WEED CONTROL IN COVER CROP NO-TILL CORN SYSTEMS

by

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A Thesis

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Master of Science

Department of Botany and Plant Pathology

West Lafayette, Indiana

August 2020

THE PURDUE UNIVERSITY GRADUATE SCHOOL
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ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Bill Johnson, for allowing me to pursue my Master's degree at Purdue University, and for his invaluable insights and knowledge. I would also like to thank Dr. Bryan Young, Dr. Shalamar Armstrong, and Dr. Dan Childs for being a part of my graduate committee, and for all of their advice and counsel. These men have helped me gain an appreciation and a passion for research and have encouraged me in my pursuit of this degree.

I'm very grateful for the help and guidance from the Purdue Weed Science technicians, including Taylor Campbell, Dustin Johnson, and Julie Young. Their organization and insight was extremely valuable to me as I planned and conducted my research.

I especially appreciate the support of my fellow graduate students, who selflessly offered their time, talents, and expertise to help me become a better student and researcher. They encouraged me and helped me learn and grow in many ways throughout my experience at Purdue.

Finally, I would like to thank the Indiana Corn Marketing Council for the funding that made this research possible. I hope and pray that this research will help farmers across the Midwest implement effective integrated weed management systems.

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ABSTRACT

In the United States and Canada, weed interference in corn (*Zea mays* L.) costs farmers nearly $4 billion per year. Weed control has been achieved primarily through herbicides and tillage. As no-till corn acres have increased, dependence on herbicides has also increased. Herbicide-resistant weed infestations have pressured many growers into other weed management practices, such as adding winter cover crops into crop rotations. Field experiments were conducted in 2017 through 2018 and 2018 through 2019 at three locations in Indiana to determine residual herbicide efficacy applied at cereal rye termination and after corn planting in cereal rye (*Secale cereale* L.) and winter-fallow no-till corn. Weed biomass and density suppression was dependent on weed species and was influenced by cereal rye biomass at termination. Weed biomass was suppressed by up to 84% by cereal rye alone. Weed biomass reduction by a residual herbicide premix was similar in both cereal rye and non-cover crop treatments in most site-years, however cereal rye and the residual herbicide premix together resulted in decreased giant ragweed (*Ambrosia trifida* L.) and summer annual grass biomass compared to the residual herbicide premix applied alone in one site year. Late-season grass weed density was reduced by residual herbicides, but was unaffected by cover crop treatment. Late-season common cocklebur density and biomass increased in cereal rye treatments compared to non-cover crop treatments.

Other field experiments were conducted at the same locations in 2017 through 2018 and 2018 through 2019 to determine the effect of cover crop species, termination timing, and chemical cover crop termination strategies on weed control and corn yield. Crimson cover (*Trifolium incarnatum* L.), cereal rye, and a cereal rye/crimson clover mix were terminated two weeks before, at, and two weeks after corn planting. All plots were terminated using glyphosate and atrazine, however others were also terminated with dicamba and acetochlor. The addition of acetochlor generally reduced early-season weed biomass or density, but not in cereal rye and cover crop mix treatments that were terminated at or after corn planting. Late-season summer annual grass biomass was reduced when cover crop biomass at termination was over 8000 kg ha^{-1}. Late-season common cocklebur density in 2018 was 450% to 800% higher in cover crops containing cereal rye, compared to crimson clover treatments. Corn yield was reduced by 23% to 67% in cereal rye and cover crop mix treatments in two out of three site-years in 2018, however corn yield was not reduced by crimson clover in either year, nor by cereal rye or the cover crop mix in 2019.

CHAPTER 1. COVER CROPS IN NO-TILL CORN SYSTEMS

1.1 Corn Production

Corn (*Zea mays* L.) is one of the world's most commonly grown crops, and is especially important to US agriculture. It accounts for more than 90 million acres planted yearly in the US. Corn is used for ethanol production, food products, and livestock feed, where it constitutes 96% of the market (Capehart 2017). Although corn has been a staple crop in the United States since the 1800's, it hasn't always dominated the industry as it does today. Corn and soybean (*Glycine max* (L.) Merr.) prevail in Midwestern agricultural crop rotations. Corn production accounts for approximately 20% of the 190 million hectares of arable land in the U.S. (USDA 2017).

Government subsidies have incentivized farmers to produce more corn since the 1930's. The original intent of early subsidies was to encourage farmers to grow more corn for food. In the 1980's, government subsidies for corn began to increase markedly. The Energy Policy Act of 2005 increased the amount of biofuel, largely corn-derived ethanol, to be mixed with gasoline sold in the U.S. from 4 billion gallons in 2006 to 7.5 billion gallons by 2012. In 2007, the Energy Independence and Security Act expanded the target to 36 billion gallons by 2022. As a result of these acts, corn production increased even more. Corn used for ethanol production consumed 1% of the supply in 1980, but rose sharply to 40% of total US corn by 2011. From 1995 to 2014, an average of 4.7 billion dollars per year was spent on subsidies for corn in the US (Capehart 2017).

1.2 Weed Control in Corn

Weed control in all agricultural crops was limited to mechanical and cultural control practices for hundreds of years before herbicides. Tillage was the primary form of weed control, as it was efficient and non-selective. Row cultivators in the 1800's provided farmers a way to reduce man hours in the field and mechanically control weeds throughout the growing season. Tillage is still widely practiced today by many farmers as an herbicide-free way to control weeds and bury weed seeds. Tillage also results in warmer and drier soil prior to planting, which prevents seedling diseases and promotes germination. Mechanical cultivation, however, does come with disadvantages: compaction below the plow pan, increased erosion, and disruption of the soil microbial community. A meta-analysis by Zuber and Villamil (2016) reported that microbial biomass and enzyme activity, measurements commonly used to indicate soil health, are generally higher in no-till soils compared to conventionally tilled soils. No-till practices have been increasing in the Midwest ever since herbicides became a viable option for satisfactory weed control. Estimates show that around 65 percent of corn and soybean growers in the Corn Belt use some form of conservation tillage (Claassen et al. 2018).

Cultural methods for controlling weeds include narrow row spacing, diversifying crop rotations, and early planting. Generally speaking, cultural weed management practices involve establishing a dense canopy early in the growing season, creating an environment where crops are more competitive, or disrupting weed species' life cycles. Early, rapid crop growth will discourage vigorous weed growth, germination, and seed production. Tharp and Kells (2001) observed that corn rows spaced 38 cm can reduce common lambsquarters emergence by up to 28% compared to corn rows spaced 76 cm. Diverse crop rotations can also be utilized in weed management. While total weed density may not change, weed diversity increases as crop diversity increases (Bellinder et al. 2004, Cardina et al. 2002, Gulden et al. 2011). This discourages the dominance of a few weed species that are accustomed to shorter rotations or monocultures. In more diverse crop rotations, weed seed banks more often contain less competitive weeds (Cardina et al. 2002).

Since the introduction of herbicides and their subsequent rise to the most popular method of weed control, weed identification has been key to controlling weeds in corn. Understanding which weed species are present in a corn field drives decisions not only about which herbicide to apply, but also proper timing and rate. Growers may change their regimen depending on the balance of broadleaf and grass weeds or annual and perennial weeds.

Glyphosate, classified as a group 9 EPSP synthase inhibitor, is the most commonly applied herbicide in the world, and continues to be an important corn herbicide. Glyphosate was first introduced in 1974, but as no crop was resistant to the herbicide, its use was limited to burndown applications or non-crop applications. It wasn't until the introduction and commercialization of glyphosate-resistant corn in 1998 that Roundup Ready (RR) corn soon became the most popular variety of corn on the market, consequently making glyphosate the most commonly applied corn herbicide . Spraying glyphosate on Roundup Ready corn gave corn farmers a cheap method to kill many weeds with a single application throughout the growing season. This effective and inexpensive form of weed control greatly lowered input costs for corn growers. As many producers have relied too heavily on single applications of glyphosate for weed control, glyphosate-resistant biotypes have developed in over 20 weed species worldwide (Heap 2020). Reliance on glyphosate has benefited farmers, since input costs are much lower compared to a more diverse herbicide program. In 2010, corn growers who reported a glyphosate-resistant weed population also reported 60 dollars per acre lower operating costs due to reliance on glyphosate, however returns were nearly 70 dollars less per acre compared to growers without a glyphosate resistance issues (Livingston et al. 2015). Common problematic weeds throughout the Midwest such as giant ragweed (*Ambrosia trifida* L.), waterhemp (*Amaranthus tuberculatus* (Moq.) J. D. Sauer), and horseweed (*Erigeron canadensis* L.) have all developed resistance to glyphosate.

Atrazine is another common herbicide utilized in corn production. It is a group 5 triazine herbicide that controls both broadleaf and grass weed species at both pre-emergent and post-emergent applications. Like glyphosate, it is one of the most widely used herbicides worldwide. Herbicide resistant weeds are also a problem for atrazine, as 46 different species have evolved resistance (Heap, 2014).

Dicamba is also a popular corn herbicide. It is a group 4 synthetic auxin herbicide that controls broadleaf weeds. With the proliferation of glyphosate resistance, dicamba use has increased. Dicamba use has also increased due to resistant soybean varieties to allow more options for POST control of broadleaf weeds in soybean systems. Synthetic auxins in general are less prone to herbicide resistance, and for this reason have been used extensively since the 1960's. Only 7 weed species have been reported to be resistant to dicamba worldwide (Heap 2020). Dicamba can be applied as a PRE application, but is more commonly applied POST.

Two other common pre-emergence corn herbicides are S-metolachlor and acetochlor. As group 15 chloroacetamide herbicides, S-metolachlor and acetochlor are soil active against emerging seedlings and are common ingredients in many herbicide premixes. Resistance to group 15 herbicides is relatively low, as only one species worldwide and no species in the U.S. have developed resistance to s-metolachlor. In the US, both Palmer amaranth and waterhemp have evolved resistance to group 15 herbicides (Heap 2020). S-metolachlor and acetochlor control grass and small-seeded broadleaf weeds and are registered for corn, soybean, peanuts, sorghum, and cotton.

Ever since Liberty Link corn was developed in 1997, glufosinate use in corn has increased, especially as an alternative to Roundup Ready corn. Since glyphosate-resistant weeds are common, glufosinate has become an increasingly popular tool for herbicide resistance management among growers. Glufosinate is a group 10 foliar, contact herbicide that inhibits glutamine synthetase and kills the plant by causing it to accumulate toxic levels of ammonia (Wild and Wendler 1993). Three species worldwide have reportedly developed resistance to glufosinate. None of these resistant biotypes are found in the Eastern Corn Belt (Heap 2020).

Herbicide premixes are a common form of chemical weed control. Premixes involve 2 or more modes of action and often contain one or more residual herbicide. Atrazine, as well as group 15 and group 27 herbicides are commonly included in residual herbicide premixes. Premixes limit the need for multiple herbicide applications throughout the growing season. Most corn herbicide premixes are commonly applied before planting or shortly after planting before the corn has emerged. Traditionally, herbicides have been applied at two timings: PRE and POST. These timings have since been divided into more specific intervals for corn herbicides.

1.3 Herbicide Resistance

Problematic weeds in the Eastern Corn Belt include horseweed, waterhemp, giant ragweed, and foxtails (*Setaria spp.*). These are all competitive weeds in corn systems. Additionally, all have evolved resistance to at least one herbicide mode of action (Heap 2020).

Herbicide resistant weeds have been evolving ever since the widespread use of herbicides. Wild carrot was reported resistant to the first synthetic herbicide, 2,4-D, in 1957, just a decade after its release. Herbicide resistance has since become a rising problem for growers ever since, complicated by dependence on herbicides as a cheap, simple, and efficient method for weed control. For many years, herbicide resistance was solved by introducing new herbicide active ingredients and modes of action to the market. As herbicide active ingredient development has stagnated, herbicide resistant weeds need to be managed with current management practices, including diversified chemical, cultural, mechanical, and biological practices. Unfortunately, herbicide resistance has evolved in 210 weed species over 21 of the 25 herbicide classes, and to 152 active ingredients. Herbicide resistance affects 61 countries around the world (Heap 2020). As herbicides maintain their popularity around the world and as usage grows in developing countries, herbicide resistance will only proliferate without integrated approaches to weed management.

Since chemical weed control has been the most popular from of weed management, mechanical, cultural, and biological weed management have taken a back seat to herbicides for most growers. More integrated approaches are needed in order to maximize herbicide efficacy and manage herbicide resistance. Integrated weed management tactics include diversifying crop rotations, introducing biological controls, tank-mixing herbicide sites and modes of action, increasing crop competition, and tillage practices. Preventative measures such as planting weed-free seed, cleaning farm equipment, and screening irrigation water do not eliminate herbicide-resistant weeds, but can delay their spread to other areas. Biological control agents may only work for specific weeds and may not provide satisfactory control. Rotating and tank-mixing multiple herbicide modes of action are the most common forms of herbicide resistance management, but these methods are dependent on the status of herbicide-resistant weeds in a field.

1.4 Cover Crops

Cover crops have been used in agriculture for thousands of years, and have been present in modern agriculture since its inception (Groff 2015). While the techniques, strategies, and goals have changed, humans have long been familiar with the benefits they provide. Early Native Americans used corn, edible beans, and squash as complementary crops that grew well together, and were used for the same reasons that modern cover crops are used. Since the early days of the United States, cover crops were implemented in the nation's agriculture. The importance of soil retention and nutrient management were recognized, and cover crops were used to alleviate erosion and replenish nitrogen. Clover, grasses, and buckwheat were planted to provide organic matter, nitrogen, and soil retention. Later, as some limited research was done, hairy vetch, various grasses, and peas established themselves as popular cover crops in the nineteenth century. It was well understood that legumes provided nitrogen to the soil, while grasses prevented erosion (Groff 2015).

Cover crop use began to decline as synthetic fertilizers and herbicides were developed and produced after World War II. Synthetic fertilizer was inexpensive to produce and easy to apply. This meant that legumes were not needed to replenish soil N, and herbicides allowed farmers to kill weeds without needing to employ alternative methods of weed control. By the 1960's, cover crops were beginning to disappear from American agriculture. The new technologies provided to farmers allowed them to manage their fields with fewer labor inputs at lower costs. Beginning in the 1990's, cover crops were reintroduced into conventional agriculture as the Sustainable Agriculture and Research Education (SARE) program was formed. SARE's mission is "to advance—to the whole of American agriculture— innovations that improve profitability, stewardship and quality of life by investing in groundbreaking research and education" (Waldron Lehner et al. 2008). Although SARE's resources are not dedicated solely to researching and promoting cover crops, it has had a positive impact on the adoption of cover crops throughout the United States. The funding and research that resulted from SARE helped introduce new cover crops, such as radishes and cereal rye, into modern agriculture. One of the main initiatives of SARE was to provide grants for farmers, researchers, and students to study and promote sustainable agricultural practices. As of 2008, 64% of farmers who had received a SARE grant reported increased profits as a result of the funding (CTIC 2017).

The reason a specific cover crop or mix of cover crops is chosen by a grower depends on the farmers goals, whether it be soil health, erosion control, weed suppression, etc. Soil type, precipitation, pest presence, climate, and the following cash crop all need to be taken into consideration. In some cases, cover crops may not solve problems or boost profits, but rather exacerbate pest problems or lead to cash crop yield loss. Problems like these caused by cover crops may lead to increased inputs, which is contrary to the goal of most cover crop systems. Understanding all of the challenges faced by the grower is paramount in order to avoid unintended consequences from a cover crop.

Cover crops prevent soil erosion by holding soil with their roots and reducing the momentum of raindrops hitting the soil. While all cover crops combat erosion to some degree, some are more effective than others. Cover crops with fibrous roots, such as cereal rye and oats, hold soil more tightly than cover crops with wide taproots, such as rapeseed or radish. (De Baets et al. 2011) demonstrated that cover crops with fibrous roots such as rye, ryegrass, and oats hold two to three times more soil during a precipitation event than cover crops with thick taproots, such as mustard and radish. Grass cover crops can be used on slopes or in high precipitation areas to reduce soil runoff.

Cover crops also provide a biological nutrient management and recycling system. Legume cover crops, such as clover or hairy vetch and various clover species, fix atmospheric nitrogen. This provides additional nitrogen to the food crop and can reduce rates of applied fertilizer. Hairy vetch, a winter hardy legume commonly used as a cover crop, can supply up to 135 kg ha^{-1} of fertilizer N to the following crop (Blevins et al. 1990). As cover crop residue decomposes over the growing season, the nutrients are released into the soil and made available to the following crop (Wagger 1989). This can be of some concern to cover crop growers since immobilized nutrients may not be mineralized in time for the growing cash crop if the cover crop is not terminated on time. Understanding cover crop termination timing and nitrogen mineralization are important for corn N uptake, since cover crop decomposition rates differ between species. These decomposition rates depend on cover crop biomass, C:N ratio, and weather (Jahanzad et al. 2016, Ranells and Wagger 1996).

Common cover crops in Indiana and the Eastern Corn Belt include cereal rye (*Secale cereale* L.), crimson clover (*Trifolium incarnatum* L.), oats (*Avena sativa* L.), and Daikon radish (*Raphanus sativus* L.). In 2016, a survey of over 1700 US farmers using cover crop reported that of fields with only one species of cover crop, cereal rye was the most planted cover crop, at over 112,900 hectares for all respondents. Oats and radish were planted over 64,300 and 52,000 hectares, respectively. Crimson clover was the most common legume cover crop in 2016, and accounted for 30,000 hectares. Mixtures were also commonly used by cover crop growers in 2016. Mixtures of 2 or more cover crop species were planted on 106,400 hectares (CTIC 2017). Managing and terminating cover crops becomes more complicated as more species are mixed. Chemical termination may also be more costly, as multiple herbicides may be needed to effectively control all species.

Weed suppression by cover crops has been studied for decades, but in order to maximize both weed suppression and herbicide efficacy, more research needs to be performed. This lack of research is partly due to cover crops being chosen primarily for reasons other than weed suppression, such as organic matter production, soil retention, nutrient management, or soil aggregation. The mechanism used to suppress weeds differs among cover crops. High above ground biomass may decrease soil nitrogen and slow weed growth, while a dense cover crop canopy intercepts light and shades weeds. Allelochemicals exuded by some cover crops can also inhibit germination or growth. The weed suppression effects due to allelochemicals alone is still widely debated for a variety of reasons due to differences in cultivars and environmental factors that influence allelochemical production and fate (Reberg-Horton et al. 2005).Understanding the mechanisms of suppression from cover crops could allow cover crop breeders to focus on aspects that maximize cover crop weed suppression. Ultimately, weed suppression by cover crops is due to multiple factors, and could potentially be enhanced by focused breeding programs.

Regardless of species, canopy cover and biomass appear to be important factors in cover crop weed suppression. While cover crop biomass and density are greatly influenced by the variable winter climate in the Eastern Corn Belt, they may also be manipulated by other management practices. Applying fertilizer to cover crops and increasing the seeding rate could both reduce weed biomass and density by providing a denser stand or increased biomass. While increasing seeding rate does not necessarily increase biomass, higher seeding rates have resulted in lower weed biomass and density. Ryan et al. (2011) reported that increasing seeding rate of cereal rye from 90 kg ha^{-1} to 210 kg ha^{-1} resulted in a 30% reduction of weed biomass.

Cereal rye, one of the most commonly planted cover crops in the US, is well known for its rapid growth rate and fibrous root system. It is especially popular in northern regions because of its cold hardiness. Some varieties of cereal rye can survive temperature down to -78 degrees Celsius (Cloutier and Andrews 1984). Both live and terminated cereal rye residues contain allelochemicals. Allelochemicals found in the shoots of cereal rye have been shown to inhibit seedling germination in weed species, although the accumulation of these allelochemicals, mostly benzoxazinones, is dependent on the cultivar and environmental conditions (Mwaja et al. 1995). The high biomass and rapid growth rate of cereal rye also contribute to nutrient immobilization, with cereal rye potentially reducing groundwater nitrate by 37% (Brandi-Dohrn et al. 1997), and holds 60 to 90% of the soil residual nitrogen in its roots and above ground tissue following over-fertilized corn (Shipley et al. 1992). Cereal rye can also reduce nitrate load in sub-surface drainage by an average of 44% (Ruffatti et al. 2019). Lacey and Armstrong (2015) also determined that cereal rye and radish absorb 60 to 80% of fall-applied nitrogen fertilizer. Cover crops can help farmers reduce nutrient runoff, which may lead to decreased fertilizer costs.

Crimson clover is a popular cover crop due to its ability to fixate nitrogen, which ideally allows growers to reduce the amount of applied nitrogen fertilizer. Almost all legumes used in cover cropping systems are winter hardy in southern states and degrade quickly due to their low C:N ratios. Ranells and Wagger (1996) found that hairy vetch and crimson clover's decomposition half-lives are 1-2 weeks shorter than cereal rye, and because of this, immobilized nitrogen is released much sooner by legumes. Research on crimson clover has suggested allelopathic effects on weeds (Dyck and Liebman 1994), but not to the same extent as cereal rye or oats. Legume residues generally do not share the same weed suppressive abilities as grass cover crops due to lower above ground biomass and higher soil nitrogen, but can still reduce weed biomass (Hoffman et al. 1993).

Oats offer dense, competitive root systems and rapid growth. Because of oats' ability to quickly produce above ground biomass, it is preferred by some growers as a winter annual weed suppressor. Oats are usually winter-killed in the Eastern Corn Belt, eliminating the need for chemical or mechanical termination. Parkin et al. (2002) reported oats immobilized as much as 86 kg N ha^{-1} when allowed to grow for 8 to 10 weeks. Retaining fall residual nitrogen in its residue is one of the reasons that oats have become a popular cover crop. Summer annual weed suppression should not be expected, winter survival is unlikely. Allelochemicals from oats have been identified as four different saponins and flavonoids, including glucosides and arabinosides (de Bertoldi et al. 2009).

Daikon radish is normally used to aerate the soil and relieve soil compaction from equipment or livestock, especially in no-till fields. Daikon radish root growth has shown to be relatively unaffected by compact soils compared to other crops, which sets it apart from other cover crops (Chen and Weil 2010). Taproots penetrating compact soils eventually decompose, leaving holes that can relieve compaction and aerate soil. Soybeans roots have been observed growing in channels left by Daikon radish (Williams and Weil 2004). Root extracts from radish have been observed to reduce johnsongrass (*Sorghum halepense* (L.) Pers.) germination by up to 50% (Uremis et al. 2009). Additionally, plant residues from other brassica species have been shown to control plant pathogenic nematodes and fungi in potato systems, without controlling beneficial and predatory nematodes. While not as effective as current fumigants, potato yields were maintained when mustard was planted and tilled in before potato planting (Collins et al. 2006, McGuire 2003). Fumigants are also expensive relative to most pesticides, and planting brassica cover crops could save potato growers up to 148 dollars per hectare (McGuire 2003).

Many factors are involved in deciding which cover crop species is the best for a given system. As growers select a cover crop for weed suppression, understanding what challenges that cover crop may present in a given field may end up costing the farmer more money. Creech et al. showed that fall-seeded annual ryegrass (*Lolium multiflorum*) allows more SCN hosts to survive (Creech et al. 2008). Conversely, Riga et al. (2001) showed that when many cover crops, including annual ryegrass, were incorporated into the soil, SCN egg populations were reduced if planted after soybean in a corn-soybean rotation. This was due to the residues from annual ryegrass triggering SCN eggs to hatch in the absence of a potential host and starving. This suggests that the order of a crop rotation in a cover crop system is important, since annual ryegrass may increase SCN population if planted before soybean, but decrease SCN population if planted before corn. Cover crops may also be an alternate host for other crop diseases, such as *Pythium* and *Fusarium* species (Acharya et al. 2017, Bakker et al. 2016). Knowing which pest problems certain cover crops can present in a field depends on many factors, including pests, annual precipitation, soil type, diseases, neighboring crops, and the following cash crop. Understanding cover crop rotations with cash crops will help avoid pest problems that could be exacerbated by cover crops.

1.5 Conclusion

As corn continues to be one of the most widely planted crops in the U.S. and around the world, research on weed management in corn has until recently focused on herbicide technology. As herbicides have driven down the need for alternative weed management practices for decades, much less focus has been placed on strategies such as rotations with cover crops. Practices involving cover crops have been around for many years, but have only recently begun to see a comeback, in part because of herbicide-resistant weeds that have plagued many growers for years. Herbicide resistance is caused by frequent, repeated herbicide applications over large weed populations. Weed suppression from cover crops could limit the spread and development of herbicide resistance. The benefits and challenges of cover crop weed suppression still require more research. Considering that many species have been used as cover crops, knowing how different species can harmonize with current corn herbicides and other weed control practices while building and maintaining soil health is in the interest of many growers. Previous research has shown that weed suppression can be achieved with most cover crops, however the degree to which cover crops can suppress individual weed species is relatively unknown. Even multi-year cover crop studies have reported differences in weed suppression and cover crop biomass from year to year (Akemo et al. 2000, Johnson et al. 1993, Yenish et al. 1996). Environment and weather contribute greatly to establishment of the cover crop, which helps determine weed suppressive ability. Knowing how to supplement and manage the weed suppression from cover crops from year to year will be critical for proper herbicide resistance management and reducing weed pressure.

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CHAPTER 2. INFLUENCE OF CEREAL RYE COVER CROP TERMINATION TIMING ON RESIDUAL HERBICIDE EFFICACY IN NO-TILL CORN

2.1 Abstract

Field experiments were conducted in 2018 and 2019 at three locations in Indiana to assess weed suppression by cereal rye (*Secale cereale* L.) and residual herbicide premixes in no-till corn (*Zea mays* L.). Cereal rye biomass ranged from 540 kg ha^{-1} to 3700 kg ha^{-1} when terminated in late April and early May. When cereal rye termination was delayed until corn planting in mid-May to mid-June, cereal rye biomass ranged from 1710 kg ha^{-1} to 6200 kg ha^{-1}. Early-season weed biomass was suppressed 27 to 84% by cereal rye residue in three of five site-years. Early-season weed biomass reduction by a residual herbicide premix was similar whether applied to cereal rye or non-cover crop treatments in four of five site-years. In one site-year, weed biomass reduction by a residual herbicide premix was 16% greater when applied to cereal rye compared to non-cover crop ground. Early season weed density reduction by cereal rye was weed species-dependent. Early-season morningglory species (*Ipomoea* spp.) and summer annual grass densities were reduced by 55 to 87%, while giant ragweed (*Ambrosia trifida* L.) and common cocklebur (*Xanthium strumarium* L.) densities were not reduced by cereal rye. By late in the growing season, summer annual grass density and biomass in cereal rye did not differ from non-cover crop treatments. However, cereal rye had two- and ten-fold higher common cocklebur density and biomass, compared to non-cover crop treatments. Corn yield was similar in all treatments in all but one site-year, when a 57% yield reduction from cereal rye was observed in 2018 due to corn stand reduction from cereal rye competition. Overall, cereal rye did not reduce residual herbicide efficacy, however the soil conditions imposed by cereal rye may have led to increased common cocklebur germination and subsequent competition with corn.

2.2 Introduction

Weed interference in corn was estimated to have caused $3.8 billion in yield loss annually from 2007 to 2013 in the United States and Canada (Soltani et al. 2016). Worldwide, 259 weed species have evolved resistance to at least one mode of action, and several species have developed resistance to multiple herbicide sites of action (Heap 2020). Since dependence on only one weed control method may lead to herbicide-resistant weed infestations, multiple strategies should be used to manage weeds and protect crop yields (Chikowo et al. 2009, Jasieniuk et al. 1996). Integrated weed management (IWM) strategies that reduce selection pressure for herbicide resistance include tillage, diversified crop rotations, biological controls, harvest weed seed destruction, and cover crops (Norsworthy et al. 2012).

Common herbicide resistant weeds in corn and soybean production in the Eastern Corn Belt include waterhemp (*Amaranthus tuberculatus* (Moq.) J. D. Sauer), horseweed (*Erigeron canadensis* L.) and giant ragweed (*Ambrosia trifida* L.). Herbicide resistance to at least two herbicide site of action groups has been documented in all of these weeds (Heap 2020). Herbicide resistance to nine herbicide modes of action used in corn production has been reported among these species in the United States (Heap 2020). Glyphosate-resistant giant ragweed, horseweed, and waterhemp populations have been reported in corn across the Eastern Corn Belt, which increases the need for alternative weed management practices such as cover crops (Heap 2020).

According to the USDA Census of Agriculture, cover cropped farmland increased from 10.3 to 15.4 million acres from 2012 to 2017 (USDA 2017). In Indiana from 2011 to 2018, cover cropped corn acres rose from 2 to 8% of total acres (IDSA 2019). Rapid cover crop adoption occurred from 2011 to 2015 in Indiana, but acreage has decreased slightly since then. Total cover crop acreage in Indiana in 2018 was 400,000 acres, or 4% of total farm land (ISDA 2019). In a national survey of cover crop users, 69% of growers had observed improved control of herbicide-resistant weeds after using cereal rye as a cover crop, even though there is very little published research to support this result (CTIC 2017).

Diversification of crop rotations can contribute to weed management. Doucet et al. (1999) showed that changes in weed density in diversified crop rotations were due primarily to changes in cultural and herbicide weed management strategies for each crop in the rotation. Integrating winter cover crops into summer crop rotations will alter weed management practices in summer annual crops. Attention to residual herbicide rotational intervals will be important for fall cover crop establishment. Weed suppression by cover crop biomass could allow growers to delay postemergence herbicide applications. Wallace et al. (2019) demonstrated that cereal rye reduces the average size of horseweed (*Erigeron canadensis* L.) and decreases the variability in horseweed size, which could increase control by appropriately timed applications of foliar herbicides.

Summer annual weed biomass suppression in corn has also been reported by others (Crutchfield et al. 1985, Yenish et al. 1996). The impacts of any cover crop in corn on the weed community are dependent the cover crop biomass and composition of the weed community. Mohler and Teasdale (1993) determined that common lambsquarters (*Chenopodium album* L.) and witchgrass (*Panicum capillare* L.) density were more sensitive than velvetleaf (*Abutilon theophrasti* Medik.) and dandelion to increasing amounts of cereal rye biomass. Bàrberi et al. (2001) reported that a cereal rye cover crop in continuous no-till corn reduced weed species diversity compared to a no cover crop control. Therefore, integrating cereal rye into crop rotations may result in overall weed seedbank reductions, but could also alter the composition of the weed community.

Above-ground cover crop biomass can prevent soil residual herbicides from reaching the soil upon application (Haramoto and Pearce 2019). If adequate precipitation or irrigation is not received to wash the herbicide off of the residue, weed control may be reduced. Ghadiri et al. (1984) observed that after herbicide application to wheat residue, 40% of the applied atrazine had reached the soil, but after 50 mm of precipitation, over 90% of the herbicide was found in the soil. Crutchfield et al. (1985) observed no difference in weed control when metolachlor was applied to wheat residue in Nebraska, and that at every rate of *S*-metolachlor, weed biomass and density decreased as wheat biomass increased from 0 to 6800 kg ha^{-1}, with 30 to 36 cm of precipitation within one month of herbicide application. Residual herbicides and cover crop residues appear to be compatible for overall weed control with proper management, even if some amount residual herbicide is initially retained by the cover crop residue (Crutchfield et al. 1985, Ghadiri et al. 1984, Haramoto and Pearce 2019, Teasdale 1993a, Teasdale et al. 2005).

Information is currently lacking on the effect of cover crops on late-season weed suppression in corn. Additionally, the effects of cereal rye on giant ragweed (*Ambrosia trifida* L.) have not been reported. While several studies in the Eastern Corn Belt have reported early season weed suppression by cereal rye in corn, additional research is needed to evaluate the efficacy of various application timings of residual herbicides in cereal rye. The objective of this experiment is to evaluate the weed suppressive ability of cereal rye throughout the growing season, as well as the compatibility of residual herbicides with cereal rye in no-till corn. We hypothesize that cereal rye will reduce early-season weed biomass and density, but will not decrease late-season weed biomass and density but not late-season biomass or density. We also hypothesize that weed control by a residual herbicide premix will be similar in cereal rye and non-cover crop treatments.

2.3 Materials and Methods

2.3.1 Experimental Design

No-till corn field studies were conducted in 2017 through 2018 and 2018 through 2019 at three locations in Indiana. The locations were Throckmorton Purdue Agricultural Center [TPAC, (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W)], Davis Purdue Agricultural Center [DPAC, (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W)], and Southeast Purdue Agricultural Center [SEPAC, (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W)]. Information regarding corn planting, herbicide applications, and data collections for all site-years is shown in Table 2.1. The experiment was a split-split-plot randomized complete block design. Main plots were cover crop treatment, which were fall-planted cereal rye or non-cover crop. Subplots were blocked within main plots and consisted of two termination timings (early vs. at-plant), which were two weeks before corn planting or at corn planting. Due to prolonged spring precipitation in 2019 that prevented field operations and corn planting, early terminations were made 5 to 6 weeks before corn planting. Sub-subplots were randomized within subplots and consisted of four herbicide strategies.

Cereal rye (Elbon™, Cisco, Indianapolis, IN 46219) (103 kg ha^{-1}) was planted in the fall of 2017 and 2018 in one of the two main plots, with the other main plot left fallow until corn planting in the spring of the following year. The following spring, all plots were planted with SmartStax™ corn, (DKC62-08RIB, Dekalb®, St. Louis, MO 63118) spaced 76 cm apart in mid-May in 2018. Due to wet weather in the spring of 2019, planting was delayed until early- to mid-June at TPAC and DPAC in 2019, and abandonment of the SEPAC location in 2019. Starter fertilizer at a rate of 34 kg N ha^{-1}, 45 kg N ha^{-1}, and 45 kg N ha^{-1} was applied at TPAC, DPAC and SEPAC, respectively. A side dress fertilizer application of 28% UAN was made near the V6 growth stage at rates of 159 kg N ha^{-1}, 166 kg N ha^{-1}, and 183 kg N ha^{-1} at TPAC, DPAC, and SEPAC, respectively.

The sub-subplots were herbicide strategies (Table 2.2), and included two herbicide applications for all treatments: one applied at termination of the cereal rye and winter annual weeds, and another applied as a post-emergence (POST) application 2 to 5 weeks after corn planting. The four different herbicide strategies were: 1) no residual, with no residual herbicides applied at termination or at POST, 2) preplant residual, with a residual herbicide premix applied at termination followed by a POST application with no residual herbicide, 3) POST residual, which consisted of a non-residual herbicide applied at termination, followed by a residual herbicide premix applied at POST, and 4) preplant + POST residual, with a residual herbicide premix included at both the termination application and at the POST application. Glyphosate (Roundup Powermax®, Bayer, St. Louis, MO 63141) was applied to all treatments at termination. Glyphosate + dicamba + diflufenzopyr (Status®, BASF, Triangle Park, NC 27560) were applied at the POST application. The residual herbicide premix applied at termination contained atrazine + S-metolachlor + mesotrione + bicyclopyrone (Acuron®, Syngenta, Wilmington, DE 19810). The residual herbicide premix applied at the POST application contained atrazine + *S*-metolachlor (Bicep II Magnum®, Syngenta, Triangle Park 27560). All herbicide applications were made with a CO_2-pressurized backpack sprayer using XR 110015 nozzles (TeeJet Technologies, Urbandale, IA 50322) for herbicide mixtures not containing dicamba. For treatments containing dicamba, TTI 11002 nozzles were used (TeeJet Technologies, Urbandale, IA 50322). A carrier volume of 140 L ha^{-1} was used to apply all herbicides. A summary of these herbicide strategies and herbicide rates is described in Table 2.2.

2.3.2 Data Collection

Cover crop biomass was collected at cover crop termination by removing above-ground biomass from a 0.25 m^2 area from each sub-subplot before termination (Table 2.4).

Two weed biomass and density evaluations were made during the growing season at each site-year: early-season and late-season (Table 2.1). Weed species evaluated at each site are shown in Table 2.3. For both early- and late-season evaluations, weeds from a 0.25 m^2 area in the front and back of the plot were counted and collected. All weed and cover crop biomass samples were oven-dried at 60 C for 48 hours before weighing.

Early-season weed biomass and density were evaluated for the dominant weed species at each site-year two to five weeks after corn planting, and just before the POST herbicide application. Biomass was summed over all species collected and is shown in Table 2.5. Weed densities for summer annual grasses were pooled over all grass species at each location (Table 2.6). Broadleaf weed densities are presented by individual species in Table 2.7. Summer annual grasses were evaluated at the site-years TPAC 2018, TPAC 2019, DPAC 2019, and SEPAC 2018. Giant ragweed was evaluated at TPAC in 2018 and 2019. Waterhemp was evaluated at DPAC in 2018 and 2019. Common cocklebur and morningglory species were evaluated at SEPAC in 2018.

Late-season weed biomass and density were evaluated in mid-September to early October. Weed biomass was collected and summed over all dominant weed species, and is shown in Table 2.8. For weed densities, summer annual grasses were pooled over all grass species at each location, and broadleaf weeds were evaluated individually. All late-season weed densities are shown in Table 2.9. Summer annual grasses were evaluated at TPAC in 2018 and 2019. Common cocklebur was evaluated at SEPAC in 2018. No late-season evaluations were made at DPAC in either year because high levels of weed control resulted in very few weeds in all plots.

Corn was harvested with a plot combine once physiological maturity was reached from the middle two rows of each sub-subplot. Weight and grain moisture levels were recorded and standardized to 15.5% moisture.

2.3.3 Data Analysis

Data were analyzed using analysis of variance (ANOVA) by PROC GLIMMIX in SAS 9.4 (SAS, 100 SAS Campus Drive, Cary, NC 27513). Weed biomass and density data were log-transformed when appropriate to meet statistical assumptions. Untransformed data are shown in all tables and figures for clarity, while the statistical significance shown is of based on the log-transformed data to satisfy statistical assumptions. The variables termination timing and herbicide strategy were fixed effects, and cover crop treatment, as well as cover crop by replication and cover crop by replication by termination timing were set as random effects. A Satterthwaite denominator degree of freedom was utilized to produce an accurate approximation of F. Means were compared using Tukey's Honest Significant Difference (HSD) at a significance level of α = 0.05. All site-years were analyzed individually due to significant site-year interactions.

2.4 Results and Discussion

2.4.1 Cereal Rye Biomass Before Termination

Termination timing was significant as a main effect in each site-year. Due to the late-October planting date at DPAC, cover crop biomass was not higher than 2200 kg ha^{-1} even in at-plant terminated plots. Delaying cereal rye termination until corn planting resulted in increased biomass for every site-year (Table 2.4).

In April and May of 2018, average monthly temperatures were 6.7 and 20 C, respectively. Compared to 30-year averages, April was 3 C cooler and May was 2.5 C warmer. Precipitation in April and May at all sites was within 2 cm of the 30-year average at all sites. Early terminations were performed two weeks before corn planting at all sites, and at-plant terminations were performed at corn planting. At the early termination timing in 2018, cereal rye biomass was 1260 kg ha^{-1} at TPAC, 1120 kg ha^{-1} at DPAC, and 3700 kg ha^{-1} at SEPAC. At-plant terminated cereal rye had higher biomass by 170% at TPAC, 53% at DPAC, and 91% at SEPAC compared to cereal rye biomass at the early termination (Table 2.4).

In 2019, spring precipitation was 4.5 to 7 cm above average through April and May at all sites. Average temperatures at all sites were within 1.5 C of 30-year averages. Early terminations were made 5 to 7 weeks before the at-plant terminations, due to the prolonged wet soil conditions that prevented field operations and corn planting. Cereal rye biomass at the early termination was 1300 kg ha^{-1} at TPAC and 540 kg ha^{-1} at DPAC. When terminated at corn planting, cereal rye biomass was 377% higher at TPAC and 294% higher at DPAC. Cereal rye biomass was not collected at SEPAC due to flooding and wet soils that prevented timely corn planting and other field operations.

Higher amounts of cereal rye biomass in at-plant terminations in 2019 compared to 2018 occurred because of delayed corn planting and later cover crop termination in 2019 relative to 2018. The lower biomass at DPAC was due to cereal rye planting that occurred on October 22nd and October 23rd, at least two weeks later than TPAC and SEPAC in both 2017 and 2018 (Table 2.1).

The cereal rye biomass at DPAC is comparable to biomass reported by Ruffo et al. (2004) in Illinois, with similar planting and termination dates. At TPAC and SEPAC, cereal rye biomass in this experiment is similar to previously published studies with similar planting and termination dates (Hayden et al. 2012, Mirsky et al. 2011, and Ryan et al. 2011). Large differences in biomass was also observed from year to year, which is similar with other studies by Hayden et al. (2012), Martinez-Feria et al. (2016), Mirsky et al. (2011), and Ryan et al. (2011). Previous studies have shown no difference in cereal rye biomass from seeding rates of 56 to 210 kg ha^{-1} in Indiana, Illinois, Kentucky, Maryland, and Pennsylvania (Masiunas 1995, Ryan et al. 2011).

The degree of weed suppression by cereal rye is dependent on the weed species that comprise the community and the cover crop biomass. Cereal rye biomass at 2200 kg ha^{-1} has been shown to reduce large crabgrass density by 49%, ivyleaf morningglory by 28%, and waterhemp by 41% compared to non-cover cropped plots (Cornelius and Bradley 2017, Malik et al. 2008). Mohler and Teasdale (1993) evaluated weed suppression thresholds at varying levels of cover crop residue and found that common lambsquarters was suppressed 98% by cereal rye at 2000 kg ha^{-1}, witchgrass was suppressed 58% by 8500 kg ha^{-1}, and velvetleaf was suppressed 26% by 17000 kg ha^{-1}. Weed species that have a light requirement for germination are much more likely to be suppressed by cover crop residues than weed species without a light requirement (Mohler and Teasdale 1993).

A scatter plot of wheat and cereal rye cover crop biomass and weed biomass data from several studies, including the data from this manuscript, is shown in Figure 2.1. Cereal rye biomass in these previously published experiments ranged from 500 kg ha^{-1} to 9000 kg ha^{-1}, and weed biomass suppression was correlated with cereal rye biomass at termination, with a correlation coefficient of $R = 0.57$. Weed biomass decreased by approximately 12% for every 1000 kg ha^{-1} of additional cereal rye or wheat biomass, and peak weed biomass suppression was estimated to occur at 8000 kg ha^{-1} of cover crop biomass.

2.4.2 Early-Season Weed Biomass

Early-season weed biomass, collected two to five weeks after corn planting and before the POST herbicide application, is shown in Table 2.5. In 2018, the interval between termination and biomass collection was between 35 and 48 days for early terminations and between 20 and 36 days for at-plant terminations. In 2019, the interval between termination and biomass collection was between 62 and 67 days for early terminations and between 13 and 27 days for at-plant terminations (Table 2.1). This prolonged period between the early termination and evaluation in 2019 allowed more weed emergence and growth, and for the residual herbicides to degrade after application. Since newly emerged weeds and weeds that had survived the application of the termination herbicide were collected, weed biomass from early terminated plots was greater in 2019 than 2018.

Giant ragweed suppression was evaluated at TPAC in 2018 and 2019. In 2018 there were no significant interactions. The main effects of termination timing and cover crop were significant. With the termination herbicide treatment effect, glyphosate plus a residual had lower giant ragweed densities then glyphosate alone when pooled over termination timing and cover crop. The effect of cover crop, pooled over termination timing and termination herbicide, showed that giant ragweed densities were higher when grown with a cover crop versus a no cover crop situation (Table 2.5). In 2019 there was a significant three-way interaction between termination timing, cover crop, and termination herbicide. The treatments that provided the highest level of suppression were treatments with glyphosate plus a residual applied at planting, and similar levels of suppression were observed with this herbicide treatment in both non-cover crop and cereal rye treatments (Table 2.5). Overall these results show that a cereal rye cover crop did not provide any benefits with giant ragweed suppression. Glyphosate plus a residual at planting provided the best suppression of giant ragweed regardless of whether or not there was a cover crop. Efficacy of residual herbicides on giant ragweed was not reduced in cereal rye residue as high as 6200 kg ha^{-1}.

At DPAC in 2018, waterhemp was the only weed evaluated, since other weed species were scarce. An interaction between cover crop and termination herbicide was significant. Glyphosate plus a residual reduced weed biomass to zero in both cereal rye and non-cover crop treatments (Table 2.5). Termination timing was not significant, which was likely due to the prevalence of glyphosate-resistant waterhemp at DPAC, which would have survived early and at-plant applications of glyphosate. In 2019, waterhemp and summer annual grasses were evaluated. A three-way interaction between cover crop, termination timing, and termination herbicide was observed. Weed biomass was lowest when glyphosate plus a residual was applied at corn planting, regardless of cover crop treatment (Table 2.5). In glyphosate-only treatments, cereal rye only suppressed weed biomass in at-plant terminations. Overall, cereal rye did not reduce herbicide efficacy on waterhemp in cereal rye biomass up to 2130 kg ha^{-1}.

At SEPAC in 2018, ivyleaf morningglory, pitted morningglory, common cocklebur, and summer annual grasses were evaluated. Interactions between cover crop and termination herbicide, as well as termination timing and termination herbicide were significant. With termination timing pooled, weed biomass in cereal rye treatments and in glyphosate plus residual plots was similar. Weed biomass in these treatments was 84 to 97% lower than non-cover cropped plots terminated with glyphosate (Table 2.5). With cover crop treatment pooled, the lowest weed biomass was observed in glyphosate plus residual plots terminated at corn planting. The glyphosate plus residual treatment reduced weed biomass in each termination timing. Overall, cereal rye and the residual herbicide premix reduced weed biomass equally.

Weed biomass was suppressed by cereal rye three of five site-years. Weed biomass was reduced more by residual herbicides than by cereal rye in all site-years, expect at SEPAC in 2018, where weed biomass in cereal rye treatments was similar to weed biomass in glyphosate plus residual treatments (Table 2.5). The difference of weed suppression by cereal rye between locations and years has also been observed by Hayden et al. (2012), Mirsky et al. (2011), and Mock et al. (2012), who also observed differences in cover crop biomass between site-years. While cereal rye seeding rate remained consistent throughout this experiment, increasing the rate would probably have resulted in lower weed biomass, as Ryan et al. (2011) and Boyd et al. (2009) reported increased weed suppression by increasing cereal rye seeding rate from 90 to 270 kg ha^{-1}, even though seeding rate above 90 kg ha^{-1} did not influence cover crop biomass.

Weed biomass reduction in glyphosate plus residual treatments was similar in cereal rye and non-cover crop plots four of five site-years, and different at TPAC in 2019, where weed biomass was lower in cereal rye. These results corroborate findings from previously published studies that have shown that residual herbicides can be integrated with cover crops without losing herbicide efficacy when cereal rye biomass is below 7000 kg ha^{-1} (Crutchfield et al. 1985, Haramoto and Pearce 2019, Teasdale 1993).

2.4.3 Early-Season Weed Density

Densities of all summer annual grass species were combined by location. Densities of broadleaf weeds were presented individually by species for each site.

2.4.4 Summer annual grass weeds

At TPAC in 2018, no interactions were observed, but termination timing and termination herbicide main effects were significant. The glyphosate plus residual treatment reduced grass density by 94% compared to glyphosate only treatments, while delaying termination from early to at-plant reduced grass density by 76% (Table 2.6). In 2019, cover crop by termination herbicide and terminating timing by termination herbicide interactions were significant. Compared to fallow plots terminated with glyphosate, cereal rye terminated with glyphosate reduced grass density by 55%, while the glyphosate plus residual treatment applied to non-cover crop treatments reduced grass density by 66% (Table 2.6).

At DPAC in 2018, summer annual grass weeds were scarce, and not evaluated. In 2019, no factors influenced grass density. While annual grass weeds were present throughout, the seed bank was irregular, and the fluctuation of the annual grass community within the experimental area led to highly variable data with no significant differences in the experimental factors.

At SEPAC in 2018, no interactions were significant. The main effects termination herbicide and termination timing influenced grass density. The glyphosate plus residual treatment reduced grass density by 65%, compared to glyphosate-only terminated plots. When pooled over cover crop and termination herbicide, delaying cover crop termination to corn planting reduced grass density by 63% (Table 2.6).

Overall, summer annual grass density reduction by the residual herbicide premix was similar in both cereal rye and non-cover crop ground at any site-year. Density reduction by cereal rye was only observed in two of five site-years. The summer annual grass suppression by cereal rye compared to non-cover crop treatments at TPAC and DPAC in 2019 is supported by Brainard et al. (2016), who observed a 58% reduction of large crabgrass density by cereal rye in Michigan. The similarity in summer annual grass density in cereal rye and non-cover crop treatments at TPAC, DPAC, and SEPAC in 2018 agrees with Moraes et al. (2009) and Teasdale et al. (1991), who reported no change in summer annual grass density in cereal rye residue in Missouri and Maryland, respectively. The reduction of summer annual grass density in 2019 but not in 2018 may have been influenced by the wet weather and soil shading by the cereal rye. Boyd et al. (2016) reported that barnyardgrass emergence increased in response to soil moisture fluctuations. The wet weather in 2019, combined with the shading by cereal rye may have prevented the soil in cereal rye treatments from drying, while soil in the non-cover crop treatments would have dried faster.

2.4.5 Broadleaf weeds

In 2018 and 2019, giant ragweed density was evaluated at TPAC. In 2018, density was influenced by cover crop treatment and by termination herbicide. Pooled across termination timing and termination herbicide, cereal rye increased giant ragweed densities by 42% (Table 2.7). The increased giant ragweed density in cereal rye treatments could have been due to the cereal rye residue which shaded the soil and increased soil moisture, which may have promoted giant ragweed emergence. Pooled across cover crop and termination timing, the residual herbicide premix applied at termination reduced giant ragweed densities by 41% compared to plots terminated with only glyphosate. In 2019, at three-way interaction between cover crop, termination timing, and termination herbicide was significant. The treatment with the lowest giant ragweed density was cereal rye terminated at corn planting with the residual herbicide premix, which reduced density by 86 to 94%, compared to all early terminated with or without the residual herbicide treatment applied at termination (Table 2.7). The highest giant ragweed density was observed in early terminated plots, as well as plots terminated with only glyphosate. Cereal rye did not reduce giant ragweed density in this experiment.

Waterhemp was evaluated at DPAC in 2018 and 2019. In 2018, a two-way interaction between cover crop and termination herbicide was significant (Table 2.7). The glyphosate plus residual treatment reduced waterhemp density to zero in both non-cover crop and cereal rye treatments. In 2019, a three-way interaction between cover crop, termination timing, and termination herbicide was observed. No differences in early terminated treatments were observed, likely because the time between termination and evaluation was 9 weeks due to the delayed planting, which would have allowed the residual herbicide premix to degrade and for waterhemp to emerge. In at-plant terminated treatments, the residual herbicide premix reduced waterhemp density by 89 to 99% in cereal rye, and by 99% in non-cover crop treatments. Residual herbicide efficacy on waterhemp was not reduced by cereal rye. These results from 2018 and 2019 disagree with other experiments that demonstrated the suppressive ability of cereal rye on waterhemp and other weedy *Amaranthus* specie; however, these studies have been performed in Alabama, Missouri, and Tennessee in cotton and soybean with no starter fertilizer. (Cornelius and Bradley 2017, Price et al. 2012, Wiggins et al. 2016). Teasdale and Pillai (2005) demonstrated that ammonium stimulates germination of another *Amaranthus* species, smooth pigweed (*Amaranthus hybridus* L.). This suggests that the increase in ammonium concentration from the starter fertilizer may have increased waterhemp emergence at DPAC, and resulted in similar density in both cereal rye and non-cover crop treatments.

Pitted morningglory, ivyleaf morningglory, and common cocklebur were evaluated at SEPAC in 2018. For morningglory species, no interactions were significant, but cereal rye as a main effect was significant (Table 2.7). Cereal rye reduced morningglory density by 87%, compared to non-cover crop treatments. (Table 2.7). These results are similar to Norsworthy et al. (2011), who also demonstrated 50% control of pitted morningglory by cereal rye. No interactions or main effects were significant for common cocklebur density (Table 2.7). The lack of broadleaf weed density reduction by residual herbicides at SEPAC is likely because of the higher tolerance of morningglory species and common cocklebur to atrazine, mesotrione, and *S*-metolachlor (Adcock and Banks 1991, Bollman et al. 2006, Mills and Witt 1989, Wesley et al. 1989). Common cocklebur was not suppressed probably because it lacks a light requirement for germination and favors higher soil moisture and low temperature fluctuations (Norsworthy and Oliveira 2007). Research on common cocklebur suppression from cereal rye is very limited, however Walters et al. (2008) found that mechanically rolled cereal rye increased common cocklebur control by 20%. No suppression was observed in this experiment, possibly because the cereal rye was not mechanically rolled.

2.4.6 Late-Season Weed Biomass

Weed biomass in mid-September to early October was only evaluated at three site-years: TPAC 2018, SEPAC 2018, and TPAC 2019. Complete weed control was observed at DPAC in both years after the POST herbicide application, and therefore biomass was not evaluated.

At TPAC in 2018, summer annual grass species were evaluated, since giant ragweed was scarce. The termination timing by herbicide strategy interaction was significant. The lowest weed biomass was observed in POST residual and PRE plus POST residual treatments in both termination timings, as well as PRE residual in at-plant terminations. Grass biomass was 78 to 98% lower in plots where any residual herbicide had been applied, regardless of termination timing, compared to the no residual treatments (Table 2.8). In 2019, a three-way interaction between termination timing, herbicide strategy, and cover crop was significant. The highest weed biomass was observed in early terminated plots that did not receive the residual herbicide premix at termination (Table 2.8). The higher weed biomass was probably due to the dense weed canopy in early terminated plots at the POST herbicide application, which intercepted herbicide and prevented a uniform distribution of residual herbicide applied with the POST herbicide treatment (Haramoto and Pearce 2019).

At SEPAC in 2018, common cocklebur was evaluated, since other weeds were scarce. No interactions were significant, and only termination timing and cover crop as main effects were significant. Common cocklebur biomass was 8.8 g m^{-2} in non-cover crop treatments, and 87.2 g m^{-2} in cereal rye treatments (Table 2.8). In at-plant terminations, common cocklebur biomass was 87.4 g m^{-2}, while common cocklebur biomass was 8.2 g m^{-2} in early terminations (Table 2.8). The increase in common cocklebur biomass in at-plant terminated cereal rye was likely due to the increased cereal rye and weed biomass at termination, which may have led to increased light interception, lower soil temperature fluctuations, and increased soil moisture, which all promote common cocklebur emergence (Norsworthy and Oliveira 2007). In at-plant terminations and in cereal rye treatments, the corn canopy was delayed which allowed common cocklebur to grow faster than in early terminated and non-cover crop treatments. The cereal rye residue prevented the corn canopy, which allowed cereal rye to grow more vigorously than in non-cover crop plots.

Common cocklebur and annual grass growth were affected by different factors, which suggests that cover crop and weed management should be altered based upon weed community composition. Where common cocklebur is present, cover crops should be terminated at least two weeks before corn planting. Where summer annual grasses are present, cover crops are unlikely to provide late-season control, and growers should apply residual herbicides. Previously published research has not evaluated late-season weed biomass in corn; however, other experiments performed in soybean production have demonstrated increased pre-harvest weed control by cover crops (Bernstein et al. 2014, Thelen et al. 2004).

2.4.7 Late-Season Weed Density

Weed densities in mid-September to early October were only evaluated at three site-years: TPAC 2018, SEPAC 2018, and TPAC 2019. Complete weed control was observed at DPAC in both years after the POST herbicide application, and therefore weed densities were not evaluated. No evaluation was performed at SEPAC in 2019 since prolonged spring precipitation and wet soils prevented timely field operations and corn planting.

At TPAC in 2018, no interactions were significant, but termination timing and herbicide strategy were significant. Delaying termination until corn planting reduced annual grass densities from 11 to 7 m^{-2} (Table 2.9). Grass densities in the no residual strategy were 28 m^{-2}. In all other herbicide strategies, grass densities were reduced by 86 to 96%. In 2019, a termination timing by herbicide strategy interaction was observed. Annual grass densities were generally higher in at-plant terminated treatments. This could have been because the dense weed canopy in plots terminated with no residual herbicide, that prevented a uniform distribution of a POST residual herbicide, which led to decreased control in early-terminated plots. Except for the preplant + POST residual treatment, grass densities were lower for each herbicide strategy when termination was delayed until corn planting. Grass density was similar in at-plant terminated treatments, regardless of herbicide strategy (Table 2.9). The application of a residual herbicide increases late-season control of summer annual grasses in both cereal rye and non-cover crop systems, while cereal rye alone does not provide control of late-emerging summer annual grasses.

At SEPAC in 2018, common cocklebur was evaluated. No interactions were significant, and only cereal rye as a main effect was significant. Cereal rye increased late-season common cocklebur density by 120% (Table 2.9). Reasons for this increase in common cocklebur density may include herbicide interception by cereal rye and increased soil moisture via shading from the cover crop residue. Cereal rye increases common cocklebur density at biomass levels between 3700 and 7080 kg ha^{-1}.

These data demonstrate that in no-till corn cover crop systems, weed species respond differentially to cover crop management and herbicide strategies. Residual herbicides provided suppression of pre-harvest summer annual grass control, however cereal rye biomass under 7080 kg ha^{-1} did not. Conversely, common cocklebur density was increased by the cereal rye residue. Understanding weed species composition in no-till corn cover crop systems is crucial for growers to tailor cover crop management strategies to achieve optimum weed control and avoid weed management complications.

No research on late-season weed density in cereal rye in corn has been published; however, late-season weed control by cereal rye in soybean production has been reported by Cornelius and Bradley (2017). They reported that while cereal rye reduced waterhemp density in Missouri compared to a non-treated control, a spring application of fomesafen and *S*-metolachlor resulted in 51% better control than cereal rye. The results from TPAC partially agree with this research in that residual herbicides are more effective at reducing late-season weed density, however the lack of a non-herbicide control in this experiment limits further comparisons of the effects of cereal rye by itself.

2.4.8 Corn Yield

At TPAC in 2018, no significant differences in corn yield were observed and yield on average was 16400 kg ha^{-1} (Table 2.10). In 2019, an herbicide strategy by termination timing interaction was observed. Because of prolonged spring precipitation, and the prolonged gap between the early cereal rye termination and corn planting in 2019, weeds competed with and shaded corn prior to the POST application in early terminated treatments without a residual herbicide premix. This stunted the corn and delayed canopy closure at TPAC in 2019 in those treatments. Treatments that involved early termination without a residual herbicide averaged 10300 to 10500 kg ha^{-1}, while all other treatments ranged from 13400 to 15800 kg ha^{-1} (Table 2.10). The highest yields were treatments that included a residual herbicide at termination and treatments that were terminated at corn planting.

At DPAC in 2018, no significant differences were observed in corn yield, and yield averaged 12000 kg ha^{-1}. In 2019, the side-dress application of fertilizer was improperly applied, and only half of the plots received fertilizer. Additionally, trampling and feeding damage from deer prevented accurate analysis.

At SEPAC in 2018, no interactions were significant, but termination timing and cover crop were significant. Corn yield at SEPAC without a cover crop was 9800 kg ha^{-1}, while a cereal rye cover crop reduced corn grain yield to 4300 kg ha^{-1} (Table 2.10). Corn yield reduction was likely due to both cereal rye shading and physical suppression in the spring and early summer, and common cocklebur competition in the fall. The cereal rye residue at SEPAC delayed the corn canopy, which then allowed common cocklebur plants that emerged after the POST application to be more competitive with the corn.

The similarity in corn yield at DPAC and TPAC in 2018 in cereal rye and non-cover crop treatments is supported by a meta-analysis by Miguez and Bollero (2005) from published studies across the US and eastern Canada. In the meta-analysis, corn yield was shown to be generally unaffected by grass cover crops, as long as nitrogen fertilizer is applied.

Corn yield loss from cereal rye at SEPAC in 2018 may have been caused by shading and physical suppression from the cereal rye, since cereal rye biomass was larger at SEPAC in 2018 than other site-years. The amount of nitrogen fertilizer applied at SEPAC also may not have been sufficient to overcome the low nitrogen levels in cereal rye treatments, compared to the non-cover crop treatments. Additionally, a low soil organic matter content of 1.7% and high amounts of cover crop residue at SEPAC may have slowed nitrogen mineralization by soil microbes compared to TPAC and DPAC.

2.5 Conclusion

Cereal rye biomass varied widely between sites and ranged from from 540 to 3700 kg ha^{-1} when terminated at least two weeks before corn planting, and 2130 to 7080 kg ha^{-1} when terminated at corn planting. The effect of cereal rye on weed biomass and density is dependent on the weed species and the cover crop biomass. Weed biomass suppression appears to be influenced by cover crop biomass and weed species. A residual herbicide premix applied at termination provides greater weed biomass and density reduction than cereal rye. Morningglory and summer annual grass density can be reduced by a cereal rye cover crop, but the density of other weed species was unaffected. The variability of weed suppression by a cereal rye cover crop should caution growers to not rely solely on postemergence herbicides and cover crops for weed control, as reduced weed densities as a result of a cover crop were infrequently observed. A cereal rye cover crop and residual herbicides are compatible for weed control in corn, and in some cases may work synergistically. Cereal rye alone did not suppress late-emerging summer annual grass biomass or density. Residual herbicides applied at cover crop termination and at POST did control late-emerging summer annual grasses. Common cocklebur emergence may benefit from the conditions provided by cereal rye residue, especially if the corn canopy is delayed or prevented because of the cover crop. Residual herbicides are still a valuable tool for weed management in no-till corn cover crop systems, and still provide weed control when applied to living cover crops and cover crop residue. For this reason, it is important for cover crop growers to use residual herbicides in an IWM system. Terminating cereal rye at corn planting may decrease corn yield if cover crop biomass at corn planting or later.

Table 2.1: Calendar dates for each event at each site. Cereal rye was planted at 103 kg ha^{-1} and terminated the following spring using glyphosate. Two weed collections were made: one before the POST herbicide application which occurred 2 to 4 WAP and one before corn harvest.[a,b,c]

	DPAC		SEPAC[c]	TPAC	
Event	2018	2019	2018	2018	2019
Cover crop planting	10/23/2017	10/22/2018	10/7/2017	10/4/2017	10/3/2018
Cover crop early termination	5/5/2018	5/6/2019	4/30/2018	4/26/2018	4/24/2019
Cover crop at-plant termination	5/19/2018	6/15/2019	5/14/2018	5/10/2018	6/12/2019
Corn planting	5/19/2018	6/15/2019	5/14/2018	5/10/2018	6/11/2019
Weed biomass collection 2-4 WAP	6/20/2018	7/12/2019	6/4/2018	6/15/2018	6/25/2019
POST herbicide application	6/20/2018	7/13/2019	6/5/2018	6/16/2018	6/25/2019
Weed biomass collection prior to corn harvest	-[b]	-[b]	9/23/2018	9/18/2018	10/4/2019

[a]Abbreviations: DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W), CC = cover crop, POST = postemergence herbicide application.
[b]Weed biomass was not collected at DPAC in Fall 2018 and 2019 due to near complete weed control in all treatments.
[c]The experiment was not carried out at SEPAC in 2019 because of prolonged spring precipitation that led to excessive soil moisture, preventing corn planting at an ideal date.

Table 2.2: Herbicides applied for four different herbicide strategies. All herbicides were applied using a CO_2-pressurized backpack sprayer.[a]

Herbicide strategy	At cover crop termination[b]		POST[c]	
	Herbicide	Rate	Herbicide	Rate
Reduced Herbicide	glyphosate[d]	1.54 kg ae ha^{-1}	dicamba[e]	0.14 kg ae ha^{-1}
			diflufenzopyr[e]	0.056 kg ai ha^{-1}
			glyphosate	1.54 kg ae ha^{-1}
Preplant residual	atrazine[f]	1.58 kg ai ha^{-1}	dicamba	0.14 kg ae ha^{-1}
	bicyclopyrone[f]	0.04 kg ai ha^{-1}	diflufenzopyr	0.056 kg ai ha^{-1}
	glyphosate	1.54 kg ae ha^{-1}	glyphosate	1.54 kg ae ha^{-1}
	mesotrione[f]	0.16 kg ai ha^{-1}		
	S-metolachlor[f]	1.43 kg ai ha^{-1}		
POST residual	glyphosate	1.54 kg ae ha^{-1}	atrazine[g]	1.82 kg ai ha^{-1}
			dicamba	0.14 kg ae ha^{-1}
			diflufenzopyr	0.056 kg ai ha^{-1}
			glyphosate	1.54 kg ae ha^{-1}
			S-metolachlor[g]	0.35 kg ai ha^{-1}
Preplant + POST residual	atrazine	1.58 kg ai ha^{-1}	atrazine	1.82 kg ai ha^{-1}
	bicyclopyrone	0.04 kg ai ha^{-1}	dicamba	0.14 kg ae ha^{-1}
	glyphosate	1.54 kg ae ha^{-1}	diflufenzopyr	0.056 kg ai ha^{-1}
	mesotrione	0.16 kg ai ha^{-1}	glyphosate	1.54 kg ae ha^{-1}
	S-metolachlor	1.43 kg ai ha^{-1}	S-metolachlor	0.35 kg ai ha^{-1}

[a]Abbreviations: POST = postermergence herbicide application.
[b]Cereal rye was either terminated two weeks before planting or at the time of corn planting. In 2019, corn planting was delayed due to wet weather, which also delayed the at-plant cereal rye termination.
[c]The POST application was made 2 to 4 weeks after corn planting at each site. For each site, all POST applications were made on the same day.
[d]Roundup Powermax®, Bayer, St. Louis, MO.
[e]Status®, BASF, Triangle Park, NC.
[f]Acuron®, Syntenta, Greensboro, NC.
[g]Bicep II Magnum®, Syngenta, Greensboro, NC.

Table 2.3: Weed species evaluated at each site.[a,b]

Site	Common name	Scientific name
TPAC	giant ragweed	*Ambrosia trifida* L.
	barnyardgrass	*Echinochloa crus-galli (L.) P. Beauv.*
	fall panicum	*Panicum dichotomiflorum Michx.*
	giant foxtail	*Setaria faberi Herrm.*
	large crabgrass	*Digitaria sanguinalis (L.) Scop.*
	yellow foxtail	*Setaria pumila (Poir.) Roem. & Schult.*
DPAC	waterhemp	*Amaranthus tuberculatus* (Moq.) J. D. Sauer
	barnyardgrass[b]	*Echinochloa crus-galli (L.) P. Beauv.*
	giant foxtail[b]	*Setaria faberi Herrm.*
	yellow foxtail[b]	*Setaria pumila (Poir.) Roem. & Schult.*
SEPAC	common cocklebur	*Xanthium strumarium* L.
	ivyleaf morningglory	*Ipomoea hederacea* Jacq.
	pitted morningglory	*Ipomoea lacunosa* L.
	barnyardgrass	*Echinochloa crus-galli (L.) P. Beauv.*
	fall panicum	*Panicum dichotomiflorum Michx.*
	giant foxtail	*Setaria faberi Herrm.*
	yellow foxtail	*Setaria pumila (Poir.) Roem. & Schult.*

[a]Abbreviations: DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W)
[b]Only present in 2019.

Table 2.4: Cover crop biomass at early and at-plant terminations for each site-year[a,b,c]

Year	Site	Early	At-plant	P-value
		kg ha^{-1}		
2018	TPAC	1260 b	3400 a	<0.001
	DPAC	1120 b	1710 a	<0.001
	SEPAC	3700 b	7080 a	<0.001
2019	TPAC	1300 b	6200 a	<0.001
	DPAC	540 b	2130 a	<0.001
	SEPAC	-[d]	-[d]	

[a]Abbreviations: TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W), DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W)

[b]Early termination was made two weeks before corn planting in 2019 and 4 to 5 weeks before corn planting in 2019. At-plant termination was made on the day of corn planting.

[c]Untransformed data are shown for clarity. Letters following values indicate statistical significance of log-transformed means within each year according to Tukey's HSD ($P \leq 0.05$).

[d]SEPAC 2019 was eliminated from the dataset as prolonged spring precipitation and wet soils prevented timely corn planting.

Table .2.5: Early-season weed biomass for each site-year at 2 to 5 weeks after corn planting and just before the POST herbicide' application. Data were pooled over 1 to 7 dominant species depending on location.[a,b]

Termination timing	Cover crop	Termination herbicide[c]	2018 TPAC[d]	2018 DPAC[e]	2018 SEPAC[f]	2019 TPAC[d]	2019 DPAC[e]	2019 SEPAC[g]
			g m^{-2}					
Early	Pooled	Pooled	18.6 a	20.0	14.7 a	83.3 a	126.9 a	-
At-plant			4.5 b	17.9	2.4 b	2.7 b	20.3 b	-
		P-value	<0.001	0.177	<0.001	<0.001	<0.001	-
Pooled	None	Pooled	15.0	22.6	14.6 a	49.8 a	76.6	-
	Cereal rye		8.1	16.2	2.6 b	36.2 b	70.6	-
		P-value	0.605	0.269	0.005	0.023	0.453	-
Pooled	Pooled	gly	20.9 a	39.8 a	15.9 a	67.2 a	101.5 a	-
		gly + residual	2.2 b	0.0 b	1.2 b	16.8 b	45.7 b	-
		P-value	<0.001	<0.001	<0.001	<0.001	<0.001	-
Pooled	None	gly	27.5 a	45.2 a	27.4 a	76.6 a	106.3 a	-
		gly + residual	2.6 b	0.0 b	1.6 b	23.1 b	46.9 b	-
	Cereal rye	gly	14.3 a	33.4 a	4.4 b	61.8 a	96.6 a	-
		gly + residual	2.0 b	0.0 b	0.8 b	10.6 c	44.5 b	-
		P-value	0.009	0.025	0.018	0.025	0.002	-
Early	Pooled	gly	34.3 a	42.6	27.6 a	133.2 a	166.9 a	-
		gly + residual	3.0 c	0.0	1.7 bc	33.4 b	86.8 b	-
At-plant		gly	7.6 b	37.7	4.1 b	5.2 c	36.0 c	-
		gly + residual	1.5 c	0.0	0.8 c	0.3 d	4.6 d	-
		P-value	0.008	0.144	<0.001	<0.001	<0.001	-

Table 2.5 (cont.)

Termination timing	Cover crop	Termination herbicide[c]	2018 TPAC[d]	2018 DPAC[e]	2018 SEPAC[f]	2019 TPAC[d]	2019 DPAC[e]	2019 SEPAC[g]
			g m^{-2}					
Early	None	Pooled	24.5	24.2	24.7	96.8	128.4	-
	Cereal rye		12.8	24.8	4.6	67.8	125.3	-
At-plant	None		5.3	20.9	4.4	2.9	24.4	-
	Cereal rye		3.5	14.8	0.5	2.6	15.7	-
		P-value	0.959	0.385	0.686	0.536	0.518	-
Early	None	gly	45.2	48.6	47.3	147.9	164.9 a	-
		gly + residual	3.8	0.0	2.1	45.8	92.0 b	-
	Cereal rye	gly	23.3	36.7	8.1	120.6	169.0 a	-
		gly + residual	2.2	0.0	1.2	21.0	81.6 b	-
At-plant	None	gly	9.8	41.9	7.5	5.4	47.7 b	-
		gly + residual	1.3	0.0	1.3	0.5	1.9 d	-
	Cereal rye	gly	5.3	29.5	0.6	5.2	24.2 c	-
		gly + residual	1.7	0.0	0.3	0.1	7.3 d	-
		P-value	0.975	0.521	0.681	0.805	0.001	-

[a]Abbreviations: TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W), DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), gly = glyphosate.

[b]Letters following values denote statistical significance of log-transformed data in each column according to Tukey's HSD ($P \leq 0.05$). Untransformed data are shown for clarity.

[c]Herbicides were applied 5 to 6 weeks before collection in 2018, and 6 to 7 weeks before collection in 2019, due to prolonged wet weather that delayed corn planting. Residual herbicide premix contains atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor.

[d]Weed species at TPAC in 2018 and 2019 include giant ragweed, barnyardgrass, fall panicum, giant foxtail, and yellow foxtail.

[e]In 2018, waterhemp was the only weed collected at DPAC. Barnyardgrass, giant foxtail, and yellow foxtail, and waterhemp were collected in 2019.

[f]Weed species collected at SEPAC in 2018 include barnyardgrass, common cocklebur giant foxtail, horseweed, morningglory spp. and yellow foxtail.

[g]SEPAC 2019 was eliminated from the data set as prolonged spring precipitation and excessive soil moisture prevented timely corn planting.

Table 2.6: Early-season summer annual grass density at for all site-years 2 to 5 weeks after corn planting, and just before the POST herbicide application. Data for the annual grass weed species were pooled over 3-5 dominant species depending on location.[a,b]

Termination timing	Cover crop	Termination herbicide[c]	2018 TPAC[d]	2018 DPAC[e]	2018 SEPAC	2019 TPAC	2019 DPAC	2019 SEPAC[e]
			Plants m^{-2}					
Early	Pooled	Pooled	39 a	-	48 a	67 a	98	-
At-plant			15 b	-	18 b	16 b	44	-
		P-value	0.039	-	0.003	<0.001	0.665	-
Pooled	None	Pooled	31	-	40	52 a	124	-
	Cereal rye		24	-	26	31 b	17	-
	P-value		0.622	-	0.720	0.165	0.852	-
Pooled	Pooled	gly	51 a	-	49 a	56 a	99	-
		gly + residual	3 b	-	17 b	26 b	43	-
		P-value	<0.001	-	0.008	<0.001	0.905	-
Early	None	Pooled	42	-	66	80	168	-
	Cereal rye		37	-	29	53	27	-
At-plant	None		20	-	14	23	81	-
	Cereal rye		10	-	22	8	7	-
		P-value	0.307	-	0.244	0.459	0.602	-
Early	Pooled	gly	74	-	72	82 a	115	-
		gly + residual	5	-	22	52 b	80	-
At-plant		gly	28	-	25	31 b	82	-
		gly + residual	2	-	11	1 c	5	-
		P-value	0.399	-	0.656	<0.001	0.601	-

Table 2.6 (cont.)

Termination timing	Cover crop	Termination herbicide[c]	2018 TPAC[d]	2018 DPAC[e]	2018 SEPAC[f]	2019 TPAC[g]	2019 DPAC[h]	2019 SEPAC[i]
			Plants m^{-2}					
Pooled	None	gly	57	-	68	77 a	180	-
		gly + residual	5	-	13	27 c	68	-
	Cereal rye	gly	45	-	31	35 b	17	-
		gly + residual	2	-	21	26 c	17	-
		P-value	0.718	-	0.263	0.009	0.384	-
Early	None	gly	77	-	110	109	205	-
		gly + residual	7	-	23	52	131	-
	Cereal rye	gly	71	-	38	54	26	-
		gly + residual	3	-	21	52	29	-
At-plant	None	gly	38	-	26	46	156	-
		gly + residual	3	-	2	2	5	-
	Cereal rye	gly	19	-	24	16	8	-
		gly + residual	1	-	21	0	5	-
		P-value	0.988	-	0.506	0.642	0.754	-

[a]Abbreviations: TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W), DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), gly = glyphosate, residual = residual herbicide premix.

[b]Untransformed means are shown in the table. Letters following values denote statistical significance of log-transformed means in each column, according to Tukey's HSD ($P \leq 0.05$).

[c]The residual herbicide premix is described in Table 2.2 and contains atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor.

[d]Annual grasses at TPAC in 2018 include barnyardgrass, fall panicum, giant foxtail, large crabgrass, and yellow foxtail

[e]Annual grass weeds were scarce at DPAC in 2018 and therefore not evaluated.

[f]Annual grass species at SEPAC in 2018 include barnyardgrass, fall panicum, giant foxtail, and yellow foxtail

[g]Annual grass species at TPAC in 2019 include barnyardgrass, fall panicum, giant foxtail, large crabgrass, and yellow foxtail

[h]Annual grass species at DPAC in 2019 include barnyardgrass, giant foxtail, and yellow foxtail

[i]SEPAC in 2019 was eliminated from the study, as prolonged spring precipitation and wet soils prevented timely corn planting.

Table 2.7: Early-season broadleaf weed densities at each site-year 2 to 5 weeks after corn planting.[a,b]

Termination timing	Cover crop	Termination herbicide[c]	2018 Giant ragweed[d]	2018 Waterhemp[e]	2018 *Ipomoea* spp.[f]	2018 Common cocklebur[f]	2019[g] Giant ragweed	2019[g] Waterhemp
			Plants m^{-2}					
Early	Pooled	Pooled	86	90	13	11	96 a	264 a
At-plant			71	85	13	5	42 b	70 b
		P-value	0.240	0.192	0.063	0.185	0.002	<0.001
Pooled	None	Pooled	46 b	89	23 a	11	81	119 b
	Cereal rye		110 a	86	3 b	5	57	215 a
		P-value	0.035	0.872	0.017	0.431	0.144	<0.001
Pooled	Pooled	gly	98 a	175 a	16	10	86 a	235 a
		gly + residual	58 b	0 b	11	6	53 b	98 b
		P-value	0.002	<0.001	0.916	0.522	<0.001	<0.001
Early	None	Pooled	53	80	21	15	102	177 a
	Cereal rye		119	101	5	6	90	61 c
At-plant	None		40	98	25	8	60	352 a
	Cereal rye		101	71	1	3	25	78 b
		P-value	0.878	0.141	0.931	0.327	0.052	0.020
Early	Pooled	gly	109	180	14	14	104 a	338 a
		gly + residual	62	0	13	7	88 a	190 ab
At-plant		gly	88	169	17	6	69 a	133 b
		gly + residual	54	0	9	5	16 b	7 c
		P-value	0.901	0.868	0.070	0.639	<0.001	<0.001

Table 2.7 (cont.)

Termination timing	Cover crop	Termination herbicide[c]	2018 Giant ragweed	2018 Waterhemp	2018 *Ipomoea* spp.	2018 Common cocklebur	2019[d] Giant ragweed	2019[d] Waterhemp
			Plants m^{-2}					
Pooled	None	gly	60	178	27	16	97 a	169 a
		gly + residual	33	0	20	7	64 bc	69 c
	Cereal rye	gly	137	172	4	4	75 ab	302 a
		gly + residual	83	0	2	5	40 c	128 b
		P-value	0.193	0.247	0.378	0.123	0.027	<0.001
Early	None	gly	70	160	20	22	101 a	217 a
		gly + residual	36	0	23	8	102 a	137 a
	Cereal rye	gly	148	201	7	6	106 a	460 a
		gly + residual	89	0	3	7	74 a	244 a
At-plant	None	gly	50	196	34	10	94 a	122 a
		gly + residual	30	0	17	6	25 ab	1 c
	Cereal rye	gly	126	142	1	2	44 a	143 a
		gly + residual	77	0	2	4	6 b	13 b
		P-value	0.926	0.704	0.052	0.545	0.027	<0.001

[a]Abbreviations: TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W), DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), gly = glyphosate, residual = residual herbicide premix.

[b]Untransformed means are shown in the table. Letters following values denote statistical significance of log-transformed means in each column, according to Tukey's HSD ($P \leq 0.05$).

[c]The residual herbicide premix is described in Table 2.2 and contains atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor.

[d]Giant ragweed was evaluated at TPAC in 2018 and 2019.

[e]Waterhemp was evaluated at DPAC in 2018 and 2019.

[f]Morningglory species and common cocklebur were evaluated at SEPAC in 2018.

[g]SEPAC in 2019 was eliminated from the study, as prolonged spring precipitation and wet soils prevented timely corn planting and other field operations.

Table 2.8: Late-season weed biomass. Data were pooled over 1 to 4 species depending on location[a,b]

Termination timing	Cover crop	Herbicide srategy[c]	2018 TPAC	2018 SEPAC	2019 TPAC	2019 SEPAC[d]
			g m^{-2}			
Early	Pooled	Pooled	1.9	8.2 b	6.5 a	-
At-plant			1.0	87.4 a	1.3 b	-
		P-value	0.072	0.002	<0.001	-
Pooled	None	Pooled	1.7	8.8 b	4.1	-
	Cereal rye		1.2	87.2 a	3.7	-
		P-value	0.856	0.016	0.843	-
Pooled	Pooled	NR	4.6 a	57.9	7.3 a	-
		PRE-R	1.0 b	56.8	1.6 b	-
		POST-R	0.1 bc	20.6	6.6 a	-
		PRE-POST-R	0.1 c	56.4	0.0 c	-
		P-value	<0.001	0.733	<0.001	-
Early	None	Pooled	2.1	3.6	5.0	-
	Cereal rye		1.6	14.0	8.0	-
At-plant	None		1.3	13.2	2.5	-
	Cereal rye		0.7	160.8	0.1	-
		P-value	0.768	0.496	0.143	-
Early	Pooled	NR	5.4 a	7.9	10.3 a	-
		PRE-R	1.8 b	6.1	3.0 b	-
		POST-R	0.1 c	14.6	12.4 a	-
		PRE-POST-R	0.1 c	5.1	0.3 c	-
At-plant	Pooled	NR	3.7 ab	107.9	4.3 bc	-
		PRE-R	0.1 c	107.6	0.2 c	-
		POST-R	0.2 c	26.5	0.9 c	-
		PRE-POST-R	0.1 c	107.7	0.0 c	-
		P-value	<0.001	0.565	0.002	-

Table 2.8 (cont.)

Termination timing	Cover crop	Herbicide strategy[c]	2018 TPAC	2018 SEPAC	2019 TPAC	2019 SEPAC[d]
			g m^{-2}			
Pooled	None	NR	5.0	16.3	7.6	-
		PRE-R	1.5	4.4	2.3	-
		POST-R	0.1	12.4	5.1	-
		PRE-POST-R	0.1	2.2	0.0	-
	Cereal rye	NR	4.2	99.6	7.0	-
		PRE-R	0.4	109.3	0.9	-
		POST-R	0.1	28.7	8.2	-
		PRE-POST-R	0.0	110.5	0.1	-
		P value	0.699	0.741	0.528	-
Early	None	NR	5.2	1.1	6.8 a	-
		PRE-R	2.9	1.6	4.3 abc	-
		POST-R	0.0	8.5	8.4 a	-
		PRE-POST-R	0.2	2.4	0.5 bc	-
	Cereal rye	NR	5.6	13.8	13.7 a	-
		PRE-R	0.8	10.6	1.7 ab	-
		POST-R	0.1	20.7	16.4 a	-
		PRE-POST-R	0.0	7.8	0.1 bc	-
At-plant	None	NR	4.7	30.5	8.4 abc	-
		PRE-R	0.1	7.2	0.2 bc	-
		POST-R	0.2	16.3	1.8 bc	-
		PRE-POST-R	0.1	2.1	0.0 bc	-
	Cereal rye	NR	2.7	185.3	0.3 bc	-
		PRE-R	0.1	208.1	0.2 bc	-
		POST-R	0.1	36.4	0.0 c	-
		PRE-POST-R	0.0	213.3	0.0 bc	-
		P-value	0.647	0.550	0.026	-

[a]Abbreviations: TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W), DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), gly = glyphosate, residual = residual herbicide premix, NR = no residual, PP-R = preplant residual, POST-R = POST residual, PP-POST-R = preplant + POST residual.

[b]Weeds were not evaluated at DPAC due to scarcity of weeds. Untransformed means are shown in the table. Letters following values denote statistical significance of log-transformed means in each column, according to Tukey's HSD ($P \leq 0.05$).

[c]The residual herbicide premix is described in Table 2.2 and contains atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor.

[d]SEPAC in 2019 was eliminated from the study, as prolonged spring precipitation and wet soils prevented timely corn planting.

Table 2.9: Late-season weed density. Data were pooled over 1 to 4 species depending on location[a,b]

Termination timing	Cover crop	Herbicide strategy[c]	2018 TPAC[d]	2018 SEPAC[e]	2019 TPAC[d]	2019 SEPAC[f]
			Plants m^{-2}			
Early	Pooled	Pooled	11 a	7	11 a	-
At-plant			7 b	10	3 b	-
		P-value	0.036	0.278	<0.001	-
Pooled	None	Pooled	9	5 b	7	-
	Cereal rye		9	11 a	7	-
		P-value	0.496	0.006	0.900	-
Pooled	Pooled	NR	28 a	9	13 a	-
		PRE-R	4 b	8	5 ab	-
		POST-R	1 b	9	8 a	-
		PRE-POST-R	1 b	6	1 b	-
		P-value	<0.001	0.517	0.002	-
Early	None	Pooled	10	4	10	-
	Cereal rye		12	10	12	-
At-plant	None		8	7	4	-
	Cereal rye		6	12	1	-
		P-value	0.703	0.229	0.173	-
Early	Pooled	NR	34	8	18 a	-
		PRE-R	6	5	10 ab	-
		POST-R	1	9	15 a	-
		PRE-POST-R	2	4	2 c	-
At-plant		NR	23	10	8 bc	-
		PRE-R	2	11	1 c	-
		POST-R	1	8	1 c	-
		PRE-POST-R	1	9	0 c	-
		P-value	0.343	0.679	0.030	-

Table 2.9 (cont.)

Termination timing	Cover crop	Herbicide strategy[c]	2018 TPAC[d]	2018 SEPAC[e]	2019 TPAC[d]	2019 SEPAC[f]
Pooled	None	NR	30	5	16	-
		PRE-R	3	3	7	-
		POST-R	1	9	6	-
		PRE-POST-R	1	3	1	-
	Cereal rye	NR	27	13	11	-
		PRE-R	5	13	4	-
		POST-R	2	8	10	-
		PRE-POST-R	1	10	1	-
		P-value	0.992	0.652	0.670	-
Early	None	NR	32	3	17	-
		PRE-R	5	1	12	-
		POST-R	1	8	10	-
		PRE-POST-R	1	2	2	-
	Cereal rye	NR	36	14	20	-
		PRE-R	7	10	8	-
		POST-R	2	10	20	-
		PRE-POST-R	2	6	2	-
At-plant	None	NR	29	8	15	-
		PRE-R	1	6	1	-
		POST-R	1	11	2	-
		PRE-POST-R	1	4	0	-
	Cereal rye	NR	17	12	1	-
		PRE-R	3	17	1	-
		POST-R	2	6	0	-
		PRE-POST-R	1	15	1	-
		P-value	0.619	0.828	0.547	-

[a]Abbreviations: TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), gly = glyphosate, residual = residual herbicide premix, NR = no residual, PRE-R = preplant residual, POST-R = POST residual, PRE-POST-R = preplant + POST residual.

[b]Data were not collected at DPAC due to a scarcity of weeds before corn harvest. Untransformed means are shown in the table. Letters following values denote statistical significance of log-transformed means in each column, according to Tukey's HSD ($P \leq 0.05$).

[c]The residual herbicide premix is described in Table 2.2 and contains atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor.

[d]Barnyardgrass, fall panicum, giant foxtail, and yellow foxtail were evaluated at TPAC in 2018 and 2019.

[e]Common cocklebur was evaluated at SEPAC in 2018.

[f]SEPAC in 2019 was eliminated from the study, as prolonged spring precipitation and wet soils prevented timely corn planting and other field operations.

Table 2.10: Corn yield at each site-year.

Termination timing	Cover crop	Herbicide strategy[c]	2018 TPAC	2018 DPAC	2018 SEPAC	2019 TPAC	2019 DPAC[d]	2019 SEPAC[d]
			kg ha^{-1}					
Early	Pooled	Pooled	16517	12185	7523 a	13010 b	-	-
At-plant			16434	11866	6652 b	14822 a	-	-
		P-value	0.777	0.428	0.033	0.013	-	-
Pooled	None	Pooled	16876	11727	9831 a	13263	-	-
	Cereal rye		16076	12324	4245 b	14569	-	-
		P-value	0.051	0.250	<0.001	0.103	-	-
Pooled	Pooled	NR	16509	11377	6626	12725	-	-
		PRE-R	15921	12415	8282	15295	-	-
		POST-R	16678	11868	6866	11865	-	-
		PRE-POST-R	16795	12441	6576	15779	-	-
		P-value	0.067	0.061	0.679	<0.001	-	-
Early	None	Pooled	16899	11829	9825	12098	-	-
	Cereal rye		16853	11624	9836	14428	-	-
At-plant	None		16135	12540	5221	13922	-	-
	Cereal rye		16016	12108	3468	15215	-	-
		P-value	0.902	0.602	0.101	0.443	-	-

Table 2.10 (cont.)

Termination timing	Cover crop	Herbicide strategy[c]	2018 TPAC	2018 DPAC	2018 SEPAC	2019 TPAC	2019 DPAC[d]	2019 SEPAC[d]
			kg ha^{-1}					
Early	Pooled	NR	16247	10933	6878	10577 b	-	-
		PRE-R	16169	12812	9235	15430 a	-	-
		POST-R	16657	12377	6986	10297 b	-	-
		PRE-POST-R	16996	12617	6994	15737 a	-	-
At-plant		NR	16771	11821	6373	14872 a	-	-
		PRE-R	15674	12019	7329	15161 a	-	-
		POST-R	16698	11358	6747	13433 a	-	-
		PRE-POST-R	16595	12266	6159	15821 a	-	-
		P-value	0.431	0.175	0.945	0.002	-	-
Pooled	None	NR	16838	11754	9040	11987	-	-
		PRE-R	16520	11483	12355	14602	-	-
		POST-R	17318	11641	9293	10595	-	-
		PRE-POST-R	16828	12028	8635	15869	-	-
	Cereal rye	NR	16179	11000	4211	13462	-	-
		PRE-R	15323	13348	4209	15988	-	-
		POST-R	16038	12094	4440	13134	-	-
		PRE-POST-R	16763	12854	4519	15690	-	-
		P value	0.269	0.384	0.596	0.373	-	-

Table 2.10 (cont.)

Termination timing	Cover crop	Herbicide strategy[c]	2018 TPAC	2018 DPAC	2018 SEPAC	2019 TPAC	2019 DPAC[d]	2019 SEPAC[e]
			kg ha^{-1}					
Early	None	NR	16468	11458	8695	9716	-	-
		PRE-R	16768	11682	13455	14406	-	-
		POST-R	17751	12047	8487	8507	-	-
		PRE-POST-R	16610	12130	8662	15764	-	-
	Cereal rye	NR	16026	10408	9386	11439	-	-
		PRE-R	15570	13942	11254	16454	-	-
		POST-R	15563	12707	10099	12087	-	-
		PRE-POST-R	17381	13103	8607	15710	-	-
At-plant	None	NR	17208	12049	5061	14258	-	-
		PRE-R	16272	11284	5014	14799	-	-
		POST-R	16885	11235	5484	14684	-	-
		PRE-POST-R	17045	11926	5326	15973	-	-
	Cereal rye	NR	16333	11593	3361	15486	-	-
		PRE-R	15075	12754	3404	15523	-	-
		POST-R	16512	11480	3395	14182	-	-
		PRE-POST-R	16145	12605	3712	15670	-	-
		P-value	0.099	0.891	0.851	0.794	-	-

[a]Abbreviations: TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W), DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), NR = no residual, PRE-R = preplant residual, POST-R = POST residual, PRE-POST-R = preplant + POST residual.

[b]To satisty statistical assumptions, data for SEPAC in 2018 were log-transformed. Untransformed data was analyzed for all other site-years. Untransformed data is shown for all site-years for clarity.

[c]Herbicide strategies are detailed in Table 2.2

[d]Data were compromised at DPAC in 2019, as the crop was damaged and improperly fertilized.

[e]SEPAC 2019 was eliminated from the dataset, since prolonged spring precipitation and wet soils prevented corn planting and other field operations.

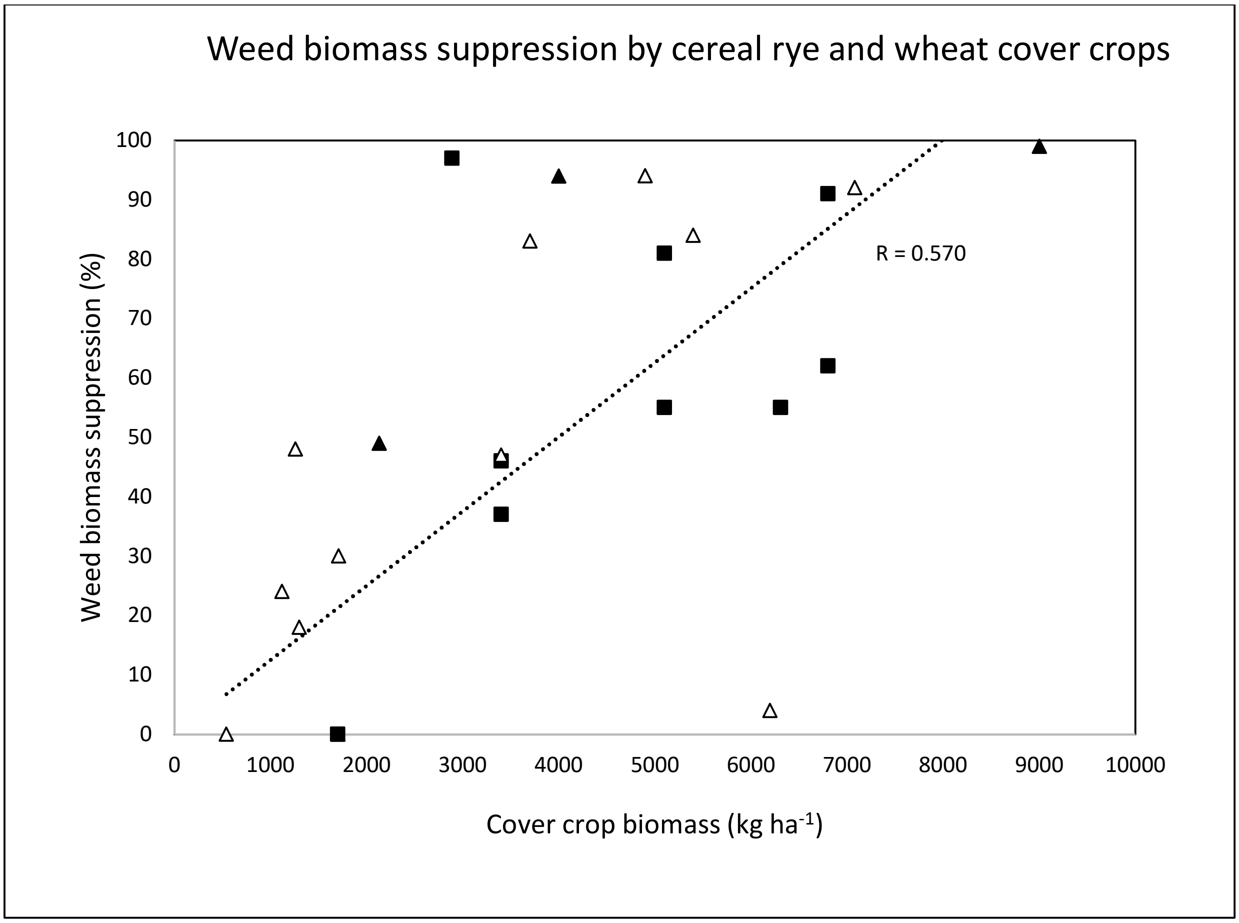

Figure 2.1: Weed biomass suppression by cereal rye and wheat cover crop residues in multiple studies. Data were taken from six studies and this study and plotted. Data were subjected to a regression analysis to determine an R value. Triangles represent data taken from studies carried out in Illinois, Indiana, and Michigan while square data points represent data taken from Nebraska. Unfilled symbols represent data taken from the research reported on in this manuscript, while filled symbols represent data taken from previously published research (Barnes and Putnam 1983, Crutchfield et al. 1985, Malik et al. 2008, Masiunas et al. 1995, Williams et al. 1998, Yenish et al. 1996).

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CHAPTER 3. IMPACT OF COVER CROP TERMINATION TIMING AND HERBICIDE DIVERSITY ON COVER CROP BIOMASS AND WEED CONTROL IN NO-TILL CORN

3.1 Abstract

Field experiments were conducted in 2017 and 2018 at three locations in Indiana to evaluate the effect of three termination timings of cereal rye (*Secale cereale* L.), crimson clover (*Trifolium incarnatum* L.), and a cereal rye-crimson clover mix on weed growth and corn (*Zea mays* L.) yield. Cover crops were terminated either two weeks before corn planting (early), at corn planting (at-plant), or two weeks after corn planting (late). Cereal rye and the cover crop mix were similar, and ranged from 490 to 5310 kg ha^{-1} terminated early, from 1800 to 8850 kg ha^{-1} terminated at-plant, and from 2220 to 10960 kg ha^{-1} terminated late. Crimson clover biomass ranged from 20 to 880 kg ha^{-1} terminate early, from 150 to 1480 kg ha^{-1} terminated at-plant, and from 320 to 2500 kg ha^{-1} terminated late. Early-season weed biomass was reduced by cover crops in three of six site-years, while early-season weed density was reduced in two of six site-years. The inclusion of dicamba and acetochlor at cover crop termination resulted in lower early-season weed density or biomass in two site-years. Late-season summer annual grass biomass was reduced when cereal rye or cover crop mix biomass was over 8000 kg ha^{-1} at termination. Late-season common cocklebur (*Xanthium strumarium* L.) density was 450 to 800% higher in treatments with cereal rye compared to crimson clover treatments. Including dicamba and acetochlor to the glyphosate and atrazine cover crop terminated resulted in better weed control in crimson clover, and early-terminated treatments. Compared to crimson clover treatments, corn yield was reduced by 23 to 67% in cereal rye and cover crop mix treatments in two out of three site-years in 2018; however, corn yield was not reduced by cereal rye or the cover crop mix in 2019 due to weed competition in early terminated and crimson clover treatments as a result of delayed corn planting. Overall, cereal rye and the cover crop mix were more weed suppressive, but also detrimental to corn yield compared to crimson clover when cover crop termination was delayed.

3.2 Introduction

3.2.1 Cover Crop Use in Corn

From 2012 to 2017, cover crop acreage in the US increased from 10.4 to 15.6 million acres (USDA 2017). In Indiana 8% of all corn (*Zea mays* L.) acres, or nearly 400,000 acres, are planted into cover crops (ISDA 2019). The increase in cover crop acreage is due in part to concerns about herbicide resistant weeds (CTIC 2017). Although many growers utilize cover crops to increase soil health, suppress weeds, and control erosion, cover crops may also cause yield loss in corn (Miguez and Bollero 2005). Proper cover crop termination is essential to benefit from cover crops while minimizing corn yield loss. Since various legume, brassica, and grass cover crops may interact with corn differently, it is important to determine appropriate termination herbicides and timing for each species.

3.2.2 Cover Crop Effects on Nitrogen Availability in Corn

Nitrogen mineralization from cover crop residue depends on multiple factors, including temperature, rainfall, plant residue C:N ratio, microbial activity, and nitrogen availability (Jahanzad et al. 2016). Cover crops with high C:N ratios, such as cereal rye and annual ryegrass (*Lolium multiflorum* Lam.), may not be able to supply sufficient mineralized nitrogen in time for corn uptake (Kuo and Jellum 2002). Due to its low C:N ratio, leguminous cover crop tissue decomposes faster than grass cover crop tissue, thus mineralizing nitrogen sooner (Ranells and Wagger 1996). Grass cover crops like cereal rye also deplete soil nitrogen more than leguminous cover crops (Shipley et al. 1992). For this reason, supplemental nitrogen fertilizer should be applied to corn if preceded by non-leguminous cover crops. The growth stage and biomass of cereal cover crops is also an important factor for nitrogen management. Martinez-Feria et al. (2016) observed that nitrogen in cereal rye terminated during vegetative stages was more readily mineralized than nitrogen in mature cereal rye. To optimize corn yield in cover crop systems, high-biomass, non-leguminous cover crops like cereal rye should be terminated at least one week before corn planting (Duiker and Curran 2005). Although leguminous cover crops can still cause corn yield reductions if terminated after corn planting, legumes are less likely than grass cover crops to cause corn yield loss (Parr et al. 2011).

3.2.3 Weed suppression by various cover crops in corn

Cereals are more weed suppressive than legumes. Yenish et al. (1996) observed that cereal rye from 4500 to 5100 kg ha^{-1} provided 50 to 67% weed control, while crimson clover from 3500 to 3700 kg ha^{-1} provided 34 to 47% weed control compared to a non-cover crop treatment in North Carolina. Ross et al. (2001) also observed greater weed suppression by cereal rye than crimson clover, even when cereal rye had less biomass, in Alberta. Mohler and Teasdale (1993) concluded that the more competitive nature of cereal rye compared to hairy vetch was due to the higher nitrogen levels under hairy vetch residue and the higher potential biomass of cereal rye compared to leguminous cover crops. Weeds that have a light requirement for germination are also more likely to be controlled by cover crops that produce higher biomass, such as cereal rye and wheat, compared to lower biomass cover crops (Teasdale 1993b). Ultimately, grass cover crops are associated with lower soil nitrogen, higher biomass, and increased light interception, compared to leguminous cover crops, which lead to increased weed suppression by grass cover crops.

3.2.4 Cover Crop Effects on Corn Yield

Winter annual grass cover crops generally produce higher biomass than leguminous cover crops and can lead to substantial yield loss if not terminated appropriately. Clark et al. (1994) observed that a cereal rye (*Secale cereale* L.) cover crop decreased corn yield by 26 to 28% when cereal rye biomass was 6390 to 7100 kg ha^{-1}, while hairy vetch (*Vicia villosa* L.) increased corn yields by 30 to 67% when biomass was 730 to 5190 kg ha^{-1} and no nitrogen fertilizer was applied. Moraes et al. (1993) also reported no yield loss from a hairy vetch cover crop, however cereal rye terminated 3 days before corn planting reduced yield by 34% with 196 kg N ha^{-1} applied at planting. Although many studies have observed no yield loss in corn from grass cover crops when nitrogen fertilizer was applied, grass cover crops and residues are generally more competitive with corn than leguminous cover crops (Miguez and Bollero 2005). However, yield loss may be due to factors other than nitrogen availability, including disease carryover, shading, insect pest shelter, and physical suppression (Acharya et al. 2017, Bakker et al. 2016).

3.2.5 Cover Crop Research

Developing strategies that maximize cover crop benefits such as erosion control, weed suppression, and soil health while preventing disease carryover, nutrient immobilization, and corn yield loss is important for corn growers utilizing cover crops in the Eastern Corn Belt. Cover crops used for weed suppression in corn need to be supplemented with residual and foliar herbicides. Research investigating the inclusion of additional herbicide modes of action at cover crop termination will allow growers to maximize weed control by cover crops and herbicides in corn production. For this reason, research on interactions between cover crops, soil nutrition, and chemical weed control is needed to understand the importance of proper cover crop termination in corn production.

The objective of this study is to assess the impact of two cover crop species and one cover crop mix on weed suppression and corn yield loss, when terminated before, during, or after corn planting. We hypothesize that delaying cover crop termination in corn will decrease corn yield and increase weed suppression. We also hypothesize that delaying termination of crimson clover will not decrease corn yield as much as cereal rye.

3.3 Materials and Methods

3.3.1 Experimental Design

Field studies were conducted in 2017 through 2018 and 2018 through 2019 at three locations in Indiana. The locations were Throckmorton Purdue Agricultural Center [(TPAC) (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W)], Davis Purdue Agricultural Center [(DPAC) (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W)], and Southeast Purdue Agricultural Center [(SEPAC) (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W)]. The calendar dates of corn planting, herbicide applications, and data collection are shown in Table 3.1. This experiment was a split-split-plot randomized complete block design. Main plots were three cover crop treatments, which were crimson clover, cereal rye, and a mix of cereal rye and crimson clover. Subplots were three termination timings, which were performed 2 weeks before, at, and 2 weeks after corn planting, which will be referred to as early, at-plant, and late terminations. In 2019, the early termination was performed 37 to 49 days before corn planting due to wet spring weather that prevented timely field operations and corn planting. Sub-subplots were three cover crop termination strategies.

Crimson clover (Dixie™, Cisco, Indianapolis, IN 46219), cereal rye (Elbon™, Cisco, Indianapolis, IN 46219), and a mix of cereal rye and crimson clover were selected based on regional popularity. Cereal rye (103 kg ha^{-1}), crimson clover (19 kg ha^{-1}), and the cover crop mix (74 kg ha^{-1}) were planted in late September to late October. The cover crop mix was comprised of 80% cereal rye seed and 20% crimson clover seed by weight. The three termination strategies were 1) glyphosate (1.54 kg ae ha^{-1}, Roundup Powermax®, Bayer, St. Louis, MO 63141) and atrazine (1.68 kg ai ha^{-1}, Aatrex®, Syngenta, Triangle Park, NC 27560), 2) glyphosate (1.54 kg ae ha^{-1}), atrazine (1.68 kg ai ha^{-1}), and dicamba (0.56 kg ae ha^{-1}, Clarity®, BASF, Triangle Park, NC 27560), or 3) glyphosate (1.54 kg ae ha^{-1}), atrazine (1.68 kg ai ha^{-1}), dicamba (0.56 kg ae ha^{-1}), and acetochlor (1.68 kg ha^{-1}, Warrant®, Bayer, St. Louis, MO 63141). Descriptions and rates of each termination herbicide are shown in Table 3.2.

All plots were planted with Smartstax® corn (DKC62-08RIB, Dekalb, Dekalb, IL 60115) in mid-May in 2018. Due to wet weather in the spring of 2019, planting was delayed until early to mid-June. Starter fertilizer at a rate of 34, 45, and 45 kg N ha^{-1} was applied at TPAC, DPAC and SEPAC, respectively. A side dress fertilizer application of 28% UAN was made near the V6 growth stage at rates of 159, 166, and 183 kg N ha^{-1} at TPAC, DPAC, and SEPAC, respectively.

A postemergence (POST) herbicide application was made two to five weeks after corn planting to all plots to control weeds that had emerged after or survived the termination application. Both termination and POST herbicide applications were made using a CO_2-pressurized backpack sprayer and a 2 m handheld boom. TTI 110015 nozzles (TeeJet Technologies, Urbandale, IA 50322) were used for applications containing dicamba, while flat fan XR 11002 nozzles (TeeJet Technologies, Urbandale, IA 50322) were used otherwise. The POST application was glyphosate (1.54 kg ae ha^{-1}) + atrazine (1.11 kg ai ha) + S-metolachlor (0.86 kg ai ha^{-1}, Bicep II Magnum®, Syngenta, Greensboro, NC) + dicamba + diflufenzopyr (0.14 + 0.056 kg ai ha^{-1}, Status®, BASF, Triangle Park, NC) after early-season weed biomass and density were evaluated.

3.3.2 Data Collection

Cover crop biomass was collected at cover crop termination by removing above-ground biomass from a 0.25 m^2 area from each sub-subplot (Table 3.3). Because crimson clover was winter-killed before the 2019 growing season and no residue was visible in the spring, crimson clover biomass was zero at all sites and did not contribute to weed suppression.

Two weed biomass and density evaluations were made during the growing season at each site-year: early-season and late-season. Calendar dates for each evaluation are shown in Table 3.1. Weed species evaluated at each site are shown in Table 3.2. For both early- and late-season evaluations, weeds from a 0.25 m^2 area in the front and back of the plot were counted and collected. All weed and cover crop biomass samples were oven-dried at 60 C for 48 hours before weighing.

Early-season weed biomass and density were evaluated for the dominant weed species at each site-year two to five weeks after corn planting, and just before the POST herbicide application. Biomass was summed over all species collected and is shown in Tables 3.4 through 3.6. Weed densities for all dominant species were pooled over all grass and broadleaf species and are shown in Tables 3.7 through 3.9. Summer annual grasses were evaluated at all six site-years. Giant ragweed (*Ambrosia trifida* L.) was evaluated at TPAC in 2018 and 2019. At DPAC, velvetleaf (*Abutilon theophrasti* Medik.) and waterhemp (*Amaranthus tuberculatus* (Moq.) J. D. Sauer) were evaluated in 2018, and only waterhemp was evaluated in 2019. Common cocklebur (*Xanthium strumarium* L.) and morningglory species (*Ipomoea* spp.) were evaluated at SEPAC in 2018 and 2019, however redroot pigweed (*Amaranthus retroflexus* L.) was also evaluated in 2019.

Late-season weed biomass and density were evaluated in mid-September to early October (Tables 3.11 through 3.16). Summer annual grasses were evaluated at TPAC in 2018 and 2019, as well as SEPAC in 2019. Common cocklebur was evaluated at SEPAC in 2018. No late-season evaluations were made at DPAC in 2018 because high levels of weed control resulted in very few weeds in all plots. Waterhemp and summer annual grasses were evaluated at DPAC in 2019.

Before the sidedress applications of nitrogen, soil samples were taken in 2019 to assess the effect of cover crops on nitrogen availability in the soil. Five 30 cm soil cores were taken from each termination timing in each cover crop four to six weeks after corn planting. Soil was dried, ground, and analyzed for extractable ammonium and nitrate.

Data were only collected from two main plots at SEPAC in 2019, due to flooding in the cover crop mix main plot that severely reduced corn stand and weed populations shortly after corn emergence. Data from the non-cover crop and cereal rye main plots were evaluated, but not from the cover crop mix main plot.

Corn was harvested with a plot combine once physiological maturity was reached from the middle two rows of each sub-subplot. Weight and grain moisture levels were recorded and standardized to 15.5% moisture.

3.3.3 Data Analysis

Data were analyzed using analysis of variance (ANOVA) by PROC GLIMMIX in SAS 9.4 (SAS, 100 SAS Campus Drive, Cary, NC 27513). Weed biomass and density data were log-transformed or square root-transformed to meet statistical assumptions. Untransformed data are shown in all tables and figures for clarity, while the statistical significance shown is of based on the log-transformed or square root-transformed data. The variables termination timing and termination herbicide were fixed effects, and cover crop treatments, as well as cover crop by replication and cover crop by replication by termination timing were set as random effects. A Satterthwaite denominator degree of freedom was utilized to produce an accurate approximation of F. Means were compared using Tukey's Honest Significant Difference (HSD) at a significance level of $\alpha = 0.05$. All site-years were analyzed separately due to a significant site-year interaction.

3.4 Results and Discussion

3.4.1 Cover Crop Biomass at Each Termination Timing

A cover crop by termination timing interaction was significant for each site-year (Table 3.3). Cover crop biomass increased from the early termination to the late termination for every site-year except for the cover crop mix at SEPAC in 2019. Most of the increase in cover crop biomass occurred from the early termination timing to the at-plant termination timing, and an increase in cover crop biomass was observed in 10 of 18 comparisons. No increases in cover crop biomass were observed from the at-plant termination timings to the late termination timings. This is likely because at-plant terminated cereal rye had already reached reproductive growth stages at the spring corn planting date and no longer produced biomass associated with vegetative growth. Cereal rye and the cover crop mix had more biomass than crimson clover at all termination timings. The crimson clover in the cover crop mix was mostly outcompeted by the cereal rye, and constituted a very small amount of the total cover crop biomass.

In April and May of 2018, average monthly temperatures were 6.7 and 20 C, respectively. Compared to 30-year averages, April was 3 C cooler and May was 2.5 C warmer. Precipitation in April and May at all sites was within 2 cm of the 30-year average at all sites.

In 2018, crimson clover biomass at the early termination for TPAC, DPAC, and SEPAC was 510, 20, and 880 kg ha^{-1}, respectively. By the late termination, crimson clover biomass had increased to 2330, 320, and 2500 kg ha^{-1} at TPAC, DPAC and SEPAC, respectively (Table 3.3). Crimson clover biomass at TPAC and SEPAC was similar to what was observed by Cornelius and Bradley (2017) and Creamer et al. (1996) in Missouri and Ohio, however biomass at DPAC was lower than in previously published literature.

Cereal rye and cover crop mix biomass averaged 4670, 1350, and 3700 kg ha^{-1} at TPAC, DPAC, and SEPAC, respectively. By the late termination, cereal rye and cover crop mix biomass increased to 7550, 2690, and 7080 kg ha^{-1} at TPAC, DPAC, and SEPAC, respectively. The lower biomass at DPAC was likely due to planting in late October, which was 16 to 19 days after planting at TPAC and SEPAC.

In 2019, spring precipitation was 4.5 to 7 cm above average through April and May at all sites. Average temperatures at all sites were within 1.5 C of 30-year averages. Early terminations were made 5 to 7 weeks before, instead of 2 weeks before the at-plant terminations, due to the prolonged wet soil conditions that prevented field operations and corn planting. Crimson clover biomass at all sites in 2019 was winter-killed, and data from crimson clover treatments in 2019 will be considered non-cover crop treatments, since no clover residue was visible in the spring. Wet spring soils and winter temperatures that had reached -23 C or lower at all sites could have contributed to the loss of the crimson clover.

Cereal rye and cover crop mix biomass were similar at every site in 2019. From the early termination timing to the late termination timing, biomass increased by 366, 237, and 72% at TPAC, DPAC, and SEPAC, respectively (Table 3.3).

Cereal rye and the cover crop mix biomass were similar within each termination timing at all sites in 2018 and 2019, even though the cereal rye seeding rate in the monoculture and the cover crop mix was 103 and 54 kg ha^{-1}, respectively. The similarity in cover crop biomass between cereal rye and the cover crop mix is supported by Boyd et al. (2009) and Ryan et al. (2011), who observed no differences in cereal rye biomass from seeding rates of 90 to 270 kg ha^{1}.

3.4.2 Early-Season Weed Biomass

Weed biomass two to five weeks after corn planting and just before the POST application is shown in Tables 3.4 through 3.6. Weed biomass was summed over all dominant weed species. The dominant weed species at each site are described in Table 3.2. Before the 2019 growing season, crimson clover was winter-killed, and was regarded as a non-cover crop treatment.

At TPAC in 2018, giant ragweed and summer annual grasses were evaluated. A cover crop by termination herbicide interaction and a termination timing by termination herbicide interaction were significant (Table 3.4). Weed biomass was lowest in cereal rye treatments for all termination herbicides, followed by the cover crop mix and then crimson clover. The cereal rye monoculture may have been more suppressive than the cover crop mix because of the higher seeding rate of cereal rye, even though biomass was similar for both. Boyd et al. (2009, Ryan et al. (2011) observed that weed biomass suppression by cereal rye increased as seeding rate increased from 90 to 270 kg ha^{-1}. Differences between termination herbicides were observed only in crimson clover, where the addition of dicamba and acetochlor to the termination herbicide decreased weed biomass by 73%, compared to the glyphosate plus atrazine treatment. Differences between termination herbicides in cereal rye and the cover crop mix may have not been observed because of the greater weed suppression in these treatments. Also, more atrazine and acetochlor may have reached the soil in crimson clover treatments due to increased herbicide interception in the cereal rye and cover crop mix. If most of the herbicide was retained by the residue, then weed control by the residual herbicides may have greatly decreased in the cereal rye and the cover crop mix, and the cover crop treatment would be more influential on early-season weed biomass. In 2019, two-way interactions between cover crop and termination herbicide, between termination herbicide and termination timing, and between cover crop and termination timing were significant (Table 3.4). Cereal rye and the cover crop mix terminated early did not reduce weed biomass compared to the non-cover crop treatments. In at-plant and late termination timings, weed biomass was 87 to 100% lower in cereal rye and cover crop mix treatments, compared to the non-cover crop treatments. The addition of acetochlor to the termination application reduced weed biomass in cereal rye and the cover crop mix by 72 and 56% compared to the non-cover crop treatment, respectively. Weed biomass was similar in all non-cover crop treatments, regardless of termination herbicide (Table 3.5).

At DPAC in 2018, waterhemp, velvetleaf, and summer annual grasses were evaluated. No interactions were significant, but termination timing and termination herbicide individually were significant (Table 3.5). Weed biomass was lowest in late terminated plots and highest in early terminated plots. This is likely due to the difference in the period of time between termination and evaluation. Early terminated treatments had two and four more weeks for weed emergence and growth to occur compared to at-plant and late terminated treatments, respectively. The addition of acetochlor to the termination application reduced weed biomass by 74 to 80%, compared to the other termination herbicides, probably because of the prevalence of grass weeds and waterhemp, a small-seeded broadleaf. The lack of weed biomass reduction by cereal rye and the cover crop mix was because of the low cover crop biomass relative to other site-years. In 2019, waterhemp and summer annual grasses were evaluated. Interactions between cover crop and timing, as well as termination herbicide and termination timing were significant (Table 3.5). The addition of dicamba and acetochlor reduced weed biomass in all termination timings by 70 to 91%, compared to the glyphosate + atrazine treatment. Weed biomass in early and at-plant termination was similar for all cover crop treatments, but for late terminated treatments, the cover crop mix reduced early-season weed biomass by 90%, compared to the non-cover crop treatments (Table 3.5). Cereal rye did not reduce weed biomass. It is unclear why weed biomass in the cover crop mix was lower than in cereal rye in late terminated treatments, however the experiment was conducted on a slight incline, which may have altered soil moisture and soil fertility between main plots.

At SEPAC in 2018, no interactions were significant, and termination timing as a main effect influenced weed biomass (Table 3.6). Compared to early terminations, delaying termination until corn planting and two weeks after corn planting reduced weed biomass by 74 to 81% (Table 3.6). In 2019, flooding in the cover crop mix main plot after corn emergence severely reduced corn stand and weed populations. Data were only collected from the cereal rye and non-cover crop treatments. A termination herbicide by termination timing interaction was significant. The late terminated plots had lower weed biomass than early termination plots for each termination herbicide, however the addition of dicamba or acetochlor to the termination herbicide did not result in lower weed biomass (Table 3.6).

Cereal rye and the cover crop mix were more suppressive of weed biomass than crimson clover in 2018 or the non-cover crop treatment in 2019, especially at later termination timings. This agrees with Ross et al. (2001), who reported cereal rye being more suppressive than clover cover crops. This suggests that the effects of residual herbicides and cereal rye on weed biomass are additive or synergistic on giant ragweed and summer annual grass biomass. The similar weed biomass in all cover crop treatments at DPAC and SEPAC demonstrate that residual herbicide efficacy on common cocklebur, morningglory species, and pigweed species is not altered by the type of cover crop. Currie and Klocke (2005) reported similar effects on Palmer amaranth (*Amaranthus palmeri* S. Watson) biomass when atrazine was applied to a wheat cover crop and to bare ground in Kansas. Carrera et al. (2004) also observed that weed biomass was similar on fallow ground and cereal rye and hairy vetch cover crops when atrazine was applied at planting in sweet corn. Overall, cover crop treatments that had cereal rye were more suppressive than crimson clover. The addition of dicamba to the termination herbicide had no effect on weed biomass, but the addition of acetochlor resulted in weed biomass reductions primarily in crimson clover and non-cover crop treatments, as well as early termination timings.

3.4.3 Early-Season Weed Density

Weed density two to five weeks after corn planting and just before the POST application is shown in Tables 3.7 through 3.9. Before the 2019 growing season, crimson clover was winter-killed, and was regarded as a non-cover crop treatment.

At TPAC in 2018, giant ragweed and summer annual grass density was evaluated. A cover crop by termination timing interaction and a cover crop by termination herbicide were significant. At every termination timing, weed density was similar in crimson clover and cover crop mix treatments, but was reduced by cereal rye (Table 3.7). The higher cereal rye seeding rate in the cereal rye monoculture compared to the cover crop mix may explain the lower weed densities in the cereal rye. Weed density was also lowest in cereal rye treatments when termination timing was pooled. The addition of acetochlor to the termination herbicide only reduced weed density in crimson clover plots. In 2019, summer annual grass density was evaluated, since giant ragweed was scarce. Interactions between cover crop and termination timing, as well as termination herbicide and termination timing, were significant. The cereal rye and cover crop mix treatments reduced grass density by 79 to 96% in at-plant and late terminations compared to the non-cover crop treatment, but not in early terminated treatments (Table 3.7). The lack of differences in suppression between cover crop treatments in the early terminated plots is likely because the time between the early termination timing and evaluation was at least two months at each site. During that time, the residual herbicides had more time to degrade compared to the at-plant and late termination timings, which resulted in increased weed emergence.

At DPAC in 2018, velvetleaf, waterhemp, and summer annual grasses were evaluated. No interactions were significant, but termination timing and termination herbicide were significant. Weed density in early terminated and at-plant terminated treatments was similar. Weed density in late terminated plots was 78 to 83% lower than early and at-plant terminated plots (Table 3.8). Including dicamba at termination did not result in lower weed density, but acetochlor reduced weed density by 77 to 83%, compared to the other termination herbicides. In 2019, waterhemp and summer annual grasses were evaluated. A two-way interaction between termination timing and termination herbicide was significant. The lowest weed density was observed at at-plant and late terminated treatments that also received dicamba and acetochlor along with glyphosate and atrazine. Within each termination timing, the addition of acetochlor to the termination herbicide reduced grass density (Table 3.8).

At SEPAC in 2018, common cocklebur, pitted morningglory, ivyleaf morningglory, and summer annual grass were evaluated. No interactions were significant, but termination timing was significant (Table 3.9). Total weed density was lower at later termination timings, probably because the period of time between termination and evaluation was shorter as termination was delayed, which would have resulted in less emergence. In 2019, common cocklebur, pitted morningglory, ivyleaf morningglory, redroot pigweed, and summer annual grasses were evaluated. Two-way interactions between termination herbicide and termination timing, as well as termination herbicide and cover crop were significant (Table 3.9). The addition of dicamba and acetochlor to the termination herbicide reduced weed density in cereal rye treatments but not in non-cover crop treatments.

The addition of acetochlor reduced weed density more often in crimson clover and non-cover crop treatments in all termination timings and in early terminated cereal rye and cover crop mix. Overall, early-season weed control with atrazine and acetochlor was not reduced by high cover crop biomass, compared to crimson clover and non-cover crop treatments. These results agree with Curran et al. (2016), who found that weed control by atrazine and *S*-metolachlor was similar in non-cover crop and cereal rye treatments. Burgos and Talbert (1996) also reported similar levels of redroot pigweed, palmer amaranth, large crabgrass (*Digitaria sanguinalis* (L.) Scop.), and goosegrass (*Eleusine indica* (L.) Gaertn.) control when atrazine and *S*-metolachlor were applied to hairy vetch, cereal rye and a non-cover crop treatment.

3.4.4 Soil Nitrogen in 2019

Soil nitrogen (N) was influenced by termination timing as a main effect at TPAC. When cover crop was pooled, soil N was 27.8, 24.0, and 20.6 kg ha^{-1} in early, at-plant, and late termination treatments, respectively (Table 3.10). The decrease in soil N as termination was delayed in the cereal rye and cover crop mix is probably due to the increased cover crop and weed biomass and the reduced time period for tissue decomposition and nitrogen mineralization. The reason for the decrease in soil N in the non-cover crop treatments as termination was delayed is likely due to the increased weed biomass in later terminations, which would have reduced the amount of available extractable soil N.

At DPAC, no interactions were observed, but cover crop was significant. Soil nitrogen was 21% lower in cereal rye treatments, compared to the fallow and cover crop mix treatments (Table 3.10). Since crimson clover was scarce in the cover crop mix, it is unlikely that crimson clover would have been responsible for the increase in soil nitrogen in the cover crop mix. The higher soil nitrogen in the cover crop mix main plot, even though biomass was similar, may have been due to a natural variation in soil fertility between plots.

At SEPAC, no interactions or main effects were significant (Table 3.10). Weed growth may have been faster in non-cover crop plots, which had more nitrogen. The increased weed growth in fallow plots would have minimized the difference in soil N between cover crop treatments.

The similarity between cover crop treatments at SEPAC and TPAC was also reported by Wayman et al. (2015), who observed similar soil-NO_3 concentration when cereal rye was terminated from late anthesis to the early milk stages. This contrasts with the decreased available soil nitrogen in cereal rye at DPAC and with Vyn et al. (2000), who reported a 31 to 36% decrease in soil-NO_3 from a wheat cover crop 30 to 35 days after corn planting.

3.4.5 Late-Season Weed Biomass

Weed biomass in mid-September to early October was collected at all site-years except for DPAC in 2018, since complete weed control was observed after the POST application in all treatments. Before the 2019 growing season, crimson clover was winter-killed, and was regarded as a non-cover crop treatment.

At TPAC, summer annual grass species were evaluated in both 2018 and 2019. In 2018, no interactions were observed, but cover crop was significant. Compared to crimson clover and the cover crop mix, cereal rye reduced grass biomass by 36% (Table 3.11). Cereal rye was more suppressive than the cover crop mix likely because the seeding rate of cereal rye in the monoculture was nearly twice as high as in the cover crop mix. Ryan et al. (2011) and Boyd et al. (2009) also observed that increasing cereal rye seeding rate resulted in lower weed biomass. In 2019, a three-way interaction between cover crop, termination herbicide, and termination timing was significant. Weed biomass was 0.1 g m^{-2} or less in all cereal rye and cover crop mix treatments when terminated at corn planting or after corn planting (Table 3.11). Since weed biomass and density was much higher in early terminated treatments, much of that weed biomass was from summer annual grasses that survived the POST herbicide application, due to herbicide interception and large weed size.

At DPAC in 2019, waterhemp and summer annual grasses were evaluated. No interactions were significant, but termination timing and termination herbicide were significant. Late-season weed biomass was highest in early terminated plots, compared to at-plant and late terminated plots (Table 3.12). Weed biomass was also lower when dicamba and acetochlor were included in the termination herbicide, compared to other termination herbicides. Weed biomass was lower in late terminated plots likely because the weed biomass was lower in those treatments prior to the POST herbicide application. The high waterhemp biomass in early terminated plots and plots that were not terminated using acetochlor had large weeds that survived the POST herbicide application. These larger waterhemp that survived the POST herbicide application were responsible for the increase in total late-season weed biomass.

At SEPAC in 2018, common cocklebur was evaluated. No interactions were significant, but cover crop and termination timing were significant. Late-season common cocklebur biomass increased 15-fold in cereal rye treatments, compared to crimson clover (Table 3.13). Biomass in the crimson clover mix was not significantly different from the cereal rye or the crimson clover. Delaying termination to after corn planting increased common cocklebur biomass 13-fold. In 2019, summer annual grasses were evaluated. No interactions or main effects were significant (Table 3.13). The POST herbicide application was made on July 8 in 2019, compared to June 5 in 2018. The later application date in 2019 would be more likely to control late-emerging common cocklebur.

Overall, late-season weed biomass was reduced by cover crop treatments that contained cereal rye at TPAC in 2018 and 2019. While late-season weed biomass in no-till cover crop corn systems has not been reported in published literature, studies investigating late-season weed control in soybean have reported increased weed control by cereal rye compared to a non-cover crop treatment (Bernstein et al. 2014, Thelen et al. 2004). The increase in common cocklebur biomass at SEPAC has not been previously reported in published literature. Differences in late-season weed biomass between termination herbicides at TPAC and DPAC in 2019 were likely not directly influenced by termination herbicides, but rather the difference in waterhemp, and summer annual grass biomass and the weed canopy at the POST herbicide application that led to survival of the POST herbicide application for some weeds.

3.4.6 Late-Season Weed Density

Weed density in mid-September to early October was evaluated at all site-years except for DPAC in 2018, since complete weed control was observed after the POST application in all treatments. Before the 2019 growing season, crimson clover was winter-killed, and was regarded as a non-cover crop treatment.

At TPAC in 2018 and 2019, summer annual grasses were evaluated. In 2018, no interactions were significant, but cover crop was significant. Compared to crimson clover, cereal rye and the cover crop mix reduced grass density by 82 and 55%, respectively (Table 3.14). Cereal rye was more suppressive than the cover crop mix. Even though cover crop biomass was similar for both the cover crop mix and the cereal rye monoculture, the cereal rye seeding rate was nearly twice as high for the cereal rye monoculture. The increased seeding rate may be why the monoculture was more suppressive. In 2019, a cover crop by termination timing interaction was significant. Grass density was similar in all early terminated plots and all non-cover crop plots. Grass density in at-plant and late terminated cereal rye and cover crop mix treatments was reduced by 90 to 98%, compared to all early terminated and non-cover crop treatments (Table 3.14). The reason for the high density in early terminated plots was probably because the high weed biomass at time of the POST herbicide application, which intercepted herbicide, and allowed some weeds to emerge before the residual herbicide reached the soil. This also may have been a result of increased herbicide leaching and degradation in early terminated plots because of the prolonged wet spring weather.

At DPAC in 2019, waterhemp and summer annual grasses were evaluated. No interactions were significant, but termination timing and termination herbicide were significant. Weed density was highest in early terminated plots and plots that did not receive acetochlor at termination (Table 3.15). The addition of acetochlor to the termination herbicide was not directly responsible for the lower late-season weed density. When acetochlor was applied at termination, early-season weed biomass and density were 70 and 67% compared to the glyphosate plus atrazine treatment, respectively. This difference in biomass and density resulted in some larger weeds, primarily waterhemp, surviving the POST herbicide application and being included in the evaluation.

At SEPAC in 2018, common cocklebur density was evaluated. No interactions were significant, but cover crop was significant. Compared to crimson clover, cereal rye and the cover crop mix increased common cocklebur density by 800 and 450%, respectively (Table 3.16). The increase in density may have occurred because of the changes in the soil conditions imposed by cover crop residue. Norsworthy and Oliveira (2007) reported that increased soil moisture and lower temperature fluctuations resulted in increased common cocklebur emergence. Since common cocklebur has no light requirement for germination, the soil conditions under cereal rye and the cover crop mix may have increased common cocklebur germination. In 2019, summer annual grasses were evaluated. No interactions or main effects were significant (Table 3.16). This may have been due to the lower cover crop biomass observed at SEPAC in 2019 compared to 2018.

3.4.7 Corn Yield

Differences in corn yield varied greatly between each year likely because of delayed corn planting in 2019. In 2019, the time period between the early termination and corn planting was extended from two weeks to five or six weeks at each site because of wet soils that prevented planting and other field operations. This allowed weeds to emerge and compete vigorously with corn before the POST application and survive well into the corn critical weed-free period.

At TPAC, a significant cover crop by termination timing interaction was seen in 2018 (Table 3.17). At-plant terminated cereal rye and late terminated cereal rye and cover crop mix treatments reduced yield compared to all early terminated treatments and crimson clover treatments. This suggests that of the three cover crop treatments, crimson clover may be terminated after corn planting without risk of corn yield loss. Terminated cover crops containing cereal rye two weeks before planting also optimized corn yield. At-plant and late termination of cereal rye led to 24 to 26% yield loss compared to early terminated treatments (Table 3.17). In 2019, a cover crop by termination timing interaction was also observed. Corn yield was lowest in early terminated non-cover crop treatments, however this was because of the high weed biomass in those plots before the POST herbicide application that stunted corn growth (Table 3.17). If corn planting would have been able to be performed earlier, yield loss would probably not have occurred in non-cover crop treatments.

At DPAC in 2018, a termination herbicide by termination timing interaction was significant. Corn yield was lowest in late terminated treatments when dicamba and acetochlor were included at termination (Table 3.18). Yield for all other treatments was similar. In 2019, a termination herbicide by termination timing interaction was also observed. When plots were terminated early without acetochlor, yields were reduced by 28% to 40%, compared to early termination with acetochlor (Table 3.18). Yields were similar in at-plant and late terminated treatments. Early terminated treatments that did not receive acetochlor at termination had higher weed biomass that competed with the corn before the POST application and resulted in decreased yields.

At SEPAC in 2018, a cover crop by termination timing interaction was significant. Compared to crimson clover treatments, both cereal rye and the cover crop mix at early, at-plant, and late termination timings reduced corn yield by 42, 55, and 70%, respectively (Table 3.19). Nutrient immobilization was only one factor in yield loss, as noticeable stand reductions occurred in at-plant and late terminations of cereal rye and the cover crop mix. Plots with stand reductions were replanted if corn populations were below 19,000 ha^{-1}, however replanting occurred in late June, and the replanted corn failed to fully canopy or produce full ears. Reasons for this stand reduction may include an increase in seedling disease incidence in cereal rye and the cover crop mix or planter inefficiencies that did not allow for proper seed depth or seed burial in high cover crop biomass. In 2019, no interactions were significant, but cover crop was significant. Data from the cover crop mix was discarded because of severe corn stand loss due to flooding after corn emergence. Cereal rye increased corn yield by 1000 kg ha^{-1} compared to the fallow treatments (Table 3.19). Reasons for the increase in corn yield may have been an increase in soil moisture because of the cereal rye residue. The soil was shaded, and the residue may have provided a wind-break in between corn rows, which would have increased soil moisture. Increases in soil moisture under cereal rye residue have been reported by Teasdale and Mohler (1993).

While corn yield reductions occurred at all site-years, yield reductions in 2019 were principally due to early-season weed competition and not directly because of cover crop suppression of corn. Yield reductions in 2018 at SEPAC were probably due to stand reduction. No significant stand reduction was observed at TPAC in 2018, which suggests that cereal rye biomass over 6000 kg ha^{-1} terminated at corn planting or later can reduce corn yield, even if corn stand is not reduced. Although Miguez and Bollero (2005) reported in a meta-analysis that corn yield was usually not reduced by grass cover crops if nitrogen fertilizer is applied, the results from TPAC in 2018 agree with Moraes et al. (1993), who reported a 34% corn yield reduction by cereal rye, even with proper nitrogen fertilization.

Growers using cover crops should terminate two weeks before planting corn to safely avoid corn yield loss, however if cover crop termination is delayed until corn planting or later, cover crop biomass of 6000 kg ha^{-1} at corn planting will significantly reduce yields. Crimson clover termination may be delayed. However, seed production did occur by two weeks after corn planting in 2018.

3.5 Conclusion

Cereal rye and cover crop mix biomass were similar at all site years, and ranged from 510 to 10960 kg ha^{-1} across all termination timings. Crimson clover was winter-killed in 2019, but biomass in 2018 ranged from 20 to 2500 kg ha^{-1}. The effect of each cover crop on early-season weed biomass and density was dependent on cover crop biomass and the weed species composition. Cereal rye and the cover crop mix are more suppressive than crimson clover, likely because of the higher biomass. Delaying cover crop termination increased the differences in weed biomass suppression between crimson clover and cereal rye. The inclusion of additional foliar and residual herbicides at cover crop termination may not result in increased weed control in cereal rye terminated at corn planting or later. Late-season grass density may be reduced if cover crop biomass is over 8000 kg ha^{-1} at termination. The increase in common cocklebur density was likely due to the change in soil conditions that resulted in increased emergence. Differences in corn yield by cover crop treatment in 2019 may have been obscured by weed competition with corn before the POST herbicide application. Overall, crimson clover may be terminated up to two weeks after corn planting without corn yield reduction with biomass up to 2500 kg ha^{-1}, while cereal rye above 6000 kg ha^{-1} should be terminated at least two weeks before corn planting to conserve corn yield.

Table 3.1: Dates of events in each site-year. Events include all data collections and herbicide applications. Weed collections were made before the POST herbicide application and one before corn harvest.[a]

Event	DPAC		SEPAC		TPAC	
	2018	2019	2018	2019	2018	2019
Cover crop planting	10/23/2017	10/22/2018	10/7/2017	10/1/2018	10/4/2017	10/3/2018
Cover crop early termination	5/5/2018	5/6/2019	4/30/2018	5/8/2019	4/26/2018	4/24/2019
Cover crop at-plant termination	5/19/2018	6/15/2019	5/14/2018	6/14/2019	5/10/2018	6/12/2019
Corn planting	5/19/2018	6/15/2019	5/14/2018	6/14/2019	5/10/2018	6/11/2019
Cover crop late termination	6/1/2018	6/21/2019	5/30/2018	6/22/2019	5/22/2018	6/19/2019
Weed biomass collection	6/20/2018	7/12/2019	6/4/2018	7/8/2019	6/15/2018	6/25/2019
POST application	6/20/2018	7/13/2019	6/5/2018	7/8/2019	6/16/2018	6/25/2019
Soil sampling	-[c]	7/16/2019	-	7/12/2019	-	6/25/2019
Weed biomass Collection	-[b]	10/10/2019	9/23/2018	10/7/2019	9/18/2018	10/4/2019

[a]Abbreviations: DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223), TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909).

[b]Weed biomass was not evaluated due to complete weed control in all treatments.

[c]Soil samples were not taken in 2018.

Table 3.2: Weed species evaluated in each site-year[a]

Site	Common name	Scientific name
TPAC	giant ragweed	*Ambrosia trifida* L.
	barnyardgrass	*Echinochloa crus-galli (L.) P. Beauv.*
	fall panicum	*Panicum dichotomiflorum* Michx.
	giant foxtail	*Setaria faberi* Herrm.
	large crabgrass	*Digitaria sanguinalis* (L.) Scop.
	yellow foxtail	*Setaria pumila* (Poir.) Roem. & Schult.
DPAC	waterhemp	*Amaranthus tuberculatus* (Moq.) J. D. Sauer
	barnyardgrass	*Echinochloa crus-galli (L.) P. Beauv.*
	giant foxtail	*Setaria faberi* Herrm.
	yellow foxtail	*Setaria pumila* (Poir.) Roem. & Schult.
	velvetleaf[b]	*Abutilon theophrasti* L.
SEPAC	common cocklebur	*Xanthium strumarium* L.
	ivyleaf morningglory	*Ipomoea hederacea* Jacq.
	pitted morningglory	*Ipomoea lacunose* L.
	barnyardgrass	*Echinochloa crus-galli (L.) P. Beauv.*
	fall panicum	*Panicum dichotomiflorum* Michx.
	giant foxtail	*Setaria faberi* Herrm.
	yellow foxtail	*Setaria pumila* (Poir.) Roem. & Schult.
	redroot pigweed[b]	*Amaranthus retroflexus* L.

[a]Abbreviations: DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W)
[b]Only present in 2018.

Table 3.3: Cover crop biomass at each termination timing at each site-year.[a,b]

		Termination timing[c]					
		2018			2019		
Site	Cover crop	Early	At-plant	Late	Early	At-plant	Late
		kg ha^{-1}					
TPAC	Crimson clover	510 e	1480 d	2330 d	0 c	0 c	0 c
	Cereal rye	5310 bc	6840 ab	8250 a	2250 b	8850 a	10000 a
	Cover crop mix	4020 c	6300 ab	6850 ab	2240 b	8130 a	10960 a
	P-value		<0.001			<0.001	
DPAC	Crimson clover	20 e	150 d	320 d	0 e	0 e	0 e
	Cereal rye	1540 c	2390 abc	4440 a	490 d	1800 bc	2220 ab
	Cover crop mix	1160 c	2990 ab	3700 ab	1030 cd	2670ab	2900 a
	P-value		<0.001			0.012	
SEPAC	Crimson clover	880 e	1230 de	2500 cd	0 c	0 c	0 c
	Cereal rye	3620 cd	6310 ab	6980 a	1640 b	3120 a	3600 a
	Cover crop mix	3770 bcd	5130 abc	7170 a	2750 ab	4300 a	3950 a
	P-value		0.026			0.019	

[a]Abbreviations: DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W)

[b]Letters following values denote statistical significance between means, according to Tukey's HSD ($P \leq 0.05$). Comparisons are made across cover crop treatment and termination timing for each year. Untransformed means are shown, but data were square root-transformed to satisfy statistical assumptions.

[c]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.4: Early-season weed biomass collected at Throckmorton Purdue Agricultural Center [(TPAC) (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W)] in 2018 and 2019[a,b,c,d]

		Termination timing[e]							
		2018				2019			
Cover crop[f]	Termination herbicide	Early	At-plant	Late	Pooled	Early	At-plant	Late	Pooled
		g m^{-2}							
Pooled	Pooled	8.9 a	4.9 b	1.3 c		80.6 a	2.0 b	1.3 c	
	P-value		<0.001				<0.001		
Clover	Pooled	14.3	9.7	2.5	8.8 a	144.8 a	4.5 b	3.8 b	51.0 a
Cereal rye		2.0	0.4	0.2	5.3 a	49.8 a	0.6 c	0.0 c	16.8 b
Mix		10.4	4.5	1.0	0.8 b	47.2 a	0.1 c	0.0 c	16.1 b
	P-value		0.067		<0.001		0.002		<0.001
Pooled	gly + atz	10.4 a	7.0 ab	2.0 de	6.5 a	101.5 a	2.6 b	0.6 c	34.9 a
	gly + atz + dba	8.2 a	4.8 ab	1.4 cd	4.8 a	87.7 a	2.2 b	1.0 c	30.3 a
	gly + atz + dba + act	8.0 a	2.9 bc	0.3 e	3.7 b	56.2 a	1.4 c	1.2 c	18.7 b
	P-value		0.013		0.018		0.004		<0.001
Clover	gly + atz	22.3	17.1	4.6	14.7 a	174.6	6.2	1.6	60.8 a
	gly + atz + dba	14.3	6.5	2.8	7.9 ab	60.4	0.2	0.1	52.0 a
	gly + atz + dba + act	6.2	5.4	0.0	3.9 c	69.5	1.5	0	40.2 a
Cereal rye	gly + atz	2.2	0.4	0.0	0.9 d	149.8	3.2	3.1	20.2 bc
	gly + atz + dba	0.6	0.6	0.4	0.6 d	72.3	1.6	0	24.6 bc
	gly + atz + dba + act	3	0.4	0.1	1.2 d	41.0	1.5	0	5.6 d
Mix	gly + atz	6.9	3.4	1.3	3.9 bc	110.0	4.1	6.6	23.7 b
	gly + atz + dba	9.6	7.3	1	6.0 abc	16.8	0.0	0	14.2 d
	gly + atz + dba + act	14.6	2.8	0.8	6.1 bc	31.1	0.1	0	10.4 cd
	P-value		0.063		<0.001		0.064		0.012

Table 3.4 (cont.)

[a]Abbreviations: gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Weed species include giant ragweed and summer annual grasses (barnyardgrass, fall panicum, giant foxtail, large crabgrass, and yellow foxtail). Summer annual grasses comprised nearly all weed species in 2019.
[c]Untransformed data are shown for clarity. Letters following values denote statistical significance of log-transformed data within each year, according to Tukey's HSD ($P \leq 0.05$).
[e]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.
[f]In 2019, crimson clover was winter-killed before the growing season, and was considered a non-cover crop (NC) treatment.

Table 3.5: Early-season weed biomass collected at Davis Purdue Agricultural Center [(DPAC) (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W)] in 2018 and 2019[a,b,c,d]

		Termination timing[d]							
		2018				2019			
Cover crop	Termination herbicide	Early	At-plant	Late	Pooled	Early	At-plant	Late	Pooled
		g m^{-2}							
Pooled	Pooled	7.9 a	1.9 b	0.1 c		128.2 a	23.5 b	9.9 c	
	P-value	<0.001				<0.001			
Clover	Pooled	6.9	1.3	0.1	2.8	119.8 ab	36.7 abc	17.4 c	58.0
Cereal rye		10.0	3.2	0.1	4.4	127.9 a	19.4 bc	10.4 cd	52.6
Mix		6.7	1.2	0.1	2.7	136.9 a	14.4 cd	1.8 d	51.0
	P-value	0.242			0.145	<0.001			0.207
Pooled	gly + atz	14.0	3.4	0.2	5.9 a	169.0 a	48.0 b	24.7 c	80.6 a
	gly + atz + dba	6.7	2.2	0.1	3.0 a	165.7 a	18.0 c	3.5 d	62.4 b
	gly + atz + dba + act	3.0	0.0	0.0	1.0 b	49.9 b	4.5 d	1.4 e	18.6 c
		0.066			<0.001	<0.001			<0.001
Clover	gly + atz	10.8	0.6	0.3	4.0	175	77.5	43.6	98.7
	gly + atz + dba	5.9	3.3	0.0	3.1	152.9	24.9	5.8	61.2
	gly + atz + dba + act	4.0	0.0	0.0	1.3	31.4	7.8	2.8	14.0
Cereal rye	gly + atz	16.7	7.9	0.2	8.3	162.5	34.4	26.5	74.5
	gly + atz + dba	8.4	1.7	0.0	3.4	174.5	20.5	3.4	66.1
	gly + atz + dba + act	4.9	0.1	0.0	1.7	46.7	3.4	1.2	17.1
Mix	gly + atz	14.5	0.1	0.2	5.5	169.4	32.1	3.9	68.5
	gly + atz + dba	5.6	1.6	0.2	2.5	169.6	8.7	1.3	59.8
	gly + atz + dba + act	0.0	0.0	0.0	0.0	71.6	2.4	0.2	24.7
	P-value	0.347			0.100	0.280			0.726

Table 3.5 (cont.)

[a]Abbreviations: gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Weed species evaluated include waterhemp and summer annual grasses (barnyardgrass, giant foxtail, and yellow foxtail). Velvetleaf was also evaluated in 2018.
[c]Untransformed data are shown for clarity. Letters following values denote statistical significance of log-transformed data within each year, according to Tukey's HSD ($P \leq 0.05$).
[d]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.6: Early-season weed biomass collected at Southeast Purdue Agricultural Center [(SEPAC) (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W) in 2018 and 2019[a,b,c,d]

		Termination timing[e]							
		2018				2019			
Cover crop	Termination herbicide	Early	At-plant	Late	Pooled	Early	At-plant	Late	Pooled
		Plants m^{-2}							
Pooled	Pooled	7.2 a	1.9 b	1.4 c		69.5 a	24.9 b	8.1 c	
	P-value	<0.001				<0.001			
Clover	Pooled	7.1	2.2	1.6	3.6	70.2	40.4	8.4	39.6
Cereal rye		9.3	2.1	1.3	4.3	68.9	9.5	7.8	28.7
Mix		5.2	1.4	1.1	2.6	-[d]	-	-	-
	P-value	0.729			0.172	0.091			0.132
Pooled	gly + atz	7.8	1.7	0.8	3.5	107.1 a	15.5 c-f	8.3 ef	43.6
	gly + atz + dba	7.2	2.8	2.4	4.1	60.0 ab	34.1 bcd	9.9 def	34.7
	gly + atz + dba + act	6.7	1.2	0.9	2.9	41.5 abc	25.2 b-e	6.1 f	24.3
		0.777			0.404	0.035			0.205
Clover	gly + atz	8.9	1.4	1.0	3.7	98.8	20.5	5.5	41.6 a
	gly + atz + dba	5.9	4.1	3.7	4.5	72.7	60.0	11.5	48.1 a
	gly + atz + dba + act	6.5	1.1	0.2	2.6	39.0	40.6	8.3	25.3 a
Cereal rye	gly + atz	8.1	2.6	0.5	3.8	115.4	10.4	11.1	45.6 a
	gly + atz + dba	11.4	2.6	2.4	5.5	47.3	8.2	8.3	21.2 a
	gly + atz + dba + act	8.5	1.2	1.0	3.5	44.0	9.8	3.9	19.2 a
Mix	gly + atz	6.4	1.2	0.9	2.9	-[d]	-	-	-
	gly + atz + dba	4.3	1.7	1.7	2.4	-	-	-	-
	gly + atz + dba + act	5.0	1.3	1.3	2.6	-	-	-	-
	P-value	0.719			0.525	0.611			0.064

Table 3.6 (cont.)

[a]Abbreviations: gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Weed species include giant ragweed and summer annual grasses (barnyardgrass, fall panicum, giant foxtail, large crabgrass, and yellow foxtail). Summer annual grasses comprised nearly all weed species in 2019.
[c]Untransformed data are shown for clarity. Letters following values denote statistical significance of log-transformed data within each year, according to Tukey's HSD ($P \leq 0.05$).
[d]Weed biomass was not evaluated in the cover crop mix main plot, since flooding in the cover crop mix main plot severely reduced corn stand and weed populations before evaluation.
[e]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.7: Early-season total weed density at Throckmorton Purdue Agricultural Center [(TPAC) (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W)] in 2018 and 2019[a,b,c,d]

		Termination timing[d]							
		2018				2019			
Cover crop	Termination herbicide	Early	At-plant	Late	Pooled	Early	At-plant	Late	Pooled
		Plants m^{-2}							
Pooled	Pooled	92 a	69 b	31 c		272 a	137 b	21 c	
	P-value		<0.001				<0.001		
Clover	Pooled	125 a	129 a	44 b	99 a	300 a	301 a	57 bc	219 a
Cereal rye		39 b	8 c	7 c	18 b	355 a	49 cd	3 d	136 b
Mix		112 a	70 ab	43 b	75 a	162 ab	62 cd	2 d	75 b
	P-value		0.015		<0.001		<0.001		<0.001
Pooled	gly + atz	85	86	36	69 ab	324 a	243 ab	26 c	197 a
	gly + atz + dba	106	69	43	73 a	337 a	149 b	20 c	169 a
	gly + atz + dba + act	83	53	15	50 b	156 b	19 c	16 c	62 b
	P-value		0.232		0.013		0.003		<0.001
Clover	gly + atz	121	186	63	123 a	323	573	63	328
	gly + atz + dba	171	119	55	115 a	411	270	58	247
	gly + atz + dba + act	83	82	15	60 b	144	56	47.5	83
Cereal rye	gly + atz	51	10	1	20 c	402	28	9	154
	gly + atz + dba	21	9	18	15 c	443	112	0	190
	gly + atz + dba + act	45	6	4	18 c	180	1	2	63
Mix	gly + atz	84	61	44	63 ab	196	121	4	111
	gly + atz + dba	128	78	57	88 ab	137	61	2	69
	gly + atz + dba + act	123	70	28	74 ab	125	1	0	46
	P-value		0.329		0.015		0.086		0.135

Table 3.7 (cont.)

[a]Abbreviations: gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Weed species evaluated include giant ragweed and summer annual grasses (barnyardgrass, fall panicum, giant foxtail, large crabgrass, and yellow foxtail). Only summer annual grasses were evaluated in 2019.
[c]Untransformed data are shown for clarity. Letters following values denote statistical significance of log-transformed data within each year, according to Tukey's HSD ($P \leq 0.05$).
[d]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.8: Early-season total weed density at Davis Purdue Agricultural Center [(6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W)] in 2018 and 2019[a,b,c]

		Termination timing[d]							
		2018				2019			
Cover crop	Termination herbicide	Early	At-plant	Late	Pooled	Early	At-plant	Late	Pooled
		Plants m^{-2}							
Pooled	Pooled	30 a	23 a	5 b		248 a	128 b	78 c	
	P-value	<0.001				<0.001			
Clover	Pooled	25	4	2	10	235	141	92	156
Cereal rye		39	45	6	30	227	132	95	151
Mix		25	19	7	17	281	111	47	146
	P-value	0.310			0.067	0.056			0.748
Pooled	gly + atz	40	41	9	30 a	295 ab	226 abc	155 bcd	225 a
	gly + atz + dba	37	24	6	22 a	347 a	136 bcd	66 d	183 a
	gly + atz + dba + act	12	3	0	5 b	100 cd	22 e	13 e	45 b
	P-value	0.677			<0.001	0.006			<0.001
Clover	gly + atz	25	4	2	10	286	258	195	246
	gly + atz + dba	46	9	5	20	336	137	62	178
	gly + atz + dba + act	4	0	0	1	82	28	19	43
Cereal rye	gly + atz	52	93	14	53	350	226	178	251
	gly + atz + dba	40	35	3	26	251	145	93	164
	gly + atz + dba + act	27	7	0	11	80	22	15	39
Mix	gly + atz	44	28	12	28	250	195	92	179
	gly + atz + dba	26	29	9	21	455	123	43	207
	gly + atz + dba + act	6	1	0	2	138	16	7	54
	P-value	0.576			0.260	0.527			0.622

Table 3.8 (cont.)

[a]Abbreviations: NC = non-cover crop, gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Weed species include giant ragweed and summer annual grasses (barnyardgrass, fall panicum, giant foxtail, large crabgrass, and yellow foxtail). Summer annual grasses comprised nearly all weed species in 2019.
[c]Untransformed data are shown for clarity. Letters following values denote statistical significance of log-transformed data within each year, according to Tukey's HSD ($P \leq 0.05$).
[d]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.9: Early-season total weed density at Southeast Purdue Agricultural Center [(SEPAC) (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W)] in 2018 and 2019[a,b,c]

		Termination timing[e]							
		2018				2019			
Cover crop	Termination herbicide	Early	At-plant	Late	Pooled	Early	At-plant	Late	Pooled
		Plants m^{-2}							
Pooled	Pooled	109 a	40 b	11 c		158 a	161 a	96 b	
	P-value	<0.001				<0.001			
Clover	Pooled	93	24	4	40	154	181	77	137
Cereal rye		130	64	18	71	163	140	114	139
Mix		104	31	12	49	-	-	-	-
	P-value	0.761			0.053	0.067			0.949
Pooled	gly + atz	115	45	15	58	189 a	220 a	129 ab	179 a
	gly + atz + dba	117	42	6	55	144 ab	170 ab	115 ab	143 a
	gly + atz + dba + act	96	32	13	47	141 ab	93 b	43 c	92 b
	P-value	0.517			0.459	0.017			<0.001
Clover	gly + atz	111	34	3	49	163	210	97	156 a
	gly + atz + dba	109	14	2	41	146	212	93	150 a
	gly + atz + dba + act	61	26	6	31	152	123	41	105 ab
Cereal rye	gly + atz	142	78	28	83	216	230	162	202 a
	gly + atz + dba	117	72	10	66	143	128	137	136 a
	gly + atz + dba + act	132	44	17	64	130	62	45	79 b
Mix	gly + atz	91	25	14	43	[d]-	-	-	-
	gly + atz + dba	125	42	6	57	-	-	-	-
	gly + atz + dba + act	97	28	16	47	-	-	-	-
	P-value	0.499			0.656	0.730			0.033

Table 3.9 (cont.)

[a]Abbreviations: NC = non-cover crop gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Weed species evaluated include common cocklebur, ivyleaf morningglory, pitted morningglory, and summer annual grasses (barnyardgrass, fall panicum, giant foxtail, and yellow foxtail). Redroot pigweed was also evaluated in 2019.
[c]Untransformed data are shown for clarity. Letters following values denote statistical significance of log-transformed data within each year, according to Tukey's HSD ($P \leq 0.05$).
[d]Weed biomass was not evaluated in the cover crop mix main plot, since flooding in the cover crop mix main plot severely reduced corn stand and weed populations before evaluation.
[e]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.10: Soil nitrogen at each site in 2019 before the sidedress N application[a]

Cover crop	Termination timing[b]	TPAC	DPAC	SEPAC
			kg N ha^{-1}	
Clover	Pooled	23.8	36.7 a	19.6
Cereal Rye		24.5	29.1 b	18.3
Mix		24.1	37.0 a	-
	P-value	0.853	0.047	0.613
Pooled	Early	27.8 a	31.9	18.6
	At-plant	24.0 b	37.4	17.7
	Late	20.6 c	33.6	20.7
	P-value	<0.001	0.266	0.376
Clover	Early	27.0	34.5	20.0
	At-plant	24.2	37.4	16.3
	Late	19.9	38.2	22.7
Cereal rye	Early	30.6	29.2	17.2
	At-plant	22.9	29.3	19.1
	Late	20.2	28.9	18.7
Mix	Early	25.9	31.9	-
	At-plant	24.7	45.5	-
	Late	21.8	33.6	-
	P-value	0.268	0.430	0.270

[a]Abbreviations: DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W), NC = non-cover crop.

[b]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.11: Late-season weed biomass collected at Throckmorton Purdue Agricultural Center [(TPAC) (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W)] in 2018 and 2019[a,b,c,d]

		Termination timing[d]							
		2018				2019			
Cover crop	Termination herbicide	Early	At-plant	Late	Pooled	Early	At-plant	Late	Pooled
		g m^{-2}							
Pooled	Pooled	0.7	0.9	1.3		16.8 a	0.6 b	0.8 b	
	P-value		0.746				<0.001		
Clover	Pooled	1.5	0.6	1.4	1.1 a	35.4	1.6	2.2	13.1 a
Cereal rye		0.2	1.6	0.3	0.7 b	10.4	0.0	0.0	3.5 b
Mix		0.5	0.6	2.2	1.1 a	4.7	0.1	0.1	1.6 b
	P-value		0.744		0.001		0.387		<0.001
Pooled	gly + atz	0.8	0.4	0.3	0.5	18.7 a	0.6 bc	0.5 bc	6.8 a
	gly + atz + dba	0.8	1.8	2.3	1.6	20.2 a	0.5 bc	1.2 bc	7.3 a
	gly + atz + dba + act	0.7	0.6	1.2	0.8	11.7 b	0.0 c	0.5 c	4.1 b
	P-value		0.183		0.082		0.010		<0.001
Clover	gly + atz	1.7	0.4	0.7	1.0	30.2 ab	3.5 a-d	1.5 b-f	11.7
	gly + atz + dba	1.3	0.8	2.7	1.6	42.0 a	1.1 b-f	3.5 abc	15.5
	gly + atz + dba + act	1.4	0.4	1.7	0.8	34.0 ab	0.1 c-f	1.6 b-f	11.9
Cereal rye	gly + atz	0.1	0.0	0.0	0.0	23.4 ab	0.0 ef	0.1 def	7.8
	gly + atz + dba	0.5	3.9	0.3	1.6	7.4 ab	0.1 ef	0.0 ef	2.5
	gly + atz + dba + act	0.1	0.9	0.7	0.6	0.3 c-f	0.1 ef	0.0 ef	0.1
Mix	gly + atz	0.5	0.8	0.1	0.5	2.4 b-e	0.0 ef	0.0 ef	0.8
	gly + atz + dba	0.5	0.5	4.0	1.7	11.1 ab	0.1 c-f	0.1 c-f	3.8
	gly + atz + dba + act	0.5	0.5	2.4	1.1	0.7 b-f	0.0 ef	0.0 f	0.2
	P-value		0.309		0.114		0.049		0.573

Table 3.11 (cont.)

[a]Abbreviations: NC = non-cover crop gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Weed species evaluated include barnyardgrass, fall panicum, giant foxtail, and yellow foxtail.
[c]Untransformed data are shown for clarity. Letters following values denote statistical significance of log-transformed data within each year, according to Tukey's HSD ($P \leq 0.05$).
[d]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.
[d]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.12: Late-season weed biomass collected at Davis Purdue Agricultural Center [(6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W)] in 2019[a,b,c]

		Termination timing[d]			
Cover crop	Termination herbicide	Early	At-plant	Late	Pooled
		g m^{-2}			
Pooled	Pooled	43.4 a	10.4 b	2.1 c	
	P-value	<0.001			
Clover	Pooled	45.1	22.3	3.8	23.7
Cereal rye		34.4	6.4	2.1	14.3
Mix		50.7	2.6	0.4	17.9
	P-value	0.344			0.141
Pooled	gly + atz	55.6	17.7	3.6	25.6 a
	gly + atz + dba	65.8	12.8	2.3	27.0 a
	gly + atz + dba + act	8.9	0.8	0.3	3.3 b
	P-value	0.330			<0.001
Clover	gly + atz	41.7	44.2	9.2	31.7
	gly + atz + dba	86.3	22.3	1.4	36.7
	gly + atz + dba + act	7.4	0.3	0.7	2.8
Cereal rye	gly + atz	51.2	3.3	1.3	18.6
	gly + atz + dba	41.3	15.7	4.9	20.6
	gly + atz + dba + act	10.7	0.2	0.0	3.6
Mix	gly + atz	73.8	5.5	0.4	26.6
	gly + atz + dba	69.8	0.4	0.7	23.6
	gly + atz + dba + act	8.6	1.9	0.1	3.6
	P-value	0.457			0.349

[a]Abbreviations: NC = non-cover crop gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Weed species evaluated include waterhemp and summer annual grasses (barnyardgrass, giant foxtail, and yellow foxtail).
[c]Untransformed data are shown for clarity. Letters following values denote statistical significance of log-transformed data within each year, according to Tukey's HSD ($P \leq 0.05$).
[d]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.13: Late-season weed biomass collected at Southeast Purdue Agricultural Center [(SEPAC) (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W)] in 2018 and 2019[a,b,c,d]

		Termination timing[e]							
		2018				2019			
Cover crop	Termination herbicide	Early	At-plant	Late	Pooled	Early	At-plant	Late	Pooled
		g m^{-2}							
Pooled	Pooled	8.5 b	50.9 ab	120.2 a		5.7	6.3	4.8	
	P-value		0.049				0.533		
Clover	Pooled	2.5	2.2	18.7	7.8 b	9.0	9.7	4.7	7.8
Cereal rye		13.4	101.6	276.3	130.5 a	2.5	3.0	5.0	3.5
Mix		9.6	49.0	65.5	41.4 ab	-	-	-	
	P-value		0.199		<0.001		0.479		0.097
Pooled	gly + atz	8.1	64.2	151.8	74.7	6.3	6.6	3.1	5.4
	gly + atz + dba	6.4	71.7	109.5	62.5	2.4	6.5	2.6	3.9
	gly + atz + dba + act	11.0	16.9	99.2	42.4	8.5	5.9	8.7	7.7
	P-value		0.295		0.743		0.640		0.672
Clover	gly + atz	1.8	3.3	42.2	15.8	9.1	13.3	6.0	9.4
	gly + atz + dba	4.0	2.0	10.1	5.4	2.2	12.3	4.9	6.5
	gly + atz + dba + act	1.7	1.4	3.7	2.3	15.7	3.6	3.2	7.5
Cereal rye	gly + atz	13.6	103.6	332.2	149.8	3.5	0.0	0.3	1.3
	gly + atz + dba	9.1	193.2	277.7	160.0	2.6	0.7	0.4	1.2
	gly + atz + dba + act	17.7	8.0	219.1	81.6	1.4	8.2	14.3	7.9
Mix	gly + atz	9.0	85.7	81.0	58.5	-	-	-	-
	gly + atz + dba	6.2	19.8	40.6	22.2	-	-	-	-
	gly + atz + dba + act	13.6	41.4	74.9	43.3	-	-	-	-
	P-value		0.403		0.400		0.444		0.459

Table 3.13 (cont.)

[a]Abbreviations: NC = non-cover crop gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Weed species evaluated include common cocklebur in 2018 and summer annual grasses (barnyardgrass, fall panicum, giant foxtail, and yellow foxtail) in 2019.
[c]Untransformed data are shown for clarity. Letters following values denote statistical significance of log-transformed data within each year, according to Tukey's HSD ($P \leq 0.05$).
[d]Weed biomass was not evaluated in the cover crop mix main plot, since flooding in the cover crop mix main plot severely reduced corn stand and weed populations before evaluation.
[e]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.14: Late-season total weed density at Throckmorton Purdue Agricultural Center [(TPAC) (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W)] in 2018 and 2019[a,b,c,d]

		Termination timing[d]							
		2018				2019			
Cover crop	Termination herbicide	Early	At-plant	Late	Pooled	Early	At-plant	Late	Pooled
		g m^{-2}							
Pooled	Pooled	7	5	6		32 a	13 b	7 b	
	P-value	0.340				<0.001			
Clover	Pooled	14	10	11	11 a	42 a	24 a	20 a	32 a
Cereal rye		2	3	1	2 c	33 a	2 b	1 b	12 b
Mix		7	3	6	5 b	21 a	2 b	1 b	8 b
	P-value	0.731			<0.001	<0.001			<0.001
Pooled	gly + atz	8	5	3	5	41	26	3	24 a
	gly + atz + dba	9	7	9	8	32	11	12	18 a
	gly + atz + dba + act	6	4	6	5	23	1	6	10 b
	P-value	0.173			0.131	0.323			<0.001
Clover	gly + atz	17	8	7	10	45	75	9	43
	gly + atz + dba	15	13	16	14	39	24	33	32
	gly + atz + dba + act	10	8	10	9	43	4	19	22
Cereal rye	gly + atz	1	0	0	0	57	1	1	20
	gly + atz + dba	3	6	2	3	30	4	2	12
	gly + atz + dba + act	1	2	3	2	14	0	0	4
Mix	gly + atz	6	6	2	5	22	2	1	8
	gly + atz + dba	9	2	10	7	28	4	1	11
	gly + atz + dba + act	7	3	6	5	15	0	0	5
	P-value	0.187			0.052	0.391			0.887

Table 3.14 (cont.)

[a]Abbreviations: NC = non-cover crop gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Weed species evaluated include barnyardgrass, fall panicum, giant foxtail, and yellow foxtail.
[c]Untransformed data are shown for clarity. Letters following values denote statistical significance of log-transformed data within each year, according to Tukey's HSD ($P \leq 0.05$).
[d]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.15: Late-season total weed density at Davis Purdue Agricultural Center [(6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W)] in 2019[a,b,c]

		Termination timing[d]			
Cover crop[e]	Termination herbicide	Early	At-plant	Late	Pooled
		$g\ m^{-2}$			
Pooled	Pooled	24 a	11 b	8 b	
	P-value	<0.001			
Clover	Pooled	17	16	7	13
Cereal rye		19	7	10	13
Mix		35	14	5	17
	P-value	0.758			0.506
Pooled	gly + atz	24	17	6	16 a
	gly + atz + dba	31	11	16	19 a
	gly + atz + dba + act	16	5	3	8 b
	P-value	0.635			<0.001
Clover	gly + atz	16	28	8	17
	gly + atz + dba	33	15	7	18
	gly + atz + dba + act	3	5	5	4
Cereal rye	gly + atz	26	5	6	12
	gly + atz + dba	21	14	34	23
	gly + atz + dba + act	12	2	1	5
Mix	gly + atz	31	18	4	17
	gly + atz + dba	40	6	6	17
	gly + atz + dba + act	33	8	4	15
	P-value	0.794			0.481

[a]Abbreviations: NC = non-cover crop gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Weed species evaluated include waterhemp and summer annual grasses (barnyardgrass, giant foxtail, and yellow foxtail).
[c]Untransformed data are shown for clarity. Letters following values denote statistical significance of log-transformed data within each year, according to Tukey's HSD ($P \leq 0.05$).
[d]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.16: Late-season total weed density at Southeast Purdue Agricultural Center [(SEPAC) (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W)] in 2018 and 2019[a,b,c]

		Termination timing[d]							
		2018				2019			
Cover crop	Termination herbicide	Early	At-plant	Late	Pooled	Early	At-plant	Late	Pooled
		g m^{-2}							
Pooled	Pooled	6	9	15		5	5	3	
	P-value	0.529				0.203			
Clover	Pooled	2	1	2	2 b	5	8	5	6
Cereal rye		11	17	27	18 a	5	1	1	2
Mix		7	10	14	11 a	[d]-	-	-	-
	P-value	0.379			0.002	0.132			0.051
Pooled	gly + atz	5	10	16	10	6	4	5	5
	gly + atz + dba	7	14	11	11	3	7	3	4
	gly + atz + dba + act	7	5	17	9	5	3	1	3
	P-value	0.393			0.866	0.067			0.956
Clover	gly + atz	1	2	2	2	6	8	9	8
	gly + atz + dba	3	1	2	2	4	12	5	7
	gly + atz + dba + act	1	2	2	1	5	4	2	4
Cereal rye	gly + atz	9	11	34	18	6	0	2	3
	gly + atz + dba	12	34	26	24	3	1	1	1
	gly + atz + dba + act	11	5	23	13	5	2	1	3
Mix	gly + atz	6	17	14	12	[d]-	-	-	-
	gly + atz + dba	6	8	5	6	-	-	-	-
	gly + atz + dba + act	9	7	26	13	-	-	-	-
	P-value	0.548			0.569	0.676			0.644

Table 3.16 (cont.)

[a]Abbreviations: NC = non-cover crop gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Weed species evaluated include common cocklebur in 2018 and summer annual grasses (barnyardgrass, fall panicum, giant foxtail, and yellow foxtail) in 2019.
[c]Untransformed data are shown for clarity. Letters following values denote statistical significance of log-transformed data within each year, according to Tukey's HSD ($P \leq 0.05$).
[d]Weed biomass was not evaluated in the cover crop mix main plot, since flooding in the cover crop mix main plot severely reduced corn stand and weed populations before evaluation.
[d]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.17: Corn yield at Throckmorton Purdue Agricultural Center [(TPAC) (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W)] in 2018 and 2019.[a]

		Termination timing[b]							
		2018				2019			
Cover crop	Termination herbicide	Early	At-plant	Late	Pooled	Early	At-plant	Late	Pooled
		kg ha^{-1}							
Pooled	Pooled	14170 a	12607 b	11769 b		14341 b	16633 a	16024 a	
	P-value	<0.001				<0.001			
Clover	Pooled	14435 a	14402 a	14004 a	14280 a	11523 b	17844 a	16963 a	15443
Cereal rye		13862 a	10818 b	10494 b	11725 b	15536 a	16069 a	16392 a	15999
Mix		14214 a	12601 ab	10808 b	12541 b	15964 a	15986 a	14716 ab	15555
	P-value	0.007			<0.001	<0.001			0.649
Pooled	gly + atz	13911	12817	12434	13054	14322	16112	15861	15431
	gly + atz + dba	13951	12621	10959	12510	13688	16886	16550	15708
	gly + atz + dba + act	14649	12383	11913	12982	15013	16901	15660	15858
	P-value	0.203			0.219	0.083			0.431
Clover	gly + atz	14460	13905	14543	14202	10341	17056	17077	14825
	gly + atz + dba	14578	14563	13459	14200	10652	18375	17903	15373
	gly + atz + dba + act	14268	14737	14011	14338	13575	18101	16720	16132
Cereal rye	gly + atz	12656	11853	15150	11873	16164	16045	16386	16198
	gly + atz + dba	13779	10339	10349	11489	14846	16787	16666	16100
	gly + atz + dba + act	15150	10263	10022	11812	15597	15376	16123	15699
Mix	gly + atz	14617	12695	11650	12987	16459	15237	14118	15271
	gly + atz + dba	13495	12961	9067	11841	15566	15496	15892	15651
	gly + atz + dba + act	14529	12149	11706	12795	15866	17226	14137	15743
	P-value	0.151			0.747	0.129			0.287

Table 3.17 (cont.)

[a]Abbreviations: NC = non-cover crop gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.18: Corn yield at Davis Purdue Agricultural Center [(DPAC) (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W)] in 2018 and 2019.[a]

		Termination timing[b]							
		2018				2019			
Cover crop	Termination herbicide	Early	At-plant	Late	Pooled	Early	At-plant	Late	Pooled
		kg ha^{-1}							
Pooled	Pooled	12273 a	11727 ab	11146 b		7335 b	10400 a	10254 a	
	P-value		0.010				<0.001		
Clover	Pooled	11941	11298	11363	11534	7645	8878	9671	8731 b
Cereal rye		13069	12501	11742	12437	7220	11067	10070	9452 ab
Mix		11808	11383	10332	11174	7140	11254	11020	9805 a
	P-value		0.739		0.257		0.057		0.045
Pooled	gly + atz	12588 a	11712 ab	11815 ab	12038	5832 c	9277 b	9991 ab	8367 b
	gly + atz + dba	11349 ab	12020 ab	11176 ab	11515	6655 c	11153 a	10638 ab	9482 a
	gly + atz + dba + act	12880 a	11450 ab	10446 b	11592	9517 ab	10768 ab	10133 ab	10139 a
	P-value		0.048		0.300		<0.001		<0.001
Clover	gly + atz	11863	11019	12032	11638	6124	7446	9465	7678
	gly + atz + dba	11094	11469	11008	11191	6912	10061	10640	9204
	gly + atz + dba + act	12865	11405	11048	11773	9897	9129	8907	9311
Cereal rye	gly + atz	13056	13386	11420	12621	5530	9909	9276	8238
	gly + atz + dba	12433	12499	12517	12483	6575	11515	10366	9486
	gly + atz + dba + act	13717	11618	11290	12208	9553	11776	10568	10632
Mix	gly + atz	12846	10732	11992	11857	5842	10477	11230	9183
	gly + atz + dba	10520	12092	10003	10872	6477	11884	10906	9756
	gly + atz + dba + act	12059	11325	9000	10795	9100	11401	10924	10475
	P-value		0.360		0.638		0.943		0.385

Table 3.18 (cont.)

[a]Abbreviations: NC = non-cover crop gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

Table 3.19: Corn yield at Southeast Purdue Agricultural Center [(SEPAC) (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W)] in 2018 and 2019.[a]

		Termination timing[c]							
		2018[b]				2019			
Cover crop	Termination herbicide	Early	At-plant	Late	Pooled	Early	At-plant	Late	Pooled
		kg ha^{-1}							
Pooled	Pooled	5412 a	4689 b	3521 c		9252	9563	9948	
	P-value		<0.001				0.492		
Clover	Pooled	7413 a	7228 a	6302 ab	6981 a	8867	8580	9633	9027
Cereal rye		4796 bc	3442 c	2057 d	3432 b	9638	10547	10262	10149
Mix		4025 c	3399 c	2203 d	3209 b	-	-	-	
	P-value		0.011		<0.001		0.454		0.403
Pooled	gly + atz	5109	5229	3566	4635	8690	10028	10477	9732
	gly + atz + dba	5505	4356	3657	4506	9578	9312	9725	9538
	gly + atz + dba + act	5621	4483	3341	4482	9489	9351	9640	9493
	P-value		0.312		0.644		0.120		0.720
Clover	gly + atz	6518	7322	6790	6877	8328	9350	9641	9106
	gly + atz + dba	7328	7461	6674	7154	9110	7639	9471	8740
	gly + atz + dba + act	8394	6900	5444	6913	9163	8751	9786	9233
Cereal rye	gly + atz	4631	4383	2022	3679	9053	10705	11313	10357
	gly + atz + dba	5034	2264	2016	3105	10046	10985	9979	10337
	gly + atz + dba + act	4723	3678	2134	3512	9815	9951	9494	9754
Mix	gly + atz	4177	3982	1885	3348	-	-	-	-
	gly + atz + dba	4154	3343	2281	3259	-	-	-	-
	gly + atz + dba + act	3746	2871	2444	3020	-	-	-	-
	P-value		0.084		0.476		0.285		0.232

Table 3.19 (cont.)

[a]Abbreviations: NC = non-cover crop gly = glyphosate, atz = atrazine, dba = dicamba, act = acetochlor.
[b]Yield data from 2018 was log-transformed to meet statistical assumptions, but untransformed data are shown for clarity.
[c]Early, at-plant, and late termination timings were two weeks before, at, and two weeks after corn planting. In 2019, corn planting was delayed, and therefore the early termination timing was made five to six weeks before corn planting.

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CHAPTER 4. COMMON COCKLEBUR (XANTHIUM STRUMARIUM L.) EMERGENCE UNDER CEREAL RYE RESIDUE FOLLOWING A RESIDUAL HERBICIDE APPLICATION

4.1 Abstract

Cover crop use has increased in the Eastern Corn Belt over the last decade. Alterations to the soil environment caused by cover crop use may affect weed seed emergence patterns. Cover crops impact soil temperature and moisture and light interception, which impact emergence of weeds. Ultimately, these changes may lead to long-term changes to weed community composition. Large-seeded weeds can germinate in the absence of light and at cooler temperatures. A species such as common cocklebur (*Xanthium strumarium* L.) may be more adapted to cropping systems that include cover crops. An experiment was conducted in 2019 on a low organic matter, silt loam soil in southern Indiana. Cereal rye was terminated with glyphosate, cut and laid across plots at 8000 kg ha^{-1}. Soil moisture was monitored from June to August, and emergence was measured every 7 to 14 days in fallow and cover cropped soil. A residual herbicide premix of atrazine + bicyclopyrone + mesotrione + *S*-metolachlor was applied to both cereal rye and fallow soil in June. Soil underneath cereal rye residue had 8 to 10% higher moisture levels throughout much of the growing season. The last date of observed emergence in fallow soil was July 23rd, while the last day of emergence in cover cropped soil was August 27th. Peak emergence was also delayed underneath cereal rye residue. Cumulative emergence was unchanged by cereal rye, however the prolongation of common cocklebur emergence implies that growers who utilize cereal rye as a cover crop may observe increased prevalence of common cocklebur late in the growing season.

4.2 Introduction

Weed community composition and diversity change depending on which weed management practices are utilized over time. Small-seeded weeds such as horseweed (*Conyza canadensis*) may be effectively controlled by tillage because of seed burial, while large-seeded weeds such as common cocklebur (*Xanthium strumarium* L.) and giant ragweed (*Ambrosia trifida* L.) may see an increase in weed densities when tilled (Bararpour and Oliver 1998, Barnes et al.

2004, Brown and Whitwell 1988, Buhler 1997)). Other environmental factors such as climate and soil type also affect weed community composition (Dale et al. 1992).

Weed seed germination can require specific parameters such as day-night temperature fluctuations, soil moisture, and red:far-red light ratio. Cropping systems, residue management practices, tillage, and other cultural practices can alter these factors. Cover crops alter the soil environment by shading the soil, resulting in higher soil moisture and lower temperature fluctuations. Teasdale and Mohler (1993) reported that soil moisture content was 10% higher under cereal rye biomass at 17,000 kg ha^{-1} compared to fallow soil. Light transmittance was greatly reduced under cereal rye residue, while soil temperature amplitude also decreased. Weed seeds may respond differentially to these environmental cues, depending of the requirements and mechanisms of germination. Midwest weed species would be well adapted to non-cover cropped soils. Altering the soil environment through cover crop use would likely lead to changes in weed emergence patterns and soil characteristics, and could ultimately lead to a change in weed species composition.

Common cocklebur is a common weed in the Midwest that is competitive with corn and soybean. A density of 12 common cocklebur plants m^{-2} reduced corn yield by 30% (Hussian et al. 2012). The common cocklebur fruit contains two seeds surrounded by a thick pericarp. One is larger and less physically impeded by the pericarp. Since common cocklebur germination is dependent upon the physical breakdown of the pericarp, this allows the larger seed to germinate, followed by the smaller seed. Germination of the second seed is dependent on moisture and temperature. Norsworthy and Oliveira (2007) determined that soil water potential above -60 kPa and low temperature fluctuations increased common cocklebur emergence. Therefore, farming practices that conserve soil moisture and reduce soil temperature fluctuations will result in increased cocklebur germination. The germination of both seeds will occur in the same growing season if soil conditions are favorable for germination, suggesting that the changes in soil conditions caused by cover crop residue could lead to prolonged common cocklebur emergence (McHargue 1921).

Some group 2 soybean herbicides such as chlorimuron and cloransulam are effective against cocklebur, but other residual herbicides such as atrazine, mesotrione, and metolachlor provide only partial control (Adcock and Banks 1991, Mills and Witt 1989, Wesley et al. 1989). Common cocklebur has developed resistance to group 2 herbicides chlorimuron, cloransulam, and imazethapyr in Illinois and Ohio, which necessitates the use of postemergence herbicides for complete control (Heap 2020). Understanding cocklebur emergence in a variety of cropping systems is important for proper common cocklebur management.

Research is needed to determine the effects of cover crop residue on soil conditions and cocklebur emergence over time. We hypothesize that a cereal rye cover crop will increase soil moisture throughout the growing season and lead to prolonged common cocklebur emergence

4.3 Materials and Methods

An experiment was conducted at Southeast Purdue Agricultural Center [(SEPAC) (4425 Country Rd 350 N Butlerville, IN 47223) (39.03, -85.53)] in an area with high common cocklebur infestations. The soil is a Cobbsfork silt loam with a texture of 18% sand, 70% silt, and 12% clay, with 1.7% organic matter. No recent tillage events had been performed at this site. The experiment was set up as a split-plot completely randomized design. The main plots were a fallow and a cereal rye treatment. All plots were terminated on 5/25/2019 with glyphosate (Roundup Powermax, Bayer, St. Louis, MO 63141) at 1.54 kg ha^{-1} using flat fan XR110015 nozzles (TeeJet Technologies, Wheaton, IL 50322). Original cereal rye biomass was nearly 3000 kg ha^{-1}. Cereal rye growing in the plot was clipped and laid flat. Additional nearby cereal rye biomass was clipped until each plot in the cereal rye block was covered by 8000 kg ha^{-1} of cereal rye residue. Subplots measured 1 m by 1 m, and were a residual herbicide premix and a no herbicide treatment. The herbicide-treated plots received an application of an herbicide premix on June 4th of atrazine + bicyclopyrone + mesotrione + S-metolachlor at rates of 1.58, 0.04, 0.16, and 1.43 kg ai ha^{-1}, respectively (Acuron, Syngenta, Greensboro, NC 19810).

Emerged common cocklebur plants were counted in each subplot and removed on June 4th. Common cocklebur was then counted and removed every 1-2 weeks through August 27th. All subplots were hand-weeded for the remainder of the experiment.

Soil volumetric water content (VWC) was measured every hour from June 26th to August 27th using WaterScout SMEC 300 Sensors and WatchDog 1000 Series data loggers (Spectrum Technologies, Aurora, IL 60504). Soil moisture probes were inserted 2.5 cm below the soil surface. The pressure pot method as described by Dane and Hopmans (2002) was used to determine soil bulk density and VWC at -60 kPa water potential. Four soil cores were taken from randomly chosen plots for the analysis.

Six 5-cm soil cores were taken from each plot sprayed with the residual herbicide premix to quantify soil residual herbicide levels. Atrazine and mesotrione were quantified using high-performance liquid chromatography/dual mass spectrometry (HPLC/ MS MS). Soil cores from two untreated plots were also taken to assess background atrazine levels.

All common cocklebur emergence data were analyzed by analysis of variance (ANOVA) using PROC GLIMMIX in SAS 9.4 (SAS, 100 SAS Campus Drive, Cary, NC 27513). Means comparisons were made using Tukey's HSD at a significance level of $\alpha = 0.05$. Common cocklebur emergence was analyzed at each evaluation timing.

4.4 Results and Discussion

4.4.1 Soil moisture

Soil underneath cereal rye residue had higher moisture content in between precipitation events. After precipitation events, soil moisture under cereal rye residue had approximately 8-10% more water compared to fallow soil throughout the growing season (Figure 4.1). In dry periods between precipitation events, fallow soil routinely dropped to 8% volumetric water content (VWC). In contrast, soils underneath the cereal rye residue never dropped below 14% VWC. Soil VWC at -60 kPa was determined via the pressure pot method to be 27%. This water potential was identified by (Norsworthy and Oliveira 2007) as the minimum potential required for cocklebur germination. Directly following precipitation events, soil moisture under cereal rye residue routinely peaked above 27%. Soil in fallow plots did not reach 27% VWC often. The higher moisture levels in the cereal rye plots may have contributed to prolonged common cocklebur emergence. Possible increased microbial activity due to the increased soil moisture may have been responsible for the breakdown of the seed coat and subsequent germination. Increased microbial activity from increased soil moisture was observed by Banerjee et al. (2016).

4.4.2 Residual herbicide soil concentration and efficacy

Residual herbicide efficacy was unaffected by the presence of cereal rye, which is consistent with previously published literature that reported no change in atrazine, carfentrazone, sulfentrazone, and metolachlor efficacy in cereal rye and wheat cover crops (Crutchfield et al. 1985, Haramoto and Pearce 2019, Teasdale 1993a). Atrazine concentrations were similar 45 DAT in cereal rye and non-cover cropped soils (10 to 11 ppb, data not shown), while mesotrione was not detected after 45 days This suggests that initial herbicide interception by the cereal rye was overcome by precipitation events that washed atrazine into the soil. One alternate explanation for this could be reduced microbial metabolism because of cooler, shaded soils; however, the increased soil moisture under cereal rye residue may have also increased microbial activity. Zak et al. (1999) determined that increased soil temperature and increased soil moisture both increased microbial respiration, but that soil temperature was more influential than soil moisture. This suggests that the cooler, but wetter soils under cover crop residue may lead to slower residual herbicide breakdown. More research on the relationship between soil moisture and soil temperature on microbial activity in cover crop systems will be needed to confirm this idea.

4.4.3 Common cocklebur emergence

Herbicide treatment was not significant for common cocklebur emergence over time but cover crop was significant (Figure 4.2). However, emergence ceased earlier in fallow treatments than in cereal rye treatments. Emergence ceased on July 23rd in fallow treatments, but continued until August 27th in cereal rye treatments. By June 27th, only 60% of the total emergence had occurred in cereal rye treatments, while 89% of the total emergence in fallow treatments had occurred (Figure 4.2). After June 4th, cocklebur continued to emerge in fallow plots for 42 days in fallow treatments, and continued for 77 days in cereal rye treatments.

A significant cover crop by herbicide interaction was observed for total common cocklebur emergence ($P = 0.023$). While the timing of common cocklebur emergence was prolonged in cereal rye treatments, ultimately no suppression by cereal rye alone was observed. Average total emergence in cereal rye and fallow treatments without an application of the residual herbicide premix was 28 plants m^{-2} (Figure 4.3). Total emergence in fallow soil applied with a residual herbicide premix was 16 plants m^{-2}, and emergence under cereal rye residue after an application of residual herbicide premix was 10 plants m^{-2}. Compared to the fallow, non-treated control, the residual herbicide premix did not reduce emergence in fallow plots. However, the residual herbicide premix applied to cereal rye residue did reduce emergence, compared to the non-treated fallow and cereal rye treatments (Figure 4.3). The reason for the increase in control by the residual herbicide premix in cereal rye treatments may have been because of the increase in soil moisture, which would lead to more herbicide in the soil solution and an increase in herbicide activity.

4.5 Conclusion

Soil environmental changes in cereal rye systems include smaller temperature fluctuations, shading, and increased soil moisture (Teasdale 1993b). Weed responses to these factors differ, with large-seeded weeds generally being less susceptible to the suppressive tendencies of cover crops (Teasdale and Mohler 1993). Long-term cover cropping will likely lead to shifts in weed populations, and specifically an increase in the percentage of large-seeded weed species such as common cocklebur, giant ragweed, and velvetleaf (*Abutilon theophrasti* L.).

Total common cocklebur emergence was unaffected by cereal rye, however emergence patterns were altered underneath cereal rye residue. The increased soil moisture in cover cropped plots likely contributed to prolonged germination, while the delayed germination could have been a result of soil shading and fewer growing degree days underneath the cereal rye residue. The increase in soil moisture and soil shading could alter emergence patterns for other weeds. Weeds without a light requirement for germination and weeds that require high soil moisture for germination are likely to benefit.

Weed management must be modified to confront changes to weed growth habits and the behavior of weed communities in cover crop systems. In cover crop systems with common cocklebur populations, additional applications of postemergence herbicides may be needed if emergence is prolonged. Where common cocklebur is problematic, terminating cereal rye early or decreasing cereal rye seeding rate could prevent prolonged common cocklebur emergence.

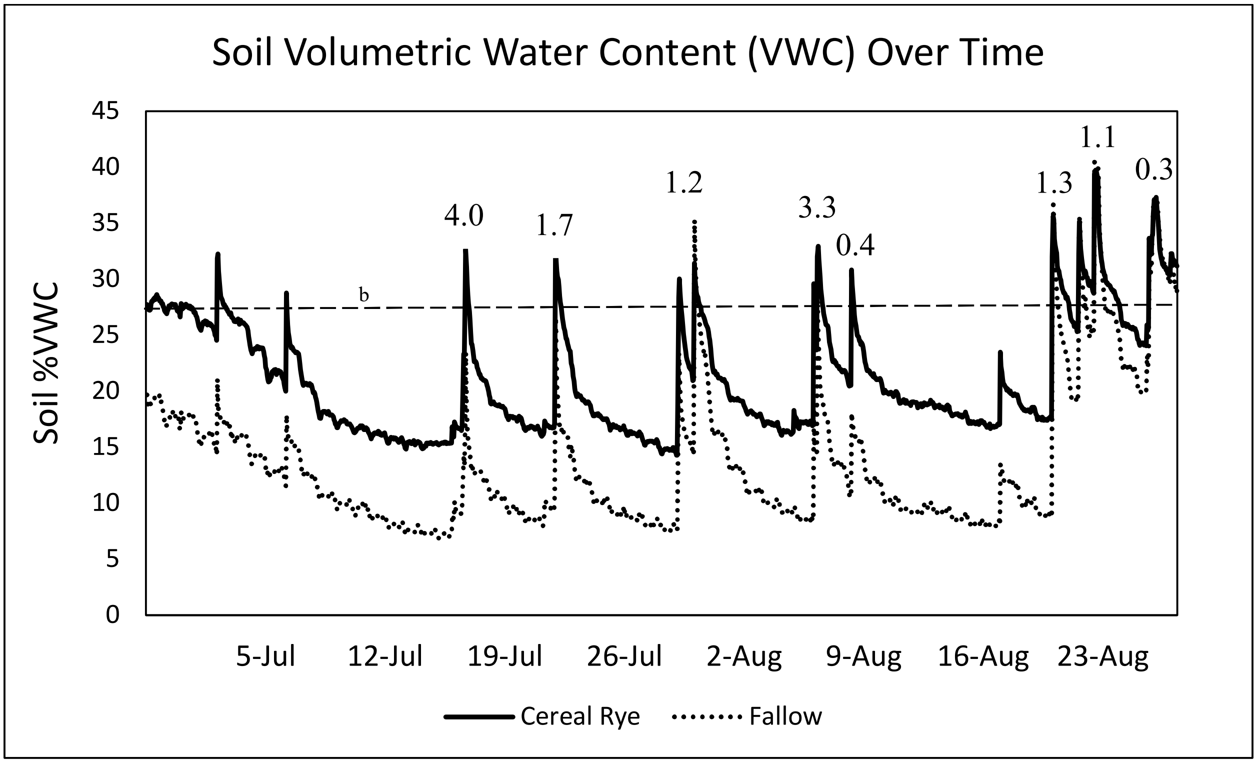

Figure 4.1: Soil VWC 2.5 cm below soil surface in fallow soil and soil covered with cereal rye biomass at 8000 kg ha^{-1}.[a]

[a]Numbers above peaks indicate precipitation near that time (cm).

[b]Soil VWC at -60 kPa, the minimum water potential required for common cocklebur germination.

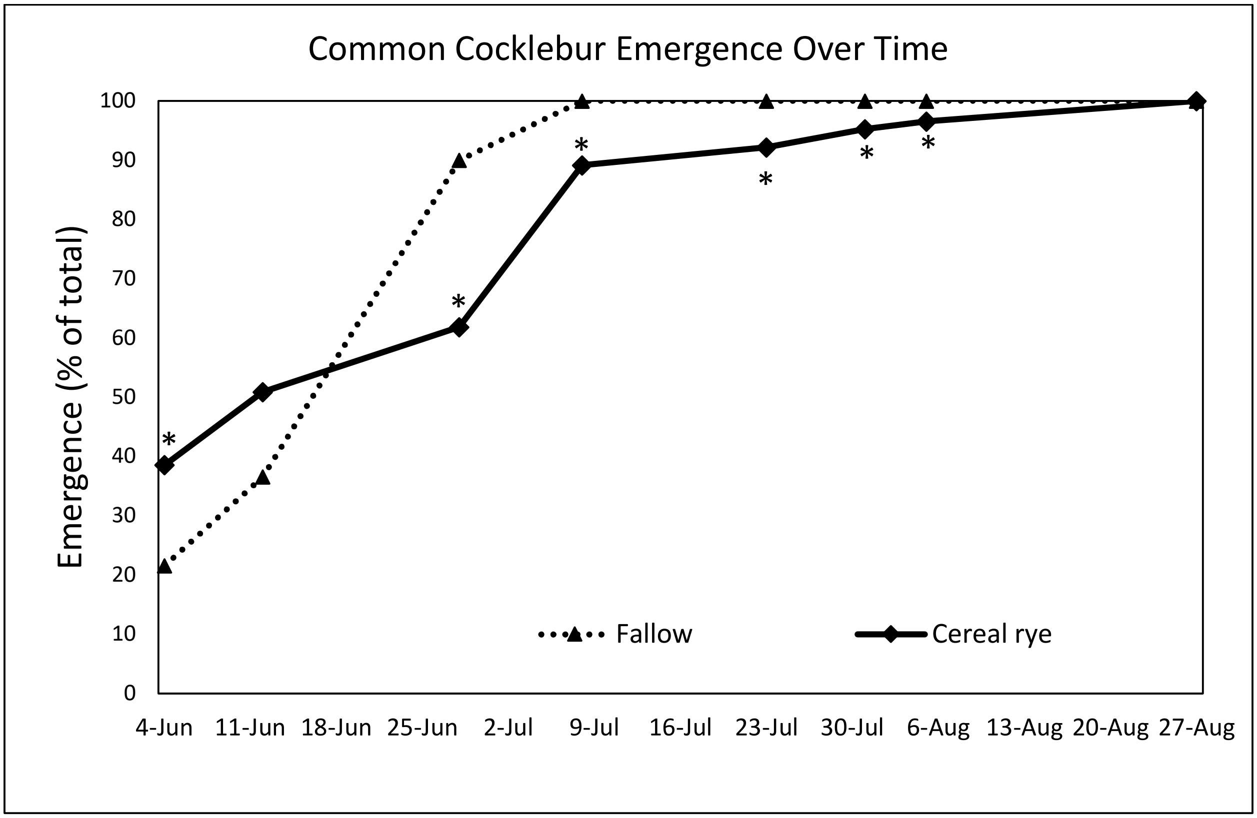

Figure 4.2: Percent of total common cocklebur emergence over time[a,b]

[a]Markers labeled with an asterisk denote statistical significance, according to Tukey's Honest Significant Difference (HSD) ($P \leq 0.05$).
[b]Data were pooled over herbicide treatment.

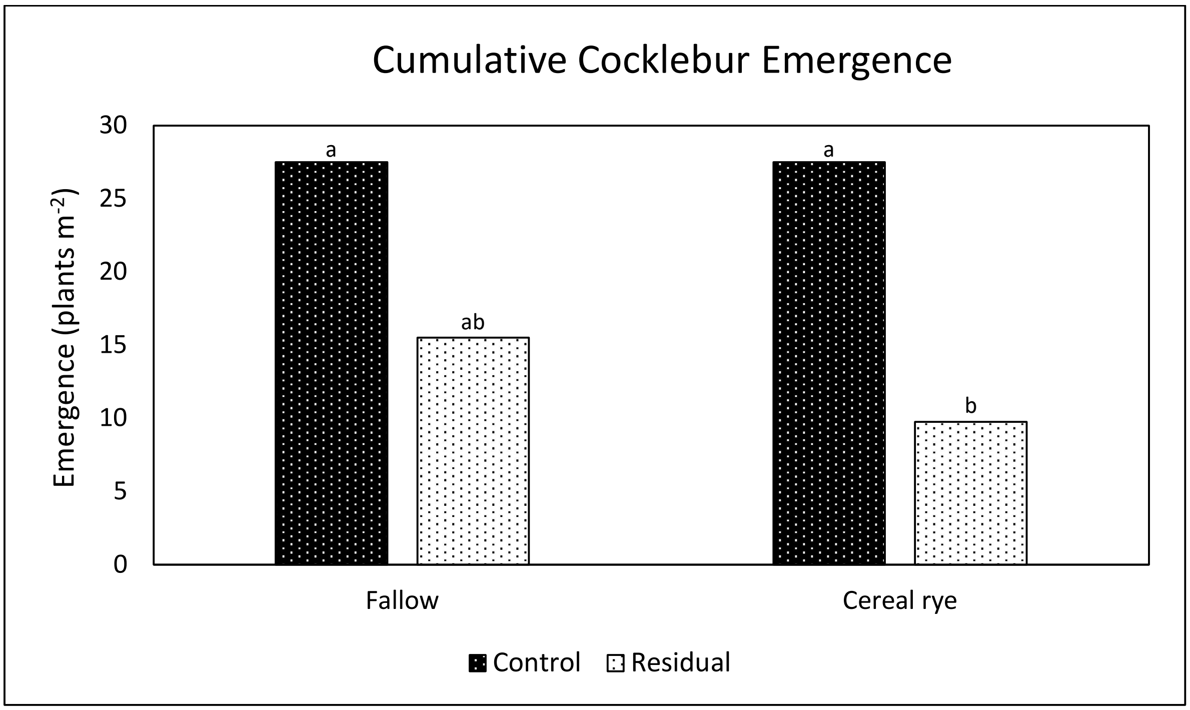

Figure 4.3: Cumulative common cocklebur emergence by cover crop and herbicide treatment from June 4th through August 27th. Letters denote statistical separation between means according to Tukey's HSD (*P*≤0.05).

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