]Abbreviations: GDDs, growing degree days.
[b]GDD base 4.4 C calculated from cereal rye seeding date to cover termination.
[c]GDD base 10 C calculated from January 1 until cover termination for horseweed emergence.
[d]Due to delays in maturity, soybeans in treatments with the unifoliate termination were harvested 4 days later than the rest of the treatments.

Table 2.3. Monthly and 30-yr average precipitation for the research studies conducted at Michigan State University in 2021, 2022, and 2023.[a]

Month	2021	2022	2023	30-year avg.[c]
	————	————	mm ————	————
Fall prior[b]	199	213	242	320
April	38	98	73	90
May	24 (19)[d]	67 (10)[d]	23 (8)[d]	110
June	177	61	23	96
July	94	32	148	86
August	99	65	124	88
September	74	50	35	81
October	97	45	118	79
Totals (April – October)	603	418	521	630

[a]Precipitation data collected from the Enviro-weather Automated Weather Station Network, https://mawn.geo.msu.edu/, Michigan State University, East Lansing, MI.
[b]Precipitation from cereal rye seeding until April 1 the following spring.
[c]30-year average precipitation data collected from the National Oceanic and Atmospheric Administration, https://www.ncdc.noaa.gov/cdo-web/datatools/normals.
[d]Precipitation after soybean planting.

Table 2.4. Cereal rye stages, heights, biomass and C:N ratios at each termination time at Michigan State University in 2021, 2022, and 2023.

	Feekes stage			Height			Biomass[a]			C:N ratio[b]	
Termination time	2021	2022	2023	2021	2022	2023	2021	2022	2023	2022	2023
				———— cm ————			———— kg ha^{-1} ————				
Early	5	5	9	36	63	61	1,074 c	2,203 c	6,546 b	15:1	18:1
At-planting	8	10.2	10	66	122	130	3,800 b	5,146 b	6,235 b	19:1	18:1
Unifoliate	10.5	10.5	10.3	135	183	155	5,754 a	6,444 a	10,429 a	69:1	46:1

[a]Treatment means were only separated for cereal rye biomass; means followed by different letters within a column are statistically different at $\alpha \leq 0.05$.

[b]C:N ratios were only analyzed for cereal rye biomass collected in 2022 and 2023.

Table 2.5. Cereal rye termination time effects on mean volumetric soil moisture at a depth of 7.6 cm taken at soybean planting in 2022 and 2023 at Michigan State University.

Cereal rye treatments	2022	2023
	——— % ———	
No cover	18.5 b[a]	9.9 b
Early termination	20.5 a	16.2 a
At-plant termination	14.7 c	10.7 b

[a]Means followed by different letters within a column are statistically different at $\alpha \leq 0.05$.

Table 2.6. Cereal rye termination time and method effects on cereal rye groundcover, and horseweed density and biomass at the POST herbicide application timing, 5-7 wks after soybean planting in 2021, 2022, and 2023 at Michigan State University.

	Cereal rye ground cover			Horseweed density		Horseweed biomass	
Cereal rye treatments	2021	2022	2023	2021	2022/2023[a]	2021	2022/2023
	——— % ———			——— plants m^{-2} ———		——— g m^{-2} ———	
No cover	0 d	0 c	0 d	172 ab	15 a	59 a	16 a
No cover + residual[c]	--	0 c	0 d	--	0 c	--	0 c
Early standing	36 c	20 b	75 bc	171 ab	14 ab	46 a	4 b
Early + roller[c]	--	20 b	73 c	--	11 b	--	4 b
At-plant standing	59 b	65 a	86 a	84 bc	1 c	7 bc	0.4 c
At-plant + roller	59 b	72 a	80 abc	86 bc	1 c	12 bc	0.2 c
At-plant + crimper	54 b	70 a	86 a	85 bc	1 c	9 bc	0.1 c
At-plant + cultipacker	53 b	67 a	83 abc	192 a	1 c	23 b	0 c
Unifoliate standing	74 a	73 a	84 ab	19 c	2 c	1 c	0 c
Unifoliate + roller	76 a	78 a	89 a	29 c	2 c	1 c	0 c

[a]Data were combined over 2022 and 2023.

[b]Means followed by different letters within a column are statistically different at $\alpha \leq 0.05$.

[c]These treatments were not present in 2021.

Table 2.7. Cereal rye termination time and method effects on horseweed density and biomass at the unifoliate termination time, ~2-3 wks after soybean planting in 2021 and combined over 2022/2023 at Michigan State University.

	Horseweed density		Horseweed biomass	
Cereal rye treatments	2021	2022/2023	2021	2022/2023
	——— plants m^{-2} ———		——— g m^{-2} ———	
No cover	110 a[a]	2	3.6 a	0.46
No cover + residual[b]	--	0	--	0
Early standing	117 a	1	2.4 a	0.39
Early + roller[b]	--	0	--	0
At-plant standing	19 b	0	0.3 b	0
At-plant + roller	0 b	0	0 b	0
At-plant + crimper	0 b	0	0 b	0
At-plant + cultipacker	0 b	0	0 b	0
Unifoliate standing	16 b	1	0.7 b	0.39
Unifoliate + roller	0 b	1	0 b	0.39

[a]Means followed by different letters within a column are statistically different at $\alpha \leq 0.05$.
[b]These treatments were not present in 2021.

Table 2.8. Cereal rye treatment and POST herbicide application interaction on horseweed density and biomass at soybean harvest in 2021 and combined over 2022/2023 at Michigan State University.

Cereal rye treatment	POST treatment[a]	Horseweed density 2021	Horseweed density 2022/2023	Horseweed biomass 2021	Horseweed biomass 2022/2023
		plants m^{-2}		g m^{-2}	
No cover	Non-effective	14 a	15 a	123.9 a	146.2 a
No cover + residual[c]	Non-effective	--	1 e	--	7.9 c
Early standing	Non-effective	5 bcd	10 b	36.6 bc	62.0 b
Early + roller[c]	Non-effective	--	8 bc	--	74.1 b
At-plant standing	Non-effective	2 cde	6 bcd	15.1 bc	69.5 b
At-plant + roller	Non-effective	9 b	6 cd	92.1 a	82.5 b
At-plant + crimper	Non-effective	3 cde	6 cd	34.6 bc	75.8 b
At-plant + cultipacker	Non-effective	5 bc	9 bc	44.0 b	63.9 b
Unifoliate standing	Non-effective	3 cde	8 bc	26.9 bc	39.2 bc
Unifoliate + roller	Non-effective	3 cde	7 bc	11.1 bc	58.4 b
No cover	Effective	0 e	1 e	0 c	5.3 c
No cover + residual[c]	Effective	--	0 e	--	0 c
Early standing	Effective	0 e	1 e	0 c	6.1 c
Early + roller[c]	Effective	--	1 e	--	4.1 c
At-plant standing	Effective	1 de	1 e	1.5 c	2.9 c
At-plant + roller	Effective	0 e	0 e	0 c	0 c
At-plant + crimper	Effective	0 e	1 e	0 c	0.5 c
At-plant + cultipacker	Effective	0 e	1 e	0 c	0.3 c
Unifoliate standing	Effective	0 e	2 de	0 c	8.9 c
Unifoliate + roller	Effective	0 e	2 de	0 c	11.1 c
Effects (P-values)					
Cereal rye treatment		0.0011	0.0006	0.0009	0.0078
POST		<0.0001	<0.0001	<0.0001	<0.0001
Cereal rye treatment x POST		0.0005	0.0161	0.0008	0.0090

Table 2.8. (cont'd)

[a]Non-effective POST = glyphosate at 1.26 kg ha^{-1} + ammonium sulfate at 2% w w^{-1}; Effective POST = glufosinate + 2,4-D choline + ammonium sulfate at 0.66 + 1.1 kg ha^{-1} + 2% w w^{-1}, respectively.

[b]Means followed by different letters within a column are statistically different at $\alpha \leq 0.05$.

[c]These treatments were not present in 2021.

Table 2.9. Cereal rye termination time and method effects on soybean stand at V2-V3 in 2022 and 2023.[a]

Cereal rye treatments	2022	2023
	——— x1000 plants ha^{-1} ———	
No cover	248 ab[b]	191 a
No cover + residual	261 a	188 a
Early standing	247 ab	170 ab
Early + roller	237 bc	167 ab
At-plant standing	224 c	99 d
At-plant + roller	248 ab	139 bc
At-plant + crimper	230 bc	157 ab
At-plant + cultipacker	226 bc	114 cd
Unifoliate standing	193 d	16 e
Unifoliate + roller	199 d	52 e

[a]Data not available for 2021.

[b]Means followed by different letters within a column are statistically different at $\alpha \leq 0.05$.

Table 2.10. Cereal rye termination time effects on soybean canopy closure from planting to 90% row closure in 2022 and 2023 at Michigan State University[a].

	50% canopy closure		90% canopy closure	
Cereal rye treatments	2022	2023	2022	2023
	———— days ————		———— days ————	
No cover	52 d[b]	64 d	87 b	81 c
Early termination	55 c	68 c	88 b	87 c
At-plant termination	58 b	78 b	88 b	103 b
Unifoliate termination	73 a	129 a	105 a	196 a[c]

[a]Canopy closure estimates obtained using a four-parameter log-logistic model used to fit canopy closure $Y = c + \frac{d-c}{1+\exp(b(\log(x)-\log(e)))}$, followed by using the ED function in R studio with the drc package (R Core Team 2023; Ritz and Strebig 2015).
[b]Means followed by different letters within a column are statistically different at $\alpha \leq 0.05$.
[c]Estimates to 90% canopy closure was beyond the length of the growing season.

Table 2.11. Main effects of cereal rye treatment and POST herbicide application on soybean yield for 2021, 2022, and 2023 at Michigan State University.

	Soybean yield		
Main effects	2021	2022	2023
Cereal rye treatment		kg ha^{-1}	
No cover	4,820 b[a]	3,577 bcd	5,929 a
No cover + residual[b]	--	4,370 a	5,784 ab
Early standing	5,072 ab	3,368 cd	5,390 bc
Early + roller[b]	--	3,612 bc	5,295 c
At-plant standing	4,377 cd	3,778 bc	4,423 d
At-plant + roller	4,728 bc	3,882 b	4,753 d
At-plant + crimper	5,013 ab	3,799 bc	4,603 d
At-plant + cultipacker	5,208 a	3,619 bc	4,453 d
Unifoliate standing	4,386 cd	2,775 e	380 f
Unifoliate + roller	4,153 d	3,114 de	1,727 e
POST[c]			
Effective	4,814	3,715 a	4,331
Non-effective	4,626	3,460 b	4,215
Effects (P-values)			
Cereal rye treatment	<0.0001	<0.0001	<0.0001
POST	0.0511	0.0186	0.2744
Cereal rye treatment x POST	0.9893	0.1027	0.9709

[a]Means followed by different letters within a column are statistically different at $\alpha \leq 0.05$.
[b]These treatments were not present in 2021.
[c]Non-effective POST = glyphosate at 1.26 kg ha^{-1} + ammonium sulfate at 2% w w^{-1}; Effective POST = glufosinate + 2,4-D choline + ammonium sulfate at 0.66 + 1.1 kg ha^{-1} + 2% w w^{-1}, respectively.

Figures

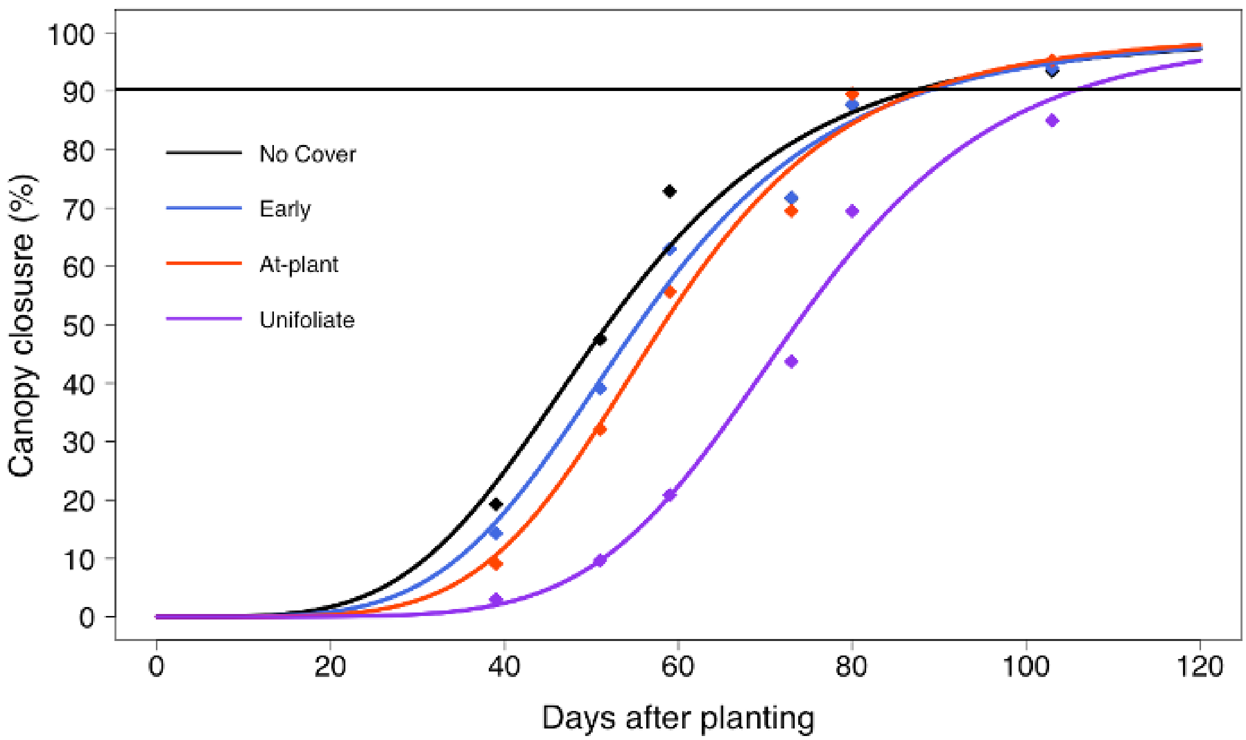

Figure 2.1. Canopy closure for soybean planted into no cover, and cereal rye terminated early, at soybean planting, and at the unifoliate stage of soybean at Michigan State University in 2022. Data are combined over termination method for each termination time.

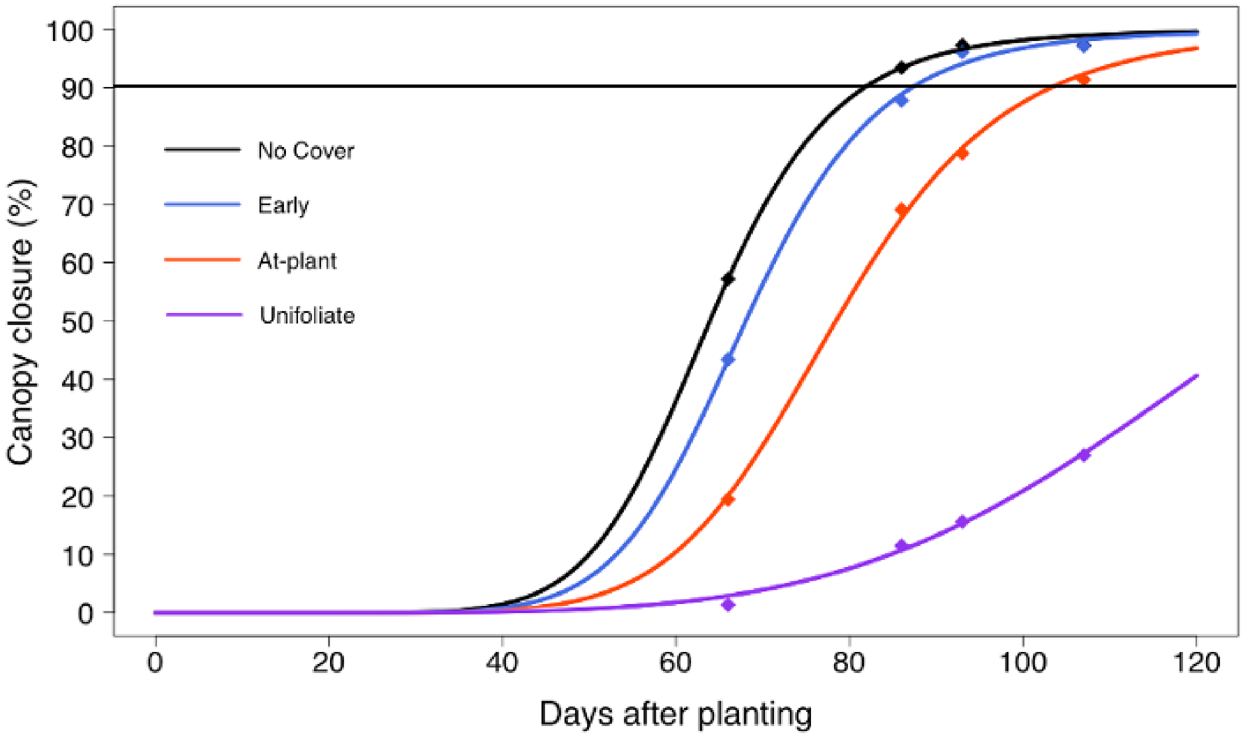

Figure 2.2. Canopy closure for soybean planted into no cover, and cereal rye terminated early, at soybean planting, and at the unifoliate stage of soybean at Michigan State University in 2023. Data are combined over termination method for each termination time.

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CHAPTER 3: COVER CROP RESPONSE TO WINTER WHEAT HERBICIDES

Abstract

Planting cover crops after wheat harvest provides farmers with an excellent opportunity to include cover crops into their crop rotation. However, several factors can affect cover crop establishment, including the potential for carryover from spring-applied winter wheat herbicides or from herbicides applied postharvest to manage weeds following winter wheat harvest. Field experiments were conducted from 2021-2023 at three Michigan locations to determine cover crop sensitivity to carryover from spring-applied winter wheat herbicides (8 site-years) and cover crop establishment following postharvest/burndown herbicide applications (5 site-years). The nine cover crops examined included annual ryegrass, cereal rye, oat, Austrian winter pea, crimson clover, red clover, Caliente mustard, oilseed radish, and dwarf Essex rapeseed. Fall cover crop biomass prior to the first hard-frost varied by site-year within each species and did not correlate with d after planting, growing degree days, rainfall, or soil type. Spring-applied winter wheat herbicides caused 10% or less cover crop injury 28 days after planting, and there was no impact on cover crop stand or biomass. All cover crops were safe to plant following spring applications of pinoxaden + fenoxaprop, mesosulfuron + thiencarbazone, pyroxsulam, thifensulfuron + tribenuron, halauxifen + florasulam, clopyralid, bicyclopyrone + bromoxynil, or pyrasulfotole + bromoxynil. However, certain herbicides applied postharvest prior to cover crop planting resulted in moderate to high injury, reduced stand, and lower cover crop biomass. All cover crops were safe to plant following glyphosate and glufosinate applications; and annual ryegrass, cereal rye, and oat were safe to plant following 2,4-D choline, and saflufenacil (25 and 50 g ha^{-1}) applications. Saflufenacil should not be applied before seeding crimson clover, red

clover, mustard, oilseed radish, or dwarf Essex rapeseed. Do not apply 2,4-D prior to seeding Austrian winter pea, crimson clover, or red clover.

Introduction

The period following winter wheat harvest presents an opportunity for growers to plant cover crops and gain benefits. Nationally, the use of cover crops is on the rise, and projected to increase (SARE 2024). From a recent SARE survey, the average grower planted 167 hectares of cover crops in 2022, 176% higher than in 2018. Cover crops planted between crop rotations provide several ecosystem services such as decreasing wind and water soil erosion, decreasing weed abundance, increasing soil organic matter, and potentially increasing crop yield (Chen et al. 2022; Langdale et al. 1991; Reicosky and Forcella 1998; Shackelford et al. 2019). Winter wheat harvest leaves bare soil prone to erosion and weed emergence; planting cover crops following wheat harvest could do both.

Chen et al. (2022) estimates that a 1% increase of cover crop acres within a county decreases tons of soil lost by wind and water erosion by 0.0056%. The potential to decrease soil loss is important for maintaining healthy soils. Integrating cover crops into a crop rotation allows for an additional method of weed control other than a herbicide or tillage. Given enough biomass, cover crops planted in late July provide fall weed suppression and decrease biomass of emerged weeds (Hodgdon et al. 2016). Cereal rye, used alone or in mixtures with broadleaves, planted after wheat harvest provides weed suppression by lowering the weed biomass and decreasing weed seed production in the spring (Baraibar et al. 2018). Previous research found that annual ryegrass alone or with or oilseed radish and terminated before corn planting provided 70% or more suppression of glyphosate-resistant horseweed in July during the main crop season (Cholette et al. 2018).

Cover crop performance may be affected by injury from herbicides used in the main crop preceding cover crop planting. Herbicide labels may have incomplete or no warnings about cover crop safety (Anonymous 2020a) and many cover crop species are not included as target crops on herbicide labels. Growers can plant non-forage cover crops after a herbicide application (Anonymous 2020a), before the rotation restriction interval expires, but grower accepts the risk of injury. The time between a spring herbicide application and cover crop planting following wheat harvest may be as few as 80 days, depending on the spring herbicide application, timing of wheat harvest, and cover crop planting date. This interval, as well as environmental conditions and herbicide chemistry, may impact the cover crop response and success.

The persistence of herbicides in soil is influenced by soil properties such as organic matter and content, and environmental conditions including precipitation and temperature (Braschi et al. 2011). Medium to coarse textured soils with >3% organic matter has the highest chance of binding herbicides and increasing the potential for carryover (Curran 2016). For example, the Group 14 herbicide flumioxazin, injured crimson clover on coarse soils, but not on finer textured soils (Rector et al. 2020). Herbicide properties including chemical structure, solubility, and volatility also affect how long an herbicide persists in the soil (Curran 2016), and greater the chance it will carry over to the next crop.

Cover crop injury from herbicide carryover is largely dependent on species. Annual ryegrass, cereal rye, and oat are more tolerant than legume and brassica cover crops to residual herbicides used in corn, soybean, and peanut production systems (Cornelius and Bradley 2017; Palhano et al. 2018; Price et al. 2020; Rector et al. 2020; Wallace 2023; Yu et al. 2015). Cereal rye planted 2 to 3 months after herbicide application in corn or soybean tolerated 25 different herbicides; however cereal rye biomass was decreased following applications of isoxaflutole, flumioxazin, cloransulam, and sulfentrazone (Cornelius and Bradley 2017). Conversely, oilseed radish, crimson clover, and dwarf Essex rapeseed were sensitive to 18 herbicides, either showing injury, reduced stand, or lower biomass (Cornelius and Bradley 2017; Palhano et al. 2018; Price et al. 2020; Rector et al. 2020; Yu et al. 2015)Click or tap here to enter text.. In winter wheat, Cholette et al. (2017) found that oilseed radish density or biomass were not affected when seeded 100 d after an application of clopyralid and pyrasulfotole + bromoxynil. Similarly, Cornelius and Bradley (2017) reported no change in oilseed radish density or stand when clopyralid was applied postemergence (POST) in corn. Additionally, flumioxazin at a reduced rate (10%) did not lower oilseed radish, crimson clover, or cereal rye biomass when applied at cover crop planting (Price et al. 2020).

Herbicide injury to cover crops can result in reduced plant height, reduced stand, and biomass reductions, but Price et al. (2020) found herbicide injury and shorter plant heights, did not necessarily lead to lower cover crop biomass. Previous research did not detect grass or broadleaf cover crop biomass differences following 30 different preemergence or postemergence herbicide applications in soybean, corn, or cotton when cover crops were planted in early September (Rector et al. 2020). Lower stand or initial injury does not always result in lower cover crop biomass. Cover crops can outgrow injury or fill areas with fewer plants. Differences between species is important, but precipitation also influences responses across years. Cornelius and Bradley (2017) found that differences in time and rainfall between the herbicide application and cover crop planting affected the cover crop stand, injury, and biomass of the species, especially in different years at the same location. With 96 cm of rainfall between herbicide application and cover crop planting, clopyralid reduced crimson clover and Austrian winter pea biomass by 82% and 42%, respectively, compared with previous years that had greater than 300 cm of precipitation.

Cover crop tolerance to spring-applied winter wheat herbicides is not well-explored. The lack of knowledge creates uncertainty for growers planting cover crops following winter wheat harvest. Postharvest herbicide applications may also pose a risk to cover crop emergence and growth. The objectives of this study were to 1) evaluate cover crop establishment and growth following spring-applied winter wheat herbicide carryover, and 2) determine if cover crop establishment and growth is impacted by postharvest/burndown herbicide applications after winter wheat harvest.

Materials and Methods

Spring Application Study. Field experiments were conducted at the Michigan State University (MSU) Agronomy Farm (Lansing, MI), Kellogg Biological Station (KBS) (Hickory Corner, MI), and Saginaw Valley Research and Extension Center (SVREC) (Richville, MI). This experiment was conducted from 2021-2023 at the three locations, excluding SVREC in 2023, for a total of 8 site-years. Soil at the Agronomy Farm was a Conover loam (fine-loamy, mixed, active, mesic Aquic Hapludalfs); at KBS, a Kalamazoo loam (fine-loamy, mixed, active, mesic Typic Hapludalfs); and at SVREC, a Tappan-Londo clay loam (fine-loamy, mixed, active, calcareous, mesic Typic Epiaquolls and fine-loamy, mixed, semiactive, mesic Aeric Glossaqualfs). Information on soil pH and organic matter are found in Table 3.1.

Experiments were arranged in a split-plot design with four replications, with herbicide treatment as the main plot and cover crop species as the subplot. Soft red winter wheat was drilled with a 1560 John Deere no-till grain drill (John Deere, Moline, IL) in the fall prior to the cover crop planting (Table 3.1). Herbicides were applied to the wheat in 3 x 27 m^2 strips in April when wheat reached Feekes stage 5. Herbicides were applied using recommended rates (Table 3.2) with a tractor-mounted, compressed air sprayer calibrated to deliver 178 L ha^{-1} at 207 kPa of pressure through 11003 AIXR nozzles (TeeJet, Spraying Systems CO., Wheaton, IL 60187).

One to two weeks following winter wheat harvest, glyphosate at 1.26 kg ae ha^{-1} + ammonium sulfate (2% w w^{-1}) was applied to the entire plot area to control volunteer winter wheat prior to cover crop planting. Nine cover crop species were seeded with a John Deere 1560 no-till grain drill (John Deere, Moline, IL) or 606NT Great Plains no-till drill (Great Plains Ag, Salina, KS 67401) perpendicular to the herbicide strips, creating 3 x 3 m^2 plots. Cover crops were seeded based on recommended rates for Michigan (Midwest Cover Crop Council 2024). The cover crops examined were annual ryegrass (*Lolium multiflorum* Gaud.) at 17 kg ha^{-1}, cereal rye (*Secale cereale* L.) at 67 kg ha^{-1}, oat (*Avena sativa* L.) at 67 kg ha^{-1}, Austrian winter pea (*Pisum sativum* L. subsp. *arvense*) at 89 kg ha^{-1}, crimson clover (*Trifolium incarnatum* L.) at 17 kg ha^{-1}, red clover (*Trifolium pratense* L.) at 9 kg ha^{-1}, Caliente mustard (white and brown; Norsworthy et al. 2005) (*Brassica juncea* L. & *Sinapsis alba* L.) at 9 kg ha^{-1}, oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.), and dwarf Essex rapeseed (D.E. rapeseed) (*Brassica napus*) each at 7 kg ha^{-1}. Due to poor seed viability Austrian winter pea was excluded from analysis in 2021.

Postharvest/Burndown Study. Field experiments were conducted in 2022 and 2023 at the MSU Agronomy Farm and KBS, and at SVREC in 2022 for a total of 5 site-years. Methods for the postharvest experiment closely follow the spring application experiment, apart from herbicide application timing. Herbicides were applied the day of cover crop seeding, with the exception of SVREC22 where rainfall immediately after herbicide application prevented cover crop seeding for 9 d. Herbicide application and planting dates, the number of days, growing degree days

(GDDs) (base 4.4 C), and precipitation between herbicide application and cover crop harvest are found in Table 3.1. Postharvest/burndown herbicide treatments and application rates are found in Table 3.2. Field conditions as well as cover crop seeding rates were similar to the spring application experiment.

Data Collection. Cover crops were visually assessed for herbicide injury 28 d after planting and again before cover crop harvest. Injury assessments were on a scale 0 (no injury) and 100 (plant death). At 28 d after planting, cover crop stand was counted in two 0.25 m^2 sub-samples per plot. Before the first hard frost in the fall, biomass from each plot was harvested from a 0.25 m^2 sub-sample, dried at 65 C for one week and then weighed. Environmental conditions such as monthly rainfall and growing degree days (GDDs) base 4.4 C were tracked using Enviroweather (mawn.geo.msu.edu) (Table 3.1).

Statistical Analysis. Before analysis, cover crop stand and biomass were standardized within each site-year. This was done by dividing the stand or biomass values from treated plots within each by the values from the control plot, which was not sprayed, then multiplied by 100 to obtain a percent of no herbicide control. This same method was employed for the postharvest experiment, normalizing values as a percent of the glyphosate control. Data were analyzed using linear mixed-effect models with the lme4 package in R Studio v 4.2.3 (Bates et al. 2015; R Core Team 2023). Each cover crop was analyzed separately by herbicide. The statistical model consisted of herbicide treatment as a fixed effect. Each site-year combination was considered an environment sampled at random from a population as suggested by Carmer et al. (1989). Environment, replication nested within environment, and the interaction between herbicide treatment and replication nested within environment were considered random effects. Replications were used as the error term for testing the effects of environment, and data were combined overall environments for each measurement. Cover crop biomass production for each species was also compared across the site-years for the no herbicide controls. Treatment means were separated using Tukey's HSD at $\alpha \leq 0.05$ for injury and cover crop stand and $\alpha \leq 0.1$ for cover biomass with the emmeans package (Lenth 2023). Normality assumptions were checked by examining histogram and normal probability plots of the residuals. Unequal variance assumptions were assessed by visual inspection of the side-by-side box plots of the residuals followed by Levene's test for unequal variances. Violin plots were created for cover crop biomass as a percent of either the no-herbicide or glyphosate controls with the ggplot2 package to show the distribution of weights and treatment means (Wickham 2016).

Results and Discussion

Spring Application Study.

Grass Cover Crops. The spring-applied herbicides did not reduce annual ryegrass, cereal rye, or oat establishment and growth. There was considerable variability in biomass production for the grass cover crops across the eight site-years (Table 3.3). Biomass in the no herbicide controls ranged from 524 to 4,272 kg ha^{-1} for annual ryegrass, 362 to 3,367 kg ha^{-1} for cereal rye, and 674 to 5,703 kg ha^{-1} for oat. No herbicide caused more than 5% injury to the three grass cover crops, 28 d after planting, and there were no differences in stand establishment compared with unsprayed controls across all eight site-years (Table 3.4). Slight injury (<4%), stunting, was observed on oat following the pinoxaden + fenoxaprop spring application. The label for Axial Bold does not give a rotation restriction for cover crops, thus this experiment confirmed the safety of planting grass cover crops after a spring application of Axial Bold (Anonymous 2020a). At harvest, the grass cover crops in treated and untreated plots had no apparent injury and no differences in biomass (Figure 3.1). Brooker et al. (2020) also found that annual ryegrass could be safely seeded 4 and 8 wk following clopyralid applications.

Legume Cover Crops. Biomass of Austrian winter pea, crimson clover, and red clover of the no-herbicide control varied by site-year and did not have a clear association with the number of GDDs or precipitation between cover crop seeding and harvest (Table 3.5 and Table 3.1). Biomass for Austrian winter pea ranged between 737 and 2,882 kg ha^{-1}, 718 and 3,272 kg ha^{-1} for crimson clover, and 245 to 2,283 kg ha^{-1} for red clover for the individual site-years. Overall, there was only minor injury (10% or less) to the legume cover crops, 28 d after planting (Table 3.6). The highest amount of injury to Austrian winter pea was 5% with stunting, from bicyclopyrone + bromoxynil and pyrasulfotole + bromoxynil. Crimson clover and red clover also had low injury (<10%), consisting of bleaching around the leaf margins, from the same herbicides. Pyrasulfotole and bicyclopyrone are WSSA Group 27 herbicides that inhibit the 4-hydroxyphenylpyruvate dioxygenase enzyme needed for carotenoid biosynthesis, ultimately protecting chlorophyll (Shaner 2014). Inhibition of this enzyme leads to bleaching. The herbicide label for Huskie indicates 4 mo and 30 cm of precipitation are needed prior to planting alfalfa, which is another legume similar to the clover species (Anonymous 2022b). Therefore, the initial injury on legumes in this study was a result low rainfall and less than 4 months between application and planting (Table 3.1). Injury dissipated by cover crop harvest and thus did not reduce stand or biomass of Austrian winter pea, crimson clover, or red clover (Table 3.6 and Figure 3.2). Similarly, Brooker et al. (2020) reported that mesotrione, an herbicide in the same chemical family as bicyclopyrone, applied prior to seeding crimson clover bleached the leaf margins, but did not reduce in crimson clover biomass at the full field use rate.

Brassica Cover Crops. Biomass for the brassica cover crops at harvest ranged from 1,581 to 6,419 kg ha^{-1} for Caliente mustard, 676 to 10,624 kg ha^{-1} for oilseed radish, and 473 to 3,440 kg ha^{-1} D.E. rapeseed (Table 3.7). Oilseed radish had 8% injury from spring applications of pyrasulfotole + bromoxynil, clopyralid, and halauxifen + florasulam, 28 d after planting (Table 3.8). Injury symptoms included discoloring and stunting. However, this injury did not last throughout the season and there was no impact on cover crop stand or biomass (Table 3.8 and Figure 3.3). Cholette et al. (2017) also observed low radish injury following pyrasulfotole + bromoxynil and clopyralid, and the injury had no impact on radish biomass. Caliente mustard and D.E. rapeseed stand and biomass were also unaffected by the herbicides. While cover crop biomass varied greatly following the herbicides, this range of biomass was also consistent in the no herbicide controls (Table 3.7 and Figure 3.3). Herbicide treatment means for cover crop biomass were close to 100% of the no herbicide control and there was no difference between herbicides. Our results indicate that the herbicides studied in the research could be applied in wheat without negatively affecting caliente mustard, oilseed radish, and D.E. rapeseed.

This experiment demonstrated that common spring-applied winter wheat herbicides had low risk for carryover to a range of cover crops planted after wheat harvest. Herbicide injury 28 days after planting, across all cover crop species and site-years, was low (0-10%) and had no impact on the cover crop stand or biomass. The time and precipitation between herbicide application and cover crop planting was sufficient for herbicide dissipation, which allowed cover crops to establish and grow unharmed. Environmental conditions between site years differed in GDDs and rainfall during the cover crop growing season but had no clear effect on cover crop biomass. In contrast, previous research correlated high precipitation between the herbicide application and cover crop planting, with lower cover crop injury or higher cover crop biomass

(Cholette et al. 2017; Cornelius and Bradley 2017; Rector et al. 2020; Tharp and Kells 2000). Planting annual ryegrass, cereal rye, oat, Austrian winter pea, crimson clover, red clover, mustard, oilseed radish, or D.E. rapeseed after wheat harvest following a spring-applied winter wheat herbicides may show initial injury but stand and biomass remain unaffected.

Postharvest/Burndown Study.

Grass Cover Crops. Annual ryegrass, cereal rye, and oat had the lowest injury and the densest stand compared with the other species. Cereal rye and oat injury was 9 to 12% following 2,4-D choline applications (Table 3.9). Injury symptoms included stunting and a light green coloration. Across treatments, annual ryegrass and oat biomass did not differ, while cereal rye biomass was higher in glufosinate and saflufenacil treatments than the glyphosate control. The high rate of saflufenacil (50 g ha^{-1}) caused 10% injury to annual ryegrass, however this did not affect cover crop stand. Cereal cover crop biomass means for each herbicide were similar and close to the glyphosate control (Figure 3.4).

Legume Cover Crops. Legume cover crops had moderate to high injury following applications of 2,4-D choline and saflufenacil at both application rates (Table 3.10). Austrian winter pea injury was 29%, 28 d after planting, following 2,4-D choline applications, but there was no impact on stand compared with the glyphosate control. Austrian winter pea injury was 28% (data not shown) at the end of the season and biomass was 15% lower than the glyphosate control (Figure 3.5). Both clover species were also affected by 2,4-D applications. Initial injury, 28 d after planting, was 34% for both clover species. Injury symptoms consisted of plant stunting and lighter plant coloration. Lower stand was also observed for red clover compared with the glyphosate control. High variability in clover stand did not separate from the glufosinate treatment, but red and crimson clover biomass ranged between 0 and 227% and 11 and 202% of the glyphosate control (Figure 3.5). Saflufenacil at 25 and 50 g ha^{-1} applied prior to crimson and red clover caused significant injury, stand reductions, and biomass reductions at the higher rate (Table 3.10 and Figure 3.5). Crimson clover and red clover biomass were 65 and 73% of the glyphosate control following 50 g ha^{-1} of saflufenacil. The clover means following applications of the lower rate of saflufenacil may not have shown stark differences between herbicide treatments, but the spread of biomass data demonstrates the unpredictable nature of cover crops. The violin plots show where biomass values group toward the lower quantiles of data for both rates of saflufenacil where biomass was as low as 2 and 20% of the glyphosate control in red clover. Overall, the legumes had greater sensitivity to 2,4-D and the clovers were more sensitivity to saflufenacil, compared with the grass cover crop species. However, both glyphosate and glufosinate could be safely applied prior to planting these species.

Brassica Cover Crops. The brassica cover crops were the most sensitive to applications of 2,4-D choline and saflufenacil compared with the grass and legume cover crops examined. Applications of 2,4-D caused more than 50% injury to the three brassica species, 28 d after planting, and reduced oilseed radish and D.E. rapeseed stand greater than 20% compared with the glyphosate control (Table 3.11). Saflufenacil at 25 and 50 g ha^{-1} also caused high injury and stand reductions for the three brassica species; however, the extent of the injury and stand loss were dependent on application rate. The 50 g ha^{-1} rate of saflufenacil caused over 50% stand reduction for all three brassica species. However, biomass of Caliente mustard was the only one reduced by 38% (Figure 3.6). Despite large reductions in cover crop stand, oilseed radish and D.E. rapeseed biomass at harvest were not reduced. Previous research has found similar results, where oilseed radish stand was reduced by 64%, but biomass was not impacted (Price et al. 2020).

All cover crop species produced a wide range of biomass across each site-year. Differences observed between cover crop stand reductions and biomass may be explained by intraspecific plant competition (Rehling et al. 2021). Cover crops with low stands, such as oilseed radish and D.E. rapeseed, accumulated more biomass per plant, which ultimately led to no change in overall biomass compared with control treatments. Glufosinate did not impact stand or biomass of any of the cover crops examined and could be used prior to planting any of these cover crops. The Sharpen label gives a 1- or 2-month rotation restriction for winter cover crops at a 25 or 50 g ha^{-1} applications rate, respectively (Anonymous 2022c). However, the label does not define which winter cover crops, and it clearly states that stands may be reduced if the cover crop is sensitive to the herbicide. Previous research has found dimethenamid-P + saflufenacil applied two to three months prior to cereal rye, oat, hairy vetch, red clover, and oilseed radish planting was safe (Ley et al. 2023; Yu et al. 2015). Our findings indicate that the period between an application and cover crop planting is crucial. Therefore, this experiment confirmed that planting close to an application of saflufenacil can be detrimental for some cover crops. The label for 2,4-D choline does not provide information on rotation restrictions for cover crops, but the herbicide has limited soil activity (Anonymous 2022a). Cover crop injury was likely due to quick cover crop emergence when 2,4-D choline was applied the same day or 1 day before cover crop planting. Both clover species in this experiment showed significant injury and reduced stands when planted close to the 2,4-D choline application.

Herbicides applied to control weeds after wheat harvest have the potential to injure cover crops planted soon after application. Planting cover crops following 2,4-D choline or saflufenacil at 25 and 50 g ha^{-1} can cause issues with cover crop establishment. Five of the cover crops, annual ryegrass, cereal rye, oat, oilseed radish, and D.E. rapeseed, were able to accumulate cover crop biomass equal to the control. However, growers may want to consider the risks of applying 2,4-D choline or saflufenacil prior to planting oilseed radish, and D.E. rapeseed due to the initial high injury and stand reduction. The three grass cover crops are safe to plant. Crimson clover, red clover, and mustard had moderate to high injury and low stand counts following 2,4-D choline and saflufenacil applications and should not be planted if one of these products are used. Austrian winter pea stand was not reduced, but biomass was affected by 2,4-D applications, therefore 2,4-d should not be applied if Austrian winter pea is to be planted. However, saflufenacil can be safely applied prior to planting Austrian winter pea. Glyphosate and glufosinate treatments had little impact on cover crop establishment and growth and can be used safely prior to planting any of the nine cover crops examined.

Tables

Table 3.1. Site descriptions including soils information, date of field operations, and time, growing degree days (GDDs)[a], and precipitation between spring herbicide applications and cover crop seeding for the spring-applied herbicide experiment (8 site-years), and GDDs and precipitation between herbicide application and cover crop harvest for the postharvest experiment (5 site-years).[b,c]

Site information	MSU21	MSU22	MSU23	KBS21	KBS22	KBS23	SVREC21	SVREC22
Soils information								
series	Conover	Conover	Conover	Kalamazoo	Kalamazoo	Kalamazoo	Tappan-Londo	Tappan-Londo
soil type	loam	loam	loam	loam	loam	loam	clay loam	clay loam
pH	7.5	6.6	6.5	6.8	6.6	6.7	7.8	7.7
Organic matter (%)	3.0	2.1	2.6	1.8	1.9	1.5	3.1	2.7
Spring herbicide experiment[d]								
herbicide application date	26 April	9 May	4 May	16 April	5 May	4 May	7 April	29 April
duration (d)	94	84	96	106	85	92	113	95
GDDs	2,331	2,382	2,470	2,538	2,490	2,732	2,547	2,867
precipitation (cm)	29	12	20.5	15	17	19	25	21
cover crop planting date	28 July	1 August	8 August	30 July	2 August	3 August	28 July	12 August
Postharvest experiment[e]								
herbicide application date	--	1 August	7 August	--	2 August	3 August	--	3 August
duration (d)	107	94	82/81	103	79	81	100	74/83
GDDs	2,395	2,005	1,686/1,715	2,365	1,772	1,838	2,389	1,529/1,827
precipitation (cm)	27.1	15.7	25.5	28.6	23.9	27.8	31.3	12.3/14.5
cover crop harvest	12 Nov.	3 Nov.	27 Oct.	10 Nov.	20 Oct.	23 Oct.	5 Nov.	25 Oct.

[a] Growing degree days were calculated using base 4.4 C. GDD and precipitation data were collected from the Enviro-weather Automated Weather Station Network (https://mawn.geo.msu.edu/).
[b] Site designations are based on the location and year of the experiment. MSU, Michigan State University (Lansing, MI); KBS, Kellogg Biological Station (Hickory Corners, MI); SVREC, Saginaw Valley Research and Extension Center (Richville, MI).

Table 3.1. (cont'd)
[c] The postharvest experiment was only conducted at MSU22, MSU23, KBS22, KBS23, and SVREC22.
[d] Duration, GDDs, and precipitation data are from the time of spring herbicide application until cover crop planting.
[e] Duration, GDDs, and precipitation data are from the time of cover crop planting/postharvest herbicide application until cover crop harvest.

Table 3.2. Herbicide products, application rates, and manufacturer information for weed control treatments in the spring-applied herbicide experiment and the postharvest experiment.[a]

Common name	Trade name	SOA	Rate	Additives[b]	Manufacturer[c]
Spring herbicide experiment			g ha^{-1}		
pinoxaden + fenoxaprop	Axial bold	1 + 1	61 + 31	--	Syngenta
mesosulfuron + thiencarbazone	Osprey Xtra	2 + 2	16 + 5	NIS + AMS	Bayer CropScience
pyroxsulam	PowerFlex HL	2	18	NIS + AMS	Corteva Agriscience
thifensulfuron + tribenuron	Affinity Broadspec	2 + 2	18.5 + 18.5	NIS	FMC Corporation
halauxifen + florasulam	Quelex	2 + 4	5.8 + 5.6	COC	Corteva Agriscience
clopyralid	Stinger	4	160	--	Corteva Agriscience
bicyclopyrone + bromoxynil	Talinor	6 + 27	46 + 313	CoAct+	Syngenta
pyrasulfotole + bromoxynil	Huskie	6 + 27	36 + 289	NIS + AMS	Bayer CropScience
Postharvest experiment					
2,4-D choline	Enlist One	4	1,064	--	Corteva Agriscience
glyphosate	Roundup PowerMax 3	9	1,260 a.e.	AMS	Bayer CropScience
glufosinate	Liberty	10	656	AMS	BASF
saflufenacil	Sharpen	14	25, 50	MSO + AMS	BASF

[a] Abbreviations: SOA = WSSA site of action group; NIS = non-ionic surfactant; AMS = ammonium sulfate; COC = crop oil concentrate; MSO = methylated seed soil.

[b] NIS (0.5% v v^{-1}) = Activator 90, AMS (1% w w^{-1}) = Actamaster, COC (1% v v^{-1}) = Herbimax, MSO (1% v v^{-1}) = Methylated Seed Oil Surfactant, Loveland Products, Inc., Greeley, CO; CoAct+ (0.26 l ha^{-1}), Syngenta Crop Protection LLC, Greensboro, NC.

[c] Manufacturer information: BASF Corporation, Research Triangle Park, NC; Bayer Crop Science, St. Louis, MO; Corteva Agriscience, Indianapolis, IN; FMC Corporation, Newark, DE; Syngenta Crop Protection LLC, Greensboro, NC.

Table 3.3. Fall cover crop biomass for the no-herbicide controls for grass cover crops for the eight site-years.[a]

Site-year	Annual ryegrass	Cereal rye	Oat
	— kg ha^{-1} (±S.E.)[b] —	— kg ha^{-1} (±S.E.) —	— kg ha^{-1} (±S.E.) —
MSU21	617 (192) c[c]	1,172 (211) ab	2,087 (536) cd
MSU22	961 (234) bc	924 (638) b	674 (200) d
MSU23	2,379 (220) b	2,080 (286) ab	4,890 (1,021) ab
KBS21	1,033 (257) bc	527 (170) b	1,542 (227) cd
KBS22	642 (69) c	2,260 (125) ab	3,410 (315) abc
KBS23	4,272 (900) a	3,367 (1,257) a	5,703 (1,083) a
SVREC21	553 (128) c	362 (105) b	2,994 (501) bcd
SVREC22	524 (181) c	2,744 (641) ab	2,928 (341) bcd

[a] Site designations are based on the location and year of the experiment. MSU, Michigan State University (Lansing, MI); KBS, Kellogg Biological Station (Hickory Corners, MI); SVREC, Saginaw Valley Research and Extension Center (Richville, MI).

[b] Values within parentheses are ± standard error.

[c] Means followed by different letters in the same column are statistically different ($\alpha \leq 0.1$).

Table 3.4. Effects of spring-applied winter wheat herbicide carry over on grass cover crop injury and stand, 28 d after planting.

	Annual ryegrass		Cereal rye		Oat	
Spring-applied herbicide	Injury	Stand[a]	Injury	Stand	Injury	Stand
	——— % (± S.E.)[b] ———		——— % (± S.E.) ———		——— % (± S.E.) ———	
pinoxaden + fenoxaprop	1 (0.6)	112 (8)	2 (1.0) a[c]	104 (6)	4 (1.2) a	104 (6)
mesosulfuron + thiencarbazone	0 (0.0)	114 (9)	0 (0.0) b	114 (6)	1 (0.7) ab	98 (3)
pyroxsulam	1 (0.6)	113 (11)	1 (0.5) ab	113 (4)	2 (1.0) ab	99 (4)
thifensulfuron + tribenuron	0 (0.2)	112 (8)	0 (0.0) b	103 (5)	0 (0.2) b	103 (3)
halauxifen + florasulam	0 (0.0)	104 (6)	0 (0.0) b	107 (7)	0 (0.0) b	96 (4)
clopyralid	0 (0.0)	109 (6)	0 (0.3) b	107 (6)	3 (1.2) ab	97 (3)
bicyclopyrone+ bromoxynil	0 (0.0)	109 (12)	0 (0.2) b	103 (4)	1 (0.3) ab	99 (5)
pyrasulfotole + bromoxynil	0 (0.2)	113 (5)	1 (0.6) ab	101 (5)	2 (0.7) ab	96 (5)

[a] Stand is presented as a % of the no herbicide control.

[b] Values within parentheses are ± standard error.

[c] Means followed by different letters in the same column are statistically different ($\alpha \leq 0.05$).

Table 3.5. Fall cover crop biomass for the no-herbicide controls for legume cover crops for the eight site-years.[a]

Site-year	Austrian winter pea	Crimson clover	Red clover
	–– kg ha^{-1} (±S.E.)[b] ––	–– kg ha^{-1} (±S.E.) ––	–– kg ha^{-1} (±S.E.) ––
MSU21	--	1,078 (120) bc	623 (96) b
MSU22	1,797 (222) ab[c]	718 (81) c	399 (12) b
MSU23	2,882 (839) a	3,272 (675) ab	2,283 (650) a
KBS21	--	1,871 (386) abc	650 (181) b
KBS22	2,755 (169) a	3,902 (725) a	1,370 (223) ab
KBS23	737 (236) b	2,850 (1,054) abc	998 (271) b
SVREC21	--	722 (143) bc	582 (128) b
SVREC22	2,761 (417) a	1,394 (311) bc	245 (63) b

[a] Site designations are based on the location and year of the experiment. MSU, Michigan State University (Lansing, MI); KBS, Kellogg Biological Station (Hickory Corners, MI); SVREC, Saginaw Valley Research and Extension Center (Richville, MI).

[b] Values within parentheses are ± standard error.

[c] Means followed by different letters in the same column are statistically different ($\alpha \leq 0.1$).

Table 3.6. Effects of spring-applied winter wheat herbicide carry over on legume cover crop injury and stand, 28 d after planting.

	Austrian winter pea		Crimson clover		Red clover	
Spring-applied herbicide	Injury	Stand[a]	Injury	Stand	Injury	Stand
	——— % (± S.E.)[b] ———		——— % (± S.E.) ———		——— % (± S.E.) ———	
pinoxaden + fenoxaprop	1 (0.5) bc[c]	101 (6)	1 (0.5) b	105 (7)	1 (0.4) bc	96 (4)
mesosulfuron + thiencarbazone	2 (1.4) abc	100 (5)	0 (0.0) b	105 (8)	0 (0.0) c	103 (5)
pyroxsulam	1 (0.3) bc	102 (5)	2 (0.7) ab	97 (5)	2 (0.8) bc	100 (4)
thifensulfuron + tribenuron	3 (1.3) abc	94 (6)	2 (0.8) ab	108 (7)	2 (0.8) bc	100 (4)
halauxifen + florasulam	2 (0.8) abc	96 (7)	1 (0.6) b	107 (6)	2 (0.8) bc	96 (4)
clopyralid	1 (0.3) bc	97 (6)	1 (0.5) b	109 (6)	4 (1.1) b	94 (5)
bicyclopyrone+ bromoxynil	5 (2.0) a	94 (7)	1 (0.6) b	105 (6)	4 (2.0) b	99 (7)
pyrasulfotole + bromoxynil	5 (1.7) a	114 (9)	4 (1.1) a	104 (5)	10 (1.7) a	100 (4)

[a] Stand is presented as a % of the no herbicide control.

[b] Values within parentheses are ± standard error.

[c] Means followed by different letters in the same column are statistically different ($\alpha \leq 0.05$).

Table 3.7. Fall cover crop biomass for the no-herbicide controls for brassica cover crops for the eight site-years.[a]

Site-year	Mustard	Oilseed radish	Dwarf Essex rapeseed
	— kg ha^{-1} (±S.E.)[b] —	— kg ha^{-1} (±S.E.) —	— kg ha^{-1} (±S.E.) —
MSU21	3,403 (977) bc[c]	5,991 (1,697) abc	2,919 (479) ab
MSU22	1,300 (609) c	676 (346) d	473 (140) c
MSU23	4,596 (695) ab	2,666 (497) cd	2,997 (751) ab
KBS21	6,419 (1,091) a	10,624 (1,968) a	3,187 (1,159) ab
KBS22	3,651 (746) abc	3,408 (301) bcd	3,440 (221) a
KBS23	4,974 (367) ab	3,866 (752) bcd	2,731 (116) abc
SVREC21	3,129 (779) bc	8,355 (2,100) ab	1,647 (493) abc
SVREC22	1,581 (121) c	1,416 (358) cd	988 (300) bc

[a] Site designations are based on the location and year of the experiment. MSU, Michigan State University (Lansing, MI); KBS, Kellogg Biological Station (Hickory Corners, MI); SVREC, Saginaw Valley Research and Extension Center (Richville, MI).

[b] Values within parentheses are ± standard error.

[c] Means followed by different letters in the same column are statistically different ($\alpha \leq 0.1$).

Table 3.8. Effects of spring-applied winter wheat herbicide carry over on brassica cover crop injury and stand, 28 d after planting.

Spring-applied herbicide	Mustard		Oilseed radish		Dwarf Essex rapeseed	
	Injury	Stand[a]	Injury	Stand	Injury	Stand
	% (± S.E.)[b]		% (± S.E.)		% (± S.E.)	
pinoxaden + fenoxaprop	1 (0.6)	110 (9)	5 (2.1) ab[c]	135 (21)	3 (1.3)	100 (7)
mesosulfuron + thiencarbazone	3 (2.4)	108 (9)	3 (2.0) b	127 (12)	3 (1.3)	112 (10)
pyroxsulam	3 (1.3)	106 (7)	2 (1.3) b	108 (5)	5 (1.5)	103 (9)
thifensulfuron + tribenuron	2 (0.8)	101 (7)	4 (1.1) b	102 (6)	5 (1.5)	97 (8)
halauxifen + florasulam	4 (1.7)	100 (5)	8 (2.0) a	117 (8)	2 (0.8)	104 (7)
clopyralid	2 (0.9)	107 (7)	8 (2.1) a	121 (11)	4 (1.4)	113 (8)
bicyclopyrone+ bromoxynil	1 (0.9)	111 (5)	3 (1.6) b	107 (6)	2 (1.7)	106 (9)
pyrasulfotole + bromoxynil	5 (1.7)	96 (5)	8 (3.1) a	106 (7)	4 (1.1)	107 (8)

[a] Stand is presented as a % of the no herbicide control.
[b] Values within parentheses are ± standard error.
[c] Means followed by different letters in the same column are statistically different ($\alpha \leq 0.05$).

Table 3.9. Effects of postharvest/burndown herbicides on grass cover crop injury and stand, 28 d after planting.

	Annual ryegrass		Cereal rye		Oat	
Postharvest herbicide	Injury	Stand[a]	Injury	Stand	Injury	Stand
	——— % (+ S.E.)[b] ———		——— % (+ S.E.) ———		——— % (+ S.E.) ———	
2,4-D choline	3 (1.4) b[c]	99 (6)	9 (4.9) a	108 (7) bc	12 (4.3) a	98 (5)
glufosinate	1 (0.9) b	102 (4)	0 (0.0) b	131 (5) a	1 (1.0) b	113 (8)
saflufenacil (25 g ha^{-1})	2 (1.6) b	110 (5)	2 (1.4) b	117 (4) ab	1 (1.2) b	102 (8)
saflufenacil (50 g ha^{-1})	10 (3.8) a	98 (5)	2 (1.5) b	116 (4) ab	3 (1.7) b	100 (9)
glyphosate	1 (0.6) b	100 (0)	0 (0.0) b	100 (0) c	3 (2.4) b	100 (0)

[a] Stand is presented as a % of the glyphosate control treatment.

[b] Values within parentheses are + standard error.

[c] Means followed by different letters in the same column are statistically different ($\alpha \leq 0.05$).

Table 3.10. Effects of postharvest/burndown herbicides on legume cover crop injury and stand, 28 d after planting.

	Austrian winter pea		Crimson clover		Red clover	
Postharvest herbicide	Injury	Stand[a]	Injury	Stand	Injury	Stand
	——— % (± S.E.)[b] ———		——— % (± S.E.) ———		——— % (± S.E.) ———	
2,4-D choline	29 (10.4) a[c]	93 (13)	34 (8.7) a	90 (13) b	34 (4.3) b	80 (8) b
glufosinate	0 (0.0) b	93 (8)	1 (0.7) c	107 (6) a	9 (1.0) c	95 (9) ab
saflufenacil (25 g ha^{-1})	4 (2.4) b	85 (6)	15 (6.7) b	73 (8) c	30 (1.2) b	52 (5) c
saflufenacil (50 g ha^{-1})	7 (3.6) b	90 (4)	26 (8.9) a	68 (9) c	57 (1.7) a	53 (4) c
glyphosate	2 (1.3) b	100 (0)	2 (1.2) c	100 (0) ab	7 (2.7) c	100 (0) a

[a] Stand is presented as a % of the glyphosate control treatment.

[b] Values within parentheses are ± standard error.

[c] Means followed by different letters in the same column are statistically different ($\alpha \leq 0.05$).

Table 3.11. Effects of postharvest/burndown herbicides on brassica cover crop injury and stand, 28 d after planting.

Postharvest herbicide	Mustard		Oilseed radish		Dwarf Essex rapeseed	
	Injury	Stand[a]	Injury	Stand	Injury	Stand
	——— % (± S.E.)[b] ———		——— % (± S.E.) ———		——— % (± S.E.) ———	
2,4-D choline	60 (9.4) b[c]	80 (9) b	57 (8.9) b	75 (10) b	52 (8.8) a	79 (13) b
glufosinate	5 (2.6) c	118 (8) a	11 (7.7) c	110 (8) a	2 (1.3) c	109 (5) a
saflufenacil (25 g ha^{-1})	58 (6.1) b	89 (6) ab	48 (6.5) b	53 (4) c	25 (8.3) b	78 (10) b
saflufenacil (50 g ha^{-1})	82 (5.5) a	31 (4) c	71 (6.9) a	49 (5) c	57 (8.8) a	43 (7) c
glyphosate	8 (4.4) c	100 (0) ab	7 (4.2) c	100 (0) a	5 (1.9) c	100 (0) a

[a] Stand is presented as a % of the glyphosate control treatment.

[b] Values within parentheses are ± standard error.

[c] Means followed by different letters in the same column are statistically different ($\alpha \leq 0.05$).

Figures

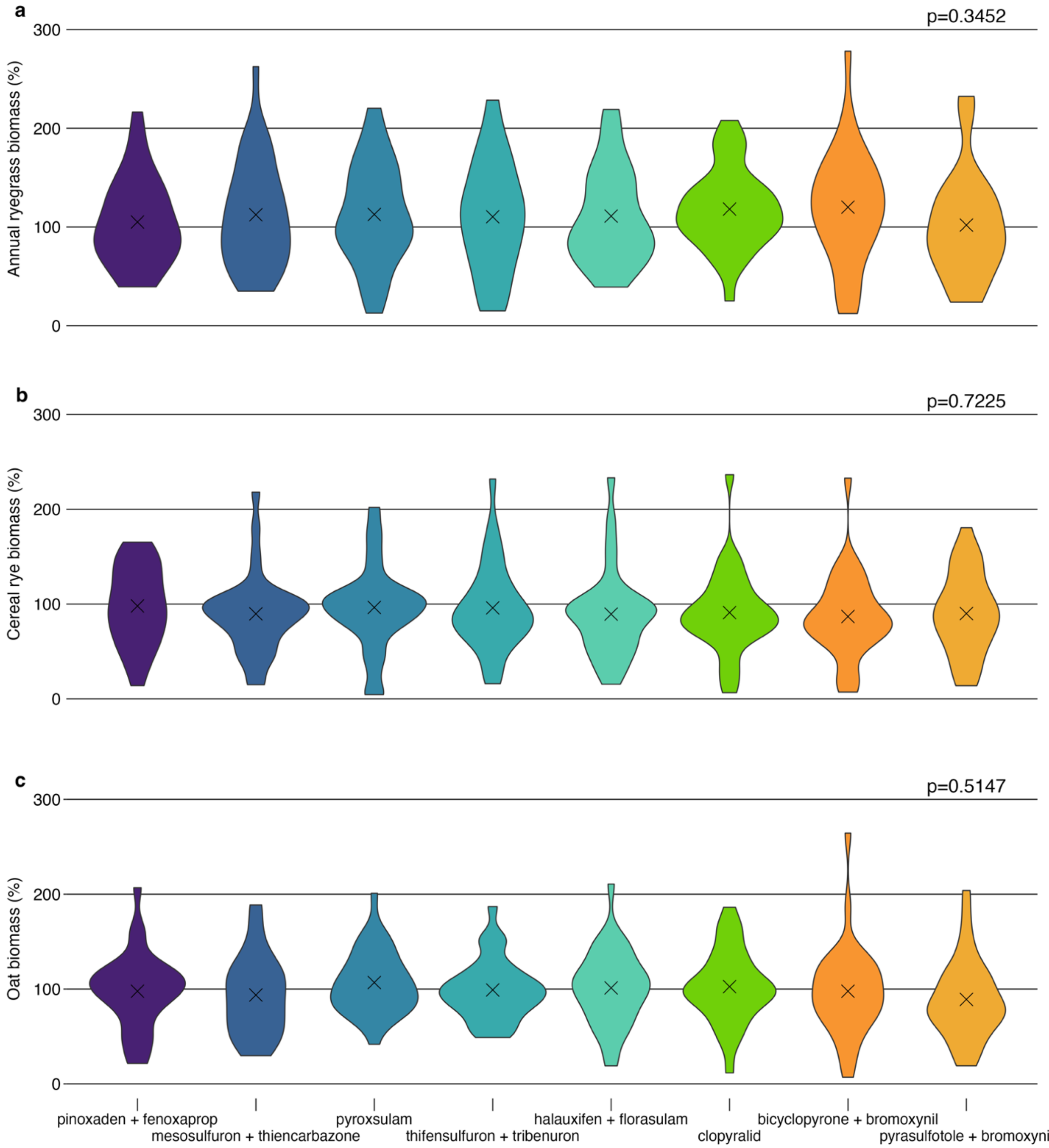

Figure 3.1. Fall dry biomass for grass cover crops planted after winter wheat harvest that was treated in the spring with various herbicides. Data are presented as a percent of the no-herbicide control and combined over eight site-years (n=32). Violin plots show the distribution of weights. Treatment means are represented by the X in the plots.

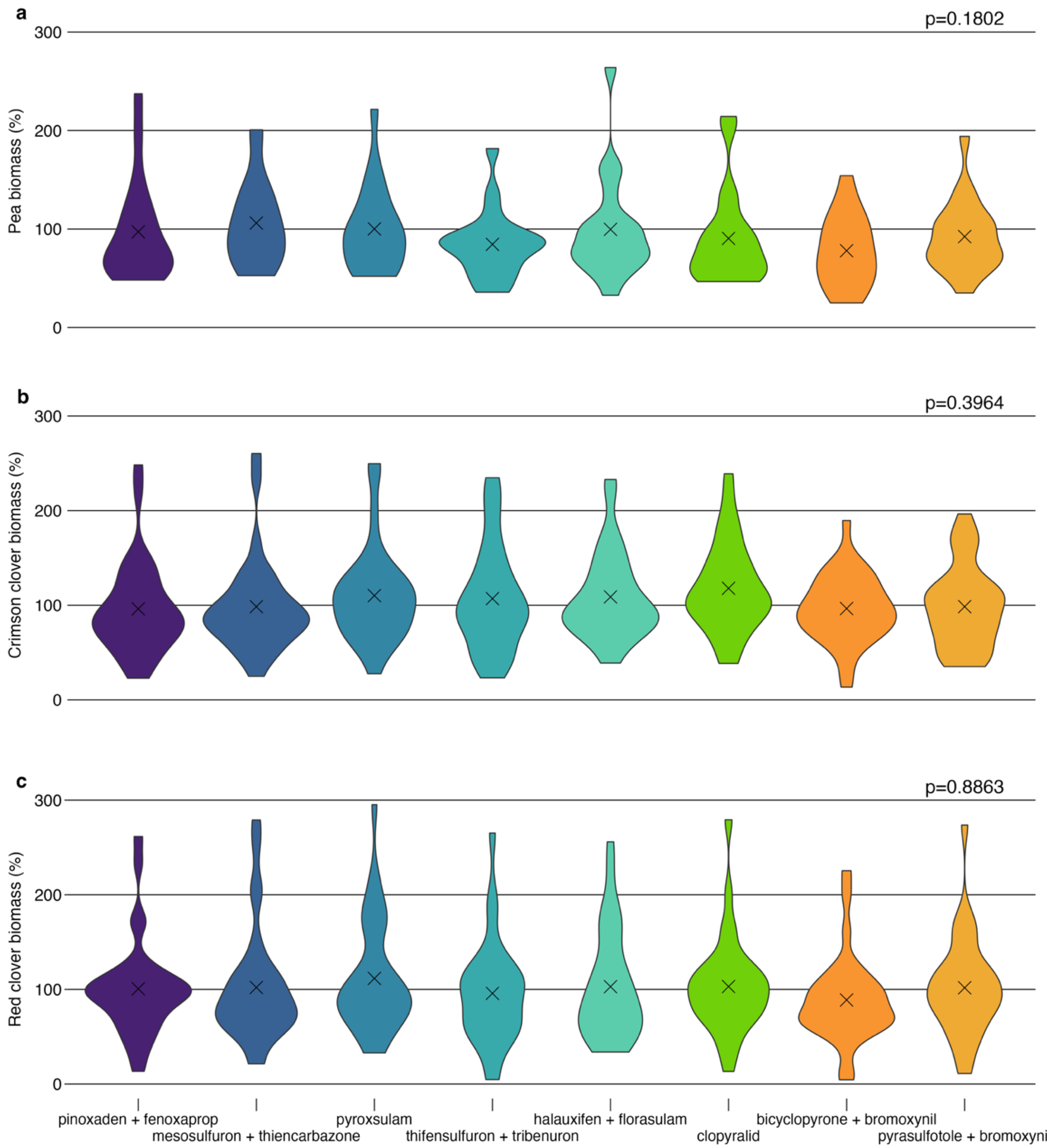

Figure 3.2. Fall dry biomass for legume cover crops planted after winter wheat harvest that was treated in the spring with various herbicides. Data are presented as a percent of the no-herbicide control and combined over eight site-years (n=32, n=28 for Austrian winter pea). Violin plots show the distribution of weights. Treatment means are represented by the X in the plots.

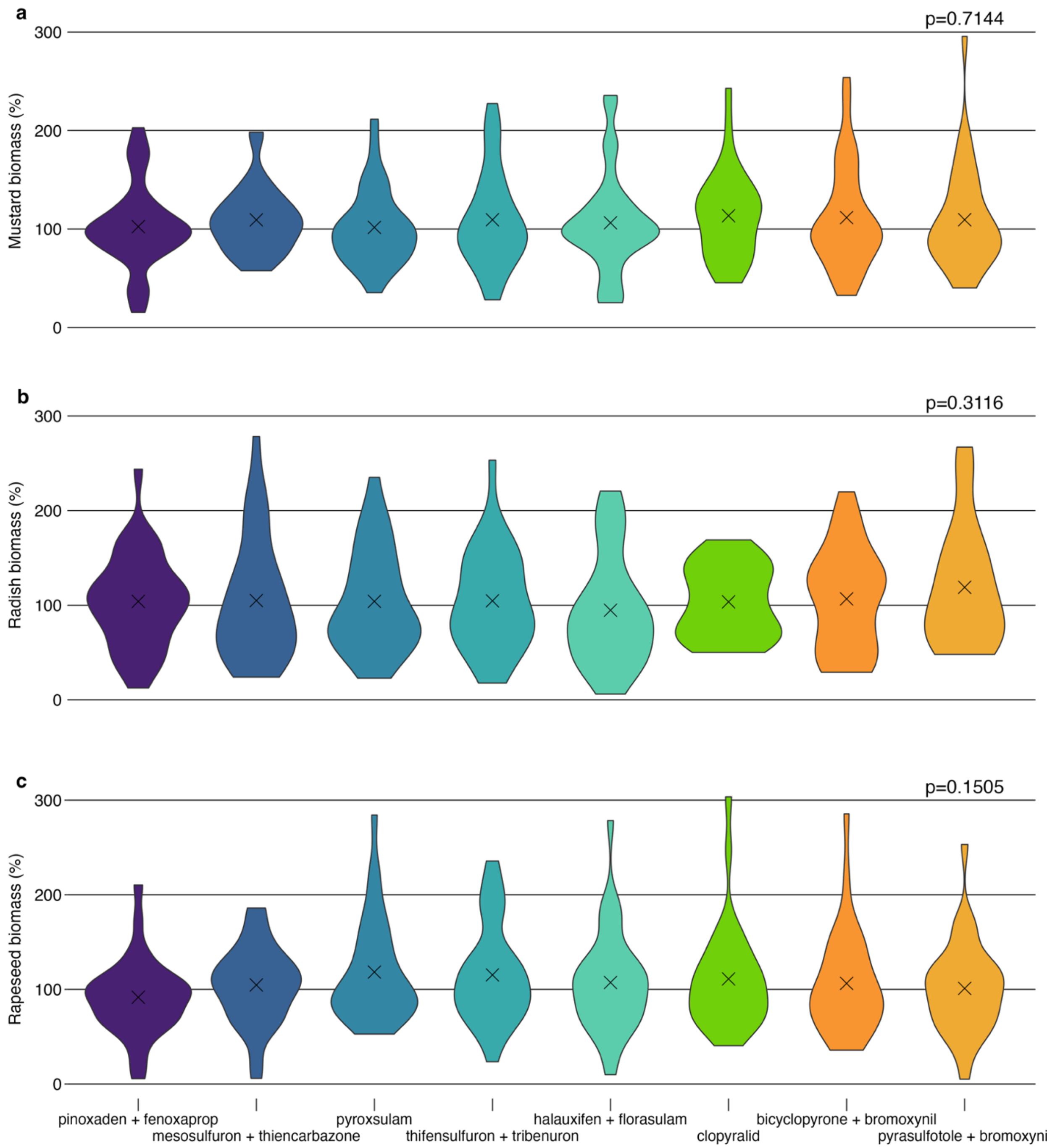

Figure 3.3. Fall dry biomass for brassica cover crops planted after winter wheat harvest that was treated in the spring with various herbicides. Data are presented as a percent of the no-herbicide control and combined over eight site-years (n=32). Violin plots show the distribution of weights. Treatment means are represented by the X in the plots.

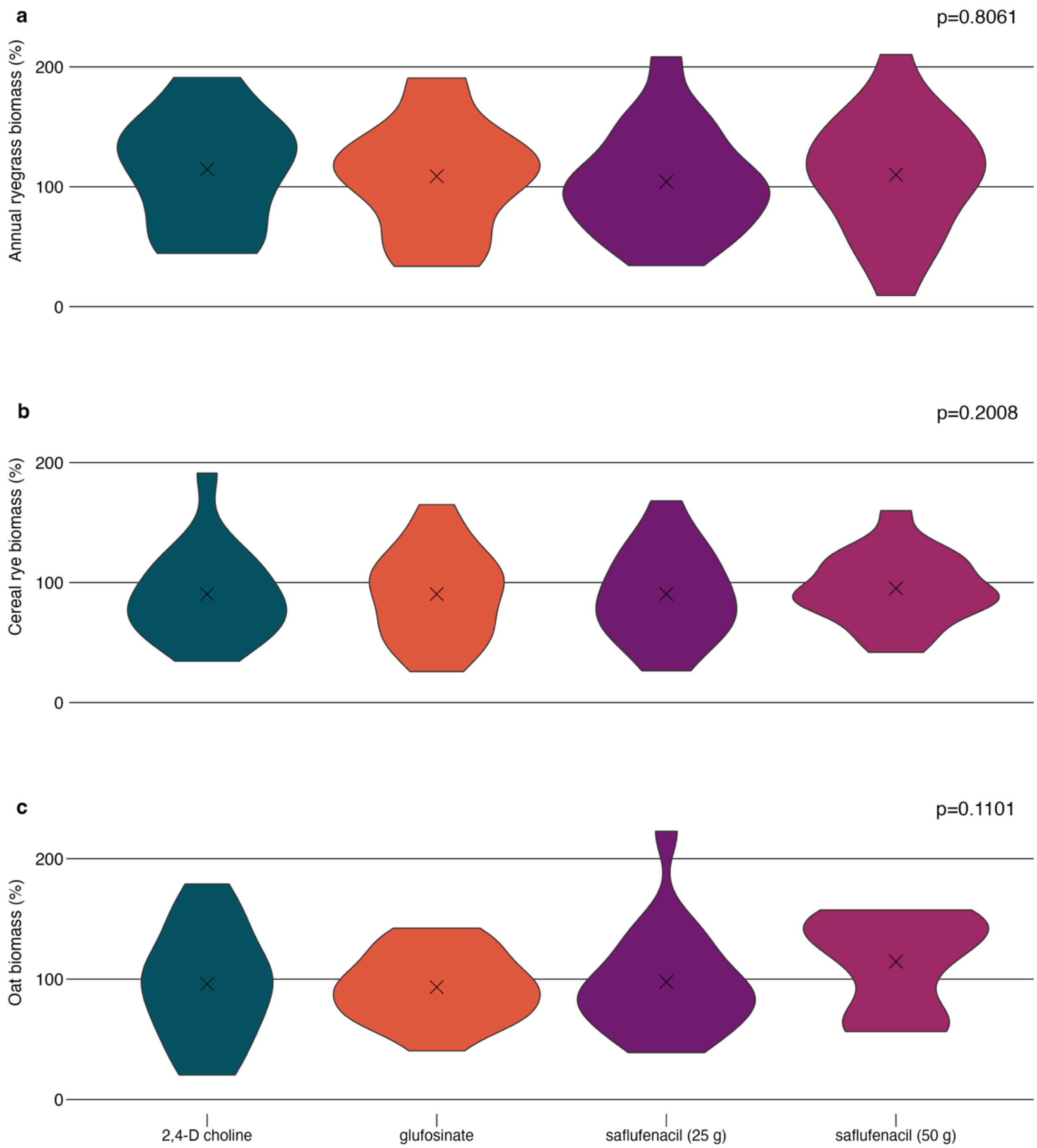

Figure 3.4. Fall dry biomass for grass cover crops planted after winter wheat harvest that was treated with postharvest herbicides. Data are presented as a percent of the glyphosate control and combined over five site-years (n=21). Violin plots show the distribution of weights. Treatment means are represented by the X in the plots.

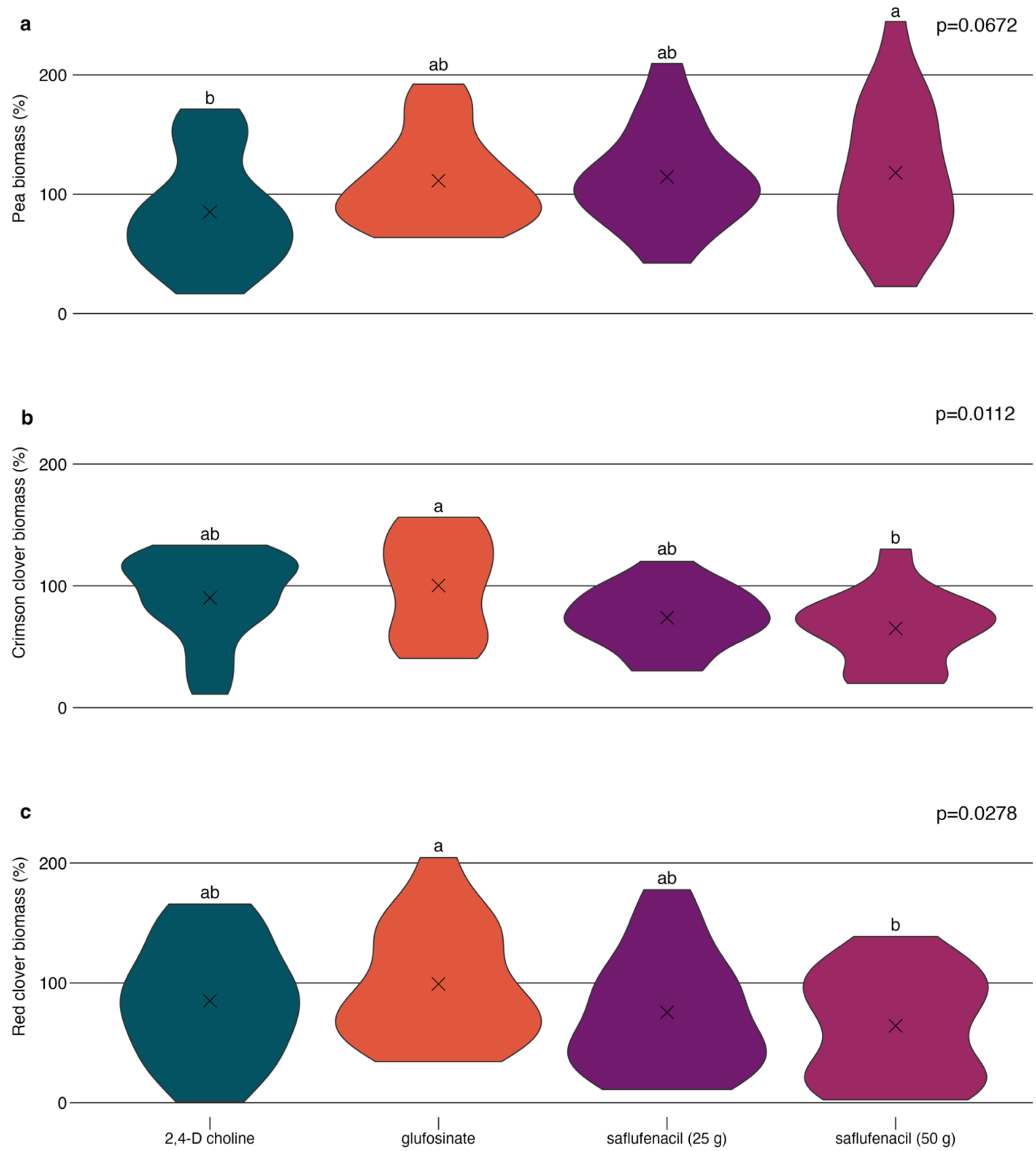

Figure 3.5. Fall dry biomass for legume cover crops planted after winter wheat harvest that was treated with postharvest herbicides. Data are presented as a percent of the glyphosate control and combined over five site-years (n=21). Violin plots show the distribution of weights. Treatment means are represented by the X in the plots and are separated with Tukey's HSD when p-values were ≤ 0.1.

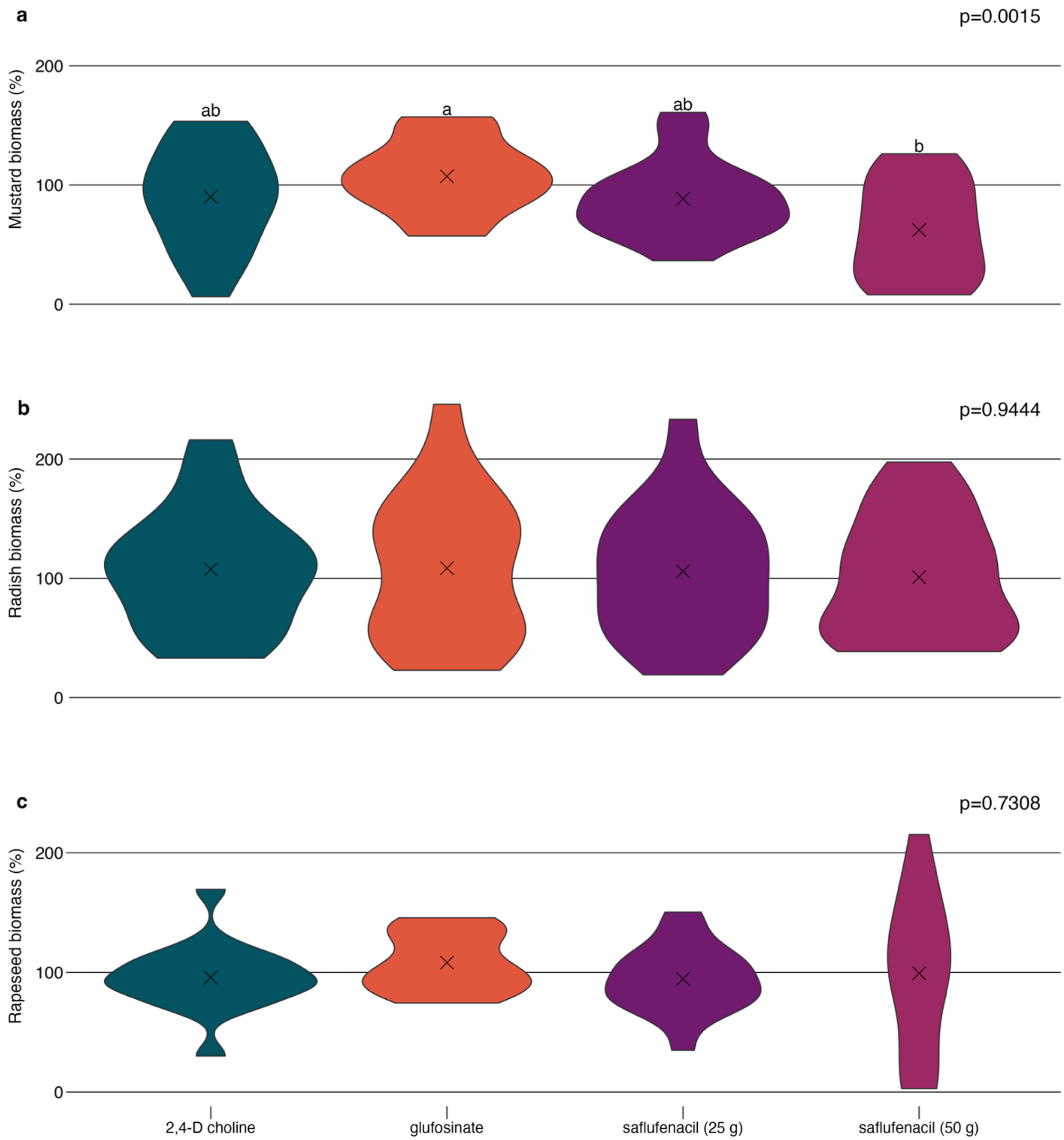

Figure 3.6. Fall dry biomass for legume cover crops planted after winter wheat harvest that was treated with postharvest herbicides. Data are presented as a percent of the glyphosate control and combined over five site-years (n=21). Violin plots show the distribution of weights. Treatment means are represented by the X in the plots and are separated with Tukey's HSD when p-values were ≤ 0.1

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