WEED CONTROL SYSTEMS IN SYNTHETIC AUXIN-RESISTANT SOYBEANS

by

Connor Hodgskiss

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. William G. Johnson

Department of Botany and Plant Pathology

Dr. Bryan G. Young

Department of Botany and Plant Pathology

Dr. Shalamar D. Armstrong

Department of Agronomy

Approved by:

Dr. Christopher Staiger

Dedicated to my family Maryetta, Lyle, Beth Ann, Logan, Taylor, and Sarah Hodgskiss

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ABSTRACT

Herbicide-resistant weed populations have become problematic throughout the Eastern Corn Belt, with 18 unique herbicide-resistant weed biotypes confirmed in Indiana alone. In response to these resistant populations, the agricultural chemical industry has responded by developing glyphosate-resistant crops paired with resistance to synthetic auxin herbicides such as dicamba and 2,4-D.

This research evaluates weed population shifts in cropping systems using row crops that are resistant to synthetic auxin herbicides. Identifying weed population shifts will allow future research to be targeted to weed species that would become more prevalent in cropping systems using synthetic auxin-resistant crops. The use of multiple sites of action will be needed in order to prevent weed shifts in both conventional and no-till corn-soybean production systems. Weed densities and species richness were reduced within field evaluations when six or more herbicide sites of action were implemented with residual herbicides in both corn and soybean years over a seven-year period. Additionally, soil seedbank weed densities and species richness were reduced within 2,4-D-resistant soybean production systems. Additional strategies other than the application of herbicides may be needed to manage weed populations in the future due to the high levels of herbicide-resistant weed populations in the Midwest.

Off-target movement of these synthetic auxin herbicides, has been a concern, and label-mandated buffer areas are required near sensitive areas. Investigation of whether cover crops can be an effective tactic in managing weeds in these label-mandated buffer areas was conducted. Cover crop utilization in buffer areas has not been investigated in Indiana. Additionally, termination timing is becoming more prominent as farm operators are increasingly terminating cover crops after planting. Our results demonstrate that using cover crops that utilize cereal rye

and that are terminated at, or after the time of soybean planting will be beneficial in suppressing waterhemp, grasses, and sometimes horseweed within label-mandated buffer areas, but not for suppression of giant ragweed. However, delaying termination of cover crops can result in soybean yield reductions and caution should be used. Terminating cover crops with glyphosate and auxin and a residual herbicide was more effective than glyphosate alone, but would not be permitted within label-mandated buffer areas.

CHAPTER 1. LITERATURE REVIEW

1.1 Efficacy of Auxin Herbicides

Herbicide-resistant weeds are a major concern for farm operators in Indiana with 18 unique herbicide-resistant weed biotypes in the state, and neighboring state Illinois having waterhemp (*Amaranthus tuberculatus* (Moq J. D. Sauer).) with multiple-resistance to five different herbicide modes of action (Heap, 2020). Due to this concern of herbicide-resistant weed populations the agricultural chemical industry has developed soybeans (*Glycine max* (L.) Merr.) that contain traits that confer resistance to either 2,4-D or dicamba. Both 2,4-D and dicamba are classified as growth regulator herbicides in group 4 of the Weed Science Society of America's (WSSA) classification and selectively control broadleaf species.

Dicamba and 2,4-D both have high levels of efficacy for controlling many glyphosate-resistant broadleaf weeds. Robinson et al. (2012) demonstrated that 2,4-D applied alone at 1120 g ae ha^{-1} provided at least 90% control of glyphosate-susceptible giant ragweed (*Ambrosia trifida* L.), velvetleaf (*Abutilon theophrasti* Medik.), common waterhemp, and common lambsquarters (*Chenopodium album* L.). Spaunhorst and Bradley (2013) reported the addition of dicamba to glyphosate resulted in 44% control of glyphosate-resistant waterhemp compared to only 5% control with an application of only glyphosate. The addition of dicamba and 2,4-D to weed management in soybean production systems will be valuable in controlling glyphosate-resistant weeds. However, shifts in weed species and communities as a result of broad acreage use of these herbicides should be monitored, as an estimated 60% of the soybean acres planted in the United States were dicamba-resistant in 2019 (Unglesbee 2019). The use of 2,4-D-resistant soybeans is expected to increase as commercialization of these varieties progresses.

Off-target movement of auxin herbicides has also become a challenge as synthetic auxin-resistant soybeans are adopted. Egan et al. (2014) conducted a meta-analysis of soybean and cotton (*Gossypium hirsutum* L.) injury to 2,4-D and dicamba and reported R^2 values of 0.62 and 0.61 when correlations of soybean injury to yield loss were evaluated for dicamba and 2,4-D respectively. Due to concerns of off-target movement, label-mandated buffer areas are required when using dicamba or 2,4-D in auxin-resistant soybean varieties. Weed control will be challenging in these buffer areas where herbicide options are limited. Cover crops are an option for farm operators to suppress weeds within buffer areas where 2,4-D and dicamba applications are restricted.

1.2 Weed Species Shifts

At any point where a weed management strategy is changed, a shift in weed communities is also likely to occur. Shifts in species have been observed due to past changes in weed management practices. One such change was observed as growers adopted no-till and conservation tillage practices. Buhler and Daniel (1988) showed that while giant foxtail (*Setaria faberi* Herm.) fresh weight was 55% higher under a no-till system, velvetleaf fresh weight decreased 94% in no-till compared to conventional. It is likely that as weed management is changed to permit POST synthetic auxin herbicide applications in soybeans, there will be a shift of species in a manner similar to when producers moved away from conventional tillage. As selection pressure increases due to an increase in 2,4-D and dicamba use in auxin-resistant soybean varieties, this could result in a shift in the predominant weed species. The commercialization of glyphosate-resistant crops resulted in a single mode of action being used on a large scale for extended periods of time (Young 2006). This resulted in high selection pressure and a population shift of species to highly reproductive annual dicots with high levels of genetic diversity and widespread glyphosate resistance (Jasieniuk et al. 1996, Johnson et al. 2009).

Legleiter (2017) conducted a four-year study in Indiana and showed that the use of synthetic auxin herbicides did not cause a noticeable species shift at one of the research locations, but shifted the weed community in a second location to more monocot species, specifically fall panicum (*Panicum dichotomiflorum* Michx.). Although this study was only conducted over the course of 4 years, the effects of a dicot-selective herbicide were beginning to show as the weed community shifted to monocot species. Legleiter (2017) showed that the most effective herbicide strategy in reducing weed densities and species richness was with the use of postemergence (POST) applied glyphosate and dicamba in conjunction with a residual herbicide applied pre-emergence (PRE). The release of synthetic auxin-resistant cotton and soybean varieties will lead to farm operators applying more synthetic auxin herbicides POST. Therefore, it is likely that there will be a shift in weed communities in the agroecosystems across the Midwest. Since synthetic auxin herbicides are effective at controlling dicot species, grasses could potentially become a more prevalent species in these cropping systems.

Shergill et al. (2017) evaluated weed shifts in continuous glyphosate- and dicamba-resistant soybean production systems over the course of 5 years in Missouri. Preemergence herbicides provided 50% more weed control compared to a glyphosate only POST application and increased yield by 2.5-fold (Shergill et al. 2017). Davis et al. (2009) reported a shift in the ratio of glyphosate-resistant and glyphosate-susceptible horseweed (*Erigeron canadensis* L.) populations (GR:GS) from 3:1 to 1:6 in response to management practices that used residual herbicides with non-glyphosate POST applications. Wilson et al. (2007) investigated weed shifts implementing high and low use rates of glyphosate and an increase in common lambsquarters occurred when low rates of glyphosate were used compared to high rates over a six-year period. However, common lambsquarters densities did not change when standard use rates were implemented.

1.3 Glyphosate-Resistant Crops

Applying the same mode of action on the same geographic areas for many years has resulted in high selectivity for herbicide-resistance across many agroecosystems (Manalil 2015). Due to the release of glyphosate-resistant crops, the dependence on glyphosate increased. This high use of glyphosate has resulted in 48 glyphosate-resistant weed species to date (Heap 2020). This high level of use caused a shift in weed species that selected for certain dicot weed species, such as those found in the *Amaranthus* family (Johnson et al. 2009). After conducting a survey in Australia, Manalil et al. (2017) showed that glyphosate-tolerant volunteer cotton had become a weed problem due to the overreliance on glyphosate for weed control, paired with the use of glyphosate-resistant cotton. The change in production practices in response to the release of these technologies was the driver for the weed population shifts, as producers used fewer sites of action (SOA) and relied heavily on glyphosate (Owen 2008). As synthetic auxin-resistant soybeans are commercialized it is important to responsibly use the available herbicide modes of action in these cropping systems to avoid repeating history and developing multiple-resistant weed species.

Wilson. et al. (2011) reported that academic weed management recommendations resulted in the average number of unique modes of action always being higher compared to farm operator practices across 7 different cropping systems. Edwards et al. (2014) reported that farm operators should include diverse herbicide strategies and with high yields should not expect to be negatively impacted economically in the short-term. Additionally, through diversifying the herbicide modes of action used, farm operators are using best management practices for herbicide resistant weeds as described by Norsworthy et al. (2012).

Reddy (2001) discussed the challenges of glyphosate-resistant crops, and one of the largest challenges is scientists communicating to growers on how to prevent large scale resistance due to dependence on a single weed management strategy. The associated challenge is not disseminating information, but rather convincing farm operators to adjust their management practices to reduce selection pressure. Those concerns are still present as the industry moves toward auxin-resistant soybeans and the possibility of becoming overly reliant on a single form of weed management, because of low commodity prices and simplicity.

1.4 Brief Introduction of Cover Crops

Recently, cover crops have regained attention in the Midwest due to their ability to reduce soil erosion and increase the biodiversity in cropping areas (Singer et al. 2007). In some regions, cover crops are utilized to reduce the amount of pesticides and nutrients, from leaching deeper into the soil or into nearby waterways. The nutrients that are taken up by the cover crop are then made available to the cash crop as the cover crop decomposes (Hartwig and Ammon 2002). Sievers and Cook (2018) showed that the total nitrogen released by cereal rye (*Secale cereal* L.) was 34.27 kg ha^{-1}, while the nitrogen released by hairy vetch (*Vicia villosa* Roth) was 99.21 kg ha^{-1}. Myers and Watts (2015) conducted a survey and found that farmers that use cover crops do so because they believe they benefit soil health, reduce erosion, fix nitrogen, and scavenge nitrogen that would otherwise leach.

The Conservation Technology Information Center (CTIC) reported that respondents who use cover crops have increased their acreage of cover crops from an average of 217 acres to 451 acres over the last five years (CTIC 2017). Some of the most commonly used cover crop species in the Midwest are cereal rye, crimson clover (*Trifolium incarnatum* L.), oats, (*Avena sativa* L.) and radish (*Raphanus sativus* L.). These cover crops are commonly used as they are easy to introduce into a cropping system. Cereal rye is a winter hardy species that produces high amounts of biomass. Legume cover crop such as crimson clover will increase ground cover and fix nitrogen. Cover crops can also provide ecosystem services to areas that are susceptible to eutrophication. For example, the use of winter annual cover crops has reduced the level of nitrates that enter the Chesapeake Bay watershed (Lee et al. 2016). Myers and Watts (2015) surveyed farm operators in the Midwest and reported that increased yield benefits are seen on corn (*Zea mays* L.) after two to three years of using cover crops. These trends are likely to continues past the 3 year mark if producers continue to implement cover crops into their cropping systems as occurred with soil nitrogen supply in research done by Gabriel et al. (2016). As acreage increases, management challenges brought on by cover crops will also be faced by many farm operators. The benefits and challenges of cover crops continue to be difficult to quantify due to the influence of environment, genetics, and management practices.

1.5 Challenges of Cover Crops:

1.5.1 Timing and Limiting Resources

While the benefits of cover crop use are apparent, there are also several challenges that should be considered. Time is a large factor that farm operators must consider. Introducing another crop into a system will take more time and labor, which is difficult to justify when growers do not directly profit from cover crops. Arbuckle and Roesch-McNally (2015) conducted a survey to inquire about the use of cover crops in Iowa and reported that over half of the respondents either agreed or strongly agreed that there generally wasn't enough time between harvest and winter in order to successfully establish cover crops. They also showed that over half of the responders were uncertain as to whether the cost of the cover crops would outweigh the potential benefits of the cover crops. The economic uncertainty of cover crop usage is a major component of the relatively low popularity of cover crops in the Midwest and should be further investigated to determine if these complex relationships can consistently produce both an agronomic and economic benefit for farm operators (Snapp et al. 2005).

Other challenges include limiting factors, such as precipitation and nutrient availability. These limiting factors can make cover crops more problematic than beneficial in some lower yielding environments which may not have the ability to sacrifice these resources in order to grow a cover crop for conservation and soil building practices (Snapp and Borden 2005; Wilke and Snapp 2008). A common theme is that cover crop benefits that are unique to a region and may not apply to other regions due to the many variables that play into the success, or failure of using cover crops. Complexity of cover crops could also be seen as a challenge as their economic benefits are hard to quantify due to multiple species being used to obtain various profit or conservation driven goals.

1.5.2 Green Bridge for Pests

Although cover crops can increase populations of beneficial insects, they can also increase the populations of detrimental insects, such as the case of true armyworm (*Spodoptera frugiperda*) populations in corn fields following a rye cover crop (Dunbar et al. 2016). Dunbar et al. (2016) found that fields with cover crops had increased (8.5% ± 0.9; mean ± SEM) defoliation of corn plants compared with fields that contained no cover crop (2.3% ± .05). In some production areas the creation of a green bridge, or leaving green biomass in the field, could also be a concern. Cover crops may be able to serve as a green bridge, which provides a living plant for insect or disease to survive on. Cover crops can allow for diseases and other pests to overwinter and harm the cash crop the following spring. Bakker et al. (2016) evaluated four diseases of corn seedlings, *F. graminearum*, *F. oxysporum*, *P. sylvaticum,* and *P. torulosum*, they demonstrated that these pathogens can also be found in roots from cereal rye cover crops. In the first year of the study all four pathogens were present in at least 26% of cereal rye root samples and in year two of the experiment, the four pathogens were found in at least 90% of all of the rye root samples taken. The pathogens ability to survive in a rye cover crop would allow for the potential of pathogens to move onto a following corn crop (Bakker et al. 2016).

1.5.3 Herbicide Carry-over

Farm operators who begin to use cover crops will also need to be more discerning on the residual herbicides that they apply to their cash crop as some residual herbicides may have carryover effects on the fall-planted cover crop. Cornelius and Bradley (2017a) observed that the legumes and oilseed radish cover crops on average tended to be more sensitive to carryover from 27 different herbicides that are commonly applied in corn and soybean. In this same experiment it was observed that cereal rye was the least sensitive out of all eight cover crop species that were evaluated and that it was not reduced by any of the 27 treatments. The eight cover crops included in this study were cereal rye, oilseed radish, winter oats, crimson clover, Austrian winter pea (*Pisum sativum* L.), hairy vetch, annual ryegrass (*Lolium multiflorum* Lam.), and winter wheat (*Triticum aestivum* L.). The use of many residual herbicides commonly applied in corn and soybean production could reduce cover crop stand (Cornelius and Bradley 2017a). The persistence of an herbicide will vary depending upon environmental factors and soil properties (Ghafoor et al. 2011).

1.6 Cover Crop Benefits:

1.6.1 Increase in Beneficial Insects

Using cover crops can create a more diverse agricultural landscape in areas where corn and soybean are predominant. Adding diversity to a monoculture cropping system can increase the diversity of beneficial insect species. One example can be seen in the beetle *Harpalus rufipes*. This beetle species is a seed predator of various key weed species, including common lambsquarters and barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.*)*. Shearin et al. (2008) reported that *Harpalus rufipes* are more than twice as likely to remain in a plot that utilizes a cover crop rather than a fallow system. Creating a more advantageous environment for beneficial insect species that forage on weed seeds will allow for a diminished seed bank for the affected weed species.

1.6.2 Erosion Control

Another benefit that is largely associated with cover crop use is reduced erosion. Many researchers have shown that cover crops are able to increase water infiltration and reduce run-off of surface water that can lead to soil erosion (De Baets et al. 2011, Kaspar et al. 2001). The run-off of surface water from agricultural fields can also lead to environmental concerns such as sediment build-up in waterways, or serving as a carrier to transport pesticides or nutrients from the original site to downstream locations. Lewan (1994) conducted research in Sweden and showed that cover crops reduced nitrogen losses by almost three times that of a conventional system. However, once the cover crop was no longer being implemented, nitrogen losses increased and were slightly larger than that of the conventional system.

1.6.3 Nitrogen Management

Cover crops, especially those in the legume family, have the potential to benefit crops by fixing nitrogen through their symbiotic relationship with *Rhizobium* bacteria. It is well known that this symbiotic relationship can increase plant available nitrogen in the soil (Peoples et al. 1995). This relationship can maintain crop yields with reduced fertilizer rates. Jahanzad et al. (2017) evaluated a potato (*Solanum tuberosum*) cropping system and found that they could significantly reduce nitrogen application rates and obtain the same yields by using an Austrian pea or radish cover crop prior to the potato cash crop. Jahanzad et al. (2017) also reported that potatoes grown after cereal rye yielded better than those grown when no previous cover crop was used.

Due to the ability of cover crops to increase nitrogen use efficiency, models have been developed to aid in determining which species of cover crops will interact with a specific environment to influence a cash crop’s fertilizer usage and ultimately a cover crop’s effect on profitability. One such model helps to determine the amount of nitrogen that a cover crop can supply for the following corn crops (White et al. 2016). Although some models may not be useful in all circumstances, creating mathematical parameters that can aid in quantifying the positive and negative effects of cover crops is important. These models would be able to aid growers in making decisions on whether cover crops would increase their economic viability, and which species they should incorporate into their own cropping system.

Cover crops can release nitrogen that was taken up at different times depending on ratio of carbon to nitrogen (C:N) that the cover crop species is composed of. Species with a high C:N ration, such as cereals, will release nitrogen slower, whereas legumes, which have a lower C:N ratio will be mineralize quickly making it accessible to the cash crop in a more timely manner (Sainju 1998).

Cover crops can also be used to reduce nitrogen loads in tile drainage. Ruffatti et al. (2018) demonstrated that using a cereal rye and daikon radish mix can reduce the NO_3-N concentration and load by 30% and 52% respectively when nitrogen was applied in the fall compared to spring when also utilizing a cover crop. Ruffatti et al (2018) also reported that cover crops reduced nitrogen loss into water drainages by 37% in soybean years when nitrogen was not applied, likely due to the cover crops changing the nitrogen cycle. Cover crop species will differ in the rate of mineralization that occurs from fall nitrogen applications to the spring. Lacey and Arrmstrong (2014) demonstrated that tillage radish residue in Illinois was rapidly mineralized with an average of 91% of the fall applied rate being inorganic N in the spring at a 0 to 20 cm depth while cereal rye resulted in only 57%. Termination timing and cover crop species will determine how quickly nitrogen is mineralized and is important for managing nitrogen.

1.6.4 Improve Soil Structure

Along with supplementing fertilizer, cover crops also benefit soil structure by breaking up the soil and creating channels with their roots. Root channels left by forage radish have been shown to enhance the water accessibility of corn by allowing the corn roots to reach deeper into the soil profile (Chen and Weil 2011). Cover crops can reduce soil compaction and increase water infiltration. Mitchellet et al. (2017) demonstrated that cover crops increase infiltration, which is thought to be due to both root development and most likely more organisms, such as earthworms, that may contribute to higher infiltration levels. Cover crops have multiple proven benefits that can make them an integral part of cropping systems that aim to develop healthier soils while lowering external inputs such as fertilizer.

1.7 Weed Suppression

If sufficient weed control could be obtained through the use of cover crops, this could reduce the need for PRE or multiple POST herbicides. PRE herbicides generally contribute more to environmental issues than other herbicides as they are applied when cropping areas are more susceptible to erosion due to less ground cover. Pantone et al. (1992) investigated atrazine run-off in Minnesota and demonstrated that PRE applications of atrazine resulted in higher atrazine concentrations in run-off than POST herbicide treatments in the runoff water. Davis et al. (2007) demonstrated that a winter wheat cover crop provided similar control of horseweed compared to a spring residual herbicide, and increased horseweed control from 13 to 0.5 plants m^{-2} compared to a fall residual in 2004 one month after a spring burndown in Indiana. However, the next year the winter wheat cover crop had up to 5.9 more plants m^{-2} compared to either a spring or fall residual herbicide application.

Cover crops can suppress weeds that emerge early in the spring (Hayden et al. 2012). This has been reported to correlate more closely with the amount of biomass present rather than the richness of cover crop species (Bybee-Finley et al. 2017). Florence et al. (2018) reported that cover crop mixtures did not provide more cover crop biomass and weed suppression when compared to productive single specie cover crops. Similarly, Teasdale et al. (1991) reported that residue cover, along with cover crop biomass, are both important factors and predictors for weed suppression. Teasdale et al. (1991) demonstrated that cover crops were able to reduce weed densities in no-till plots early in the growing season, but that weeds eventually became equivalent to no-cover crop controls later in the season. Early season suppression without the use of residual herbicides can lead to challenges later in the season as demonstrated by Teasdale et al. (1991).

Cover crop biomass is an important component of weed suppression, as cover crops can compete with weed species for sunlight. Some small seeded weeds require sunlight for germination, and cover crops can prevent sunlight from reaching the weed seed, which can reduce emergence (Teasdale and Daughtry 1993). Cholette et al. (2018) reported correlations of cover crop ground cover and biomass with horseweed density (0.17 and 0.21, respectively) and biomass (0.30 and 40, respectively), however these correlations were weak and the authors suggested that this could be due to the inherent variability when implementing biological weed management practices. Additional correlations between weed density and cover crop biomass were reported by Teasdale et al. (1991) in Maryland with large crabgrass (*Digitaria sanguinalis (L.) Scop)*, goosegrass (*Eleusine indica* (L.), stinkgrass (*Eragrostis cilianensis* (All.) Vignolo ex Janch)., carpetweed (*Mollugo verticillata* L)., and common lambsquarters density being negatively correlated with cover crop biomass with an $r^2 = 0.75$ at the 0.01 level. Allowing a cover crop to produce too much biomass may negatively affect cash crop yields (Palhano et al. 2018).

Cornelius and Bradley (2017b) demonstrated that the use of multiple cover crop species (Austrian winter pea, hairy vetch, crimson clover, oilseed radish, winter oats, annual ryegrass, cereal rye, and winter wheat) can suppress winter annual weed species. A 23 to 72% reduction in winter annual weed emergence was observed when cover crop treatments were compared to the non-treated control. The primary winter annuals in this study included henbit (*Lamium amplexicaule* L.), common chickweed (*Stellaria media* (L.) Vill.) and field pennycress (*Thlaspi arvense* L.). However, the cover crops provided less suppression than the herbicide treatment, which provided a 99% decrease in winter annual emergence. Loux et al. (2017) reported that cover crops in the absence of herbicides controlled redroot pigweed (*Amaranthus* retroflexus L.) and Palmer amaranth (*Amaranthus palmeri* S. Watson) 49 and 29% respectively, demonstrating that cover crops suppress weed emergence when compared to non-treated controls. However, the treatments that included herbicides in this study showed 100 and 96% control of redroot pigweed and Palmer amaranth, respectively (Loux et al. 2017). Barnes and Putnam (1983) conducted another study in Michigan and had similar results. In this case a rye cover crop reduced weed biomass by 94% when compared to a trial that had no cover crops. Both of the previously mentioned studies showed an increase in control of early emerging spring weeds compared to a no cover crop control. Using rye as a cover crop was effective at controlling several weed species. However, additional weed control methods are needed in order to effectively manage areas with high weed pressure (De Bruin et al. 2005).

De Bruin et al. (2005) showed that a cereal rye cover crop reduced the density of common lambsquarters and common cocklebur (*Xanthium Strumarium* L.), but did not have an effect on giant ragweed or common ragweed (*Ambrosia artemisiifolia* L.). De bruin et al (2005) and Kunz et al. (2017) also reported that like Cornelius and Bradley (2017b), cover crops reduced the biomass of weeds present when compared to a non-treated control and that some species are more affected than others.

The CTIC surveyed producers from across the United States and reported that 25% of producers agreed that cover crops always help them to control their herbicide-resistant weeds (CTIC 2017). The CTIC also reported that cereal rye was the cover crop that most producers listed as helping with herbicide-resistant weed management. Wiggins et al. (2015) performed a study in Jackson, TN and showed that crimson clover and hairy vetch provided 62 and 58% control of Palmer amaranth, respectively two weeks before POST application treatments were used. However, the authors did note that cover crops were not effective as a weed suppressant for some species throughout the entire growing season. Cover crops have been reported to increase winter weed densities in some situation as demonstrated by Mock et al. (2012) when fall seeded Italian ryegrass and wheat had 53 weeds m^{-2} compared to a nontreated check and spring applied herbicide having 27 and 2 winter weeds m^{-2} respectively in Indiana.

Determining the proper termination timing for cover crops can be a challenge from the perspective of weed management. Soybeans have a higher yield potential the earlier they are planted (Specht et al. 2014). However, as cover crops are terminated earlier, weed suppression may decrease due to lower cover crop biomass. Therefore, the termination timing of a cover crop is an important variable to consider when using cover crops, and depending on the environmental conditions, could have a significant impact on the following cash crop yield. It is also important that other weed management strategies, such as herbicides, are incorporated into these cover crop systems in order to obtain complete control of multiple weed species.

1.8 Cover Crops and Cash Crop Yield

Ruffo et al. (2004) observed that winter cover crops, including cereal rye, did not have a negative impact on soybean yield when the winter cover crops were terminated prior to soybean planting. Yield reductions of 11% in corn following an annual ryegrass or wheat cover crop have been reported in Indiana compared to residual herbicide programs in the fall or spring (Creech et al. 2008). Cover crops prior to corn can have negative effect, especially when they are not terminated prior to corn planting. Soybeans are more resilient to cover crop residues, which is likely due to their ability to develop nodules and take advantage of atmospheric nitrogen.

1.9 Cereal Rye

Cereal rye was reported as the most planted cover crop across the U.S. in the 2016 to 2017 growing season (CTIC 2017). Cereal rye is popular due to being a winter hardy species that excels in scavenging nitrogen and producing high levels of biomass that aid in weed suppression. Cereal rye has been reported as one of the most effective cover crops for suppression of *Amaranthus* species (Loux et al. 2017). Palhano et al. (2018) demonstrated that cereal rye in Arkansas produced the most biomass and allowed for the lowest level of Palmer amaranth emergence out of 7 cover crops that were observed in a no-till cotton cropping system. However, weed suppression is not limited to *Amaranthus* species as cereal rye has been reported to have 86% or better weed suppression of broadleaves and grasses when used in no-till corn production (Yenish et al. 2009). Weed suppression has also been reported when combining cereal rye with a legume like hairy vetch and providing 68 to 72% suppression of winter annual weed emergence (Cornelius and Bradley 2017b). Cereal rye contains allelopathic compounds present that can inhibit weed seed germination and root growth (Barnes et al. 1987). The two primary allopathic chemicals observed in cereal rye are 2,4-dihydroxy-1,4(2 H)-benzoxazin-3-one (DIBOA) and 2(3H)-benzoxazolinone (BOA) which can provide control of weed emergence ranging from 0 to 81% at rates varying from 25 to 100 kg ha^{-1} 14 days after being sprayed with concentrated amounts of the allelopathic compounds. (Barnes and Putnam 1987). It is important to note that these levels of DIBOA and BOA are higher than what would be found in normal field environments, but does show their potential for weed suppression.

Cereal rye can reduce the amount of NO_3 that would otherwise run off (Kaspar et al. 2007). Cereal rye has also been reported to be a more effective scavenger of nitrogen following a corn cash crop by recovering 39% of radio-labeled nitrogen when compared to a crimson clover monoculture that only recovered 4% (Ranells and Wagger 1997). The ability for cereal rye to scavenge nutrients such as nitrogen makes it an ideal cover crop for improving water quality by recovering nitrogen that may otherwise run-off into waterways. These attributes are appealing as they can help prevent unintended environmental issues such as eutrophication simply by having a cereal rye cover crop, especially in field borders, similar to those mandated by the label for synthetic auxin herbicides. Cereal rye is a popular cover crop that is used for weed control, as it produces high quantities of vegetative biomass that can suppress weeds. Cereal rye is popular among growers, as it can produce over 8,000 kg ha^{-1} biomass and is easy to incorporate into modern Midwest cropping rotations.

One disadvantage of a cereal rye cover crops was reported by Haramoto et al. (2019) in that within cereal rye rows in one of two years evaluated, average spray deposit size and percent coverage of 2,4-D was lower compared to no cover crop or between cereal rye rows. Additionally, in that same year higher coefficients of variance (CV) were reported for average deposit size, number of deposits, and spray coverage. Cover crop interception of herbicides can result in coverage and deposition issues and variability.

1.10 Crimson Clover

Tubbs et al. (2013) conducted research in Georgia where cotton following a crimson clover cover crop had a higher yield and higher gross revenue than trials following rye, wheat, or no cover crop. The yield increase observed in this study could be a result of the atmospheric nitrogen that is fixed by crimson clover, and demonstrates the appeal of using crimson clover as a cover crop in a cotton cropping system. The amount of nitrogen fixed by legumes was compiled and showed that crimson clover would fixate 124 to 185 kg N ha^{-1} (Peoples et al. 1995). The use of crimson clover to fix nitrogen at these levels make it a valuable cover crop to improve soil fertility and plant nutrition. Ross et al. (2001) showed that compared to rye, clover provides more ground cover. Cornelius and Bradley (2017b) observed that crimson clover had similar weed reduction as Austrian pea, hairy vetch, oilseed radish, and winter oat, which were able to reduce winter annual weeds by 23% to 36% when compared to a non-treated control. However, the previously mentioned cover crops were unable to give comparable control to the fall herbicide treatment which resulted in a 99% reduction of winter annual weeds. Clover in combination with cereal rye would give the combined advantages of nitrogen fixation, nutrient use efficiency, and potentially increased weed suppression early in the growing season.

1.11 Summary Statement

The use of synthetic auxin herbicides in auxin-resistant soybean will likely result in a shift to more tolerant monocot species. Weed shifts can be mitigated with integrated management practices in order to prevent unnecessary weed shifts. This potential shift could result in a need to alter weed management practices to manage new problematic weed species.

Non-chemical weed control methods will be needed in label-mandated buffer areas that have herbicide restrictions in synthetic auxin-resistant soybean production systems. Cover crops are an option for weed suppression in buffer areas that will be required by the synthetic auxin-resistant soybean labels. Additionally, cover crops can contribute to an integrated weed management system to control glyphosate-resistant weed species in buffer areas where synthetic auxins will not be permitted. Cover crops provide many benefits, but also have many challenges that will require changes in crop and weed management. The use of a cover crop in buffer areas of auxin-resistant soybean may be an effective way to improve grower experiences by beginning with small acreages and be utilized in tandem with new herbicide technologies.

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CHAPTER 2. EFFECTS OF HERBICIDE MANAGEMENT PRACTICES ON THE DENSITY AND RICHNESS IN 2,4-D- RESISTANT CROPPING SYSTEMS IN INDIANA

2.1 Abstract

Development and release of 2,4-D-resistant soybean varieties allows for post-emergence (POST) applications of 2,4-D in soybeans. With the likely increase in POST applications of 2,4-D in soybean, shifts in weed populations may occur. A long-term field trial was conducted at two locations over seven years in a corn-soybean rotation. Weed populations were subjected to four herbicide strategies with variable levels of 2,4-D reliance. The strategies used included: 1) diversified glyphosate strategy with six herbicide sites of action (SOA); 2) 2,4-D reliant strategy with three SOA; 3) diversified 2,4-D reliant strategy with seven SOA at TPAC and six SOA at SEPAC; and 4) fully diversified strategy with eight SOA. Soil residual herbicides were utilized for both corn and soybean years, except for the 2,4-D reliant strategy which only utilized a residual herbicide during the corn years. Increases in densities of weeds tolerant to 2,4-D herbicides, such as monocots, occurred after three years of selection pressure, and more than doubled after five years of selection pressure. Early-summer evaluations at either site after six years in 2019 had at least a 52% reduction in weed densities for all diversified herbicide strategies as compared to the 2,4-D reliant strategy. Early-summer weed species richness were reduced by at least 30% for treatments that included six or more SOA when compared to the 2,4-D reliant strategy, which contained three sites of action, and did not utilize a residual herbicide in years that soybeans were grown. The soil seedbank at one location in the 2,4-D reliant strategy had a 79% higher density of weeds compared to the next highest treatment and consisted of 90% monocot species during the latter two growing seasons. Using three sites of action with residual herbicide only implemented in years that corn was grown also resulted in up to 30% higher species richness within the soil seedbank of conventionally tilled systems compared to herbicides strategies with six or more SOA with residual herbicides applied every year, and up to 10% in the no-till system compared with using eight SOA and residual herbicides applied every year. Both early-summer and seedbank assessments support utilizing six or more SOA to decrease weed densities and species richness compared to a herbicide strategy with only 2,4-D, glyphosate, and atrazine being utilized over the seven-year period. This research demonstrates that integrating multiple SOA and overlapping

residual herbicides into a herbicide management plan will reduce total weed densities and overall species richness. In order to delay unnecessary weed shifts farm operators need to use diversified herbicide strategies with more than three SOA, even though glyphosate, 2,4-D, and atrazine may provide high levels of weed control early on year to year basis.

2.2 Introduction

Globally crops are threatened by pests, with the most prominent threat being weeds, which are responsible for 34% of the crop damage due to pests (Oerke 2006). In recent years herbicides have been the most widely used pesticide group in the United States making up approximately 47% of pesticides use (Grube et al. 2011). Herbicides that allow for selective weed control within crops allow for control of problematic species with in-crop applications. One such selective herbicide is 2,4-dichlorophenoxyacetic acid (2,4-D), which has been used for decades to control broadleaf species in grass crops (Hume 1987). Soybeans have been developed that contain traits that confer resistance to 2,4-D, glyphosate, and glufosinate and marketed commercially as Enlist E3® soybeans (Corteva Agrisciences, 9330 Zionsville Road, Indianapolis, Indiana, United States) (Wright et al. 2010). These soybean varieties will allow for 2,4-D, glyphosate, and glufosinate to be safely sprayed to selectively control broadleaf weeds within a broadleaf crop.

Due to the widespread occurrence of ALS- and glyphosate-resistant broadleaf weeds, the adoption of Enlist E3® soybeans will primarily be for use of 2,4-D herbicide to provide control of broadleaves. Due to this selectivity, synthetic auxins, like 2,4-D have been used in rice, small grains, and corn for over 75 years to control broadleaf weeds in grass crops or fallow areas (Blackman 1945). Within the synthetic auxins site of action, 2,4-D belongs to phenoxy-carboxylic-acid chemical family and is classified by the Weed Science Society of America’s (WSSA) as a group number 4 (WSSA 2014). The naturally occurring auxin hormones within a plant regulate the elongation of plant cells and stomatal opening, among many other functions of plant growth

(Acharya and Assmann 2009, Davis and Cleland 2010). The accumulation of auxins in a plant due to exposure to synthetic auxin herbicides causes a loss of Aux/IAA repressors that is thought to result in two genes involved with abscisic acid biosynthesis to be overexpressed. This overexpression leads to an increase in ethylene, hydrogen cyanide, and abscisic acid which can lead to several forms of plant injury including; senescence, stem and leaf curling, cell death, and growth inhibition (Grossmann 2010). The different forms of plant injury can lead to decreases in important plant processes such as stomatal aperture, transpiration, and carbon assimilation and can result in plant death (Grossman 2000).

Changes in crop management practices, such as herbicide application, tillage, and crop rotation often result in shifts in weed species composition (Blackshaw et al. 2001, Buhler 1995, Davis et al. 2009, Thomas et al. 2004), especially when new methods of weed control are implemented. Heard et al. (2003) showed that weed populations were negatively affected in life stage transitions (i.e. emergence, survival, reproductive rate, and seedbank change) by the implementation of genetically modified herbicide-tolerant beet (*Beta vulgaris* L spp. *vulgaris.*) and oilseed rape (*Brassica napus* L.), due to the use of herbicides available for these herbicide-tolerant crops. However, herbicide-tolerant corn (*Zea mays* L.) did not have as large of an effect on life stage transitions on weed species when compared to a conventional treatment. This is likely due to the residual herbicides that are commonly used in conventional corn production (Heard et al. 2003). The introduction of new weed management techniques to any production system will alter the weed community based on the life stage transition that is impacted by the new control method. Hume et al. (1991) observed that when tillage was reduced from conventional tillage to zero tillage with a disc seeder, foxtail barley became the dominant species. Indirect shifts in weed communities were observed in a survey by the American Soybean Association when glyphosate-resistant crops were introduced and a shift to reduced-tillage and no-till practices occurred as a response to the new technology (Cerdeira and Duke 2006). Adoption of reduced tillage practices may persist as another effective POST control option becomes available with 2,4-D-resistant soybeans.

A shift of weed species requires both selection pressure and inherent variation within a population (Stebbins 1999). The most recent major shift in weed communities was noted when glyphosate-resistant crops were introduced. Young (2006) proposed that if the applications of glyphosate continued to be delayed, and that if glyphosate continued to be heavily relied on, that a shift into glyphosate tolerant species would likely occur. This could also result in the development of glyphosate-resistant weed species. Widespread glyphosate use throughout the United States acting as the selection pressure combined with several weed species with high levels of genetic variation resulted in a shift in the weed community towards glyphosate-resistant weed biotypes of which 17 unique weeds are resistant to glyphosate in the United States alone (Charles M Benbrook 2012, Gasquez 1997, Johnson et al. 2009b, Heap 2020).

With 2,4-D as a new SOA to be used in soybeans, it is likely that 2,4-D, in combination with glyphosate, will be important components to most herbicide applications within Enlist E3 soybeans. Currently 25 weeds have developed resistance to 2,4-D (Heap, 2020). The number of 2,4-D-resistant weed species and areas infested is likely to increase due to an increase in acreage planted with 2,4-D-resistant soybeans. If other SOA are not utilized in herbicide programs there will likely be a shift into species that are tolerant to 2,4-D, as was predicted when glyphosate-resistant crops were increasing in acreage (Young 2006).

Diversified weed management strategies such as the utilization of multiple herbicide SOA are necessary to prevent shifts to more problematic weed species. One challenge in promoting the use of more than two SOA is that 2,4-D and glyphosate can provide control of several key weed species without any additional SOA at a relatively low cost. Miller and Norsworthy (2016) reported that applications of high use rates of 2,4-D in combination with glyphosate was sufficient for controlling both susceptible and glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson). Robinson et al. (2012) showed that applications of 2,4-D in combination with glyphosate provided 97% control of velvetleaf (*Abutilon theophrasti* Medik), waterhemp (*Amaranthus tuberculatus* (Moq.) J. D. Sauer), and common lambsquarters (*Chenopodium album* L.). Therefore, the addition of 2,4-D as a site of action in soybean cropping systems will be a valuable tool in weed management due to enhanced control of these problematic weed species.

Information on the potential affects that 2,4-D-resistant soybeans will have on weed communities is not currently available. As interest in growing 2,4-D-resistant soybeans increases it will be vital that this information is obtained to aide farm operators in making effective and sustainable weed management decisions.

The objective of this research is to identify shifts in the weed community both for weed density and species richness parameters, as well as any shifts that may occur when separated into monocot and dicot species under different herbicide practices in a corn-soybean crop rotation.

2.3 Material and Method

2.3.1 Field Sites

Long-term experiments were conducted at two locations in Indiana, the Throckmorton Purdue Agriculture Center [TPAC (40.30°N, 86.90°W)] and the Southeast Purdue Agriculture Center [SEPAC (39.03°N, 85.83°W)] for seven consecutive years (2013-2019). The TPAC location soils consist predominantly of a Toronto-Millbrook silty clay loam complex with a pH of 6.1, soil organic matter (SOM) of 2.6%, and a cation exchange capacity (CEC) of 10.6 meq 100 g^{-}

[1]. TPAC received fall or spring primary tillage with a chisel plow. Secondary tillage was done with a field cultivator. SEPAC is a no-till location where the soils consist primarily of a poorly-drained Cobbsfork silt loam which has 1.7% SOM, a pH of 5.1, and a CEC of 7.7 100 meq 100 g^{-1}. Fertility programs were adjusted for each site and utilized recommendations for optimal crop yield in the region. The SEPAC location has more winter-annual species and a more diverse weed community compared to the TPAC location. Initiated in 2013, corn (*Zea mays* L.) with transgenic resistance to both glyphosate and glufosinate was planted in alternating years (2013, 2015, 2017 and 2019), and 2,4-D-resistant soybeans (*Glycine max* (L). Merr.) were planted in rotation (2014, 2016, and 2018). Corn was planted at 80,000 seeds ha^{-1}, while soybean seeding rates were 350,000 seeds ha^{-1}.

2.3.2 Experimental Design & Herbicide Treatments

The experimental design was a randomized complete block with six replications. Plots were 6 m wide and 15 m in length and consisted of eight rows spaced 76 cm apart. Field trial corners were marked using global positioning systems (GPS) to ensure that locations were consistent from year to year. Four treatments were evaluated over a 2-year corn-soybean rotation. Herbicide strategies included were referred to as follows: 2,4-D-reliant, diversified glyphosate, diversified 2,4-D, and fully diversified, each of which had three, six, seven, and eight SOA used, respectively at TPAC and three six, six, and eight SOA respectively used at SEPAC. More specific details regarding herbicide strategies can be found in Tables 2.1 and 2.2. Herbicide applications were made with a CO_2-propelled 3 m backpack sprayer at 4.8 km h^{-1}. Booms were equipped with AIXR11003 nozzles (Teejet Technologies, 1801 Business Park DR, Springfield, IL 62703). Herbicide strategies were specifically designed to be effective for the major weed species at each research location, and to be complimentary to the type of tillage practice at each location. The primary weed species at SEPAC were a wide variety of grasses, including giant foxtail (*Setaria faberi* Herrm.), yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.), barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.), and large crabgrass (*Digitaria sanguinalis* (L.) Scop.), and horseweed (*Erigeron canadensis* L.). Giant ragweed (*Ambrosia trifida* L.) and foxtail species (*Setaria* spp.) were the dominant species at the TPAC location. Burndown treatments made at the SEPAC location where sprayed targeting two weeks before planting, while pre-emergence (PRE) applications were applied near planting at the TPAC location. Post-emergence (POST) applications were made in early-summer when weeds were 10 to 15 cm tall, or when corn reached 75 cm in height. Application information can be found in Table 2.3.

2.3.3 Soil Seedbank Data Collection

In order to characterize weed communities at each location, sixteen soil cores were collected randomly from each plot (minimum of 1 m distance from the edge of the plot) and placed in a container prior to spring tillage at TPAC or burndown applications at SEPAC. Each core measured 5.7 cm in diameter and 7.6 cm in depth. Weed densities and species richness are presented in the units of 3000 cm^{-3} due to volume being the most accurate unit of measurement for our collection methods. The following formula shows the calculations for determining volume of soil that densities and species richness are presented in:

$$V = \pi r^2 h = \pi (2.85\ cm)^2 \times 7.6\ cm = 194\ cm^3 \times 16\ soil\ cores = 3104\ cm^3$$

This was rounded down to 3000 cm^3 to allow for 3.5% loss of soil during collection and transport. Other studies have presented soil seedbank densities in terms of area such as m^{-2} (Carter and Ivany 2006, Conn et al. 1984, Menalled et al. 2001, Moonen and Barberi 2004). Seed density on a volume basis (cm^3) has also previously been utilized to compare spatial analysis methods within soil seedbanks (Bigwood and Inouye 1988). Soil cores collected were homogenized by hand

and placed in 25 by 50 cm flats with soil spread evenly to and approximate depth of 2.5 cm. Flats were placed in a greenhouse in Lafayette, IN where a 16-hour photoperiod was maintained using 600 W high pressure sodium lights, and temperatures were set to approximately 26 C. Flats were watered twice a day for eight weeks. Weed species and densities were recorded biweekly, with emerged weeds removed from flats at each evaluation. After four weeks, soil was manually mixed to promote germination of weeds that had not yet emerged. Soil from the SEPAC location was placed in containers and put in cold storage for approximately 3 months to break dormancy of any winter-annual seeds still present in the soil. The SEPAC soil was then placed back in the greenhouse and the characterization process was repeated for another eight-week period. Weed species data were compiled to calculate density and richness as a whole, as well as divided into monocot and dicot species. Total, monocot, and dicot densities and species richness for each treatment were analyzed using PROC GLIMMIX in SAS 9.4 (SAS, 100 SAS Campus Drive, Cary, NC 27513-2414, USA) with year being a repeated measure. Differences in means were separated using Tukey's Honest Significant Difference (HSD) test (α=0.05).

2.3.4 Field Data Collection and Analysis

Prior to spring tillage or burndown, two 1-m^2 quadrants were established 4.5 m in from the front and back of each plot and 1 m in from the edge of the plot. Due to the long-term nature of this project quadrants were placed in the same location every year. Weed density and species counts were recorded prior to spring tillage, as well as prior to herbicide application events throughout the year. Weed counts and species richness taken prior to POST applications are hereafter referred to as "early-summer" evaluations. One exception was in 2019 when a glyphosate application was made at the SEPAC location to manage weeds prior to a delayed planting. Total weed densities and species richness were compiled and analyzed, as well as separated into monocot and dicot species. Weed densities and species richness were analyzed using SAS 9.4 PROC GLIMMIX procedure with year being a repeated measure. Means were separated using Tukey's HSD test (α=0.05). Yield data were collected by harvesting the middle four rows from each plot at physiological maturity for each crop. Data were subjected to analysis of variance using PROC GLIMMIX in SAS with year being a repeated measure. Soybeans and corn were weighed and sampled for moisture using a digital field monitor and a bench grain moisture tester (Dickey John GAC 2100 Grain Moisture Tester, DICKEY-john, 5200 DICKEY-john road, Auburn, IL 62615).

2.4 Results and Discussion

2.4.1 Spring weed density and species richness

Total weed density and monocot density were both influenced by an interaction between the herbicide strategy and year (P=0.0394 and P <0.0001, respectively) at the TPAC location (Table 2.4). Dicot density was influenced by both year and herbicide strategy, but lacked interaction of factors. The highest weed density at the TPAC location occurred in 2018 and is likely due to a winter with a higher than average snowfall which provided an insulating cover for winter-annual species. In the spring of 2019 the total species density declined and was similar to the majority of the previous years (Figure 2.1). The 2,4-D reliant treatment had a higher total weed density as well as a higher density of monocots compared to the other herbicide strategies. Dicot density was 32% higher in the 2,4-D reliant treatment at the tilled location compared to all other herbicide strategies (Table 2.5). These results demonstrate that in a tilled system, utilizing three SOA over seven years and only implementing a residual herbicide in years that corn is grown will result in a higher weed density of both dicots and monocot when compared to more robust herbicide strategies that use six or more sites of action.

The total and monocot species richness at TPAC were both influenced by an interaction between herbicide strategy and year (*P*=0.0337, *P* <0.0001) (Table 2.4). The high species richness in 2019 is likely the result of not being tilled in the fall of 2018 due to wet field conditions. The 2,4-D reliant strategy had dicot and monocot species richness similar to the diversified 2,4-D and fully diversified strategies. The years with the highest dicot species richness were 2013, 2014, and 2019 (data not shown). The initial two years likely had higher dicot species richness due to treatment effects not being seen in the initial year (2013) and continuing to be high in 2014 due to germination of dicots from the soil seedbank. The high number of dicot species in 2019 can be explained by the late application of a pre-emergence herbicide relative to other years (Table 2.3) resulting in more dicots emerging and being recorded due to the delayed field seasons as a result of high precipitation.

At SEPAC, the no-till location, total, dicot, and monocot weed densities were only influenced by year (*P* <0.0001) (Table 2.4). When observing only dicot species, 2013 and 2018 had the highest densities. High dicot densities in 2013 were expected due to being the initial year of the experiment. This was not observed in 2019 due to more effective SOA being utilized to control waterhemp within corn years in the rotation. Monocot density was greatest in 2017 and 2018 (data not shown). The increase in monocot density in these years is likely a result of increasing annual bluegrass (*Poa annua* L.) densities. However, this was not observed in 2019 due to increased precipitation resulting in environmental conditions that may not be optimal for germination of monocots and specifically annual bluegrass. Total and dicot species richness at SEPAC were influenced by both year and herbicide strategy individually, while monocot species richness was influenced by year only (P<0.0001) (Table 2.4). However, the TPAC location in 2018 had the highest total weed densities out of all years. The number of dicot and monocot species did not differ between herbicide strategies. The primary weed species at the SEPAC location in the spring was annual bluegrass. Since this was a no-till site with the burndown timing two weeks before planting, this allowed annual bluegrass time to produce seed and increase in density over the years this study was conducted. This resulted in annual bluegrass becoming the primary weed present at the spring weed control timing. This explains the higher percentage of the total density that is made up of monocots in all herbicide strategies and years at the SEPAC location.

Utilizing more than six SOA reduced weed densities at the tilled site in the spring in all strategies. Weed densities, primarily winter-annual species, were increased at the tilled site after a 7-year period of using 2,4-D, glyphosate, and atrazine in corn years, with all other herbicide strategies having total weed densities of 60% or less than the 2,4-D reliant herbicide strategy. Managing early-season weeds has important implications in relation to reducing seed production as well as limiting hosts of disease and insects that can damage cash crops. Creech et al. (2005) first reported soybean cyst nematode reproduction on purple deadnettle, demonstrating the importance of controlling winter-annual weeds early in the growing season. The 2,4-D reliant strategy was not as effective at reducing weed densities compared to herbicide strategies with 6 or more SOA. This is the first report evaluating the early-season weed control with varying levels of 2,4-D selection pressure over a long period of time. We demonstrate the importance of utilizing multiple SOA in order to reduce spring weed densities both in the early years of commercialization and future years to extend the longevity of this technology.

2.4.2 Early-summer post-emergence application weed densities and species richness

Total, dicot, and monocot weed densities at the TPAC location were influenced by an interaction between herbicide strategy and year [P=0.0004, P=0.0029, and P<0.0004 respectively (Table 2.6)]. The total, monocot, and dicot weed densities at SEPAC were all also influenced by an interaction between herbicide strategy and year (P<0.0001, P=0.0013, and P<0.0001). The total and monocot species richness at SEPAC were influenced by an interaction between herbicide strategy and year [*P*=0.0014 & *P*=0.004 respectively (Table 2.6)], while the dicot species richness was only influenced by each factor individually. The 2,4-D reliant treatment had a higher density of total weed species, as well as monocot and dicot species when compared to all other treatments across both locations. The highest total and monocot weed densities occurred in 2018 and reflected observations in the spring evaluations. In 2019, monocots comprised over 95% of the total weeds present in early-summer evaluations and made up over 97% of the weeds in the 2,4-D reliant plots at TPAC (Figure 2.2). Increases in densities of weeds tolerant to 2,4-D herbicides, such as monocots, occurred after three years of selection pressure, and more than doubled after five years of selection pressure (Figure 2.2). The increase in weed densities did not occur, and densities remained constant when 6 or more SOA were utilized.

In 2018 weed densities peaked, and were nearly double the number of weeds than the next highest year at SEPAC (Figure 2.3). This is likely due to additional weed emergence after the POST application in 2017, and the lack of activity from residual herbicides due to limited precipitation; therefore, causing a large increase in densities, specifically in the plots managed with only three SOA. Dicots were present in higher densities and species number within the 2,4-D reliant treatment in two of the three years that soybeans were grown at TPAC, and in soybeans in 2018 at SEPAC, compared to the other 3 treatments; but this was not always the case during years corn was grown (Figures 2.3 & 2.4). Dicot species richness was 28% higher in the 2,4-D reliant treatment at SEPAC (Table 2.7).

Species richness was highest in the 2,4-D reliant treatment in every year soybeans were grown at TPAC (Figure 2.4). Gibson et al. (2016) reported that high species richness was observed within soil seedbanks in continuous glyphosate-resistant soybeans compared with other soybean cropping systems, and that lowest species densities were observed within continuous corn. The high species richness in 2,4-D reliant treatment is due to only three SOA being implemented to control a broad spectrum of weed species. Similarly, monocot species richness within the 2,4-D reliant treatment was higher in soybean years (Figure 2.4). The next highest treatment in species richness at TPAC contained 74% fewer species than the 2,4-D reliant treatment. This demonstrates the importance of using multiple sites of action to reduce species richness in corn and soybean rotational systems to prevent shifts to monocot dominated weed populations, and reduce the selection pressure for herbicide-resistance to develop (Norsworthy et al. 2012). Implementing an herbicide strategy with 6 or more SOA decreased both weed densities and species richness compared to a strategy that utilized only 3 SOA. Weed densities for total, dicots, and monocots had at least 76, 6, and 60 more weeds m^{-2} within the 2,4-D reliant strategy compared to all other strategies at both locations. Similarly, Gibson et al. (2016) estimated that best management practices made on academic recommendations would result in 40% lower weed densities in 10 years based on the linear regression of weed population density changes through time compared with general practices by farm operators. Weed species richness for the diversified glyphosate, diversified 2,4-D, and fully diversified was 30% or less of the 2,4-D reliant richness across both sites in this study.

2.4.3 Soil seedbank weed densities and species richness

The total and monocot weed densities and species richness were both influenced by an interaction between herbicide strategy and year at the TPAC location (Table 2.8). However, the TPAC dicot weed density was only influenced by herbicide strategy (*P*=0.0002), while the TPAC dicot species richness was influenced both by herbicide strategy and year [*P*=0.0113 and *P*=0.0262

(Table 2.8)]. The dicot density at the TPAC location was highest in the diversified 2,4-D strategy, which was also similar to the 2,4-D reliant strategy, however, the diversified glyphosate, and fully diversified strategies had the lowest dicot densities with 4 and 2 dicots per 3000 cm^{-3}, respectively (Table 2.9). Dicot species richness was similar across all years except 2014; however, the fully diversified strategy had fewer dicot species than the 2,4-D reliant strategy. The 2,4-D reliant strategy at TPAC had 79% more weeds compared to the next highest treatment which was the diversified 2,4-D herbicide strategy (Figure 2.5). The 2,4-D reliant strategy at TPAC consisted of at least 90% monocot species in 2018 and 2019 (Figure 2.5). The species richness at TPAC was highest in the 2,4-D reliant strategy having twice as many species as any other strategy, while herbicide strategies with 6 or more sites of action used over a two-year corn-soybean rotation remained more consistent across years. Davis et al. (2005) has previously reported differences in weed species composition due to different management practices of tillage and reduced input systems.

The 2,4-D reliant strategy in 2018 resulted in at least two times greater monocot and total densities than any other year. The species richness for both monocots and total weeds was greater in 2018 having an average of 1.5 more species in the POST measurements and at least 1 more species in the soil seedbank than any other treatment. Both early-summer and seedbank assessments support utilizing six or more SOA to decrease weed densities and species richness compared to a herbicide strategy with 2,4-D, glyphosate, and atrazine in corn years.

2.4.4 Crop Yield

The TPAC location had no differences in yield within soybean years. However, in corn years after the year of initiation, the 2,4-D reliant and diversified 2,4-D treatments yield was at least 7% lower than the fully diversified treatment. In 2019, corn yield was only reduced in the diversified 2,4-D treatment, resulting in an 11.5% yield reduction (data not shown). Yield reductions are likely due to weed competition, however, 2,4-D injury to corn could have an effect on yields when used in combination with glyphosate which was observed in 2019 (Soltani et al. 2019). Injury from 2,4-D could be eliminated through the use of corn varieties that are more tolerant to 2,4-D, such as Enlist® corn varieties (Corteva Agrisciences, 9330 Zionsville Road, Indianapolis, Indiana, United States).

The results from this research provide new evidence of weed community responses under varying 2,4-D selection pressures in soybean production systems. The addition of 2,4-D to the herbicide strategy did not improve the overall weed control, as the diversified glyphosate and diversified 2,4-D had similar species richness and densities at the early-summer assessments across all years and sites. The addition of 2,4-D was not as important to weed management in soybeans as utilizing multiple sites of action and utilizing overlapping residual herbicides to obtain high levels of weed control.

The effectiveness of treatments with additional SOA demonstrate the benefit of overlapping residual herbicides to obtain an extended period of weed control. The value of utilizing sequential residual herbicide application has been shown to be effective in providing 97% control of Palmer amaranth, compared to 86% control when no residual was applied during a POST application (Sarangi and Jhala 2019). The 2,4-D reliant herbicide strategy did not have a residual within the PRE or POST application in soybean years, which was a factor in why more species where observed in early-summer evaluations compared to the other treatments (Figures 2.2 & 2.3).

Hume (1987) has reported that 2,4-D applied over many years reduced the number of susceptible plants, which allowed for species with a higher tolerance to 2,4-D to increase. The trend seen by Hume (1987) was also observed in this research within the 2,4-D reliant treatment as 2019 had 119 fold more monocots m^{-2} when compared to the initiation of the experiment in 2013. Throughout the same time period dicot species in 2,4-D reliant plots were 5 times higher in 2019 than in 2013 due to residual herbicides only being utilized in years that corn was grown. The increase in both susceptible and tolerant species provides further evidence that overlapping residuals are important in addition to using multiple SOA. Reducing weed populations is also beneficial for reducing the rate of evolution of herbicide resistant weed species (Diggle and Neve 2003).

In conclusion, residual herbicides and utilizing multiples SOA provides a consistent method to reduce weed densities and species richness. Shergill et al. (2017) similarly, reported that residual herbicides applied prior to POST glyphosate applications resulted in greater than 50% reduction in weed densities and a 250% increase in yield compared to glyphosate alone. However, reduction in weed densities and increase in yield were not observed in the first year, but after the 4th year. Although, we did not observe consistent increases in yield, increases of 52% in weed density were observed in the 2,4-D reliant treatment compared to other herbicide strategies in the early-summer evaluations.

The use of residual herbicides is needed in order to reduce the selection pressure imposed on weed species of economically important herbicides, such as glyphosate, 2,4-D, and atrazine (Johnson et al. 2012). Loux et al. (2011) reported that in glyphosate-resistant corn at least 90% control of redroot pigweed (*Amaranthus retroflexus* L.), ivyleaf morningglory (*Ipomoea hederacea* Jacq.), and giant ragweed was achieved with PRE herbicides. The highest yielding treatments in the same study included two- or three-way combination of a PRE herbicides at 50% or higher of the recommended rate.

Riar et al. (2013) reported that 36% of producers thought the cost of using multiple effective modes of action was a concern in cotton, rice, and soybean production systems. Edwards et al. (2014) established that although herbicide costs of best management practices to control herbicide-resistant weeds was 36% higher in Illinois and Indiana compared to general practices by farm operators net returns were not different in either the short or long-term. Using residual herbicides with multiple SOA to slow evolution of herbicide-resistant weed species and unnecessary weed shifts is attainable, and likely economical in the long-term. Farm operators need to use several SOA and include residual herbicides in both corn and soybean years even though glyphosate, 2,4-D, and atrazine in corn years may provide high levels of weed control early on as 2,4-D-resistant soybeans are commercialized.

Weed shifts have been previously reported due to changes in herbicide use. Sprague et al. (1997) reported Palmer amaranth from Kansas and waterhemp from Illinois had become difficult to control with ALS herbicides due to resistance of ALS herbicides. Johnson et al. (2009) discussed weed shift after the introduction of glyphosate-resistant cropping systems shifting from perennial grass and broadleaf species to a composition of annual weed species with resistance to glyphosate. The continuous use of glyphosate resistant crops has previously been observed to result in increased species richness for biennials, prostrate species, and winter-annuals (Schwartz et al. 2015). Wilson et al. (2007) evaluated weed shifts over six years with a low and high rate of glyphosate and reported an increase in common lambsquarters when low rates of glyphosate were used compared to high rates. However, common lambsquarters densities remained similar when standard use rates were implemented. Wilson et al. (2011) compared academic recommended practices to general farm operator practices and concluded that academic recommendations on average included more unique herbicide modes of action in seven different cropping systems. To date no research has been published that examines the impact of 2,4-D on weed species shifts in 2,4-D-resistant soybean production systems. Our work showed that utilizing 2,4-D with a minimum of only two other sites of action over the course of seven years in a corn-soybean rotation will result in both increased weed densities and species richness within both conventionally and no-tilled production systems. Using three sites of action with residual herbicides only applied in years that corn was grown also resulted in up to 30% higher species richness within the soil seedbank of conventionally tilled systems compared to herbicides strategies with six or more sites of action and residual herbicides applied every year, and up to 10% in the no-till system compared with using eight sites of action and residual herbicides applied every year.

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Table 2.1: Herbicide Strategies used in both corn and soybean years at the Throckmorton Purdue Agriculture Center. Table adapted from Legleiter T (2017) Dicamba and 2,4-D Utilization in Growth Regulator Resistant Soybean. Ph.D. dissertation. Lafayette, IN: Purdue University. 123-124 pa

Herbicide strategy	Crop	Timing	Herbicide	Rate (g ha^{-1})	WSSA SOA group #	Tradename	Manufacturer
Diversified Glyphosate (Diversified Gly)	Corn	PRE	atrazine	1100	5	Lexar EZ	Syngenta
			s-metolachlor	1100	15		
			mesotrione	141	27		
		POST	atrazine	1120	5	AAtrex	Syngenta
			glyphosate	1100	9	Roundup Powermax	Monsanto
			topramazone	12	27	Impact	AMVAC
	Soybean	PRE	chlorimuron	18	2	Fierce XLT	Valent
			flumioxazin	69	14		
			pyroxasulfone	87	15		
		POST	glyphosate	1426	9	Flexstar GT	Syngenta
			fomesafen	353	14		
2,4-D Reliant	Corn	PRE	atrazine	2200	5	AAtrex	Syngenta
		POST	2,4-D	560	4	Weedar 64	Nufarm
			glyphosate	1100	9	Roundup Powermax	Monsanto
	Soybean	Early POST	2,4-D	1120	4	Enlist One	Dow AgroSciences
			glyphosate	1120	9	Roundup Powermax	Monsanto
		Late POST	2,4-D	1120	4	Enlist One	Dow AgroSciences
			glyphosate	1120	9	Roundup Powermax	Monsanto

Table 2.1 continued

Diversified 2,4-D (Div 2,4-D)	Corn	PRE	atrazine	1100	5	Lexar EZ	Syngenta
			s-metolachlor	1100	15		
			mesotrione	141	27		
		POST	2,4-D	560	4	Weedar 64	Nufarm
			glyphosate	1100	9	Roundup Powermax	Monsanto
	Soybean	PRE	chlorimuron	18	2	Fierce XLT	Valent
			flumioxazin	69	14		
			pyroxasulfone	87	15		
		POST	2,4-D	1120	4	Enlist One	Dow AgroSciences
			glyphosate	1120-	9	Roundup Powermax	Monsanto
Fully Diversified 2,4-D (Fully Div.)	Corn	PRE	atrazine	1100	5	Lexar EZ	Syngenta
			s-metolachlor	1100	15		
			mesotrione	141	27		
		POST	atrazine	1120	5	AAtrex	Syngenta
			glufosinate	450	10	Liberty	BASF
			topramazone	12	27	Impact	AMVAC
	Soybean	PRE	chlorimuron	13	2	Valor XLT	Valent
			flumioxazin	38	14		
		POST	2,4-D	1120	4	Enlist One	Dow AgroSciences
			glyphosate	1120	9	Roundup Powermax	Monsanto
			pyroxasulfone	180	15	Zidua	BASF

[a]Prior to 2018 2,4-D amine was used in place of Enlist One.

Table 2.2: Herbicide strategies used in corn and soy years at the Southeast Purdue Agriculture Center. Table adapted from Legleiter T (2017) Dicamba and 2,4-D Utilization in Growth Regulator Resistant Soybean. Ph.D. dissertation. Lafayette, IN: Purdue University. 125-126 pb

Herbicide Strategy	Crop	Timing	Herbicide	Rate (g ha^{-1})	WSSA SOA Group #	Tradename	Manufacturer
Diversified Glyphosate (Diversified Gly)	Corn	Burndown	atrazine	1120	5	AAtrex	Syngenta
			glyphosate	1100	9	Roundup Powermax	Monsanto
			saflufenacil	75	14	Verdict	BASF
			dimethenamid-P	656	15		
		POST	atrazine	1120	5	AAtrex	Syngenta
			glyphosate	1100	9	Roundup Powermax	Monsanto
			topramazone	12	27	Impact	AMVAC
	Soybean	Burndown	chlorimuron	30	2	Canopy	DuPont
			metribuzin	600	5	Tricor 75DF	Syngenta
			glyphosate	1100	9	Roundup Powermax	Monsanto
			saflufenacil	25	14	Sharpen	BASF
		POST	cloransulam	35	2	FirstRate	DowAgroSciences
			glyphosate	1100	9	Roundup Powermax	Monsanto
2,4-D Reliant	Corn	Burndown	atrazine	1680	5	AAtrex	Syngenta
			2,4-D	560	4	Weedar 64	Nufarm
			glyphosate	1100	9	Roundup Powermax	Monsanto
		POST	2,4-D	560	4	Weedar 64	Nufarm
			glyphosate	1100	9	Roundup Powermax	Monsanto
	Soybean	Burndown	2,4-D	1120	4	Enlist One	DowAgroSciences
			glyphosate	1120	9	Roundup Powermax	Monsanto
		Early POST	2,4-D	1120	4	Enlist One	DowAgroSciences
			glyphosate	1120	9	Roundup Powermax	Monsanto
		Late POST	2,4-D	1120	4	Enlist One	DowAgroSciences
			glyphosate	1120	9	Roundup Powermax	Monsanto

Table 2.2 continued

Diversified 2,4-D (Div 2,4-D)	Corn	Burndown	atrazine	1120	5	AAtrex	Syngenta
			glyphosate	1100	9	Roundup Powermax	Monsanto
			saflufenacil	75	14	Verdict	BASF
			dimethenamid-P	656	15		
		POST	2,4-D	560	4	Weedar 64	Nufarm
			glyphosate	1100	9	Roundup Powermax	Monsanto
	Soybean	Burndown	chlorimuron	30	2	Canopy	DuPont
			metribuzin	600	5	Tricor 75DF	Syngenta
			2,4-D	1120	4	Roundup Powermax	Monsanto
			glyphosate	1120	9	Sharpen	BASF
		POST	2,4-D	1120	4	Enlist One	DowAgroSciences
			glyphosate	1120	9	Roundup Powermax	Monsanto
Fully Diversified 2,4-D (Fully Div)	Corn	Burndown	atrazine	1120	5	AAtrex	Syngenta
			glufosinate	450	10	Roundup Powermax	Monsanto
			saflufenacil	75	14	Verdict	BASF
			dimethenamid-P	656	15		
		POST	atrazine	1120	5	AAtrex	Syngenta
			glufosinate	450	10	Liberty	BASF
			topramazone	12	27	Impact	AMVAC
	Soy bean	Burndown	chlorimuron	30	2	Canopy	DuPont
			metribuzin	600	5	Tricor 75DF	Syngenta
			glyphosate	1100	9	Roundup Powermax	Monsanto
			saflufenacil	25	14	Sharpen	BASF
		POST	cloransulam	35	2	FirstRate	DowAgroSciences
			2,4-D	1120	4	Enlist One	DowAgroSciences
			glyphosate	1120	9	Roundup Powermax	Monsanto

[a]Prior to 2018 Clarity was used in place of Xtendimax.

Table 2.3: Application dates at TPAC and SEPAC from 2013 to 2019.[a]

Site	Crop	Application	2013	2014	2015	2016	2017	2018	2019
TPAC	Corn	PRE	May 9		May 2		April 28		May 21
		POST	June 7		June 2		June 8		June 14
	Soybean	PRE		May 27		May 8		May 10	
		Early POST		June 26		June 1		June 7	
		POST		July 10		June 13		June 18	
		Late POST		July 21		June 25		July 18	
	Late POST in Fully Diversified 2018 Only)							July 3	
SEPAC	Corn	PRE	May 8		April 28		April 23		May 8
		POST	June 20		June 3		June 22		July 23
	Soybean	PRE		May 8		May 13		April 30	
		Early POST		June 18		June 14		June 5	
		POST		June 25		June 29		June 5	
		Late POST		July 15		July 9		June 19	

[a]Abbreviations: PRE=pre-emergence, POST= post-emergence, TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

Table 2.4: ANOVA for the influence of herbicide strategy, year and the interaction of the two on total weed density, total weed species richness, dicot density, dicot species richness, monocot density, and monocot species richness, in late-April of each year prior to spring weed control methods at SEPAC and TPAC from 2013 to 2019.[a]

	Factors & interactions	SEPAC			TPAC		
		Total weed species	Dicot weed species	Monocot weed species	Total weed species	Dicot weed species	Monocot weed species
		P					
Density	Herbicide Strategy	0.3329	0.0998	0.6942	<.0001	0.0028	<.0001
	Year	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Herbicide Strategy x Year	0.9968	0.939	0.9984	0.0394	0.7863	<.0001
Species richness	Herbicide Strategy	0.0254	0.0388	0.578	0.0041	0.0167	0.0136
	Year	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Herbicide Strategy x Year	0.9952	0.9902	0.868	0.0337	0.1104	<.0001

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

Table 2.5: Influence of year on dicot density at the Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909). from 2013 to 2019 in late-April prior to spring weed control methods.[a,b,c]

Herbicide strategy	Dicot weed species
	Plants m^{-2}
Diversified Gly	13 b
2,4-D Reliant	19 a
Div 2,4-D	12 b
Fully Div	11 b

[a]Abbreviations: Gly= glyphosate and Div=Diversified.
[b]Means followed by the same letter are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).
[c] Dicot species: giant ragweed *(Ambrosia trifida*), common chickweed *(Stellaria media*.), henbit *(Lamium amplexicaule*), Common lambsquarters *(Chenopodium album)*, velvetleaf *(Abutilon theophrasti*), prostrate knotweed *(Polygonum aviculare)*, wild mustard *(Sinapis arvensis)*, buttercup *(Ranunculus spp.)*, Mousetail *(Myosurusminimus*L.), Shepherd's purse *(Capsella bursa-pastoris*), Whitlow-grass *(Draba spp.)*, common dandelion *(Taraxacum officinale*), common sunflower *(Helianthu sannuus*.), Canada horseweed *(Erigeron canadensis*), Eastern black nightshade *(Solanum ptycanthum*), mouseear chickweed *(Cerastium fontanum*), bulbous buttercup *(Ranunculus bulbosus*), field pepperweed *[Lepidium campestre*], small-flowered bittercress *(Cardamine parviflora*), rayless mayweed *(Matricaria discoidea)*, field speedwell *(Veronica agrestis*.), Pennsylvania smartweed *(Persicaria pensylvanica*), Ivyleaf morningglory *(Ipomoea headracea*), common ragweed *(Ambrosia artemisiifolia*), prickly sida *(Sida Spinosa).*

Table 2.6: ANOVA of the influence of herbicide strategy, year and the interaction of the two on total weed density, total weed species richness, dicot density, dicot species richness, monocot density, and monocot species richness in mid-June at early-summer evaluations at SEPAC and TPAC from 2013 to 2019.[a]

	Factors & interactions	SEPAC			TPAC		
		Total weed species	Dicot weed species	Monocot weed species	Total weed species	Dicot weed species	Monocot weed species
		P					
Density	Herbicide Strategy	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Year	<.0001	<.0001	<.0001	0.0004	0.0029	0.0004
	Herbicide Strategy x Year	<.0001	0.0013	<.0001	<.0001	<.0001	<.0001
Species richness	Herbicide Strategy	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Year	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Herbicide Strategy x Year	0.0014	0.0853	0.004	<.0001	<.0001	<.0001

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

Table 2.7: Influence of herbicide strategy on dicot weed species richness from 2013 to 2019 at the South East Purdue Agriculture Center (SEPAC, 4425 County Rd 350 N Butlerville, IN 47223) in early-summer (mid-June).[a,b,c]

Herbicide strategy	Dicot weed species richness
	m^{-2}
Diversified Gly	2.7 b
2,4-D Reliant	4.6 a
Div 2,4-D	3.3 b
Fully Div	2.6 b

[a]Abbreviations: Gly=glyphosate and Div=Diversified
[b]Means followed by the same letter are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).
[c] Dicot species: velvetleaf (*Abutilon theophrasti),* redroot pigweed (*Amaranthus retroflexus),* waterhemp (*Amaranthus tuberculatus)* ,common ragweed (*Ambrosia artemisiifolia)* , giant ragweed (*Ambrosia trifida),* common lambsquarters (*Chenopodium album),* Jimsonweed, (*Datura stramonium),* spotted spurge (*Chamaesyce maculata)* , Canada horseweed (*Erigeron canadensis)* , ivyleaf morningglory (*Ipomoea hederacea)* , pitted morningglory (*Ipomea lacunosa),* carpetweed (*Mollugo verticulata),* yellow Sorrel (*Oxalis stricta),* creeping buttercup, (*Ranuculus repens),* prickly sida (*Sida spinosa),* horsenettle (*Solanum carolinense),* Eastern black nightshade (*Solanum ptycanthum),* common dandelion (*Taraxacum officinale),* field speedwell (*Veronica persica)* ,common cocklebur (*Xanthium strumarium)*

Table 2.8: ANOVA of the influence of herbicide strategy, year and the interaction of the two on total weed density, total weed species richness, dicot density, dicot species richness, monocot density, and monocot species richness, in the soil seedbank at SEPAC and TPAC 2013 to 2019. Means followed by the same letter are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).

	Factors & interactions	SEPAC			TPAC		
		Total weed species	Dicot weed species	Monocot weed species	Total weed species	Dicot weed species	Monocot weed species
		P					
Density	Herbicide strategy	0.5737	0.2278	0.6334	<.0001	0.0002	<.0001
	Year	<.0001	<.0001	<.0001	<.0001	0.4717	<.0001
	Herbicide strategy x Year	0.9995	0.2773	1	<.0001	0.5952	<.0001
Species richness	Herbicide strategy	0.0086	0.0627	0.0374	<.0001	0.0113	<.0001
	Year	<.0001	<.0001	<.0001	<.0001	0.0262	<.0001
	Herbicide strategy x Year	0.6304	0.5898	0.7493	0.0492	0.6229	0.0003

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

Table 2.9: Influence of 2,4-D herbicide strategy on dicot weed densities at the Throckmorton Purdue Agricultural Center (TPAC, 8343 US-231, Lafayette, IN 47909) from 2013 to 2019 on soil seedbank.[a,b,c]

Herbicide Strategy	Dicot weed species
	Plants 3000 cm^{-3}
Diversified Gly	4 b
2,4-D Reliant	10 ab
Div 2,4-D	18 a
Fully Div	2 b

[a]Abbreviations: Gly=glyphosate and Div=Diversified.
[b] Means followed by the same letter are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).
[c] Dicot Species: giant ragweed (*Ambrosia trifida)*, lambsquartes (*Chenopodium album*), creeping spurge (*Chamaesyce serpens*), horseweed (*Erigeron canadensis*), ivyleaf morningglory (*Ipomoea hederacea*), henbit (*Lamium amplexicaule*), carpetweed (*Mollugo verticilata*), yellow woodsorrel (*Oxalis stricta*), common purslane (*Portulaca oleracea*), prickly sida (*Sida spinosa*), Eastern black nightshade (*Solanum ptycanthum*), chickweed (*Stellaria media*), speedwell (*Veronica persica*) common cocklebur (*Xanthium strumarium*).

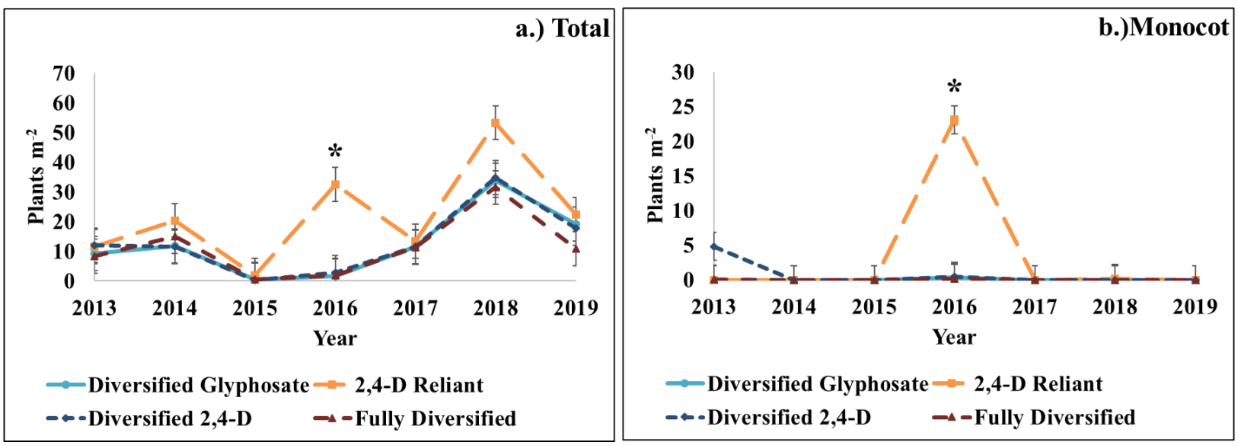

Figure 2.1: a.) Total and b.) monocot densities at the Throckmorton Purdue Agricultural Center (TPAC, 8343 US-231, Lafayette, IN 47909) in late-April of each year. Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy prior to spring control. Asterisk represents significance between treatments within that year. Corn was grown in 2013, 2015, 2017 and 2019, and soybeans were grown in 2014, 2016, and 2018.

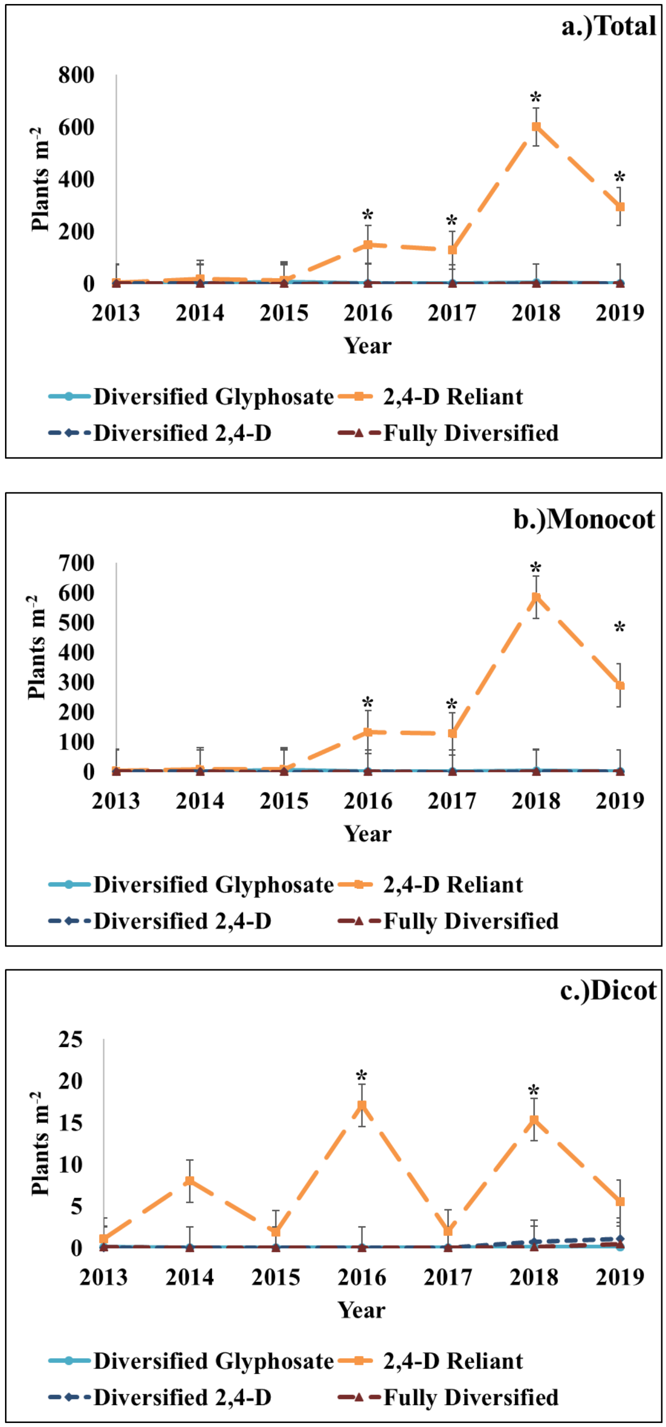

Figure 2.2: a.) Total, b.) monocot and c.) dicot weed densities from the Throckmorton Purdue Agricultural Center (TPAC, 8343 US-231, Lafayette, IN 47909) in mid-June. Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year influenced by an interaction between year and herbicide strategy in early-summer. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

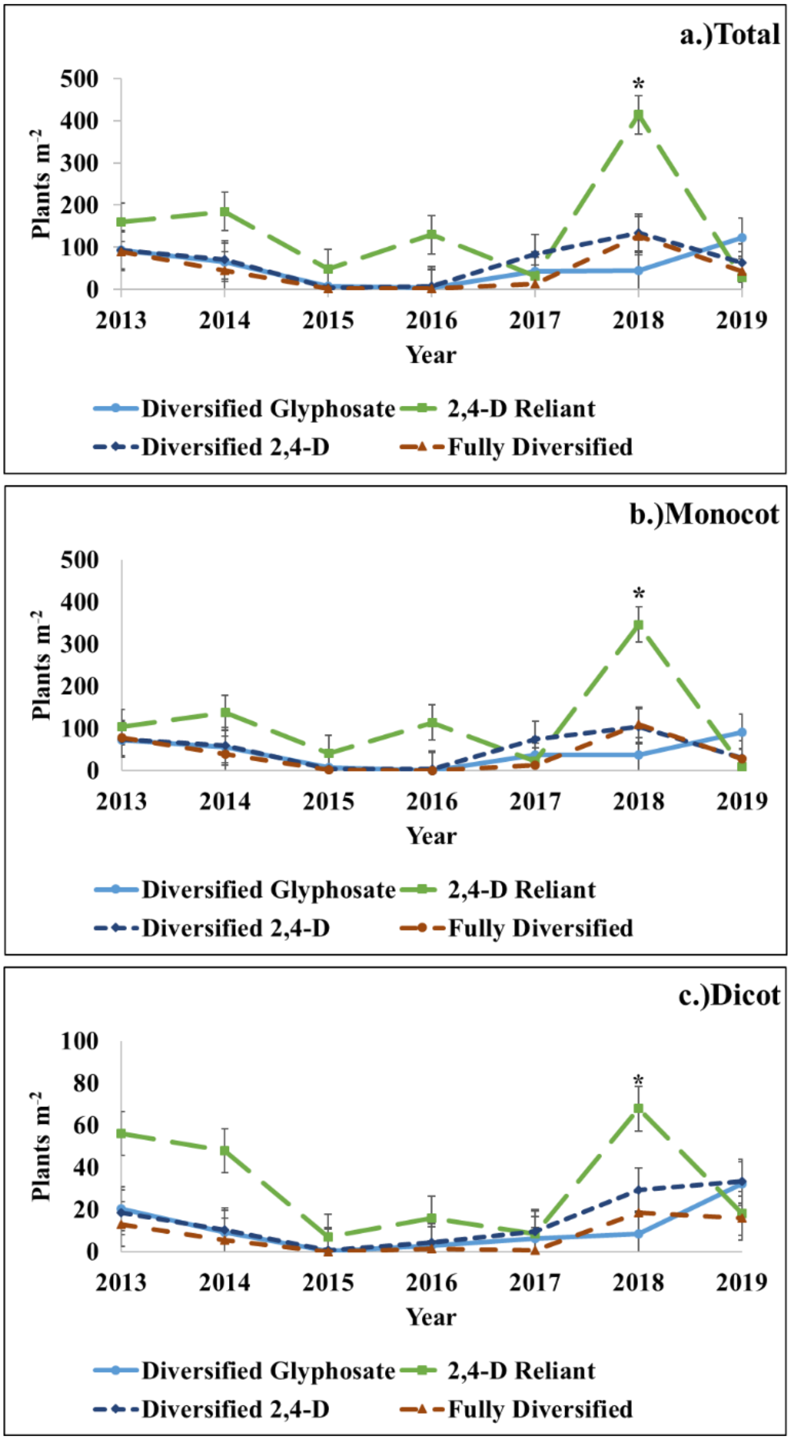

Figure 2.3: a.)Total, b.)monocot and c.)dicot weed densities from the South East Purdue Agriculture Center (SEPAC, 4425 County Rd 350 N Butlerville, IN 47223) in mid-June. Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy in early-summer. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

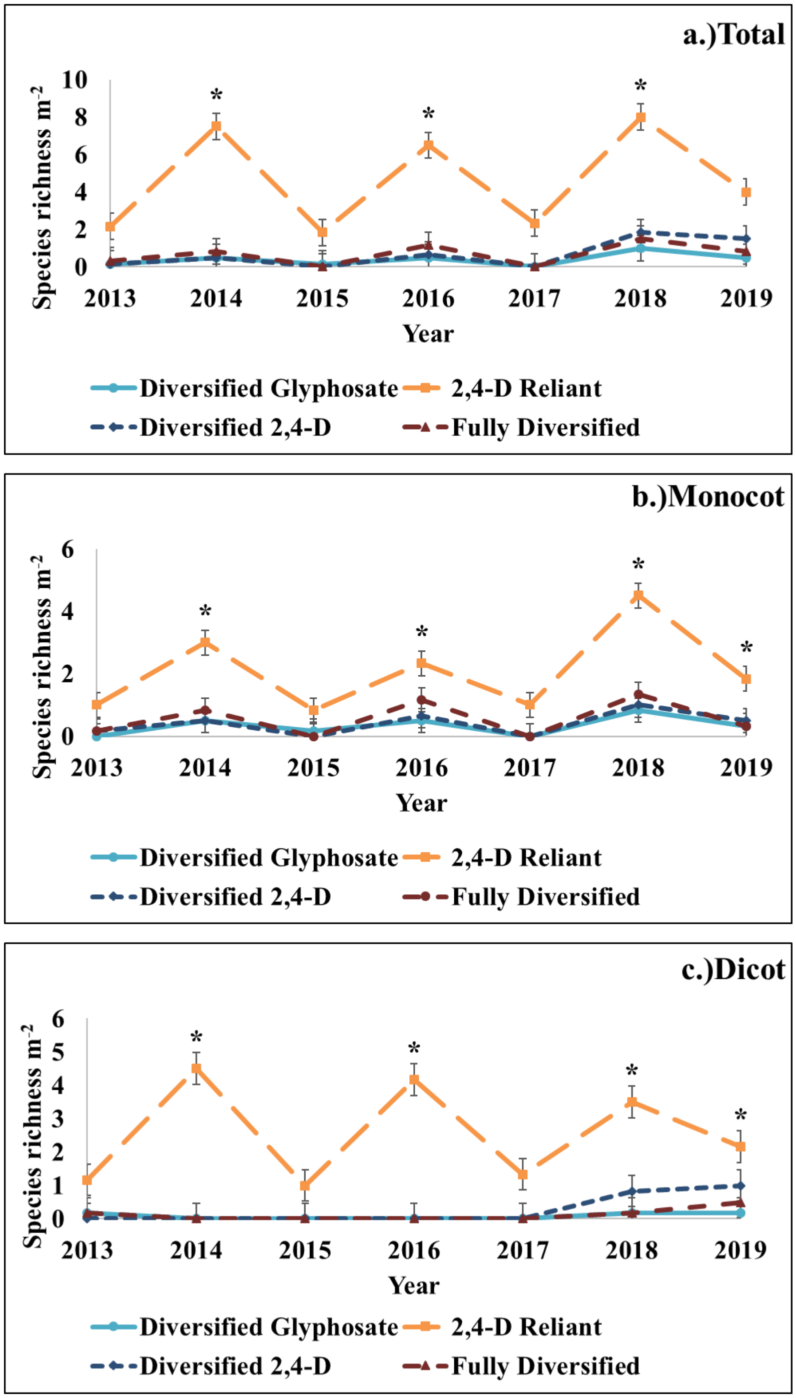

Figure 2.4: a.) Total, b.) monocot and c.) dicot weed species richness from the Throckmorton Purdue Agricultural Center (TPAC, 8343 US-231, Lafayette, IN 47909) in mid-June. Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy in early-summer. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

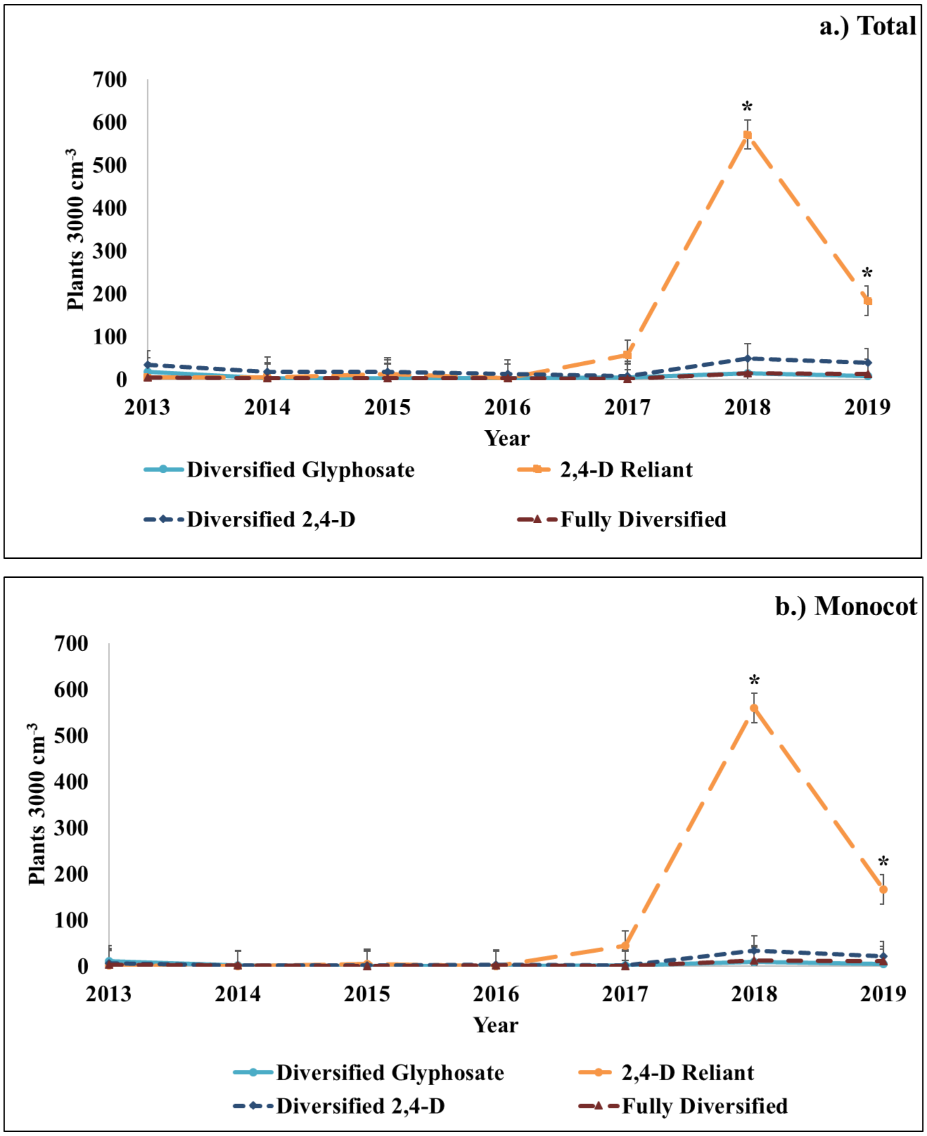

Figure 2.5: a.) Total and b.) monocot weed species density from the Throckmorton Purdue Agricultural Center (TPAC, 8343 US-231, Lafayette, IN 47909) in late-April of each year. Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy on soil seedbank. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

CHAPTER 3. EFFECTS OF HERBICIDE MANAGEMENT PRACTICES ON THE DENSITY AND RICHNESS OF WEEDS IN DICAMBA-RESISTANT CROPPING SYSTEMS IN INDIANA

3.1 Abstract:

The addition of dicamba as a weed control option in soybeans (*Glycine max* (L.) Merr) is a valuable tool. However, this technology must be utilized with other herbicide sites of action (SOA), in order to reduce selection pressure on weed communities to ensure its prolonged usefulness. A long-term trial was conducted for seven years at two locations in Indiana. This research evaluates weed community densities and species richness with four levels of dicamba selection pressure in a corn (*Zea mays* L.) -soybean rotation. Species richness was higher in the dicamba reliant strategy. The dicamba reliant strategy had 2 additional species at the no-till site and 3 additional species at the tilled site at the conclusion of the study. Using six or more SOA reduced species richness in both tilled and no-till system, and reduced weed densities within tilled sites compared to the dicamba reliant strategy with three SOA. Higher total species richness occurred in the dicamba reliant treatment each of the last 4 years of the study. The dicamba reliant strategy at the tilled site had higher monocot densities, which made up at least 84% of the total weed density. Averaging treatments across years, the dicamba reliant treatment had 50, 16, and 48 times more total, dicot, and monocot weed densities respectively, than the next highest treatment at one of the locations at early-summer evaluations. The soil seedbank at the tilled site was affected by the varying herbicide strategies. The dicamba reliant strategy had greater than 43% higher total weed density than all other treatments primarily due to having a monocot density that was at least 71% higher than the other treatments. All herbicide strategies had similar dicot species densities in the soil seedbank. Utilizing a less diversified herbicide strategy with only three SOA, with no residual herbicides in

soybean years, over the course of seven years has resulted in higher total weed densities, composed primarily of monocots. Species richness decreased as more SOA and residual herbicides were implemented into the herbicide programs. The fully diversified strategy with eight SOA had the lowest total weed species richness in the soil seedbank at the tilled location, supporting the early-summer evaluations.

3.2 Introduction:

Weeds are the most damaging of pests in agronomic production systems, with competition from weeds causing higher yield losses than insect or pathogen pests (Oerke 2006). Herbicides are the primary source of control for weeds in corn and soybean crops in the United States (Gianessi and Reigner 2007). Selective herbicides, such as dicamba, a group 4 herbicide, have been useful for several decades for targeting specific weeds in monocot field crops (Canode and Robocker 1970). Dicamba controls broadleaf weeds within grass crops, as grasses are able to effectively metabolize the herbicide in order to prevent injury (Chang and Born 1971). With the recent commercialization of dicamba-resistant soybean varieties, the use of dicamba has increased substantially. Approximately 60% of the soybean acres in the United States were dicamba-resistant in 2019 (Unglesbee 2019).

Weed management practices impose selection pressures that drive shifts in weed communities. Documented cases of weed shifts due to changes in weed management have occurred as a result of tillage, irrigation systems, herbicide use, and crop rotation (Brim-DeForest et al. 2017; Davis et al. 2009; Johnson and Coble 1986; Johnson et al. 2009; Menalled et al. 2001; Tuesca et al. 2001). Shifts in weed species have also been observed when comparing glyphosate-resistant cropping systems to conventional herbicide systems. Late-emerging weed species have been shown to be more prevalent in cropping systems that are glyphosate-resistant, and rely on post-emergent (POST) herbicide applications (Swanton et al. 2010). Johnson et al. (2009) discussed the concern of weed populations shifting to more problematic and herbicide-resistant weed biotypes that will reduce the usefulness of technologies such as glyphosate-resistant crops.

One of the most prevalent weed shifts in modern history occurred as a result of the wide scale adoption of glyphosate-resistant corn, soybean, and cotton (*Gossypium hirsutum* L.) (Dill et al. 2008). This led to glyphosate being applied to many acres more than one application per season with little diversity in herbicide strategies used. This selected for glyphosate-resistant biotypes, which Young (2006) argued would be a negative implication of this technology. Without using an integrated weed management approach, weed shifts into more tolerant, and resistant, species will occur as a result of widespread adoption of dicamba-resistant soybeans. Both species richness and evenness were both greater when crop rotations were not implemented or were continually planted to glyphosate-resistant traits (Young et al. 2013). A survey of Nebraska farmers in 2017 showed that 20% had planted soybean resistant to dicamba and glyphosate, and that 60% of those used dicamba, glyphosate, or the combination of the two as their only source of POST weed control (Werle et al. 2018b). Although research has shown that dicamba can be a valuable tool for controlling problematic weeds (Chahal and Johnson 2012), it is important to use multiple effective SOA in order to reduce the selection pressure for dicamba-resistant biotypes (Shergill et al. 2017).

Dicamba-resistant soybean varieties were introduced to be commercially grown prior to the 2017 growing season, and were developed to aid producers in controlling problematic herbicide-resistant broadleaf weeds. The state of Indiana has several herbicide-resistant weed species that present challenges to growers including: horseweed (*Erigeron Canadensis* L.), giant ragweed (*Ambrosia trifida* L.), waterhemp (*Amaranthus rudis* (Moq.) J. D. Sauer), and Palmer amaranth (*Amaranthus palmeri* S. Watson) (Heap 2020). Horseweed specifically, had glyphosate-resistance detected in anywhere from 15 to 78% of horseweed populations across all regions of Indiana over 12 years ago (Davis et al. 2008). These herbicide-resistant weeds pose a threat to corn and soybean yield. Giant ragweed can reduce yields of soybean as much as 52% with densities of only 2 plants per a 9 meter row, and can reduce corn yields by up to 90% under high giant ragweed densities (Baysinger and Sims 1991; Harrison et al. 2001). The addition of dicamba as an active ingredient in soybeans will provide in-season control options for several glyphosate-resistant broadleaf weed species, as the addition of dicamba to glyphosate increased the control of glyphosate-resistant Palmer amaranth, waterhemp, and horseweed to at least 95% (Johnson et al. 2010). Byker et al. (2013) found that 900 g ae ha^{-1} of glyphosate + 600 g ae ha^{-1} of dicamba applied preplant, followed by a POST application of 900 g ae ha^{-1} of glyphosate + 300 g ae ha^{-1} of dicamba resulted in at least 95 % horseweed control in dicamba-resistant soybeans across three locations in Ontario, Canada. However, Spaunhorst and Johnson (2016) reported that utilizing dicamba as a pre-emergence (PRE) alone could result in less than 50% control of glyphosate-resistant Palmer amaranth, but when used with metribuzin control increased to 67 to 72%. It will be important to utilize dicamba-resistant soybeans with multiple other SOA and residual herbicides in years that both corn and soybean are grown.

Currently there are only two reported species that have evolved resistance to dicamba in the United States (Heap, 2020). The two species with reported resistance are kochia (*Kochia scoparia*) and prickly lettuce (*Lactuca serriola* L.), both common in small grains production, where crop rotation is minimal and dicamba is applied year after year and auxins are heavily relied upon (Fernandez-Cornejo et al. 2011). Therefore, there is a reasonable concern that dicamba-resistance will evolve as auxin-resistant soybean varieties are used on more acreage. Although dicamba-resistance could evolve a shift towards more tolerant monocot species is likely to occur without implanting residual herbicides and would likely be a more immediate concern.

The objective of this research is to identify shifts in the weed community, in terms of both weed density, and species richness in a corn-soybean rotation with varying levels of dicamba selection pressure.

3.3 Materials and Methods

3.3.1 Field Sites

A field trial in a corn-soybean rotation was initiated in 2013 and continued through the 2019 growing season. Experiments were conducted at two locations, one near Lafayette, Indiana at the Throckmorton Purdue Agricultural Center [TPAC (40.30°N, 86.90°W)] and the second near Butlerville, Indiana at the South East Purdue Agricultural Center [SEPAC (39.03°N, 85.83°W)]. Global positioning system (GPS) coordinates were taken to mark the corners of the trial areas due to the long-term nature of this project to ensure the trials remained in the same location throughout the seven-year period. Corners of the trial area were additionally marked to ensure trial remained in the same location from year to year. The TPAC site was a conventional till site on a Toronto-Millbrook complex that was chisel plowed in the fall and disked and field cultivated in the spring. The soil at TPAC has an organic matter of 2.6%, a pH of 6.1, and a cation exchange capacity (CEC) of 10.6 meq 100 g^{-1}. The primary weed species at TPAC were foxtail species (*Setaria* spp.) and fall panicum (*Panicum dichotoflorium* Michx.). The SEPAC site was no-till on a poorly-drained Cobbsfork silt loam with an organic matter of 1.7%, pH of 5.1, and a CEC of 7.7 meq 100 g^{-1}. This location was maintained using no-till practices, with a burndown herbicide application made two weeks prior to planting. Fertility programs were adjusted for each site and utilized recommendations for optimal crop yield in the region. SEPAC has a diverse weed community consisting of many winter-annual species, one of the most abundant being horseweed. Corn was planted in 2013, 2015, 2017, and 2019 at a rate of 80,000 seeds ha^{-1}, while soybeans were planted in 2014, 2016, and 2018 at a rate of 350,000 seeds ha^{-1}. Corn hybrids used had traits that conferred resistance to both glufosinate and glyphosate. Soybean varieties used were resistant to dicamba and glyphosate.

3.3.2 Experimental Design & Herbicide Strategies

The experimental design at each site was a random complete block with 6 replications. Herbicide strategies were developed to evaluate weed community shifts as SOA are implemented into a two-year corn-soybean cropping system. The four treatments were labeled as follows: 1) dicamba reliant, 2) diversified glyphosate, 3) diversified dicamba, and 4) fully diversified consisting of three, six, seven, and eight SOA, respectively, at the TPAC location and three, six, six, and eight SOA, respectively, at the SEPAC location (Tables 3.1 and 3.2). Herbicides used at each of the two locations were chosen in order to control the problematic weeds at each location. Herbicide applications were made with a 3 m CO_2 -propelled backpack sprayer calibrated to deliver 140 L ha^{-1} at 4.8 km h^{-1}. Flat fan AIXR11002 nozzles (Teejet Technologies, 1801 Business Park DR, Springfield, IL 62703) were used to apply treatments that did not contain dicamba, while TTI11003 nozzles (Teejet Technologies, 1801 Business Park DR, Springfield, IL 62703) were used for dicamba applications. Herbicide application dates for each year can be found in Table 3.3. During corn years, two applications were made to each plot, including a PRE or burndown, followed by a POST when weeds were 10 to 15 cm tall, or when corn reached 76 cm in height. POST applications were made in mid-June and are hereafter referred to as “early-summer” evaluations. During soybean years a PRE (TPAC) or burndown (SEPAC), was applied followed by a POST application when weeds were 10 to 15 cm. An early-POST followed by a late-POST application was used in the dicamba reliant strategy due to the lack of a soil residual herbicide in soybean years.

3.3.3 Field Data Collection

In order to monitor changes over time in weed density and species richness within plots, two 1-m^2 quadrats were placed 4.5 m from the back and front of each plot, and 1 m from plot edges. These quadrats were placed in the same location every year. Weed densities and species richness were recorded prior to initial spring weed control (tillage or burndown herbicide application) and postemergence herbicide applications. Trials were harvested once crops reached physiological maturity, and grain weight and moisture for reach plot was recorded. Weed density and richness were partitioned into total weed measurements, as well as separated into dicot and monocot categories. Data were subjected to analysis of variance (ANOVA) using SAS 9.4 PROC GLIMMIX procedure (SAS, 100 SAS Campus Drive, Cary, NC 27513-2414, USA) with year treated as a repeated measure. Means separation was conducted using Tukey's Honest Significant Difference (HSD) test (α=0.05).

3.3.4 Soil Seedbank Data Collection

Prior to spring tillage at TPAC or burndown at SEPAC, 16 soil cores were randomly sampled from each plot to assess weed seedbank composition. Cores measured 5.7 cm in diameter and were collected to a depth of 7.6 cm, resulting in approximately 3,000 cm^3 of soil from each plot. Pareja et al. (2016) determined that 85% of all seeds in a reduced tillage system, and 28% in a conventional tillage system were in the top 5 cm of soil. Cores were homogenized and placed into 25 cm by 50 cm soil flats in a greenhouse in West Lafayette, IN, where the seeds were allowed to germinate for 8 weeks. Greenhouse conditions were established as a 16-hour photoperiod with 600 W high pressure sodium lights, with a temperature of approximately 26 C.

Weed density and species were recorded every two weeks, and weeds were removed by hand after each recording date. Following data collection at the fourth week, the soil was mixed thoroughly to promote germination of additional seeds remaining in flats. After the eight-week period was complete, the TPAC soil was discarded; however, soil from SEPAC was allowed to dry, then placed in cold storage for approximately three months to break dormancy of winter annual weed species that were prevalent at that location. The process was then repeated for another eight weeks. Weed densities and species richness are presented per 3000 cm^3. The following equation shows the calculations for determining volume of soil that densities and species richness are presented in:

$$V = \pi r^2 h = \pi(2.85)^2 \times 7.6\, cm = 194\, cm^3 \times 16\, soil\ cores = 3104\, cm^3.$$

This was rounded down to 3000 cm^3 to allow for 3.5% loss of soil during collection and transport. Other studies have presented soil seedbank densities in terms area such as m^{-2} (Carter and Ivany 2006, Conn et al. 1984, Menalled et al. 2001, Moonen and Barberi 2004). Seed density on a volume basis (cm^3) has also previously been utilized to compare spatial analysis methods within soil seedbanks (Bigwood and Inouye 1988). The data were analyzed all together, referred to as “total” and separated into monocots and dicots. All data were subjected to ANOVA using SAS 9.4 PROC GLIMMIX procedure, with year serving as a repeated measure, and means were separated using Tukey’s HSD test (α=0.05).

3.4 Results:

3.4.1 Spring weed density and species richness

Total and dicot weed densities at the TPAC location were affected by both herbicide strategy and year, while monocot density was influenced by the interaction of year and herbicide strategy (Table 3.4). Total weed density was highest in 2018, followed by 2014, 2017, and 2019 (data not shown). Weed densities in 2019 were likely high due to not being tilled in the fall, as a result of field conditions which were too wet prior to winter freezing, resulting in a high weed density the following spring. The fully-diversified herbicide strategy had lower total and dicot densities than the dicamba reliant strategy at TPAC by at least 38% (Table 3.5). The differences in densities supports using multiple effective SOA, which is also a best management practice for reducing the likelihood of herbicide resistance (Norsworthy et al. 2012). However, Hurley et al. (2009) reported that soybean producers only used multiple herbicides "sometimes or rarely", because of cost and lack of simplicity. The total, dicot, and monocot species richness at TPAC were only influenced by year (Table 3.4). The total and dicot species richness in 2019 were similar to the highest species richness recorded over the 7 years that this research was conducted. Monocot species richness was near zero in spring of 2019 likely due to most monocots having not yet emerged (data not shown).

Total, dicot, and monocot densities were all influenced by a herbicide strategy by year interaction at the SEPAC location (Table 3.4). The monocot densities in 2017 were at least 32% higher than the 2013 to 2016 period, however an interaction with herbicide strategy did occur (Figure 3.1). This change in monocot densities is primarily due to the increase in annual bluegrass (*Poa annua* L.). In 2019, annual bluegrass accounted for 62% of the total weed density. Annual bluegrass increased due to producing seed early in the spring, prior to the application of a burndown treatment that was targeted for two weeks prior to planting (Mitich 1991).

The total weed species richness for SEPAC was only influenced by year, while dicot and monocot species richness were influenced by year and herbicide strategy (Table 3.4). The total species richness in 2019 was 7, which was the highest since 2014, when 9 species were reported. The fully diversified strategy had a dicot species richness that was 18% lower than the diversified glyphosate and a monocot species richness that was 23% higher than the diversified glyphosate or dicamba reliant strategies (Table 3.6). It was expected that both monocot and dicot species richness would decline. The reason for the fully diversified strategy having the highest monocot species richness could be due to reduced competition by the winter-annual dicot species that were present at low levels in this herbicide strategy. Implementing eight SOA at the tilled site reduced monocot densities by 2 plants m^{-2} and resulted in 7 fewer dicot plants m^{-2} compared to the dicamba reliant strategy. Dicamba used with seven other SOA reduced plant densities under tilled conditions while reductions in plant density were not observed at the no-till site primarily due to the large amount of annual bluegrass.

3.4.2 Early-summer post-emergence application weed densities and species richness

Total, monocot, and dicot weed densities and species richness were all influenced by an interaction between herbicide strategy and year at the TPAC location (Table 3.7). Total weed density averaged across years was highest in the dicamba reliant treatments, with 64 weeds per m^2. Of the 64 weeds in these plots, an average of 84% were monocots (Figure 3.2). The highest monocot densities were observed in 2018, averaging 42 monocots m^{-2} at TPAC. However, in 2018 all treatments at TPAC that utilized more than 6 or more SOA had lower monocot densities and a lower monocot species richness. By 2019, monocots accounted for over 90% of the total weed density at the TPAC location. The dicamba reliant treatment had a higher dicot species richness compared to all other treatments in years that soybeans were grown (Figure 3.3). This is possibly due to the lack of one dominant weed species, which allowed other dicot species to find a niche that is usually inhabited by a dominant weed species such as giant ragweed or pigweeds. Total, dicot, and monocot species richness were always higher in soybean years in the dicamba reliant strategy (Figure 3.3). The increased species richness in soybean years is likely either due to the lack of atrazine used, or soybeans being a less competitive crop compared to corn for some weed species (Knake and Slife 1962, Moolani et al. 1963).

Dicot species richness was 38% higher in the dicamba reliant treatment compared to all other herbicide strategies at SEPAC (Table 3.8). This also resulted in the dicamba reliant strategy having a higher total species richness in four out of the seven years at SEPAC (Figure 3.4). SEPAC had a higher total species richness, due to a more diverse weed population, particularly winter-annual dicot species.

The research presented in this study is the first to date to evaluate weed community shifts in dicamba-resistant soybeans rotated with corn and showed that species richness will increase if dicamba is used with only glyphosate, and atrazine in corn. Shergill et al. (2017) evaluated weed shifts in dicamba-resistant continuous soybeans, but did not evaluate shifts in dicamba-resistant soybeans rotated with corn. Species richness was highest at both sites in the dicamba reliant strategy resulting in 2 more species at the no-till site and 3 more species at the tilled site compared to all other herbicide strategies.

Using six or more SOA with residual herbicides in both corn and soybean years resulted in a 98% decrease compared to using three SOA with a residual only in corn years. Using six or more SOA reduced species richness in both tilled and no-till system, and reduced weed densities within tilled sites compared to a herbicide strategy that only implements dicamba and glyphosate in soybean years with the addition of atrazine in corn years. Weed populations were reduced by 50% in continuous corn when included more unique herbicide modes of action (Wilson et al. 2011). Shergill et al. (2017) previously evaluated weed shifts in varying glyphosate and dicamba selection pressures within continuous soybeans over the course of five years. The addition of corn in rotation with dicamba-resistant soybeans will have large implications on weed communities due to the broad spectrum of herbicides utilized within in corn that are not implemented in soybeans, such as the use of atrazine and 4-hydroxyphenylpyruvate dioxygenase (HPPD) herbicides such as mesotrione, tembotrione, and topramezone.

3.4.3 Soil seedbank weed densities and species richness

Total and monocot weed densities within the soil seedbank at the TPAC location were influenced by a year by herbicide strategy interaction, while dicot weed densities were only influenced by year (Table 3.9). Total and monocot densities were highest in 2018 and 2019, but all other years were similar (Figure 3.5). The dicamba reliant strategy had greater than 43% higher total weed densities than all other treatments due to having a higher monocot density that was at least 71% higher than the other treatments (Figure 3.5). All herbicide strategies had similar dicot densities. Utilizing a less diversified herbicide strategy with only three SOA, with no residual herbicides in soybean years, over the course of seven years has resulted in those plots having higher total weed densities, composed primarily of monocots.

Only monocot weed species richness was influenced by a herbicide strategy by year interaction at TPAC, while total and dicot weed species richness were influenced by each factor individually (data not shown). Species richness decreased as more SOA were implemented into herbicide programs, and the fully diversified strategy resulted in the lowest total weed species richness at the TPAC location, supporting the in-field observations (Table 3.10). The fully diversified herbicide strategy also resulted in a 31% reduction in dicot species richness. Total weed density at SEPAC was 968 plants m^{-2} in 2019, 85% of those being monocots, compared to the next highest being 556 plants m^{-2} in 2018 (Table 3.11). Species richness was also highest in 2019 with 17.9 species, with the next highest species richness being 15.4 species in 2019 at SEPAC (data not shown). The soil seedbank assessments at TPAC reflects what occurred within early-summer evaluations as the dicamba reliant treatment had higher total weed density compared to other treatments and was primarily composed of monocots. This research for the first time evaluates the effect on the soil seedbank that varying levels of dicamba selection pressure and the use of residual herbicides in both corn and soybean can have on a soil seedbank within both tilled and no-till fields using dicamba-resistant soybeans in rotation with corn. We report that using only glyphosate, dicamba and atrazine, in corn years, resulted in a 43% increase in total weed density compared with treatments using six or more SOA, while effects of differing herbicide strategies were less impactful within a no-till system. This is likely the result of total weed densities within the no-till system being largely composed of annual bluegrass. Gibson et al. (2016) did not observe changes in species richness or weed density in a long-term study involving 156 field comparing academic recommended practices to the general practices used by the farm operator. However, Gibson et al. (2016) did predict that best management practices made on academic recommendations would result in 40% lower weed densities in ten years based on the linear regression of weed population density changes through time.

Davis et al. (2005) has previously reported differences in weed seedbank composition due to different management practices, and found that no-till systems had higher species diversity within no-till systems compared to conventional systems. In this study we did not compare between the two locations with different tillage practices; however, the no-till site had at least twice as many species in all years and herbicide strategies as the tilled location.

3.4.4 Crop Yield

Differences in crop yield were only observed in 2016 at the SEPAC location with the diversified dicamba treatment having a yield that was on average 8% higher than the dicamba reliant treatment (data not shown) all other crop yield across years were similar within the two locations. The results from this experiment suggest that over a seven-year period negative impacts from weed shifts on yield are not likely.

This research is the first published report to evaluate weed community response to varying levels of dicamba selection pressure in dicamba-resistant soybeans rotated with corn. Shergill et al. (2017) evaluated evolution of glyphosate resistance and weed shifts in dicamba and glyphosate-resistant soybeans grown continuously for five years.

Soil seedbank analysis supported the observations from early-summer evaluations at the TPAC location. In both the total and monocot weed densities in the dicamba reliant treatment had at least 43% more weeds than the next highest treatment. The total weed densities taken in early-summer at TPAC were 84% monocots, while the densities within the soil seedbank were only 56% monocots. Wilson et al. (2007) also reported that in field densities of kochia in a six-year study were supported by soil seedbank analysis as both decreased due to varying herbicides strategies. We demonstrated that utilizing six or more SOA and residual herbicides in both corn and soybean years reduced weed densities compared to three SOA and using a residual herbicide only in corn years. Shergill et al. (2017) found similar results as residual herbicides applied prior to POST glyphosate applications resulted in a greater than 50% reduction in weed densities and a 250%

increase in yield compared, to glyphosate alone. However, reduction in weed densities and increase in yield were not observed in the first year, but after the 4th year.

Wilson et al. (2007) reported that corn yields were not influenced by varying glyphosate rates until the sixth year of a long-term trial, indicating that reduction in yield may not be observed in the short-term. Wilson et al. (2007) also reported that increases in common lambsquarters were observed in treatments with lower glyphosate rates within a corn, sugar beet (*Beta vulgaris*), and spring wheat (*Triticum aestivum* L.) rotation compared to continuous corn, likely due to sugar beet and spring wheat being less competitive than corn. Additionally, common lambsquarters in-field and soil seedbank assessments showed increasing densities when low rates of glyphosate were applied, but the soil seedbank analysis did not increase as rapidly as the in-field evaluations

Species richness within the dicamba reliant treatment at TPAC was higher for total, dicot, and monocots by 3.5, 2, and 1.3 species, respectively, compared to all other herbicide strategies at early-summer evaluations. The other three treatments did not differ from each other. A similar result occurred within the soil seedbank as the dicamba reliant treatment had 0.7 more species than the next highest treatment. Species richness was higher in the dicamba reliant treatments assessed both in early-summer evaluations and in seedbanks. A shift into more diverse weed species occurred due to fewer SOA being implemented in both corn and soybean years, but more importantly due to the lack of a residual herbicide in years that soybean was grown. Shifts in weed seedbanks were expected due to the changes in herbicide management practices, as differences in arable weed seedbanks have been observed due to differences in production practices in both organic and conventional cropping systems (Rotchés-Ribalta et al. 2017).

The increase in species richness in the dicamba reliant treatment is a result of this program having at least three fewer SOA than the other treatments, and more importantly, the lack of a residual herbicide implemented in soybean years. Ovejero et al. (2013) and Tharp and Kells (2002) have shown that the use of residual herbicides increases overall weed control. Jhala et al. (2017) reported that soil applied residual herbicides followed by residual POST applications provided 82% control of common waterhemp, while herbicide strategies without a PRE reported 45% control at harvest. Using sequential applications of soil residual herbicides also reduced weed densities and weed species richness in this study.

Diggle and Neve (2003) showed that an additional benefit associated with using multiple herbicides in combination with each other, as opposed to in rotation with each other, is that it will significantly delay the rate of herbicide-resistance. Residual herbicides are often disregarded due to having less of a visual effect, however, their use can help reduce shifts toward species that are tolerant to POST herbicides, and ultimately increase the longevity of new herbicide technologies, such as dicamba-resistant soybeans. Edwards et al. (2014) established that although herbicide costs of best management practices to control herbicide-resistant weeds was 36% higher in Illinois and Indiana compared to general practices by farm operators net returns were not different in either the short- or long-term.

The implementation of residual herbicides is needed to reduce selection pressure imposed on weed species by economically important herbicides, such as glyphosate, 2,4-D, and atrazine (Johnson et al. 2012). Riar et al. (2013) reported that 36% of producers found the cost of using multiple effective modes of action was a concern in cotton, rice, and soybean production systems. Additionally, in a survey of certified crop advisors, only 14% marked that preemergence or residual chemicals were the most effective way to fight herbicide-resistant weeds, and 20% answered that multiple modes of action were the best (Asmus et al. 2013). We demonstrated that farm operators need to utilize both multiple herbicide SOA and sequential applications of residual herbicides in order to decrease the densities and species richness of weed communities in corn rotated with dicamba-resistant soybeans, which has not been previously evaluated.

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Table 3.1: Herbicide strategies used in both corn and soybean years at the Throckmorton Purdue Agriculture Center (TPAC). POST= post-emergence, PRE= pre-emergence, Early POST= early post-emergence, and Late POST= late post-emergence. Table adapted from Legleiter T (2017) Dicamba and 2,4-D Utilization in Growth Regulator Resistant Soybean. Ph.D. dissertation. Lafayette, IN: Purdue University. 156-157 p[a]

Herbicide strategy	Crop	Timing	Herbicide	Rate (g ha^{-1})	WSSA SOA group #	Tradename	Manufacturer
Diversified Glyphosate (Diversified Gly)	Corn	PRE	atrazine	1100	5	Lexar EZ	Syngenta
			s-metolachlor	1100	15		
			mesotrione	141	27		
		POST	atrazine	1120	5	AAtrex	Syngenta
			glyphosate	1100	9	Roundup Powermax	Monsanto
			topramazone	12	27	Impact	AMVAC
	Soybean	PRE	chlorimuron	18	2	Fierce XLT	Valent
			flumioxazin	69	14		
			pyroxasulfone	87	15		
		POST	glyphosate	1426	9	Flexstar GT	Syngenta
			fomesafen	353	14		
Dicamba Reliant	Corn	PRE	atrazine	2200	5	AAtrex	Syngenta
		POST	dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1100	9	Roundup Powermax	Monsanto
	Soybean	Early POST	dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1120	9	Roundup Powermax	Monsanto
		Late POST	dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1120	9	Roundup Powermax	Monsanto

Table 3.1 Continued

Herbicide strategy	Crop	Timing	Herbicide	Rate (g ha^{-1})	WSSA SOA group #	Tradename	Manufacturer
Diversified Dicamba (Div Dicamba)	Corn	PRE	atrazine	1100	5	Lexar EZ	Syngenta
			s-metolachlor	1100	15		
			mesotrione	141	27		
		POST	dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1100	9	Roundup Powermax	Monsanto
	Soybean	PRE	chlorimuron	18	2	Fierce XLT	Valent
			flumioxazin	69	14		
			pyroxasulfone	87	15		
		POST	dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1120	9	Roundup Powermax	Monsanto
Fully Diversified (Fully Div)	Corn	PRE	atrazine	1100	5	Lexar EZ	Syngenta
			s-metolachlor	1100	15		
			mesotrione	141	27		
		POST	atrazine	1120	5	AAtrex	Syngenta
			glufosinate	450	10	Liberty	BASF
			topramazone	12	27	Impact	AMVAC
	Soybean	PRE	chlorimuron	13	2	Valor XLT	Valent
			flumioxazin	38	14		
		POST	dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1120	9	Roundup Powermax	Monsanto
			pyroxasulfone	180	15	Zidua	BASF

[a]Prior to 2018 Clarity was used in place of Xtendimax.

Table 3.2: Herbicide strategies used in corn and soybean years at the Southeast Purdue Agriculture Center (SEPAC). POST= post-emergence, PRE= pre-emergence, Early POST= early post-emergence, and Late POST= late post-emergence. Table adapted from Legleiter T (2017) Dicamba and 2,4-D Utilization in Growth Regulator Resistant Soybean. Ph.D. dissertation. Lafayette, IN: Purdue University. 158-159 p[a]

Herbicide strategy	Crop	Timing	Herbicide	Rate (g ha^{-1})	WSSA SOA group #	Tradename	Manufacturer
Diversified Glyphosate (Diversified Gly)	Corn	Burndown	atrazine	1120	5	AAtrex	Syngenta
			glyphosate	1100	9	Roundup Powermax	Monsanto
			saflufenacil	75	14	Verdict	BASF
			dimethenamid-P	656	15		
		POST	atrazine	1120	5	AAtrex	Syngenta
			glyphosate	1100	9	Roundup Powermax	Monsanto
			topramazone	12	27	Impact	AMVAC
	Soybean	Burndown	chlorimuron	30	2	Canopy	DuPont
			metribuzin	600	5	Tricor 75DF	Syngenta
			glyphosate	1100	9	Roundup Powermax	Monsanto
			saflufenacil	25	14	Sharpen	BASF
		POST	cloransulam	35	2	FirstRate	DowAgroSciences
			glyphosate	1100	9	Roundup Powermax	Monsanto
Dicamba Reliant	Corn	Burndown	atrazine	1680	5	AAtrex	Syngenta
			dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1100	9	Roundup Powermax	Monsanto
		POST	dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1100	9	Roundup Powermax	Monsanto
	Soybean	Burndown	dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1120	9	Roundup Powermax	Monsanto
		Early POST	dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1120	9	Roundup Powermax	Monsanto

Table 3.2 Continued

Herbicide strategy	Crop	Timing	Herbicide	Rate (g ha^{-1})	WSSA SOA group #	Tradename	Manufacturer
			glyphosate	1120	9	Roundup Powermax	Monsanto
Diversified Dicamba (Div Dicamba)	Corn	Burndown	atrazine	1120	5	AAtrex	Syngenta
			glyphosate	1100	9	Roundup Powermax	Monsanto
			saflufenacil	75	14	Verdict	BASF
			dimethenamid-P	656	15		
		POST	dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1100	9	Roundup Powermax	Monsanto
	Soybean	Burndown	chlorimuron	30	2	Canopy	DuPont
			metribuzin	600	5	Tricor 75DF	Syngenta
			dicamba	560	4	Roundup Powermax	Monsanto
			glyphosate	1120	9	Sharpen	BASF
		POST	dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1120	9	Roundup Powermax	Monsanto
Fully Diversified (Fully Div)	Corn	Burndown	atrazine	1120	5	AAtrex	Syngenta
			glufosinate	450	10	Roundup Powermax	Monsanto
			saflufenacil	75	14	Verdict	BASF
			dimethenamid-P	656	15		
		POST	atrazine	1120	5	AAtrex	Syngenta
			glufosinate	450	10	Liberty	BASF
			topramazone	12	27	Impact	AMVAC
	Soybean	Burndown	chlorimuron	30	2	Canopy	DuPont
			metribuzin	600	5	Tricor 75DF	Syngenta
			glyphosate	1100	9	Roundup Powermax	Monsanto
			saflufenacil	25	14	Sharpen	BASF
		Early POST	cloransulam	35	2	FirstRate	DowAgrosciences

Table 3.2 Continued

Herbicide strategy	Crop	Timing	Herbicide	Rate (g ha^{-1})	WSSA SOA group #	Tradename	Manufacturer
Fully Diversified (Fully Div)	Soybean		dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1120	9	Roundup Powermax	Monsanto
		Late POST (2014 & 2018 ONLY)	dicamba	560	4	Xtendimax	Monsanto
			glyphosate	1120	9	Roundup Powermax	Monsanto

[a]Prior to 2018 Clarity was used in place of Xtendimax.

Table 3.3: Application dates at TPAC and SEPAC from 2013 to 2019.

Site	Crop	Application	2013	2014	2015	2016	2017	2018	2019
TPAC	Corn	PRE	May 9		May 2		April 28		May 21
		POST	June 7		June 2		June 8		June 14
	Soybean	PRE		May 27		May 8		May 10	
		Early POST		June 26		June 1		June 7	
		POST		July 10		June 13		June 18	
		Late POST		July 21		June 25		July 18	
	Late POST in Fully Diversified (2018 Only)							July 3	
SEPAC	Corn	PRE	May 8		April 28		April 23		May 8
		POST	June 20		June 3		June 22		July 23
	Soybean	PRE		May 8		May 13		April 30	
		Early POST		June 18		June 14		June 5	
		POST		June 25		June 29		June 5	
		Late POST		July 15		July 9		June 19	

[a]Abbreviations: PRE=pre-emergence, POST= post-emergence, TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

Table 3.4: ANOVA table for the influence of herbicide strategy, year and the interaction of the two on in-field total, dicot, and monocot density and species richness in late-April prior to spring weed control methods at SEPAC and TPAC from 2013 to 2019.[a]

	Factors & interaction	SEPAC			TPAC		
		Total weed species	Dicot weed species	Monocot weed species	Total weed species	Dicot weed species	Monocot weed species
		P					
Density	Herbicide strategy	0.8948	0.6735	0.1909	0.0028	0.0294	0.0103
	Year	<.0001	<.0001	<.0001	<.0001	<.0001	0.0015
	Herbicide strategy x Year	0.0184	0.0008	0.0035	0.7319	0.6477	0.0065
Species richness	Herbicide strategy	0.2893	0.0488	0.0021	0.072	0.0959	0.1484
	Year	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Herbicide strategy x Year	0.7478	0.7632	0.0724	0.8345	0.9449	0.0573

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

Table 3.5: Influence of dicamba herbicide strategies on in-field total and dicot densities pooled from 2013 to 2019 in late-April prior to spring weed control at the Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909).[a,b,c]

Herbicide strategy	Total weed species	Dicot weed species
	———Plants m^{-2}———	
Diversified Gly	14 ab	14 ab
Dicamba Reliant	20 a	18 a
Div Dicamba	15 ab	15 ab
Fully Div	11 b	11 b

[a]Abbreviations: Gly= glyphosate, Div=Diversified.
[b]Means followed by the same letter within columns are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).
[c] Species: giant ragweed *(Ambrosia trifida*), common chickweed *(Stellaria media*), henbit *(Lamium amplexicaul*.), Common lambsquarters *(Chenopodium album),* velvetleaf *(Abutilon theophrasti*.), prostrate knotweed *(Polygonum aviculare),* wild mustard *(Sinapis arvensis.),* buttercup *(Ranunculus spp.),* Mousetail *(Myosurusminimus*), Shepherd's purse *(Capsella bursa-pastoris*), Whitlow-grass *(Draba spp.),* common dandelion *(Taraxacum officinale*), common sunflower *(Helianthu sannuus*), Canada horseweed *(Erigeron canadensis*), Eastern black nightshade *(Solanum ptycanthum*), mouseear chickweed *(Cerastium fontanum*), bulbous buttercup *(Ranunculus bulbosus*), field pepperweed *(Lepidium campestre*), small-flowered bittercress *(Cardamine parviflora*), rayless mayweed *(Matricaria discoidea),* field speedwell *(Veronica agrestis*), Pennsylvania smartweed *(Persicaria pensylvanica*), Ivyleaf morningglory *(Ipomoea headracea*), common ragweed *(Ambrosia artemisiifolia*), prickly sida *(Sida Spinosa),* giant foxtail *(Setaria faberi*), annual bluegrass (*Poa annua*), bromegrass (*Bromus spp.)*

Table 3.6: Influence of herbicide strategies on in-field dicot, and monocot weed species richness at SEPAC and total weed species richness at TPAC pooled from 2013 to 2019 in late-April prior to spring weed control.[a,b,c]

Herbicide strategy	SEPAC		TPAC
	Dicot weed species	Monocot weed species	Total weed species
	———Species richness m^{-2}———		
Diversified Gly.	4.5 a	1.0 b	2.9 a
Dicamba Reliant	4.4 ab	1.0 b	3.0 a
Div Dicamba	4.3 ab	1.2 ab	2.7 a
Fully Div	3.7 b	1.3 a	2.4 a

[a]Abbreviations: Gly= glyphosate, Div=Diversified, TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).
[b]Means followed by the same letter within columns are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).
[c]TPAC Species: Species: giant ragweed *(Ambrosia trifida*), common chickweed *(Stellaria media*), henbit *(Lamium amplexicaul*.), Common lambsquarters *(Chenopodium album),* velvetleaf *(Abutilon theophrasti*.), prostrate knotweed *(Polygonum aviculare),* wild mustard *(Sinapis arvensis*.*),* buttercup *(Ranunculus spp.),* Mousetail *(Myosurusminimus*), Shepherd's purse *(Capsella bursa-pastoris*), Whitlow-grass *(Draba spp.),* common dandelion *(Taraxacum officinale*), common sunflower *(Helianthu sannuus*), Canada horseweed *(Erigeron canadensis*), Eastern black nightshade *(Solanum ptycanthum*), mouseear chickweed *(Cerastium fontanum*), bulbous buttercup *(Ranunculus bulbosus*), field pepperweed *(Lepidium campestre*), small-flowered bittercress *(Cardamine parviflora*), rayless mayweed *(Matricaria discoidea)*, field speedwell *(Veronica agrestis*), Pennsylvania smartweed *(Persicaria pensylvanica*), Ivyleaf morningglory *(Ipomoea headracea*), common ragweed *(Ambrosia artemisiifolia*), prickly sida *(Sida Spinosa),* giant foxtail *(Setaria faberi*), annual bluegrass (*Poa annua*), bromegrass (*Bromus spp.)*
SEPAC species: wild garlic (*Allium vineale*), common ragweed (*Ambrosia artemisiifolia*) , giant ragweed (*Ambrosia trifida*), common yellow rocket (*Barbarea vulgaris*), bromegrass (*Bromus spp.*), shepherd's purse (*Capsella bursa-pastoris*), small-flowered bittercress (*Cardamine parviflora*) ,mouseear chickweeed (*Cerastium vulgatum*), common lambsquarters (*Chenopodium album*), Canada thistle (*Cirsium arvense*), smooth crabgrass (*Digitaria ischaemum*), large crabgrass (*Digitaria sanguinalis*), whitlow-grass (*Draba spp.*), barnyardgrass (*Echinochloa crus-gali*), Canada horseweed (*Erigeron canadensis*), fleabane (*Erigeron spp.*), Carolina geranium (*Geranium carolinianum*) , foxtail barley (*Hordeum jubatum*) , ivyleaf, morningglory (*Ipomoea hederacea*), pitted Morningglor (*Ipomoea lacunosa*), prickly lettuce (*Lactuca serriola*), henbit(*Lamium amplexicaule*), purple deadnettel (*Lamium purpureum*), mousetail (*Myosurus minimus*), yellow Woodsorrel (*Oxalis stricta*), broadleaf Plantain (*Plantago majo*)*r*, annual bluegrass (*Poa annua*), corn buttercup (*Ranunculus arvensis*), cressleaf groundsel (*Senecio glabellus*), giant foxtail (*Setaria faberi*), yellow foxtail (*Setaria pumila*), green foxtail (*Setaria viridis*), Eastern black nightshade (*Solanum ptycanthum*), common chickweed (*Stellaria media*), common dandelion (*Taraxacum officinale*), field pennycress (*Thlaspi arvense*), field speedwell (*Veronica agrestis*) , common cocklebur (*Xanthium strumarium*)

Table 3.7: ANOVA table for the influence of herbicide strategy, year and the interaction of the two on in-field total, dicot, and monocot density and species richness in mid-June at early-summer evaluations from 2013 to 2019.[a]

	Factors & interactions	SEPAC			TPAC		
		Total weed species	Dicot weed species	Monocot weed species	Total weed species	Dicot weed species	Monocot weed species
		P					
Density	Herbicide strategy	0.1453	<.0001	0.3358	<.0001	<.0001	<.0001
	Year	<.0001	<.0001	<.0001	0.0004	<.0001	0.0002
	Herbicide strategy x Year	0.8785	0.0006	0.4074	<.0001	<.0001	<.0001
Species richness	Herbicide strategy	<.0001	<.0001	0.0131	<.0001	<.0001	<.0001
	Year	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Herbicide strategy x Year	0.0297	0.3254	0.0012	<.0001	<.0001	0.002

[a] Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

Table 3.8: Influence of dicamba herbicide strategies on in-field dicot weed species richness pooled from 2013 to 2019 in mid-June at early-summer evaluations the South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).[a,b,c]

Herbicide strategy	Dicot weed species
	Species richness m^{-2}
Diversified Gly	2.7 b
Dicamba Reliant	4.5 a
Div Dicamba	2.8 b
Fully Div	2.3 b

[a]Abbreviations: Gly= glyphosate, Div=Diversified.
[b]Means followed by the same letter are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).
[c] velvetleaf (*Abutilon theophrasti),* redroot pigweed (*Amaranthus retroflexus),* waterhemp (*Amaranthus tuberculatus)* ,common ragweed (*Ambrosia artemisiifolia)* , giant ragweed (*Ambrosia trifida),* common lambsquarters (*Chenopodium album),* Jimsonweed, (*Datura stramonium),* spotted spurge (*Chamaesyce maculata)* , Canada horseweed (*Erigeron canadensis)* , ivyleaf morningglory (*Ipomoea hederacea)* , pitted morningglory (*Ipomea lacunosa),* carpetweed (*Mollugo verticulata),* yellow Sorrel (*Oxalis stricta),* creeping buttercup, (*Ranuculus repens),* prickly sida (*Sida spinosa),* horsenettle (*Solanum carolinense),* Eastern black nightshade (*Solanum ptycanthum),* common dandelion (*Taraxacum officinale),* field speedwell (*Veronica persica)* ,heart-leaf cocklebur (*Xanthium strumarium)*

Table 3.9: ANOVA table for the influence of herbicide strategy, year and the interaction of the two on total, dicot, and monocot density and species richness of soil seedbank from 2013 to 2019.[a]

	Factors & interactions	SEPAC			TPAC		
		Total weed species	Dicot weed species	Monocot weed species	Total weed species	Dicot weed species	Monocot weed species
		P					
Density	Herbicide strategy	0.92	0.0541	0.8875	<.0001	0.2608	<.0001
	Year	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Herbicide strategy x Year	0.9998	0.9828	0.9972	0.0002	0.997	<.0001
Species richness	Herbicide strategy	0.0083	0.0946	0.1524	<.0001	<.0001	<.0001
	Year	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	Herbicide strategy x Year	0.9958	0.9792	0.8853	0.4649	0.842	0.0001

[a] Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

Table 3.10: Influence of herbicide strategies on total weed species richness at SEPAC and total and dicot species richness at TPAC from 2013 to 2019 within the soil seedbank.[a,b,c]

Herbicide strategy	SEPAC	TPAC	
	Total weed species	Total weed species	Dicot weed species
	Species richness 3000 cm^{-3}		
Diversified Gly	12.1 AB	4.9 ab	3.4 a
Dicamba Reliant	11.7 B	5.4 a	3.2 a
Div dicamba	13.2 A	4.1 bc	3.2 a
Fully Div	12.3 AB	3.4 c	2.2 b

[a]Abbreviations: Gly= glyphosate, Div=Diversified, TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), and SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).
[b]Means followed by the same letter with columns are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).
[c] TPAC Species: giant ragweed (*Ambrosia trifida),* lambsquartes (*Chenopodium album*), smooth crabgrass (*Digitaria ischaemum*), large crabgrass (*Digitaria sanguinalis*), barnyardgrass (*Echinochloa crus-gali*), goosegrass (*Eleusine indica*), creeping spurge (*Chamaesyce serpens*), horseweed (*Erigeron canadensis*), wooly cupgrass (*Eriochloa villosa*) ivyleaf morningglory (*Ipomoea hederacea*), henbit (*Lamium amplexicaule*), carpetweed (*Mollugo verticilata*), yellow woodsorrel (*Oxalis stricta*), fall panicum (*Panicum dichotomiflorum*), common purslane(*Portulaca oleracea*), giant foxtail(*Setaria faberi*), yellow foxtail (*Setaria pumila*), green foxtail (*Setaria viridis*), prickly sida (*Sida spinosa*), Eastern black nightshade (*Solanum ptycanthum*), Johnson grass (*Sorghum halepense*), chickweed (*Stellaria media*), speedwell (*Veronica persica*) common cocklebur (*Xanthium strumarium*). SEPAC species: velvetleaf (*Abutilon theophrasti),* wild garlic (*Allium vineale*) ,redroot pigweed (*Amaranthus retroflexus*), waterhemp (*Amaranthus tuberculatus*), common ragweed (*Ambrosia artemisiifolia*), giant ragweed (*Ambrosia trifida*), common yellow rocket (*Barbarea vulgaris*), canola (*Brassica napus*), sheperd's purse (*Capsella bursa-pastoris*), hairy bittercress (*Cardamine hirsuta*) , small-flowered bittercress (*Cardamine parviflora*), common lambsquarters (*Chenopodium album*), Canada horseweed (*Erigeron canadensis*), yellow nutsedge (*Cypersus esculentus*), cryptocarya spp. (*Cryptocarya spp.*) , Jimsonweed (*Datura stramonium*) , smooth crabgrass (*Digitaria ischaemum*) , large crabgrass (*Digitaria sanguinalis*) , whitlow-grass (*Draba spp.*), common barnyardgrass (*Echinochloa crus-galli*), goosegrass (*Eleusine indica*), spotted spurge (*Euphorbia maculata*), Carolina geranium (*Geranium carolinianum*) , Venice mallow (*Hibiscus trionum*), ivyleaf morningglory (*Ipomoea hederacea*) , pitted morningglory (*Ipomoea lacunosa*), henbit (*Lamium amplexicaule*), carpetweed (*Mollugo verticillata*), yellow sorrel (*Oxalis stricta*), cressleaf groundsel (*Packera glabella*), fall panicum (*Panicum dichotomiflorum*), common pokeweed , (*Phytolacca americana*), annual bluegrass (*Poa annua*), common purslane (*Portulaca oleracea*), creeping buttercup (*Ranuculus repens*), curly dock (*Rumex Crispus*), giant foxtail (*Setaria faberi*), yellow foxtail (*Setaria pumila*), green foxtail (*Setaria viridis*), prickly sida (*Sida spinosa*), Eastern black nightshade (*Solanum ptycanthum*), Johnsongrass (*Sorghum halepense*), common Chickweed (*Stellaria media*) dandelion (*Taraxacum officinale*), field pennycress (*Thlsapi arvense*), field speedwell (*Veronica persica*), common cocklebur (*Xanthium strumarium*)

Table 3.11: Influence of herbicide strategies on soil seedbank total, monocot, and dicot weed densities at SEPAC and dicot weed densities at TPAC from 2013 to 2019.[a,b,c,d]

Year	SEPAC			TPAC
	Total weed species	Dicot weed species	Monocot weed species	Dicot weed species
	Plants 3000 cm^{-3}			
2013	289 c	111 a	178 c	121 a
2014	119 c	50 b	69 c	36 b
2015	212 c	142 a	71 c	24 b
2016	55 c	43 b	11 c	13 b
2017	114 c	48 b	66 c	12 b
2018	556 b	108 a	413 b	21 b
2019	968 a	145 a	823 a	24 b

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

[b]Means followed by the same letter with columns are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).

[c]Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, and 2016, and 2018.

[c]TPAC species: giant ragweed (*Ambrosia trifida)*, lambsquartes (*Chenopodium album*), creeping spurge (*Chamaesyce serpens*), horseweed (*Erigeron canadensis*), ivyleaf morningglory (*Ipomoea hederacea*), henbit (*Lamium amplexicaule*), carpetweed (*Mollugo verticilata*), yellow woodsorrel (*Oxalis stricta*), common purslane(*Portulaca oleracea*), prickly sida (*Sida spinosa*), Eastern black nightshade (*Solanum ptycanthum*), chickweed (*Stellaria media*), speedwell (*Veronica persica*) common cocklebur (*Xanthium strumarium*). SEPAC species: velvetleaf (*Abutilon theophrasti),* wild garlic (*Allium vineale*) ,redroot pigweed (*Amaranthus retroflexus*), waterhemp (*Amaranthus tuberculatus*), common ragweed (*Ambrosia artemisiifolia*), giant ragweed (*Ambrosia trifida*), common yellow rocket (*Barbarea vulgaris*), canola (*Brassica napus*), sheperd's purse (*Capsella bursa-pastoris*), hairy bittercress (*Cardamine hirsuta*) , small-flowered bittercress (*Cardamine parviflora*), common lambsquarters (*Chenopodium album*), Canada horseweed (*Erigeron canadensis*), yellow nutsedge (*Cypersus esculentus*), cryptocarya spp. (*Cryptocarya spp.*) , Jimsonweed (*Datura stramonium*) , smooth crabgrass (*Digitaria ischaemum*) , large crabgrass (*Digitaria sanguinalis*) , whitlow-grass (*Draba spp.*), common barnyardgrass (*Echinochloa crus-galli*), goosegrass (*Eleusine indica*), spotted spurge (*Euphorbia maculata*), Carolina geranium (*Geranium carolinianum*) , Venice mallow (*Hibiscus trionum*), ivyleaf morningglory (*Ipomoea hederacea*) , pitted morningglory (*Ipomoea lacunosa*), henbit (*Lamium amplexicaule*), carpetweed (*Mollugo verticillata*), yellow sorrel (*Oxalis stricta*), cressleaf groundsel (*Packera glabella*), fall panicum (*Panicum dichotomiflorum*), common pokeweed , (*Phytolacca americana*), annual bluegrass (*Poa annua*), common purslane (*Portulaca oleracea*), creeping buttercup (*Ranuculus repens*), curly dock (*Rumex Crispus*), giant foxtail (*Setaria faberi*), yellow foxtail (*Setaria pumila*), green foxtail (*Setaria viridis*), prickly sida (*Sida spinosa*), Eastern black nightshade (*Solanum ptycanthum*), Johnsongrass (*Sorghum halepense*), common Chickweed (*Stellaria media*) dandelion (*Taraxacum officinale*), field pennycress (*Thlsapi arvense*), field speedwell (*Veronica persica*), common cocklebur (*Xanthium strumarium*)

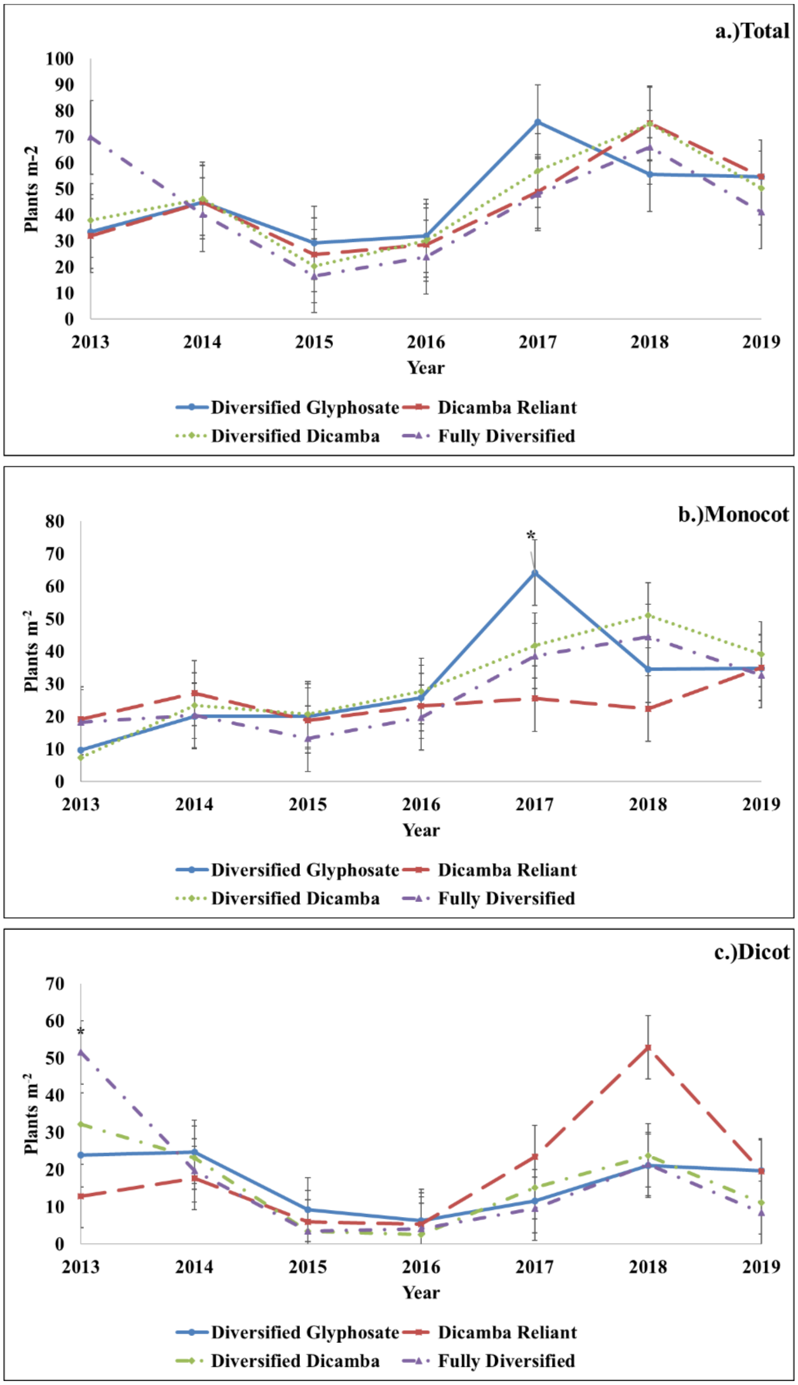

Figure 3.1: a.) Total, b.) monocot, and c.) dicot densities at the South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223) in late-April. Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy prior to a spring weed control. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

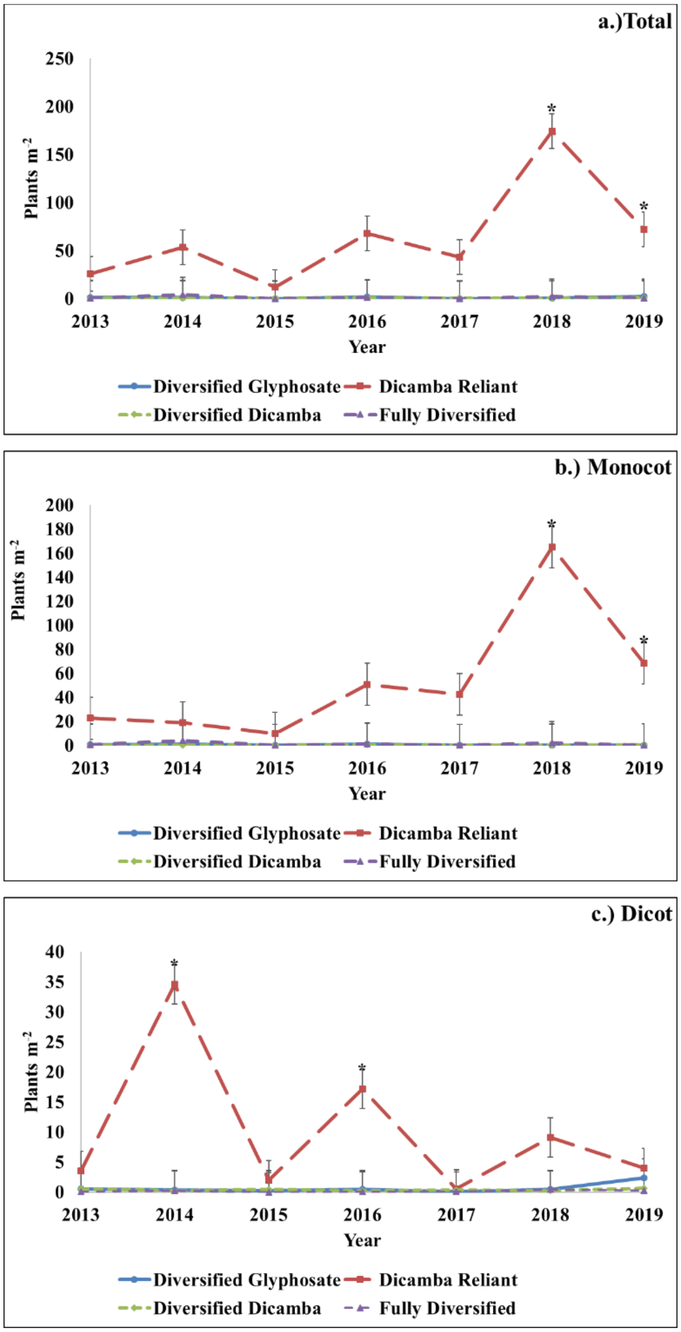

Figure 3.2: a.) Total, b.) monocot, and c.) dicot in-field densities at the TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) in mid-June. Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy at early-summer evaluations. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

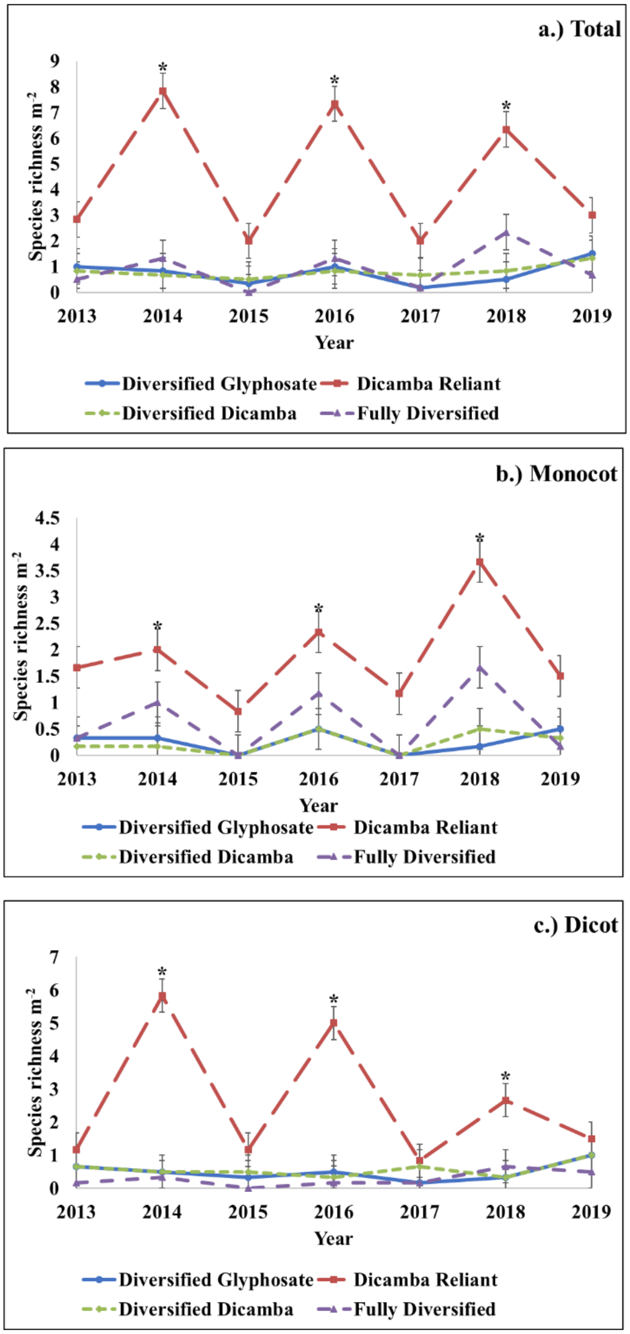

Figure 3.3: a.) Total, b.) monocot, and c.) dicot in-field species richness at the Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) in mid-June. Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy at early-summer evaluations. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

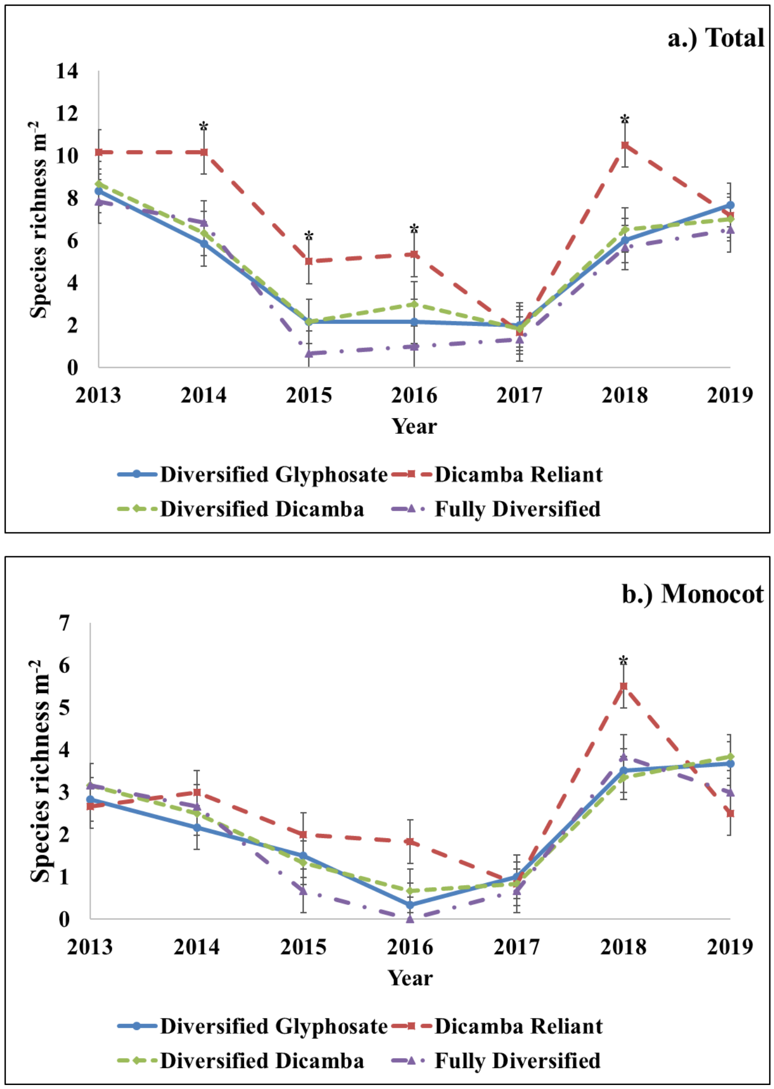

Figure 3.4: a.) Total and b.) monocot in-field species richness at the South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223) in mid-June. Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy at early-summer evaluations. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

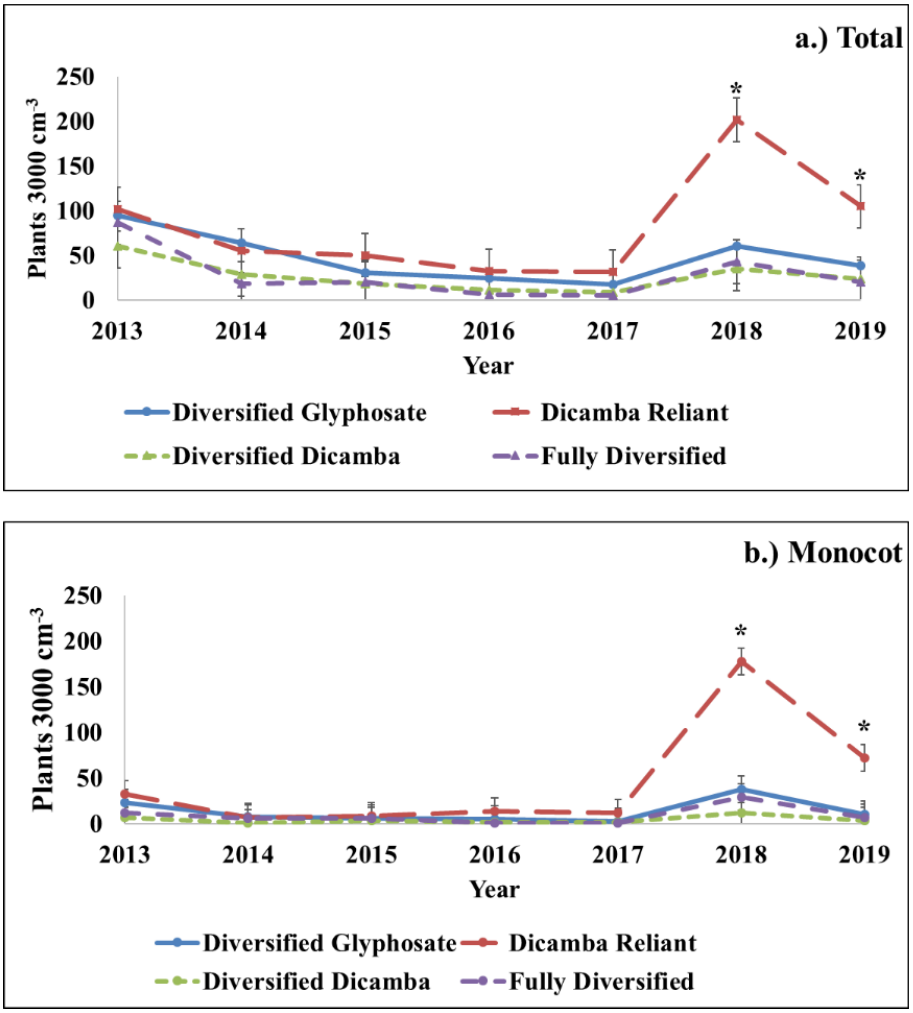

Figure 3.5: a.) Total and b.) monocot soil seedbank densities from the Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909). Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown 2014, 2016, and 2018.

CHAPTER 4. UTILIZING CEREAL RYE & CRIMSON CLOVER FOR WEED SUPPRESSION WITHIN BUFFER AREAS IN DICAMBA-RESISTANT SOYBEANS

4.1 Abstract

As herbicide-resistant weeds become more problematic in the Eastern Corn Belt producers will consider the use of cover crops to control weeds, especially in the label-mandated buffer areas of dicamba-resistant soybeans (*Glycine max* (L.) Merr.) where dicamba use is not allowed. Three cover crops species terminated at three timings with three herbicide strategies were evaluated for their effect on weed suppression and soybean yield in dicamba-resistant soybeans. Delaying termination to at soybean planting, or after, and using a cereal rye or mix cover crop (*Secale cereal* L.) increased cover crop biomass by at least 40% compared to terminating early or using a crimson clover (*Trifolium incarnatum* L.) cover crop without cereal rye. Weed densities of problematic weed species were evaluated in early-summer prior to a blanket post-emergence (POST) application. Cereal rye had 75% less horseweed compared to crimson clover at two of four site-years. Horseweed at the other two site-years was influenced by the interaction between cover crops and herbicide strategy. Crimson clover terminated with glyphosate alone resulted in 81% more horseweed than other treatments. The addition of dicamba and a residual herbicide to glyphosate at the time of cover crop termination improved horseweed control by at least 69% at all site-years compared to applications of glyphosate alone. Utilizing a mix cover crop for grass suppression was beneficial at three of six site-years reducing densities by at least 67% when used alone or with delayed termination compared to early terminated crimson clover. Grass suppression was 29% higher when termination timing was delayed to after soybean planting compared to the earliest timing at all site-years. Cereal rye or the mix cover crop terminated at, or after soybean planting

reduced waterhemp densities by 87% compared to the two early termination timings of crimson clover and the earliest termination timing of the mix at one of two site-years. Giant ragweed (*Ambrosia trifida* L.) densities were not reduced by cover crops. Reductions in soybean grain yield from 10 to 31% at three of six site-years were due to delaying termination from before soybean planting to at, or after soybean planting. Cover crops alone were generally not as effective as using an herbicide strategy that contained dicamba and residual herbicides. However, within label-mandated buffer areas where dicamba cannot be used, a cover crop containing cereal rye with delayed termination to at soybean planting could be utilized to improve suppression of horseweed, grasses, and waterhemp, but not giant ragweed.

4.2 Introduction

Herbicide-resistant weeds are a major concern across the Midwest. Indiana alone has 18 unique herbicide-resistant weed biotypes, and Illinois has weed species with multiple-resistance to 5 different herbicide sites of action (Heap 2020). To help combat herbicide-resistant weeds, the agri-chemical industry developed and released soybean varieties that are resistant to dicamba (Behrens et al. 2007). The use of dicamba-resistant soybeans rose from 20 million acres in 2017 to more than 60 million acres in 2019 (Hettinger 2019).

Spaunhorst and Johnson (2016) reported that dicamba provided similar control of glyphosate-resistant Palmer amaranth in one year and improved control by 29% in another year compared to 2,4-D applications when pooled to include applications applied alone or in combination with S-metolachlor and metribuzin. Similar research was conducted in Missouri by Spaunhorst and Bradley (2013) who reported that dicamba in combination with glyphosate provided 16 to 36% more control glyphosate-resistant waterhemp than dicamba alone. Kruger et al. (2010) demonstrated that the diglycolamine salt of dicamba provided 97% control of 30 cm glyphosate-resistant horseweed 28 days after treatment in Indiana. Therefore, dicamba will be useful in managing some of Indiana's herbicide-resistant weed species.

The herbicide label for dicamba products used in dicamba-resistant soybeans requires buffer areas where dicamba cannot be applied. Counties that contain endangered plant species require a 17.4 m buffer around the entire soybean field (Anonymous 2020a; Anonymous 2020b). Buffers up to 30.5 m wide are required for sensitive areas (Anonymous 2020a). A sensitive area is considered a body of water, or uncultivated non-residential area (Anonymous 2020a).

Cover crops are an option to supplement weed control within buffer areas where dicamba applications are not permitted. Additionally, cover crops may be a weed control option outside of buffer areas and reduce the selection pressure for herbicide-resistant weed species. Cover crops with proper management have shown potential to suppress weeds, especially when used in tandem with an appropriate herbicide program (Davis et al. 2007; Loux et al. 2017; Wiggins et al. 2015). Loux et al. 2017 reported that herbicides controlled redroot pigweed (*Amaranthus* retroflexus L.) and Palmer amaranth (*Amaranthus palmeri* S. Watson) 100 and 96%, respectively, at the end of the season compared to cover crops which provided 49 and 29% control, respectively.

Maclaren et al. (2019) indicated that cover crop biomass influenced resource uptake and weed biomass, which was composed of primarily *Lolium spp*, but included 35 other species. They showed that early-season nitrogen uptake and late-season light interception by high biomass producing cover crops reduced weed biomass. Teasdale et al. (1991) demonstrated that cover crop biomass and weed density of large crabgrass (*Digitaria sanguinalis (L.) Scop*), goosegrass (*Eleusine indica* (L.), stinkgrass (*Eragrostis cilianensis* (All.) Vignolo ex Janch)., carpetweed (*Mollugo verticillata* L)., and common lambsquarters (*Chenopodium album L*.) was correlated with cover crop biomass with an $R^2 = 0.75$ at the 0.01 level in Maryland. Furthermore, Maclaren et al. (2019) demonstrated that cereal crops that produce large amounts of biomass quickly were more effective in reducing weed biomass compared to legume species. Cover crops have potential to be used as a weed control method in both organic agriculture, as well as part of an integrated pest management approach in conventional agriculture. Palhano et al. (2018) showed that cover crops used in conventional production suppressed Palmer amaranth emergence by 65 to 100% in cotton when compared to no cover crop. Cover crop species that have high carbon to nitrogen (C:N) ratios, such as cereals, provided Palmer amaranth suppression up to eight weeks after cotton planting. Teasdale and Abdul-Baki (1998) showed that using cover crops does not eliminate the need for herbicides due to higher weed biomass in the absence of herbicides which can result in lower cash crop yields. Additionally cover crops such as cereal rye with high C:N ratios will decompose at a slower rate than legumes that have lower C:N rations (Sievers and Cook 2018), and provide ground cover and additional weed suppression for a longer period of time.

Although cover crops may not always suppress weed density within a field, they can delay the growth of key weed species, such as Palmer amaranth, extending herbicide application window to control problematic weeds (Montgomery et al. 2017). Cover crops can also have other indirect effects on weed management such as increasing the activity of weed seed predators when compared to fallow ground (Shearin et al. 2008). Cereal rye can reduce the number of winter annuals by 72% compared with a non-treated control. Although cover crops are beneficial in reducing winter annual weeds they are not as effective as a fall herbicide program of glyphosate + 2,4-D + sulfentrazone + chlorimuron-ethyl, which provided 99% control of winter annual weed emergence compared to the non-treated control (Cornelius and Bradley 2017). However, Mock et al. (2012) showed that annual ryegrass (*Lolium perenne* L. *spp. multiflorum*) increased the number of winter annuals present compared to a non-treated control.

Horseweed suppression by cover crops has been evaluated across many regions. Davis et al. (2007) reported that a winter wheat cover crop provided similar horseweed suppression 4 months after in-crop applications compared to a spring or fall residual herbicide across two years in Indiana. Pittman et al. (2019) reported that horseweed densities in late March were similar, or lower in roller-crimped cover crops compared to fall residual herbicide applications in Virginia. Christenson (2015) reported that horseweed suppression with winter rye at soybean R1 and R6.5 was similar to all herbicide treatments, however winter wheat and winter barley were not as effective at suppressing horseweed in Kansas. Cholette et al. (2018) reported that annual ryegrass alone or in combination with crimson clover was the most consistent cover crop out of 17 species and mixtures for suppressing horseweed in Ontario. Cholette et al. (2018) reported correlations of cover crop ground cover and biomass were correlated with horseweed density (0.17 and 0.21, respectively) and biomass (0.30 and 40, respectively); however, these correlations were considered weak and the authors suggested that this could be due to the inherent variability when implemented biological weed management practices.

Cover crops can be beneficial for weed control purposes. However, it is important that cover crops are managed correctly in order to reduce any negative impacts on cash yield. Potential reductions in yield have been reported in several vegetable crops when cover crops were implemented (Leavitt et al. 2011, Lotz et al. 1997). Corn yield following a cereal rye cover crop was 36% of the corn yield planted into soybean stubble in Missouri (Johnson et al. 1993). Creech et al. (2008) reported yield reductions of 11% when using an annual ryegrass or wheat cover crop compared to fall or spring residual herbicide strategies prior to corn at one site in Indiana. Choosing an appropriate cover crop and terminating in an effective and timely manner is important to prevent negative impacts on cash-crop yield.

If cover crops are to be used on a large scale in agricultural production systems they will need to be integrated with technological advances in herbicide-resistant traited grain crops. Utilizing cover crops within buffer areas of dicamba-resistant soybeans can benefit producers from a weed control standpoint. Furthermore, using cover crops can reduce selection pressure on herbicide-resistant weeds allowing for a more sustainable weed management strategy which will be needed in tandem with future technologies to manage problematic weeds.

The purpose of this research was to evaluate cover crop use in dicamba-resistant soybean systems, and the specific objectives were: 1.) To determine the effectiveness of cover crop species, termination timing of cover crops, and herbicide strategy on weed control, 2.) Observe whether cover crops can replace dicamba for weed suppression within label-mandated buffer areas, and 3.) Evaluate cover crop species, termination timing, and herbicide strategy on soybean yield.

4.3 Materials and Methods

4.3.1 Site Description

This experiment was conducted in 2 growing seasons which included seeding of cover crops in the fall of 2017 through soybean harvest in 2018 and repeated in the fall of 2018 through soybean harvest of 2019. Field experiments were conducted at the Throckmorton Purdue Agriculture Center (TPAC) near Lafayette, Indiana (40.29°N, 86.91°W); the Southeast Purdue Agriculture Center (SEPAC) near Butlerville, Indiana (39.03°N, 85.53°W); and the Davis Purdue Agricultural Center (DPAC) near Farmland, Indiana (40.26°N, 85.16°W). The TPAC location was primarily a Toronto-Octagon complex in 2018 and a Toronto-Millbrook complex in 2019. These soils had an organic matter of 2.6%, pH of 6.3, and a cation exchange capacity of 10.6 meq 100 g^{-1}. The TPAC site historically undergoes tillage as a form of weed control. SEPAC is a no-till location where the soil is a Cobbsfork silt loam with an organic matter of 1.7%, pH of 6.1, and a

CEC of 5.6 meq 100 g^{-1}. The DPAC location is also no-till and has 3.6% organic matter, a pH of 6.0, CEC of 15.8 meq 100 g^{-1}, and is primarily a Pewamo silty clay loam. The SEPAC location had more winter annual species and a more diverse weed community when compared to the TPAC and DPAC locations.

4.3.2 Experimental Design & Herbicide Treatments

The experimental design was a split plot with four replications. Field plots were 3 m wide and 9 m in length. The experiment consisted of three main blocks, (cover crop systems): 1) cereal rye; 2) crimson clover; and 3) cereal rye and crimson clover mixture seeded at 80:20 ratio by weight, hereafter referred to as "mix". The DPAC location in 2018 only had two replications due to saturated soil conditions that resulted in failed cover crop establishment in half of the trial area. Planting dates for each location can be found in Table 4.1. Cereal rye was seeded at a rate of 101 kg ha^{-1}, crimson clover at 20 kg ha^{-1}, and the mix was seeded at 78 kg ha^{-1}. Due to cold weather conditions during the winter of 2019 the crimson clover winter-killed and was considered a fallow treatment for the 2019 growing season at all locations.

Each main block (cover crop) contained a full factorial design with two main factors, each having three sub-factors. The two main factors being termination timing and herbicide strategy. The three termination timings were before planting (BP), at planting (ATP), and after planting (AFP). The three different herbicide strategies used to terminate the cover crops were glyphosate alone, utilized in order to simulate weed control within label-mandated buffer areas where dicamba is not allowed. Buffer areas are required by dicamba herbicide labels for Roundup Ready 2 Xtend® (Monsanto Company 800 North Lindbergh Boulevard, Saint Louis, Missouri, United States) to reduce the possibility of damage caused by off target movement. The other two herbicide strategies were used to simulate weed control outside of buffer areas. The two outside buffer area termination strategies were glyphosate + dicamba, and glyphosate + dicamba + a residual herbicide. The residual herbicide used was determined based on the primary weed species present at each location. The residual herbicide used at the SEPAC and DPAC location changed for the AFP termination timing due to label restrictions of the residual herbicide used for the previous two timings. Rates of each herbicide and the residual herbicide used at each location can be found in Table 4.2.

Termination of cover crops via herbicide applications were made with a 3 m CO_2-propelled back pack sprayer calibrated to deliver 140 L ha^{-1} at 143 kPa. The nozzles used were those recommended by the dicamba herbicide label being a TTI11003 (Teejet Technologies, Wheaton, IL), an AIXR 11003 (Teejet Technologies, Wheaton, IL) for glyphosate applications. The primary weed species at SEPAC were a wide variety of grasses [Approximate composition included: barnyardgrass (*Echinochloa crus*-galli (L.) P. Beauv) (2%), large crabgrass (2%), annual bluegrass (*Poa annua L.*) (8%), fall panicum (*Panicum dichotomiflorum* Michx.) (34%), and foxtail species (*Setaria spp.*) (54%)] and horseweed in 2018 and common waterhemp (*Amaranthus tuberculatus* (Moq.) J. D. Sauer) in 2019. At the TPAC location giant ragweed, and grasses [Approximate composition included: large crabgrass (2%), smooth crabgrass (*Digitaria ischaemum (Schreb.) Schreb. ex Muhl.*) (3%), fall panicum (15%), barnyardgrass (17%), and foxtail species (67%)]. The DPAC weed flora was primarily common waterhemp and a mix of grass species [Approximate composition included: smooth crabgrass (1%), large crabgrass (4%), foxtail species (18%), barnyardgrass (32%), and fall panicum (45%)].

An additional blanket POST herbicide application was made when weeds were an average height of 10 to 15 cm. This POST application contained glyphosate in addition to a residual herbicide. The specific herbicides and rates used can be found in Table 4.2.

4.3.3 Data Collection

Biomass of each cover crop was taken prior to terminating cover crops in the spring, along with weed biomass present from a 0.25 m^2 quadrat out of at least 5 plots from within each of the three main cover crop blocks. The objective of this sample collection was to determine the effect of each cover crop type on early season weed control, as well as to track the growth of cover crop biomass between the three termination timings. Soybeans were planted at a rate of 350,000 seeds ha^{-1}. Cover crop seeding, cover crop termination, soybean planting, blanket POST and soybean harvesting dates can be found in Table 4.1. Densities of the primary weed species were recorded from two quadrats out of every plot prior to the application of a blanket POST over the entire trial area for maintenance. The primary weed species that were collected at each site can be found in Table 4.3. The quadrants used were either 0.25- or 1-m^2, depending on the density of weeds at the time of data collection. The biomass of those species was collected, dried, and weighed for a single weed biomass for every plot. The key weed species that were collected at each location varied (Table 4.3). The plots were harvested using a small plot combine and yields were adjusted to 13% moisture.

4.3.4 Statistical Analysis

Correlations between cover crop biomass and early-season weed biomass were conducted using the SAS 9.4 PROC CORR procedure, and all other data was analyzed using SAS 9.4 PROC GLIMMIX procedure (SAS, 100 SAS Campus Drive, Cary, NC 27513-2414, USA). The densities and biomass of individual species were analyzed using a log transformation in order to normalize the data and gain constant variance. Random variables were cover crop, cover crop*replication, and cover crop*replication*termination time. Random variables were used to describe the split-split-plot error, while fixed variables included termination timing and herbicide strategy. Cover crop was a random variable due to being the main block within the trial design. A Satterthwaite denominator degree of freedom was utilized to produce an accurate approximation of F. Analysis was similar to that described by Yang (2010) for balanced split-plot designs. Although a log transformation was used to analyze data for clarity purposes, untransformed data is presented. All means were separated using Tukey Honest Significant Difference (HSD) test at alpha=0.05. Due to differences in soil type and predominant weed species, all sites were analyzed separately. Years were separated due to crimson clover winter-killing in 2019, resulting in a fallow treatment. Significant interactions within each site can be found in Tables 4.4 through 4.7.

4.4 Results and Discussion

4.4.1 Cover Crop and Weed Biomass Prior to Cover Crop Termination

Cover crop biomass increased as termination timing was delayed from before soybean planting to at soybean planting, and when cereal rye or the mix was used. The DPAC location in 2019 was removed from evaluating weed suppression from cover crops as cover crop stand was poor due to winter-kill. Two-way interactions of cover crop by termination timing occurred at all site-years, except for TPAC in 2018 and SEPAC in 2019. This interaction occurred due to cover crops having two additional weeks to grow as termination timing was delayed from before soybean planting to at soybean planting. However, cover crop biomass usually did not increase when delayed from at soybean planting to after soybean planting due to cover crops transitioning from the vegetative to reproductive growth stages and damage from the planting equipment. Cover crop biomass at TPAC in 2019 was at least 59% higher when a cover crop using cereal rye or mix was terminated at, or after, soybean planting compared to other treatments (Table 4.4, $P<0.0001$). Similarly, SEPAC in 2019 and TPAC in 2018 had at least 61% more cover crop biomass by using a cereal rye or mix cover crop (Table 4.4, $P<0.0001$, and $P<0.0001$, respectively). Delaying termination to at, or after, planting resulted in at least 40% more cover crop biomass compared to the before soybean planting termination (Table 4.4). At SEPAC in 2018 crimson clover terminated before soybean planting had at least 71% less biomass compared to all other treatments ($P=0.0433$). Using cereal rye or mix terminated at, or after soybean planting resulted in the highest cover crop biomass. This is consistent with what Haramoto and Pearce (2019) showed in Kentucky in that delaying termination from six weeks before planting to three weeks before planting resulted in a 35% increase in a wheat monoculture biomass.

Using cover crops that contain cereal rye that is terminated at the time of soybean planting resulted in early season weed suppression both outside of, and within buffer areas in dicamba-resistant soybean production systems. This is supported by the correlation between cover crop biomass and early season weed biomass of 0.42 ($P<0.0001$). The correlation resulted in evidence that as cover crop biomass increases the variability in early-season weed biomass tends to decline (Figure 4.1). Baraibar et al. (2018) also reported that cover crop biomass was one of the most important variables for predicting spring weed biomass along with cover crop type and the number of growing degree days accumulated in Pennsylvania. Delaying cover crop termination from before soybean planting to at soybean planting resulted in increased cover crop biomass. However, additional increases in biomass were not observed when delaying further to after soybean planting.

Interactions between cover crop by termination timing occurred at TPAC in 2019 for weed biomass ($P=0.0072$). Weed biomass from the at planting termination at TPAC in 2018 is not presented due to lost samples. In 2019 crimson clover plots terminated at, or after, soybean planting resulted in weed biomass that was at least 63% higher than all other treatments, but was similar to cereal rye terminated at planting and the mix terminated after planting (Table 4.5). Weed biomass at TPAC in 2018 was affected by termination time and cover crop (*P* =0.0036 and *P*<0.0001, respectively). Using a cover crop containing cereal rye reduced weed biomass by 81%, while delaying termination from at soybean planting to after soybean planting reduced weed biomass by 60% (Table 4.5). Weed biomass at SEPAC in 2018 were influenced by cover crop and termination timing (*P* = 0.0069 and *P*<0.0001, respectively). Crimson clover had 69% more weed biomass than cereal rye or the mix (Table 4.5). Delaying the termination of cover crops until after soybean planting resulted in a 78% reduction in weed biomass at SEPAC in 2018 (Table 4.5). In order to suppress early emerging weeds, cereal rye should be terminated at soybean planting. Hayden et al. 2012 found that a rye or rye plus vetch mix reduced weed biomass by at least 94% compared to no cover crop in early May. Rosario-Lebron et al. (2019) showed that earlier terminations resulted in less residue coverage by the cover crop, resulting in higher weed densities primarily large crabgrass, goosegrass, and white clover (*Trifolium repens L.*) with evaluations being made from early vegetative stage of soybeans through canopy closure, which was similar to our results.

When cereal rye or the mix termination was delayed from before soybean planting to at planting at least a 40% increase in cover crop biomass occurred across all site-years compared with crimson clover. However, delaying the termination time of cover crops from at soybean planting to after planting only resulted in an increase in cover crop biomass at one site-year due to cover crops having completed vegetative growth and transitioning into reproductive growth. Using a cover crop that contained cereal rye reduced early season weed biomass by at least 69% at three of five site-years. An interaction between cover crop and termination timing occurred at the other two site-years with the crimson clover terminated at or after soybean planting having at least 70% more weed biomass compared to cereal rye terminated at any timing.

4.4.2 Horseweed Densities Prior to Blanket POST

Horseweed was evaluated at five site-years. In 2018 horseweed density was influenced by a cover crop by termination timing interaction at DPAC (*P* =0.0402). Terminating crimson clover after soybean planting resulted in 47% higher horseweed densities compared to all other treatments (Table 4.6). Using cereal rye resulted in the lowest horseweed densities within each termination timing. In 2018 horseweed densities at SEPAC were influenced by an interaction between herbicide strategy and termination timing (*P* =0.04). Terminating before soybean planting with a herbicide strategy that utilized glyphosate and dicamba resulted in at least a 88% reduction in horseweed density compared to using glyphosate alone at, or before soybean planting (Table 4.6). The use of dicamba in the herbicide strategy tended to be beneficial across all timing in reducing horseweed densities, while the use of a residual herbicide applied after soybean planting had higher horseweed densities than the same herbicide strategy applied before soybean planting (Table 4.6). Davis et al. (2005) established that glyphosate-resistant horseweed occurred at this site by conducting a dose response under greenhouse conditions. Rates of 1.8 kg ae ha^{-1} were needed to reduce horseweed biomass by 50% compared to the average of four susceptible populations which only required an average of 0.3 kg ae ha^{-1} of glyphosate to reduce horseweed biomass by 50%. Crimson clover terminated with glyphosate alone resulted in at least 74% more horseweed compared to all other cover crop by herbicide strategy combinations at TPAC and DPAC in 2018 (Table 4.6, *P* =0.0077, and *P* =0.0439). The DPAC horseweed densities were influenced by herbicide strategy in both years with the addition of dicamba providing at least 74% more control of horseweed (Table 4.6).

In 2018 SEPAC horseweed densities were influenced by cover crop (P<0.0001), while in 2019 both cover crop and herbicide strategy were significant (*P* =0.0287 and *P*<0.0001, respectively). In both years cover crops containing cereal rye had 75% less horseweed compared to crimson clover. In 2019 utilizing a residual herbicide gave 92 and 97% more horseweed control compared to a glyphosate plus dicamba or glyphosate alone herbicide strategy, respectively.

Wallace et al. (2019) previously observed that cover crops containing cereal rye provided suppression of horseweed and reduced horseweed size prior to being exposed to an herbicide application. In this research cereal rye suppression of horseweed was variable across site-years. At TPAC in 2018, horseweed densities were similar except for the crimson clover terminated with glyphosate only resulting in 81% higher horseweed densities. In 2018 DPAC had 94% less horseweed in cereal rye and the mix terminated after soybean planting compared to crimson clover (Table 4.6). Similar variability in horseweed control occurred in a winter wheat cover crop compared to fall and spring residual herbicide programs in Indiana with differences occurring over two years (Davis et al. 2007). The differences were due to the variability in cover crop due to environmental conditions which resulted in cover crops providing similar control to a spring residual herbicide in 2004 and being less effective than a spring residual in 2005 (Davis et al. 2007).

This study provides evidence that the addition of dicamba and a residual herbicide to glyphosate at the time of cover crop termination will improve horseweed control by at least 69% at all site-years compared to glyphosate alone prior to dicamba-resistant soybeans. Cover crops containing cereal rye reduced horseweed densities by 94 to 97% compared to crimson clover when terminated after soybean planting at DPAC in 2018. Pittman et al. (2019) reported that treatments with cereal rye and legume monocultures provided similar horseweed suppression in late March in Virginia. In this study crimson clover did not provide similar horseweed control at all locations due to lower biomass and data collection occurring later in the growing season. However, cover crop interactions with termination time and herbicide strategy occurred at two of five site years.

At both site-years where an interaction with cover crop occurred it was either due to high horseweed densities in the glyphosate only terminated crimson clover or the crimson clover terminated after soybean planting. Treatments with cereal rye were always similar to the treatment with the lowest horseweed density. In dicamba label-mandated buffer areas the best results were in cereal rye or mix terminated at planting to optimize horseweed suppression and limit any reductions in soybean yield. Additionally, contrasts ran in the cereal rye cover crop between a glyphosate only herbicide strategy versus a glyphosate plus dicamba herbicide strategy showed that the two herbicide strategies provided similar horseweed suppression at four of five site-years at 0.05 level of significance. Cereal rye was beneficial for horseweed suppression to replace dicamba use in buffer areas at four of five site-years evaluated. Horseweed densities were reduced by using a cover crop containing cereal rye, delaying termination of the cover crop, and using a herbicide strategy with glyphosate in combination with dicamba and a residual herbicide compared to terminating a crimson clover cover crop early with glyphosate alone. Delaying termination of cover crops was not as effective at reducing horseweed densities compared to selecting the appropriate cover crop species and herbicide strategies.

4.4.3 Grass Densities Prior to Blanket POST

Grass densities were evaluated at all 6 site years and tended to be lower when termination timing was later and when using the mix cover crop. The after-planting termination timing resulted in a 29% reduction in grass compared to the before soybean planting termination timing (Table 4.7) The mix cover crop resulted in at least a 67% reduction in grass densities compared to crimson clover at three out of six site-years. Grass densities at SEPAC and DPAC in 2018 were affected by an interaction of cover crop by termination timing (P =0.0291 and P =0.0105, respectively). Interactions occurred due to the before planting terminations of all cover crops tending to not reduce grass densities, and the crimson clover terminated at soybean planting not reducing grass densities. However, cereal rye and the mix terminated at or after soybean planting generally resulted in the lowest grass densities. Cereal rye and the mix terminated after soybean planting resulted in 0 grass being present prior to the application of a POST, while a grass density of 90 plants m^{-2} occurred in early terminated crimson clover treatments (Table 4.7).

In 2019 all sites were affected by termination timing, with the after-planting termination providing at least 73% more grass control than the earliest termination, similar to what occurred in 2018 at the TPAC location. The SEPAC and DPAC locations were both affected by herbicide strategy in 2019 (P = 0.0004 and P =0.0029, respectively). The addition of dicamba and a residual herbicide to glyphosate lowered grass densities by at least 53% at both sites compared to the glyphosate alone herbicide strategy (Table 4.7).

Cereal cover crop residue can reduce grass densities 83% compared to residue free treatments prior to cotton (Vasilakoglou et al. 2006). We report that delaying termination timing of cover crops can provide at least 29 to 73% more grass control than terminating before planting. However, delaying termination timing was not as effective as herbicide strategies with glyphosate in combination with dicamba and a residual herbicide. The addition of a residual herbicide in combination with dicamba and glyphosate can provide up to 53% more control of grass weeds than glyphosate alone, observed at three out of six site-years. Within dicamba label-mandated buffer areas terminating cover crops at soybean planting that utilize cereal rye would be the most effective strategy for suppression grass weeds, while maintaining soybean grain yield. Additionally, contrasts were conducted to compare the glyphosate only herbicide strategy to the glyphosate plus dicamba herbicide strategy within the cereal rye cover crop. Similar grass suppression occurred at all site-years between the two herbicide strategies at a 0.05 level of significance. A cereal rye cover crop terminated with glyphosate alone provided similar weed suppression as a glyphosate plus dicamba herbicide strategy within label-mandated buffer areas where dicamba use is not permitted.

4.4.4 Giant Ragweed Densities Prior to Blanket POST at TPAC

Giant ragweed was evaluated at two of the six site-years. In 2018, the addition of a residual herbicide increased giant ragweed control by 50% compared to the glyphosate plus dicamba herbicide strategy (Table 4.8, $P<0.0001$). A herbicide strategy by termination timing interaction in 2019 was due to high densities of giant ragweed occurring at the before planting termination timing in all cover crops and at the at planting timing for cereal rye and crimson clover. The cover crop mix terminated at planting and all cover crops terminated at the latest timing had 61% lower densities than any of the early terminated cover crops (Table 4.8). The addition of dicamba to glyphosate at the after-soybean planting termination resulted in at least a 36% reduction in giant ragweed compared to using glyphosate alone (Table 4.8).

The effects of cover crops on giant ragweed has not been studied extensively. Cereal rye was reported to reduce giant ragweed biomass at one site-year in Minnesota; however, the density of giant ragweed was not reduced (Bruin et al. 2005). We did not report any suppression of giant ragweed densities by the cover crops used in this study, and cover crops would not be useful within dicamba label-mandated buffer areas for suppression of giant ragweed. Giant ragweed densities were reduced by 61 to 87% with a delayed termination timing to at or after soybean planting, and using a residual herbicide in combination with dicamba, and glyphosate for the cereal rye and mix, and glyphosate plus dicamba for the mix at planting in one of two site-years.

4.4.5 Waterhemp Densities and Biomass Prior to Blanket POST

Waterhemp was evaluated at three of the six site-years. Delaying termination to after soybean planting reduced waterhemp densities by at least 43% compared to other termination times at DPAC; however, an interaction with herbicide strategy did occur (Table 4.9). Interactions occurred due to termination with glyphosate at the two earliest termination timings and the glyphosate plus dicamba at the earliest termination having high waterhemp densities. Terminating with a herbicide strategy that contained glyphosate plus dicamba in addition to a residual herbicide reduced waterhemp densities by at least 89% both years at DPAC. Crimson clover had 67% higher waterhemp densities compared with the cereal rye and the mix at DPAC in 2018 (Table 4.9, $P<0.0001$).

Waterhemp densities at SEPAC were influenced by a herbicide strategy by cover crop by termination time interaction ($P = 0.0085$). This interaction occurred due to cereal rye terminated before soybean planting with only glyphosate having 97% more waterhemp than cereal rye terminated after planting with glyphosate in combination with dicamba and a residual herbicide (Table 4.9). Utilizing a glyphosate plus dicamba plus a residual herbicide reduced waterhemp densities by 60 and 69%, respectively, compared to the glyphosate plus dicamba or glyphosate alone.

Rye cover crops have also been evaluated prior to glyphosate- and glufosinate-resistant soybeans with appropriate herbicides. Rye reduced Palmer amaranth densities by 50% compared to other cover crops or, a non-treated, in the absence of herbicides (Loux et al. 2017). We report similar results in that cover crops with higher biomass reduced waterhemp densities, and the use of a residual herbicide resulted in lower densities in all three site-years. However, we report that in dicamba-resistant soybeans the use of a residual herbicide in cover crops provides 60% more control of waterhemp then using an herbicide strategy of glyphosate plus dicamba or glyphosate alone. Mirsky et al. (2011) observed that total weed densities can be reduced by as much as 33% when delaying termination of cover crops in the spring in Pennsylvania. Using a cover crop with dicamba-resistant soybean technology and when terminated with glyphosate in combination with dicamba and a residual herbicide improved waterhemp control by 69% compared to early terminations with glyphosate alone. The use of a herbicide strategy with glyphosate in combination with dicamba and a residual herbicide increased waterhemp suppression by 78% at the two earlier timings terminated with glyphosate alone both years at DPAC. In dicamba label-mandated buffer areas using a cover crop that utilizes cereal rye and terminating at soybean planting would be the best option for waterhemp suppression while mitigating any yield reductions. Contrasts were conducted to compare waterhemp suppression when terminating cereal rye with glyphosate compared with glyphosate plus dicamba. Similar suppression only occurred at one of the three site-years evaluated at a 0.05 level of significance, and a glyphosate only herbicide strategy was never similar to glyphosate in combination with dicamba and a residual herbicide. Cereal rye will only sometimes provide similar waterhemp suppression within label-mandated areas were dicamba use is not permitted.

4.4.6 Soybean Yield

Soybean yields in 2018 were reduced all site-years when termination was delayed. However, in 2019 yield reductions were not observed. Two-way interactions of cover crop by termination timing occurred at DPAC in 2018 (P =0.0051). Soybean yield tended to be lower when cereal rye or the mix were terminated at or after soybean planting. The mix terminated at or after soybean planting and cereal rye terminated after soybean planting resulted in yield reductions of 18 to 24% compared to the cereal rye terminated at planting (Table 4.10).

In 2018 soybean yield at DPAC was influenced by an interaction of cover crop by herbicide strategy (P =0.0224). The highest yielding treatment was the cereal rye terminated with glyphosate in combination with dicamba and a residual herbicide. The treatments that differed from the highest yielding treatment were at least 17% lower and included the mix terminated with glyphosate plus dicamba, the mix terminated with glyphosate in combination with dicamba and a residual herbicide and cereal rye terminated with glyphosate alone (Table 4.10).

In 2018 the SEPAC location was affected by termination timing (P<0.0001). As termination timing was delayed from before soybean planting to at, or after, soybean planting 18 and 31% reductions in soybean yield, respectively, occurred.

Termination timing is becoming more relevant as producers are increasingly terminating cover crops after planting to obtain more cover crop biomass (CTIC 2017). Ruffo et al. (2004) reported that when cereal rye was terminated prior to soybeans in Illinois reduction in yield were not observed, similar to our results in 2018. However, in a different study in Illinois reductions of up to 31% have been observed in cereal rye terminated at soybean planting compared to conventional treatments, which is similar to what was observed at TPAC in 2018 (Liebl et al. 1992). Nutrient analysis was conducted on cover crop biomass in 2019 due to yield reductions in 2018. As termination of cover crops was delayed past planting carbon and nitrogen increased by at least 40 and 68% respectively at the TPAC location (data not shown). Delayed termination of cover crops has potential to cause nutrient deficits for the cash crop. We report that negative impacts on yield can occur if cover crops are terminated after soybean planting, which has rarely been documented. Although using cereal rye and delaying termination would be beneficial from a weed management standpoint within buffer areas for grasses horseweed and waterhemp, it may have negative impacts on soybean yield in some years by reducing soybean yield as much as 31% compared to early termination times.

The use of cover crops within dicamba label-mandated buffer areas would allow for small scale use by farm operators who have not previously used cover crops. The use of a cereal rye or mix terminated at, or after soybean planting generally resulted in reduced weed densities for horseweed with cereal rye or mix providing 75% more control compared to crimson clover at two of four site-years. Grass densities were reduced by at least 29% at all site-years, and waterhemp by 87% when terminating at or after planting with cereal rye or the mix compared to earlier terminated crimson clover or mix at one of three site-years. However, reductions in soybean yield ranging from 10 to 31% did occur at three of six site-years due to delaying termination timing. If cover crops are implemented outside of buffer areas a cereal rye or mix cover crop terminated at soybean planting with a residual herbicide would be the most effective at suppressing most weed species and optimizing soybean yields. Giant ragweed densities were never reduced by the use of cover crop; however, delayed termination timing was beneficial in one of two site years when implemented with a herbicide strategy. Additionally, when herbicide strategies with dicamba and a residual were delayed to after soybean planting giant ragweed densities were reduced by at least 79% compared to any herbicide strategies used before soybean planting. Residual herbicides should always be implemented to reduce the number of individual weeds that are exposed to POST applications of glyphosate and dicamba. As herbicide-resistance issues continue to rise globally farm operators will need to implement additional integrated weed management strategies to prevent reductions in cash-crop yields. Integrated weed management strategies like cover crops will also allow for a more sustainable use of dicamba-resistant soybean technology.

4.5 Literature Cited

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Table 4.1: Date of cover crop planting, termination times, planting, POST application, and harvest at all three of the trial locations.[a,b]

	TPAC		SEPAC		DPAC	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Cover Crop Planted	9/26/2017	10/03/2018	9/22/2017	10/3&18/2018[c]	10/27/2017	10/22/2018
BP Termination	4/26/2018	4/23/2019	4/30/2018	5/8/2019	5/5/2018	5/6/2019
Planting	5/10/2018	6/3/2019	5/14/2018	6/4/2019	5/17/2018	6/7/2019
AP Termination	5/23/2018	6/11/2019	5/29/2018	6/12/2019	6/2/2018	6/21/2019
Blanket POST Application	6/16/2018	6/26/2019	6/5/2018	7/09/2019	6/14/2018	7/13/2019
Harvest	10/24/2018	10/14/2019	10/25/2018	11/25/2019	10/22/2018	11/05/2019

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), BP=Before Planting; and AP=After Planting.
[b]The before planting termination was much longer than originally intended due to adverse weather condition in the spring of 2019 causing an extended delay in planting time.
[c]Cereal rye at SEPAC in 2019 was reseeded due to poor emergence resulting in two cover crop planting dates.

Table 4.2: Herbicides used and rates which were applied for the three cover crop termination timings & the blanket POST application.[a,b,c]

Site & timing	Active ingredient	Rate (kg ha^{-1})	Formulation	Manufacturer	Address
Used at all sites for termination	Dicamba	0.57	Xtendimax®	Bayer	Leverkusen, Germany
Used at all sites for termination & blanket POST	Glyphosate	1.28	Roundup Powermax®	Bayer	Leverkusen, Germany
All TPAC terminations, and blanket POST at SEPAC & TPAC	Cloransulam-methyl	0.009/0.027/0.044 [a]	FirstRate®	Corteva	Zionsville, IN
Residual at DPAC BP and ATP	Sulfentrazone + imazethapyr	0.32 + 0.065	Authority® Assist	FMC	Market Street, PA
Residual at SEPAC BP and ATP	Flumioxazin + chlorimuron-ethyl	0.085 + 0.029	Valor® XLT	Valent	Walnut Creek, CA
Residual at DPAC & SEPAC AFP	Acetochlor	1.49	Warrant®	Bayer	Leverkusen, Germany
Blanket POST at DPAC	Fomesafen	0.2	Flexstar®	Syngenta	Greensboro, NC
Blanket POST at SEPAC (2019 only)	Glyphosate + fomesafen	1.13 + 0.24	Flexstar GT 3.5®	Syngenta	Greensboro, NC

[a] Three different rates of cloransulam-methyl were used in this experiment. The 0.044 kg ha^{-1} was used at the two earliest terminations at TPAC, the 0.027 kg ha^{-1} rate was used as the blanket POST application at SEPAC, and the 0.009 kg ha^{-1} rate was used at the late termination timing & the blanket POST applications at TPAC. This was done in order to follow maximum use rates determined from the label.

[b] Fomesafen was added to the blanket POST application in 2019 at the SEPAC location due to waterhemp being much more prevalent than the previous year.

[c]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), BP=Before Planting, ATP=At Planting, and AFP=After Planting.

Table 4.3: Key weed species at each of the trial locations that were collected for biomass and recorded for density.[a,b,c]

TPAC	SEPAC	DPAC
Grasses[b]	Grasses	Grasses
Morningglory (*Iopomea spp*.)	Morningglory	Morningglory
Horseweed (*Erigeron canadensis L*.)	Horseweed	Horseweed
Giant ragweed (*Ambrosia trifida L*.)	Common ragweed (*Ambrosia artemisiifolia L*.)	Waterhemp
Common lambsquarters (*Chenopodium album L*.)	Common cocklebur (*Xanthium stumarium L.*)	
Velvetleaf (*Abutilon theophrasti Medik*.)	Waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer), 2019 only]	

[a]Abbreviations: TPAC= TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340).

[b]Grass species and approximate composition at the two sites; TPAC: large crabgrass (*Digitaria sanguinalis (L.)* (2%), smooth crabgrass (*Digitaria ischaemum (Schreb.) Schreb. ex Muhl*.) (3%), fall panicum (*Panicum dichotomiflorum Michx.)* (15%), barnyardgrass (*Echinochloa crus*-galli (L.) P. Beauv) (17%), and foxtail species (*Setaria spp.*) (67%), SEPAC: barnyardgrass (2%), large crabgrass (2%), annual bluegrass (*Poa annua L.*) (8%), fall panicum (34%), and foxtail species (54%), DPAC: smooth crabgrass (1%), large crabgrass (4%), foxtail species (18%), barnyardgrass (32%), and fall panicum (45%).

[c]Waterhemp was added at the SEPAC location in 2019 because the trial was moved to an area where waterhemp was more prevalent.

Table 4.4: Influence of cover crop and termination timing on cover crop biomass prior to termination in the spring at three sites in Indiana in 2018 and 2019.[a,b,c]

Site	Year	Cover Crop	Termination timing			
			BP	ATP	AFP	Pooled
			kg ha^{-1}			
TPAC	2018	Crimson clover	1476	1870	2619	1988 b
		Cereal rye	3709	4921	6685	5105 a
		Mix	3208	7313	9127	6549 a
		Pooled	2798 b	4701 a	6144 a	
	2019	Crimson clover	0 c	0 c	0 c	0 b
		Cereal rye	2091 b	5063 a	8893 a	5349 a
		Mix	1412 b	5451 a	5407 a	4090 a
		Pooled	1168 b	3505 b	4766 b	
SEPAC	2018	Crimson clover	1068 b	4338 a	4051 a	3152 b
		Cereal rye	4355 a	6832 a	8023 a	6403 a
		Mix	3658 a	6126 a	7298 a	5694 a
		Pooled	3027 b	5766 a	6458 a	
	2019	Crimson clover	10	0	0	3 b
		Cereal rye	2714	5819	6086	4873 a
		Mix	4033	8144	7434	6537 a
		Pooled	2252 b	4654 a	4517 a	
DPAC	2018	Crimson clover	40 e	257 d	580 c	292 b
		Cereal rye	1067 bc	2763 a-c	4285 a	2705 a
		Mix	1125 a-c	6481 ab	3593 ab	3733 a
		Pooled	744 c	3167 b	2819 a	

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), BP=Before Planting, ATP=At Planting, AFP=After Planting.

[b]Data were log-transformed before analysis, however untransformed mean values are presented based on the interpretation of the transformed data.

[c]Means followed by the same letter within each site-year and pooled data are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

Table 4.5: Influence of cover crop and termination timing on weed biomass prior to cover crop termination in the spring at three sites in Indiana in 2018 and 2019.[a,b,c,d,e]

Site	Year	Cover crop	Termination timing			
			BP	ATP	AFP	Pooled
			kg ha^{-1}			
TPAC	2018	Crimson clover	369	-[e]	157	263 a
		Cereal rye	24	-	19	22 b
		Mix	83	-	14	49 b
		Pooled	159 a	-	63 b	
	2019	Crimson clover	112 cd	848 ab	1034 a	665
		Cereal rye	29 cd	166 bc	111 cd	102
		Mix	21 d	93 cd	317 bc	144
		Pooled	54 b	369 a	487 a	
SEPAC	2018	Crimson clover	396	509	100	335 a
		Cereal rye	154	138	9	100 b
		Mix	103	175	33	104 b
		Pooled	217 a	274 a	47 b	
	2019	Crimson clover	549	670	450	556 a
		Cereal rye	69	11	32	37 b
		Mix	47	21	20	29 b
		Pooled	222	234	168	
DPAC	2018	Crimson clover	37 b-d	177 ab	541 a	252 a
		Cereal rye	17 d	54 b-d	53 cd	41 b
		Mix	123 a-d	247 a-c	81 a-d	150 a
		Pooled	59 b	159 a	255 a	

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC=South East Purdue Agricultural Center (4425 County Rd 350 N Butlerville, IN 47223), DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), BP= Before Planting, ATP=At Planting, and AFP= After Planting.
[b]Data were log-transformed before analysis, however untransformed mean values are presented based on the interpretation of the transformed data.
[c]Means followed by the same letter within site-year and pooled data are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.
[d]Weeds that made up more than approximately 5% of the density combined for biomass measurements included: TPAC: chickweed (*Stellaria media* (L.) Vill.)
(52%), and henbit (*Lamium amplexicuale* L.) (18%), giant ragweed (21%), SEPAC: buttercup (*Ranaunculaceae arvensis* L.) (6%), (chickweed (7%), bittercrest (*Cardamine hirsuta*) (7%), foxtail spp. (10%), horseweed (11%), field speedwell (*Veronica agrestis* L.) (17%), and annual bluegrass (Poa annua L.) (20%),.and DPAC: chickweed (6%), fall panicum (6%), field speedwell (*Veronica agrestis* L.) (16%), foxtail spp. (18%), horseweed (19%), and waterhemp (26%).
[e]Weed biomass missing data for the ATP timing at TPAC in 2018.

Table 4.6: Influence of cover crop, termination timing, and herbicide strategy on early-summer horseweed density prior to a POST application at three sites in Indiana in 2018 and 2019.a,b,c

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
				Plants m^{-2}			
TPAC	2018	Gly	Crimson clover	0.50	2.63	0.75	1.29 a
			Cereal rye	0.50	0.25	0.00	0.25 b
			Mix	0.38	0.13	0.25	0.25 b
		Gly + dicamba	Crimson clover	0.13	0.38	0.13	0.21 b
			Cereal rye	0.00	0.00	0.25	0.08 b
			Mix	0.25	0.00	0.00	0.08 b
		Gly + dicamba + residual	Crimson clover	0.00	0.13	0.25	0.13 b
			Cereal rye	0.00	0.25	0.13	0.13 b
			Mix	0.25	0.00	0.00	0.08 b
		Pooled	Crimson clover	0.21	1.04	0.38	0.54
			Cereal rye	0.50	0.17	0.13	0.15
			Mix	0.29	0.04	0.08	0.14
		Gly	Pooled	0.46	1.00	0.33	0.60 a
		Gly + dicamba		0.13	0.13	0.13	0.13 b
		Gly + dicamba + residual		0.08	0.13	0.13	0.11 b
		Pooled	Pooled	0.22	0.42	0.19	
SEPAC	2018	Gly	Crimson clover	29	42	19	30
			Cereal rye	4	4	3	4
			Mix	2	1	1	1
		Gly + dicamba	Crimson clover	5	3	9	6
			Cereal rye	0	1	1	1
			Mix	0	0	1	0
		Gly + dicamba + residual	Crimson clover	0	5	20	8
			Cereal rye	0	1	1	1
			Mix	0	0	1	0
		Pooled	Crimson clover	11	17	16	15 a
			Cereal rye	4	2	2	2 b
			Mix	1	0	1	1 b
		Gly	Pooled	12 a	16 ab	8 a-c	12 a
		Gly + dicamba		2 cd	1 b-d	4 a-d	2 b
		Gly + dicamba + residual		0 d	2 b-d	7 a-c	3 b
		Pooled	Pooled	4	6	6	

Table 4.6 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
SEPAC	2019	Gly	Crimson clover	66	132	36	73
			Cereal rye	21	21	8	17
			Mix	5	13	9	9
		Gly + dicamba	Crimson clover	36	2	18	22
			Cereal rye	8	11	0	6
			Mix	19	11	3	11
		Gly + dicamba + residual	Crimson clover	5	1	6	4
			Cereal rye	1	0	0	0
			Mix	0	0	0	0
		Pooled	Crimson clover	36	45	20	32 a
			Cereal rye	21	10	3	8 b
			Mix	8	8	4	6 b
		Gly	Pooled	31	48	18	32 a
		Gly + dicamba		21	9	7	12 b
		Gly + dicamba + residual		2	0	2	1 c
		Pooled	Pooled	18	19	9	
DPAC	2018	Gly	Crimson clover	14	57	55	42 a
			Cereal rye	1	1	2	1 b
			Mix	3	14	3	6 b
		Gly + dicamba	Crimson clover	0	0	21	7 b
			Cereal rye	0	0	0	0 b
			Mix	0	2	4	2 b
		Gly + dicamba + residual	Crimson clover	0	0	32	11 b
			Cereal rye	0	0	0	0 b
			Mix	1	1	1	1 b
		Pooled	Crimson clover	5 b	19 b	36 a	20 a
			Cereal rye	1 b	0 b	1 b	0 b
			Mix	1 b	5 ab	2 b	3 ab
		Gly	Pooled	5	24	20	16 a
		Gly + dicamba		0	1	8	3 b
		Gly + dicamba + residual		0	0	11	4 b
		Pooled	Pooled	2 b	8 ab	13 a	

Table 4.6 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
DPAC	2019	Gly	Pooled	34	27	22	27 a
		Gly + dicamba		1	10	10	7 b
		Gly + dicamba + residual		1	4	4	3 b
		Pooled	Pooled	12	14	12	

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), Gly=Glyphosate, BP= Before Planting, ATP=At Planting, and AFP= After Planting.
[b]Data were log-transformed before analysis, however untransformed mean values are presented based on the interpretation of the transformed data.
[c]Means followed by the same letter within site-year and pooled data are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

Table 4.7: Influence of cover crop, termination timing, and herbicide strategy on grass density in early-summer at three sites in Indiana prior to a POST application in 2018 and 2019.a,b,c,d

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
				Plants m^{-2}			
TPAC	2018	Gly	Crimson clover	15	11	8	11
			Cereal rye	14	37	58	36
			Mix	5	0	14	6
		Gly + dicamba	Crimson clover	46	8	8	21
			Cereal rye	17	80	3	33
			Mix	10	3	0	4
		Gly + dicamba + residual	Crimson clover	4	13	0	6
			Cereal rye	10	5	2	6
			Mix	6	2	0	3
		Pooled	Crimson clover	21	11	5	12 a
			Cereal rye	14	41	21	25 a
			Mix	7	2	5	4 b
		Gly	Pooled	11	16	27	18 a
		Gly + dicamba		24	30	4	19 ab
		Gly + dicamba + residual		7	7	1	5 b
		Pooled	Pooled	14 a	18 ab	10 b	
TPAC	2019	Gly	Crimson clover	32	31	7	23
			Cereal rye	40	24	7	24
			Mix	42	30	17	29
		Gly + dicamba	Crimson clover	28	21	4	17
			Cereal rye	48	9	2	20
			Mix	29	9	8	15
		Gly + dicamba + residual	Crimson clover	41	5	10	19
			Cereal rye	57	3	7	22
			Mix	23	3	17	14
		Pooled	Crimson clover	33	19	7	20
			Cereal rye	40	12	5	22
			Mix	31	14	14	20
		Gly	Pooled	38 a	28 a-c	10 b-d	25
		Gly + dicamba		35 ab	13 a-d	4 cd	17
		Gly + dicamba + residual		40 ab	4 d	11 a-d	18
		Pooled	Pooled	38 a	15 b	9 b	

Table 4.7 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
SEPAC	2018	Gly	Crimson clover	126	20	15	54
			Cereal rye	84	10	0	31
			Mix	28	1	0	10
		Gly + dicamba	Crimson clover	97	10	0	36
			Cereal rye	72	8	0	27
			Mix	15	0	0	5
		Gly + dicamba + residual	Crimson clover	50	4	0	18
			Cereal rye	26	18	0	15
			Mix	14	0	0	5
		Pooled	Crimson clover	91 a	11 c	5 c	36 a
			Cereal rye	84 ab	12 c	0 c	24 a
			Mix	19 bc	0 c	0 c	6 b
		Gly	Pooled	79	10	5	32 a
		Gly + dicamba		61	6	0	22 ab
		Gly + dicamba + residual		30	7	0	12 b
		Pooled	Pooled	57 a	8 b	2 c	
SEPAC	2019	Gly	Crimson clover	59	5	3	24
			Cereal rye	52	27	14	31
			Mix	67	44	13	41
		Gly + dicamba	Crimson clover	56	12	7	28
			Cereal rye	37	17	15	23
			Mix	59	33	14	35
		Gly + dicamba + residual	Crimson clover	19	10	4	11
			Cereal rye	17	13	7	12
			Mix	44	14	8	22
		Pooled	Crimson clover	45	9	5	20
			Cereal rye	52	19	12	22
			Mix	57	30	11	33
		Gly	Pooled	59	27	10	32 a
		Gly + dicamba		51	22	12	29 a
		Gly + dicamba + residual		27	12	6	15 b
		Pooled	Pooled	46 a	20 b	9 c	

Table 4.7 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
DPAC	2018	Gly	Crimson clover	146	65	0	70
			Cereal rye	19	10	0	9
			Mix	10	1	0	3
		Gly + dicamba	Crimson clover	70	31	2	34
			Cereal rye	26	2	0	6
			Mix	5	1	0	2
		Gly + dicamba + residual	Crimson clover	55	13	8	25
			Cereal rye	12	1	0	4
			Mix	8	0	0	3
		Pooled	Crimson clover	90 a	36 ab	3 de	43 a
			Cereal rye	15 bc	4 c-e	0 e	6 b
			Mix	7 cd	1 e	0 e	3 b
		Gly	Pooled	50	25	0	26
		Gly + dicamba		35	11	1	13
		Gly + dicamba + residual		25	5	3	11
		Pooled	Pooled	37 a	14 b	1 c	
DPAC	2019	Gly	Pooled	40	89	16	48 a
		Gly + dicamba		27	18	2	16 b
		Gly + dicamba + residual		33	11	8	17 b
		Pooled	Pooled	33 a	39 a	9 b	

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), Gly=Glyphosate, BP= Before Planting, ATP=At Planting, and AFP= After Planting.
[b]Data were log-transformed before analysis, however untransformed mean values are presented based on the interpretation of the transformed data.
[c]Means followed by the same letter within site-year and pooled data are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.
[d] Grass species and approximate composition at the three sites; TPAC: large crabgrass (2%), smooth crabgrass (3%), fall panicum (15%), barnyardgrass (17%), and foxtail species (67%), SEPAC: barnyardgrass (2%), large crabgrass (2%), annual bluegrass (8%), fall panicum (34%), and foxtail species (54%), DPAC: smooth crabgrass (1%), large crabgrass (4%), foxtail species (18%), barnyardgrass (32%), and fall panicum (45%).

Table 4.8: Influence of the interaction between cover crop and termination timing on early-summer giant ragweed density prior to a POST application at the Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) in 2019.[a,b,c]

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
				Plants m^{-2}			
TPAC	2018	Gly	Crimson clover	69	54	56	60
			Cereal rye	20	11	60	30
			Mix	49	19	14	27
		Gly + dicamba	Crimson clover	23	18	4	15
			Cereal rye	17	88	10	38
			Mix	10	37	7	18
		Gly + dicamba + residual	Crimson clover	23	5	6	11
			Cereal rye	13	10	3	9
			Mix	8	43	1	17
		Pooled	Crimson clover	38	25	22	29
			Cereal rye	20	37	24	26
			Mix	22	33	8	21
		Gly	Pooled	46	28	43	39 a
		Gly + dicamba		16	48	7	24 a
		Gly + dicamba + residual		15	19	3	12 b
		Pooled	Pooled	26	32	18	
TPAC	2019	Gly	Crimson clover	251	113	110	158
			Cereal rye	260	96	47	134
			Mix	136	193	59	129
		Gly + dicamba	Crimson clover	203	130	32	121
			Cereal rye	274	65	13	117
			Mix	149	115	36	100
		Gly + dicamba + residual	Crimson clover	240	117	66	141
			Cereal rye	182	42	23	82
			Mix	235	83	49	122
		Pooled	Crimson clover	231	120	69	140
			Cereal rye	260	68	28	111
			Mix	173	130	48	117
		Gly	Pooled	216 a	134 ab	72 bc	140 a
		Gly + dicamba		208 a	103 ab	27 d	113 b
		Gly + dicamba + residual		219 a	81 bc	46 cd	115 b
		Pooled	Pooled	214 a	106 b	48 c	

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and [a]Abbreviations:Gly=Glyphosate, BP=Before Planting, ATP=At Planting, and AFP= After Planting.
[b]Data were log-transformed before analysis, however untransformed mean values are presented based on the interpretation of the transformed data.
[c]Means followed by the same letter with site-year and pooled data are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

Table 4.9: Influence of interaction between herbicide strategy, termination time, and cover crop on early-summer waterhemp densities prior to a POST application at two locations in Indiana in 2018 and 2019.[a,b,c,d]

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
				Plants m^{-2}			
SEPAC	2019	Gly	Crimson clover	562 ab	480 ab	459 ab	502
			Cereal rye	915 a	439 ab	438 ab	597
			Mix	474 ab	181 ab	361 ab	339
		Gly + dicamba	Crimson clover	328 ab	206 ab	291 ab	289
			Cereal rye	429 ab	386 ab	396 ab	404
			Mix	334 ab	371 ab	489 ab	398
		Gly + dicamba + residual	Crimson clover	109 ab	189 ab	197 ab	165
			Cereal rye	202 ab	232 ab	29 b	154
			Mix	147 ab	189 ab	43 ab	126
		Pooled	Crimson clover	333 ab	290 ab	316 ab	315
			Cereal rye	915 a	352 a	287 b	385
			Mix	318 ab	247 ab	298 ab	288
		Gly	Pooled	650 a	356 a	419 ab	479 a
		Gly + dicamba		364 ab	344 ab	392 ab	368 b
		Gly + dicamba + residual		153 b	203 ab	89 c	148 c
		Pooled	Pooled	389 a	297 a	300 a	
DPAC	2018	Gly	Crimson clover	291	279	2	191
			Cereal rye	28	11	1	13
			Mix	82	8	0	30
		Gly + dicamba	Crimson clover	92	36	8	45
			Cereal rye	27	5	0	11
			Mix	51	7	0	19
		Gly + dicamba + residual	Crimson clover	32	13	9	18
			Cereal rye	8	2	0	3
			Mix	8	2	0	3
		Pooled	Crimson clover	138 a	109 a	6 b	85 a
			Cereal rye	26 ab	6 b-d	0 cd	11 b
			Mix	47 a	6 bc	0 d	28 b
		Gly	Pooled	123 a	99 bc	1 e	77 a
		Gly + dicamba		63 ab	16 cd	3 e	27 a
		Gly + dicamba + residual		16 cd	6 de	3 e	8 b
		Pooled	Pooled	70 a	40 b	2 c	

Table 4.9 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
DPAC	2019	Gly	Pooled	308 ab	116 a-c	56 b-c	160 a
		Gly + dicamba		673 a	50 b-d	6 de	243 a
		Gly + dicamba + residual		67 cd	4 e	1e	24 b
		Pooled	Pooled	349 a	56 b	21 b	

[a]Abbreviations: SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), Gly=Glyphosate, BP=Before Planting, ATP=At Planting, and AFP=After Planting.

[b]Data were log-transformed before analysis, however untransformed mean values are presented based on the interpretation of the transformed data.

[c]Means followed by the same letter within site-year and pooled data are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

[d]Waterhemp was only evaluated at SEPAC in 2019.

Table 4.10: Influence of cover crop, termination timing, and herbicide strategy on soybean yield at three locations in Indiana in 2018 and 2019.[a,b,c]

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
				kg ha^{-1}			
TPAC	2018	Gly	Crimson clover	4859	4477	4379	4572
			Cereal rye	5049	4807	4274	4710
			Mix	5271	4472	4187	4643
		Gly + dicamba	Crimson clover	4431	4086	4031	4183
			Cereal rye	5093	4743	3564	4467
			Mix	4896	4386	3882	4388
		Gly + dicamba + residual	Crimson clover	4851	4175	4235	4420
			Cereal rye	4831	4465	3628	4308
			Mix	5164	4514	3331	4336
		Pooled	Crimson clover	4713	4246	4215	4391
			Cereal rye	5049	4672	3822	4495
			Mix	5110	4457	3800	4456
		Gly	Pooled	5060	4585	4280	4642 a
		Gly + dicamba		4806	4405	3826	4346 b
		Gly + dicamba + residual		4949	4384	3732	4355 b
		Pooled	Pooled	4938 a	4458 b	3946 c	
TPAC	2019	Gly	Crimson clover	4387 ab	4905 ab	4866 ab	4719
			Cereal rye	4981 ab	5223 a	5321 a	5175
			Mix	4213 ab	4948 ab	5223 a	4795
		Gly + dicamba	Crimson clover	4527 ab	5254 a	4694 ab	4825
			Cereal rye	4948 ab	5272 a	5121 ab	5113
			Mix	4385 ab	5143 a	4483 ab	4670
		Gly + dicamba + residual	Crimson clover	4351 ab	3733 ab	4575 ab	4220
			Cereal rye	4516 ab	5192 a	4996 ab	4901
			Mix	4192 ab	3399 b	4806 ab	4132
		Pooled	Crimson clover	4422	4631	4711	4588 ab
			Cereal rye	4981	5229	5146	5063 a
			Mix	4263	4497	4838	4533 b
		Gly	Pooled	4527 a-c	5025 ab	5137 ab	4896 a
		Gly + dicamba		4620 a-c	5223 a	4766 a-c	4870 a
		Gly + dicamba + residual		4353 bc	4108 c	4792 a-c	4418 b
		Pooled	Pooled	4500	4785	4898	

Table 4.10 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
SEPAC	2018	Gly	Crimson clover	3496	3120	3223	3280
			Cereal rye	3795	3223	2512	3177
			Mix	3788	3193	2606	3196
		Gly + dicamba	Crimson clover	3746	3058	2718	3174
			Cereal rye	4141	2817	2110	3023
			Mix	3616	3381	2675	3224
		Gly + dicamba + residual	Crimson clover	3866	3119	2792	3259
			Cereal rye	4068	3290	2559	3306
			Mix	4452	3317	2774	3514
		Pooled	Crimson clover	3703	3099	2911	3237
			Cereal rye	3795	3110	2394	3168
			Mix	3952	3297	2685	3311
		Gly	Pooled	3693	3179	2780	3217
		Gly + dicamba		3834	3085	2501	3140
		Gly + dicamba + residual		4129	3242	2708	3360
		Pooled	Pooled	3885 a	3169 b	2663 c	
SEPAC	2019	Gly	Crimson clover	2801	2925	2538	2754
			Cereal rye	3368	3103	3569	3347
			Mix	2513	2982	3656	3050
		Gly + dicamba	Crimson clover	2698	2854	2791	2781
			Cereal rye	3805	3260	3567	3544
			Mix	3034	3074	3751	3286
		Gly + dicamba + residual	Crimson clover	3278	2625	2967	2957
			Cereal rye	3503	3449	3528	3493
			Mix	2799	2985	3555	3113
		Pooled	Crimson clover	2926	2801	2765	2831
			Cereal rye	3368	3271	3555	3461
			Mix	2782	3014	3654	3150
		Gly	Pooled	2894	3003	3254	3050
		Gly + dicamba		3179	3063	3370	3204
		Gly + dicamba + residual		3193	3020	3350	3188
		Pooled	Pooled	3089	3028	3325	

Table 4.10 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
DPAC	2018	Gly	Crimson clover	3191	3310	2788	3096 ab
			Cereal rye	2790	2998	2664	2817 b
			Mix	3360	2838	2840	3013 ab
		Gly + dicamba	Crimson clover	3287	2742	23165	3065 ab
			Cereal rye	3094	3308	2860	3102 ab
			Mix	3094	2682	2214	2663 b
		Gly + dicamba + residual	Crimson clover	2840	2992	22859	2897ab
			Cereal rye	3484	3875	2864	3407 a
			Mix	3015	2590	2642	2749 b
		Pooled	Crimson clover	3106 abc	3015 abc	2938 abc	3019
			Cereal rye	3060 abc	3394 a	2796 bc	3083
			Mix	3156 ab	2703 c	2566 c	2808
		Gly	Pooled	3046	3049	2764	2958
		Gly + dicamba		3187	2911	2747	2903
		Gly + dicamba + residual		3113	3152	2788	3018
		Pooled	Pooled	3108	3037	2766	
DPAC	2019	Gly	Pooled	3077	3443	4019	3513
		Gly + dicamba		3519	3662	3535	3572
		Gly + dicamba + residual		3418	3618	3549	3528
		Pooled	Pooled	3338	3575	3701	

[a]Abbreviations: TPAC= Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC=South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), Gly=Glyphosate, BP=Before Planting, ATP=AT Planting, and AFP=After Planting.
[b]Means followed by the same letter within site-year and pooled data are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

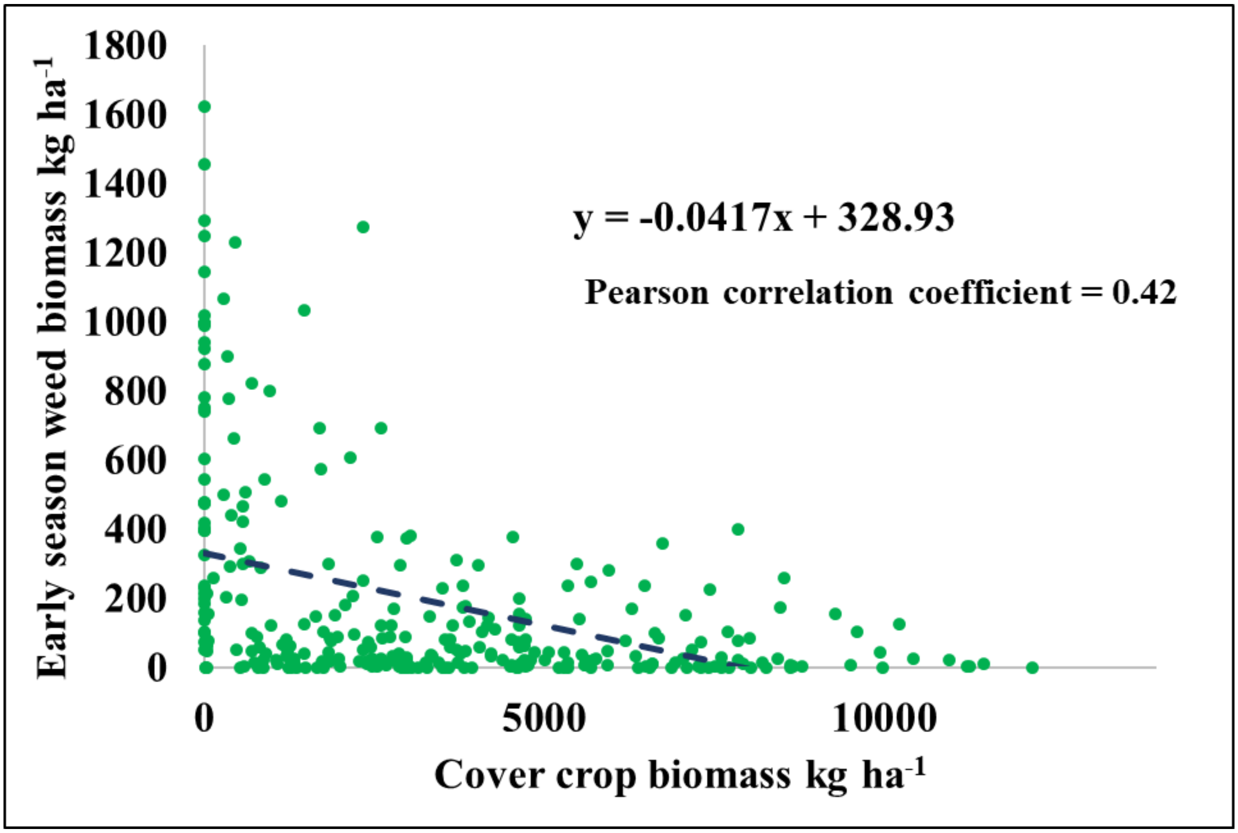

Figure 4.1: Correlation of early season (April and May) weed biomass by cover crop biomass across three sites in Indiana in 2018 and 2019. Sites included the Throckmorton Purdue Agricultural Center (TPAC, 8343 US-231, Lafayette, IN 47909), the South East Purdue Agricultural Center (SEPAC, 4425 County Rd 350 N Butlerville, IN 47223), and the Davis Purdue Agriculture Center (DPAC, 6230 N State Rd 1 Farmland, IN 47340-9340). Pearson correlation coefficient of 0.42 at $P<0.0001$.

CHAPTER 5. UTILIZING CEREAL RYE & CRIMSON CLOVER FOR WEED SUPPRESSION WITHIN BUFFER AREAS OF 2,4-D-RESISTANT SOYBEANS

5.1 Abstract

Cover crops can be utilized to suppress weeds via direct competition for sunlight, water, and soil nutrients. Research was conducted to determine if cover crops can be used in label mandated buffer areas in 2,4-D-reistant soybean (*Glycine max* (L.) Merr.) cropping systems. Delaying termination of cover crops containing cereal rye (*Secale cereal* L.) to at, or after, soybean planting resulted in a 25 to over 200% increase in cover crop biomass compared to crimson clover (*Trifolium incarnatum* L.). However, terminating later had variable impacts on spring weed suppression and did not always result in greater spring weed suppression. Cover crop species were not as important as termination timing and herbicide strategy in reducing weed densities. Cover crops alone or with herbicides only reduced horseweed (*Erigeron Canadensis* L.) densities at two of five site-years. Horseweed densities were reduced by at least 68% at five of six site years when using glyphosate in combination with 2,4-D and a residual herbicide, compared to glyphosate alone. Using cover crops in buffer areas terminated with glyphosate alone did not provide similar horseweed control as an effective 2,4-D application. Cover crops did not reduce giant ragweed densities, but did reduce grass densities at four of six site-years. Delaying the termination of cover crops from before soybean planting to after soybean planting was an effective way to control grasses within and outside of buffer areas. Grass densities were reduced by 54% when cereal rye was terminated at planting compared with early terminated crimson clover. Cereal rye reduced waterhemp (*Amaranthus tuberculatus* (Moq.) J. D. Sauer) densities by 45% at one of three site years. Utilizing glyphosate plus 2,4-D plus a residual herbicide reduced waterhemp densities by at

least 62%. Cereal rye terminated at, or after planting was beneficial within buffer areas for control of waterhemp, grass, and sometime horseweed densities, but not giant ragweed densities. However, yield reductions were observed of 14 to 41% when cover crops termination was delayed to after soybean planting at three of six site-years. Terminating cereal rye at planting provided suppression of grasses and waterhemp within buffer areas and had similar yield to the highest yielding treatment in all but one site-year.

5.2 Introduction

Weeds are the most costly and damaging pest to crops in the United States (Oerke 2006). In recent years weeds that have become resistant to herbicides used extensively in soybean have made management more difficult. Currently the state of Indiana has 18 reported weed biotypes that are resistant to herbicides (Heap 2020). Using an integrated approach to manage weeds will be necessary as resistance issues continue to increase with problematic weeds such as waterhemp now having resistance to five site-of-action groups (Evans et al. 2019). The failure of herbicides to control these weeds is problematic and has led the agri-chemical industry to develop genetically modified crops that are resistant to herbicides such as glyphosate, glufosinate, isoxaflutole, dicamba, and 2,4-D. 2,4-D-resistant soybeans were commercialized in 2019 and it is anticipated that their acreage will grow rapidly because of high efficacy on glyphosate and acetolactate synthase-resistant broadleaf weed species, commonly found in soybean production.

The addition of 2,4-D to glufosinate has resulted in at least 94% control of both glyphosate-resistant and susceptible waterhemp at heights up to 35 cm, demonstrating the usefulness of these Enlist E3® soybean varieties, which confer resistance to both 2,4-D and glufosinate, from a weed management standpoint (Craigmyle et al. 2013). Glyphosate-resistant and 2,4-D amine tolerant Palmer amaranth was controlled better with glyphosate in combination with 2,4-D choline compared with 2,4-D amine or glyphosate alone which some Palmer amaranth biotypes have tolerance to demonstrating the benefit of Enlist E3® soybeans for Palmer amaranth management (Spaunhorst and Johnson 2017) . Chahal and Johnson (2012) documented that the addition of 2,4-D to glyphosate provided a 65% reduction in glyphosate-resistant horseweed biomass, showing the benefits of using 2,4-D for horseweed control in soybeans. Additionally, Robinson et al. (2012) observed that applications of 2,4-D in combination with glyphosate provided 97% control of several problematic weeds in soybeans including, velvetleaf (*Abutilon theophrasti* Medik), waterhemp (*Amaranthus tuberculatus* (Moq.) J. D. Sauer), giant ragweed, and common lambsquarters (*Chenopodium album* L.).

However, buffer areas, which do not receive applications of 2,4-D, are required for 2,4-D-resistant soybeans. Buffers of 9 m in length between downwind sensitive areas and areas sprayed with 2,4-D are required by the label (Anonymous 2017). Managing glyphosate- and ALS-resistant weeds in these buffer areas where 2,4-D applications are not permitted could be challenging. Cover crops may be a useful method of weed suppression within these buffer areas. Covers crops should be used with appropriate herbicides strategies in order to properly manage weeds within field crops, and specifically soybeans (Loux et al. 2017; Reeves et al. 2005; Yenish et al. 1996). Loux et al. 2017 reported that cover crops without herbicides provided only 14% control of waterhemp compared to 83% control with a PRE followed by POST herbicides program averaged across sites. Reddy (2001) observed that cover crops used with a PRE-only herbicide resulted in lower cash-crop yields compared to a no-cover crop conventional till system. However, when used in tandem with a POST herbicide application to control late emerging weeds, negative impacts on yield were only observed when Italian ryegrass (*Lolium perenne* L. *ssp multiflorum* (Lam.) Husnot) was used as a cover crop. Davis et al. (2007) reported that a winter wheat cover crop provided similar horseweed suppression 4 months after in-crop applications compared to a spring or fall residual herbicide across two years. Christenson (2015) reported that horseweed suppression with winter rye at soybean R1 and R6.5 was similar to all herbicide treatments, however winter wheat and winter barley were not as effective at suppressing horseweed. Cholette et al. (2018) reported that annual ryegrass alone or in combination with crimson clover was the most consistent cover crop out of 17species and mixtures for suppressing horseweed in Ontario. Cholette et al. (2018) reported correlations of cover crop ground cover and biomass were correlated with horseweed density (0.17 and 0.21, respectively) and biomass (0.30 and 40, respectively), however these correlations were weak and the authors suggested that this could be due to the inherent variability when implemented biological weed management practices. Teasdale et al. (1991) also reported a correlation between cover crop biomass and weed density in Maryland of large crabgrass (*Digitaria sanguinalis (L.) Scop)*, goosegrass (*Eleusine indica* (L.), stinkgrass (*Eragrostis cilianensis* (All.) Vignolo ex Janch)., carpetweed (*Mollugo verticillata* L)., and common lambsquarters was correlated with cover crop biomass with an $r^2 = 0.75$ at the 0.01 level.

Weed suppression via cover crops can also reduce the selection pressure applied to problematic weed species by reducing the number of weeds exposed to herbicide applications. An example of this was observed by Palhano et al. (2018) who reported that cover crops in a conventional cotton production system suppressed Palmer amaranth (*Amaranthus palmeri* S. Watson) emergence by 65 to 100% compared to areas without a cover crop. Furthermore, cover crops are included in best management practices to reduce herbicide resistance described by Norsworthy et al. (2012).

Maclaren et al. (2019) showed that cover crop biomass influenced resource uptake and weed biomass. They showed that early-season nitrogen uptake and late-season light interception by high biomass producing cover crops reduced weed biomass, which was composed primarily of *Lolium spp*., but included 35 other species. Furthermore, Maclaren et al. (2019) demonstrated that cereal crops that produce large amounts of biomass quickly were more effective in reducing weed biomass compared to less aggressive legume species. Legumes have also been commonly used as a cover crop due to their ability to fix nitrogen. Although, legume cover crops can fix nitrogen for cash crops their low C:N ratio decompose quickly and often fails to provide weed suppression comparable to cereal crops (Sievers and Cook 2018). Mock et al. (2012) showed that Italian ryegrass increased the number of winter annuals present compared to a non-treated control, demonstrating that cover corps may not always be beneficial for weed control. When implementing cover crops into a production system it is important to manage appropriately as corn yield reductions up to 36% have occurred after a rye cover crop (Johnson et al. 1993). Creech et al. (2008), also observed 11% reductions in corn yield in Indiana when annual ryegrass (*Lolium multilflorum* Lam.) or winter wheat (*Triticum aestivum* L.) cover crops were used compared to other herbicide strategies for winter annual weed control with additional applications of glyphosate were used for in-season weed control in all treatments. Increases in corn yield have been reported when legume species, such as white clover (*Trifolium repens* L.), red clover (*Trifolium pretense* L.), or barrel medic (*Medicago truncatula*) are used as cover crops in corn production. (Hively et al. 2001).

If cover crops are to be grown on a large number of acres they will need to be used in addition to other technologies, such as 2,4-D-resistant soybeans. This research was conducted to determine if cover crops can be used in label-mandated buffer areas in 2,4-D-resistant soybeans, and cover crops can replace 2,4-D for weed control within buffer areas. The effectiveness of three cover crops, terminated at three timings, with three different herbicide strategies were evaluated for their impact on both weed control and soybean yield at three locations in Indiana.

5.3 Materials and Methods

5.3.1 Site Description

Field trials were conducted at three locations in Indiana in 2018 and 2019 to evaluate weed suppression and the impact on yield provided by three cover crops, terminated at three different times, with three different herbicide strategies. Experiments were conducted at the Throckmorton Purdue Agricultural Center (TPAC), near Lafayette, IN (40.29°N, 86.91°W), the South East Purdue Agricultural Center (SEPAC), near Butlerville, IN (39.03°N, 85.53°W), and the Davis Purdue Agricultural Center (DPAC), near Farmland, IN (40.26°N, 85.16°W). The TPAC soil was primarily a Toronto-Millbrook complex that has historically been tilled. The soil at TPAC has an organic matter (OM) of 2.6% with a pH of 6.3 and a cation exchange capacity (CEC) of 10.6 meq 100 g^{-1}. The SEPAC location was predominantly a Cobbsfork silt loam that is poorly drained. The SEPAC soil has an OM of 1.7%, a pH of 6.1, and a CEC of 5.6 meq 100 g^{-1}, and is in no-till management. The DPAC location primarily a Pewamo silty clay loam that was also in no-till management. The DPAC soil has on OM of 3.6%, a pH of 6.0, and a CEC of 15.8 meq 100 g^{-1}.

5.3.2 Experimental Design and Herbicide Treatments:

The experimental design was a split-block with a factorial arrangement of treatments and four replications. The main blocks were the three cover crops, cereal rye, crimson clover, and an 80:20 by weight, mixture of the two respectively, that is here after referred to as the “mix”. Respective seeding rates for cereal rye, crimson clover, and the mix are as follows; 101 kg ha^{-1}, 20 kg ha^{-1}, and 78 kg ha^{-1}. Planting dates for cover crops can be found in Table 5.1. Due to abnormally cold weather conditions during the winter of 2019 the majority of crimson clover across all three locations winter-killed. DPAC in 2018 only had two replications due to saturated soil conditions.

Within each cover crop there was a factorial treatment arrangement of three termination timings and three herbicide strategies to terminate the cover crops. The three termination timings that were implemented in this study were before soybean planting (BP), at soybean planting (ATP), and after soybean planting (AFP). Specific dates for these termination times in both years can be found in Table 5.1. The three herbicide strategies that were utilized in this experiment were a glyphosate only termination, a glyphosate in combination with 2,4-D, and glyphosate plus 2,4-D, plus a residual herbicide. The residual herbicide changed with site and termination timing due to label restrictions, and key weed specie targets at each location. The rates of each herbicide used can be found in Table 5.2. The glyphosate only herbicide strategy was used to evaluate cover crop weed suppression within buffer areas that are required by Enlist E3® (Corteva Agrisciences, 9330 Zionsville Road, Indianapolis, Indiana, United States) soybeans. These buffer areas are required in order to reduce off target movement that has become a concern as synthetic auxin-resistant soybeans have been commercialized. The two herbicide strategies that utilize 2,4-D were used to simulate weed suppression across an entire field, or outside of buffer areas.

All herbicide applications were made using a 3 m CO_2 propelled backpack sprayer that was calibrated to deliver 140 L ha^{-1} at 143 kPa. Nozzles recommended by herbicide labels were used, being an AIXR 11003 (Teejet Technologies, Wheaton, IL). The primary weed species at SEPAC were a wide variety of grasses and horseweed in 2018 and common waterhemp in 2019. At the TPAC location giant ragweed, fall panicum (*Panicum dichotomiflorum* Michx.), and foxtail species (*Setaria spp*.) were the predominant weed species. The DPAC weed flora was primarily common waterhemp and a mix of grass species. Key species at each location are summarized in Table 5.3.

A blanket POST application was made after all cover crops had been terminated. The specific time of this blanket POST can be found in Table 5.1 and the herbicides used can be found in Table 5.2. The blanket POST was sprayed when average weed height across all plots was 10 to 15 cm.

5.3.3 Data Collection:

Prior to the termination of cover crops, both cover crop and weed biomass was collected from at least five plots within each cover crop block using a 0.25 m^2 quadrant. This was done to evaluate any early season weed suppression by the three different cover crops, as well as to observe the increase in cover crop biomass as termination time was delayed. Soybeans were planted at a rate of 350,000 seeds ha^{-1} and soybean planting dates can be found in Table 5.1. Prior to the application of the blanket POST, densities were taken of key weed species at each location. These densities were taken from two quadrants in the front and back of each plot using either a 0.25 or 1 m^2 quadrant, which were averaged for a single value of plants m^{-2} for each plot. The dried biomass of all key weed species were then weighed for a single biomass, referred to as early-summer weed biomass. The plots were harvested using a small plot combine and yields were adjusted to 13% moisture. The results reported in this manuscript focus on weed densities prior to the blanket POST application and are referred to as early-summer densities.

5.3.4 Statistical analysis

Correlations between cover crop biomass and weed biomass were done using SAS 9.4 PROC CORR procedure, and all other data was analyzed using the PROC GLIMMIX procedure in SAS 9.4 (SAS, 100 SAS Campus Drive, Cary, NC 27513-2414, USA). The densities and biomass collected were subjected to a log-transformation to analyze data. However, for clarity purposes, untransformed data is presented. The variables of termination time and herbicide strategy were fixed effects, while cover crop, cover crop*replication, and cover crop*replication*termination time were random effects. A Satterthwaite denominator degree of freedom was utilized to produce an accurate approximation of F. Analysis was similar to that described by Yang (2010) for balanced split-plot designs. Mean separations were identified using Tukey's Honest Significant Difference (HSD) test with an alpha=0.05. The three locations were analyzed separately due to differences in soil types and key weed species present. Interactions and factors that were significant can be found in Tables 5.4 through 5.7.

5.4 Results

5.4.1 Cover Crop and Weed Biomass Prior to Cover Crop Termination

Termination timing and cover crop species influenced cover crop biomass. Two-way interactions occurred between cover crop and termination timing both years at TPAC (P =0.0433 and P<0.0001, respectively) and in 2019 at SEPAC (P =0.0183). In 2018 crimson clover terminated at, or before soybean planting provided at least 60% less biomass than cover crops containing cereal rye at any termination time, however the late terminated crimson clover was similar in 2018 to cereal rye and mix (Table 5.4). At both sites in 2019 cereal rye and the mix produced more biomass than the crimson clover, due to the crimson clover being winter-killed. At TPAC in 2019, delaying the termination of a cereal rye or the mix to at, or after soybean planting resulted in a 70% increase in cover crop biomass compared to all other treatments (Table 5.4). Haramoto and Pearce (2019) reported that delaying cover crop termination from 6 weeks before planting to 3 weeks before planting increased cover crop biomass by 35% for a wheat monoculture in Kentucky. In 2018 cover crop biomass was influenced by cover crop and termination timing at SEPAC (*P* <0.0001, *P* <0.0001) and DPAC (*P* =0.0039, and *P* <0.0001). Crimson clover had at least a 55% less biomass than cereal rye or the mix. Terminating cover crops before soybean planting reduced biomass by at least 50% compared to later terminations (Table 5.4). Lawson et al. (2015) found similar results in that a vetch cover crop alone provided 33% less biomass when compared to mixtures with rye over a five-year period in the Pacific Northwest. Appelgate et al. (2017) reported that mixtures containing rye or rye alone always provided 53% more biomass than any of the 8 other individual species evaluated in Iowa.

Correlations were determined between cover crop biomass and early season weed biomass. A Pearson correlation coefficient of 0.38 (P<0.0001) was reported. As cover crop biomass increased the variability of the early season weed biomass decreased (Figure 5.1). Using cover crops with cereal rye and terminating at or after planting provided higher biomass compared to the earliest terminated cover crops or crimson clover, which would be beneficial in reducing the variability of early season weed suppression that occurs due to increased cover crop biomass. Baraibar et al. (2018) reported that some of the most important variables for predicting spring weed biomass (r^2=0.47) in Pennsylvania were growing degree days, cover crop type, and cover crop biomass.

A two-way interaction between cover crop and termination timing affected the weed biomass prior to cover crop termination at DPAC in 2018 (*P*<0.0001), and both SEPAC and TPAC in 2019 (*P* = 0.0122 and *P*<00001, respectively). Terminating crimson clover after soybean planting resulted in the highest weed biomass, with 89% more biomass than other treatments at DPAC in 2018 (Table 5.5). Terminating crimson clover at, or after soybean planting increased weed biomass by at least 91% compared to treatments that utilized a cover crop that contained cereal rye at SEPAC and TPAC in 2019. Similarly, terminating cereal rye before soybean planting in 2019 at TPAC reduced weed biomass by at least 82% compared to all other treatments, except the mix terminated before, and at soybean planting (Table 5.5). At SEPAC in 2019, terminating a cover crop containing cereal rye at any time reduced weed biomass by at least 79% compared to crimson clover (Table 5.5).

In 2018 weed biomass at both SEPAC and TPAC were affected by termination timing (P =0.0186 and P =0.0186, respectively). Delaying termination from before soybean planting to after soybean planting reduced weed biomass by 33 and 50% respectively for TPAC and SEPAC (Table 5.5). In 2018, the TPAC location weed biomass was also influenced by cover crop (P<0.0001), with cereal rye and the mix reducing weed biomass by 98 and 91% respectively compared to crimson clover (Table 5.5). Reductions of weed biomass by cereal rye of 91% and higher have previously been documented by Werle et al. (2018) in Nebraska.

Delaying termination with cover crops containing cereal rye to at, or after soybean planting resulted in 25% increase in cover crop biomass compared to crimson clover plots at any termination. Weed biomass was variable ranging from 6 to 2436 kg ha^{-1}. However, cover crops containing cereal rye never had weed biomass that exceeded 177 kg ha^{-1}, while crimson clover terminated after soybean planting at TPAC in 2019 had weed biomass of 2436 kg ha^{-1} (Table 5.5). Caution should be used when delaying cover crop termination due to possible negative impacts on cash-crop yield, and the possibility of seed production by cover crops producing volunteers that compete with the cash-crop for resources (Keene et al. 2017). Terminating later had variable impacts on early season weed biomass. This is likely due to weed biomass increasing as termination timing is delayed.

Utilizing cover crops containing cereal rye reduced early-season weed biomass at four of six sites. Additionally, at four of six site-years a cover crop terminated at the later timing had similar weed biomass to earlier timings, which would indicate that delayed termination is beneficial as weed biomass is not increasing from before soybean planting to after soybean planting (Table 5.5). Using cereal rye or the mix and terminating at or after soybean planting reduced early weed biomass by 90% compared to the highest weed biomass at three of six site years.

5.4.2 Early-summer Horseweed Densities Prior to Blanket POST

Horseweed was evaluated at all six site-years. Cover crops have been reported to reduce horseweed densities by 52% relative to a fallow control immediately prior to a preplant burndown across two years in Pennsylvania (Wallace et al. 2019). Davis et al. (2007) reported that a winter wheat cover crop in Indiana provided similar control of horseweed to a spring residual application one month after in-crop applications with 0.2 and 0.1 horseweed m^{-2} respectively, and more horseweed control than a fall residual one month after burndown with 12.5 fewer horseweed m^{-2}. The SEPAC location in 2019 was influenced by a two-way interaction of herbicide strategy by termination timing (P =0.0014). Utilizing glyphosate plus 2,4-D at, or after soybean planting, or glyphosate in combination with 2,4-D and a residual herbicide at any termination time resulted in a 0 horseweed densities compared to all other treatments that had 14 to 22 horseweed m^2 , except the glyphosate in combination with 2,4-D and a residual herbicide before soybean planting. (Table 5.6). Davis et al. (2005) established that glyphosate-resistant horseweed was at SEPAC by conducting a dose response under greenhouse conditions. Rates of 1.8 kg ae ha^{-1} were needed to reduce horseweed biomass by 50% compared to the average of four susceptible populations which only required an average of 0.3 kg ae ha^{-1} of glyphosate, which explains the efficacy of glyphosate with 2,4-D and a residual at this site. Furthermore, Kruger et al. (2010) demonstrated that 2,4-D could provide 90% control of glyphosate-resistant horseweed at a height of 30 cm or smaller. However, the efficacy of 2,4-D decreased to 81% when horseweed heights were greater than 30 cm.

In 2018 horseweed densities at TPAC were affected by the interaction of cover crop by herbicide strategy (*P* =0.0382). Crimson clover and the mix terminated with glyphosate alone resulted in at least 19% more horseweed than the cereal rye terminated with glyphosate alone or, the crimson clover or mix terminated with an herbicide strategy containing 2,4-D (Table 5.6). In both years the TPAC locations had low horseweed densities, due to cover crops producing high biomass in 2018 and competition with giant ragweed in 2019. Horseweed densities at DPAC in 2019 were influenced by herbicide strategy (P =0.0003) and were at least 64% lower when a herbicide strategy including both glyphosate and 2,4-D was utilized (Table 5.6).

Using a cover crop containing cereal rye at SEPAC in 2018 reduced horseweed densities by at least 93% compared to crimson clover (Table 5.6, *P*<0.0001). Davis et al. (2007) found similar results when comparing a winter wheat cover crop to a fall residual herbicide, with the cover crop providing 96% more control of horseweed one month after burndown, however this did not occur in the second year of the experiment. Horseweed densities were reduced by at least 68% across five of six site years when using glyphosate in combination with 2,4-D and a residual, compared to glyphosate alone. Cover crops only improved horseweed control when interacting with herbicide strategy at one site, while the addition of 2,4-D improved horseweed control at all sites. Using cover crops in buffer areas terminated with glyphosate alone did not provide similar horseweed control as an effective 2,4-D application. Contrasts within cereal rye comparing the glyphosate alone to glyphosate plus 2,4-D showed that similar horseweed suppression between the two herbicide strategies was observed at four of six site years at the 0.05 level of significance. However, cereal rye terminated with glyphosate alone only provided similar horseweed control to glyphosate in combination with 2,4-D and a residual at two site-years. Cereal rye terminated with glyphosate alone provided similar horseweed control to cereal rye terminated with glyphosate plus 2,4-D more often than not, and would allow for better weed control within label-mandated buffer areas. The use of a residual herbicide within buffer areas would likely alleviate some of the differences when an 2,4-D was not used to terminate the cereal rye cover crop.

5.4.3 Early-summer Grass Densities Prior to Blanket POST

Grass control was evaluated at all six site-years. Delaying termination timing to after soybean planting reduced grass densities at all six site-years. However, the amount that grass densities were reduced was highly variable ranging from 41 to 98%. Three-way interactions between cover crop, termination timing, and herbicide strategy affected grass densities at both SEPAC (P = 0.0019) and DPAC (P =0.019) in 2018 (Table 5.7). In 2018 grass densities at DPAC were 0 m^{-2} at the latest termination except for crimson clover terminated herbicide strategies using 2,4-D (Table 5.7).

In both 2018 and 2019 TPAC grass densities were affected by termination timing (P = 0.0009 and P = 0.0001, respectively). When terminated after soybean planting grass densities were reduced by 71% in 2019 compared to when termination was before soybean planting and reduced by 41% when terminated at soybean planting compared to before soybean planting in 2018. (Table 5.7). In 2019, DPAC grass densities were at least 87% lower when termination was delayed to at, or after planting compared to before soybean planting (Table 5.7, P = 0.0128). Delaying the termination of cover crops from before soybean planting to after soybean planting was an effective way to control grasses within and outside of buffer areas. In 2018, TPAC grass densities were reduced by at least 54% when a cereal rye cover crop was utilized compared to crimson clover (Table 5.7, *P* = 0.295). Contrasts were conducted to determine if a glyphosate only herbicide strategy provided similar grass suppression to a glyphosate plus 2,4-D herbicide strategy. At five of six site-years the glyphosate alone herbicide strategy had similar grass densities to the glyphosate in combination with 2,4-D within the cereal rye cover crop at the 0.05 level of significance. Dhima et al. (2006) reported reductions in barnyardgrass and bristly foxtail (*Setaria verticillate (L.) Beauv*.) in Greece due to winter cereal cover crop mulches and attributed this to allelopathy. Our research showed that termination timing reduced grass densities, but we did not evaluate allelopathic effects. Few researchers have assessed the effects of cover crop and termination timing on grass densities. In order to reduce grass densities within buffer areas, delay termination of cover crops containing cereal rye to at or after soybean planting as this provided over 41% reduction in three of six site-years in this research. Norsworthy et al. (2011) reported that a rye cover crop provided 10 to 11% additional goosegrass (*Eleusine indica* (L.) Gaertn.) control compared to fallow plots when glyphosate plus pyrithiobac was applied to one-leaf cotton. Control of grasses with cover crops is variable and needs to be utilized with an effective herbicide program (Johnson et al. 1993). The effect of termination timing and cover crops on grass weed control has minimal documentation.

5.4.4 Early-summer Giant Ragweed Densities Prior to Blanket POST at TPAC

Giant ragweed was evaluated at two of six site-years. Delaying cover crop termination to at, or after soybean planting reduced giant ragweed densities by 54 and 78%, respectively, compared to the earliest termination time in 2019 (*P* = 0.022), however termination did not influence giant ragweed densities in 2018 (Table 5.8). Cover crops did not affect giant ragweed densities in either year. Utilizing glyphosate in combination with 2,4-D and a residual herbicide provided 80 and 26% more control than glyphosate alone in 2018 (P =0.0073) and 2019 (P = 0.0018), respectively (Table 5.8). Previous research on the influence of cover crops and termination time on giant ragweed is minimal. Bruin et al. (2005) reported cereal rye reduced giant ragweed biomass, but not density at one site year in Minnesota. However, the influence of herbicide strategies on giant ragweed has been reported by several researchers. Ganie and Jhala (2017) reported that 2,4-D in combination with glufosinate provided at least 81% control of giant ragweed compared to a non-treated control, but was similar to glufosinate applied alone. The use of 2,4-D as an additional mode of action will allow for better weed POST management practices as described by Norsworthy et al. (2012) as implementing multiple modes of action will likely extend the longevity of the 2,4-D-resistant technology. Delaying termination of cover crops was beneficial in reducing giant ragweed densities in 2019. Termination timing did not influence giant ragweed densities in 2018. Giant ragweed densities in 2019 were reduced by later termination timings due to the delayed soybean planting as a result of a wet spring. The delay in soybean planting in 2019 allowed for giant ragweed to emerge without having to compete with a soybean crop, or living cover crop for five weeks between the first termination timing and the at planting termination. Cover crops should not be used to control giant ragweed in buffer areas, as we report that herbicide strategies with 2,4-D were the only control method that reduced giant ragweed densities in both years. Contrasts conducted showed the use of cereal rye provided similar suppression when terminated with glyphosate or glyphosate plus 2,4-D at a 0.05 level of significance. However, the use of a residual herbicide increased giant ragweed control.

5.4.5 Early-summer Waterhemp Densities and Biomass Prior to Blanket POST

Waterhemp was evaluated at three of six site-years. Waterhemp densities at DPAC in 2018, and SEPAC in 2019 were affected by a herbicide strategy by termination timing interaction (Tables

5.9, *P* =0.0063 and *P* =0.0002, respectively). Delaying termination to at, or after planting, and using glyphosate in combination with 2,4-D and a residual herbicide reduced waterhemp densities by at least 92% compared to glyphosate alone at the two earlier timings, or glyphosate plus 2,4-D at the early timing at DPAC in 2018. (Table 5.9) At SEPAC Utilizing glyphosate plus 2,4-D plus a residual herbicide after-soybean planting reduced waterhemp densities by at least 34% compared to all other treatments (Table 5.9).

In 2018 DPAC waterhemp densities were reduced by 45% in cereal rye compared to crimson clover (Table 5.9, *P* =0.0364). However, in 2019 waterhemp densities at DPAC were only affected by termination time and herbicide strategy used (*P*<0.0001, and *P*<0.0001, respectively). Terminating at and after soybean planting reduced waterhemp densities by 65 and 93% respectively compared to the earliest timing (Table 5.9). Additionally, using glyphosate in combination with 2,4-D and a residual herbicide reduced waterhemp densities by at least 93% compared to other herbicide strategies (Table 5.9).Steckel et al. (2003) evaluated waterhemp under percentages of shade from 0 to 99% and found that increased shade reduced waterhemp biomass and seed production, which would be beneficial in late terminated cereal rye cover crops. Additionally, waterhemp under 99% shade had mortalities of 97 and 84% respectively in May and June.

Tharp and Kells (2002) found similar results when residual herbicides were used in combination with glyphosate providing an average of 20% more visual control of redroot pigweed (*Amaranthus retroflexus L.*) and common lambsquarters (*Chenopodium album L.*) compared to applications of glyphosate alone across four years in Michigan. Hay et al. (2019) reported that appropriate herbicide strategies resulted in 97% control of pigweeds in Kansas grain sorghum across 6 site-years, while a winter wheat cover crop provided only 50% reductions in pigweed density and biomass at half of those site-years. Similar results were found in this study as one of the two sites with established cover crops had reductions of 45% when a cereal rye cover crop was utilized compared to crimson clover alone (Table 5.9). Cover crops will be a useful integrated weed management practice to aid in controlling waterhemp, but need to be used in tandem with appropriate herbicide programs to achieve acceptable levels of control. Contrasts showed that cereal rye terminated with glyphosate alone only provided similar control as the glyphosate plus 2,4-D at the DPAC in 2018 (P=0.1478). Cornelius and Bradley (2017) reported that cover crops reduced late season waterhemp biomass from 21 to 40%, but this was not comparable to the 97% reduction in late season waterhemp emergence provide by a spring PRE residual herbicide. Norsworthy et al. (2011) reported that cover crops could provide control of Palmer amaranth in cotton ranging from 0 to 91% with no herbicide, while in combination with herbicides at one-leaf cotton stage provided 94% or greater control of Palmer amaranth. We report that cover crops will be beneficial in reducing waterhemp densities both within and outside of label-mandated buffer areas.

5.4.6 Soybean Yield

Soybean yield at TPAC in 2018 was influenced by a three-way interaction between cover crop, termination timing, and herbicide strategy (P =0.008). Delaying termination of cover crop to the latest timing resulted in a 16% reduction in soybean yield compared to the earlier timings at TPAC in 2018. All treatments terminated before planting and at planting were similar to the highest yielding treatment, while all crimson clover treatments terminated after planting were similar to the highest yielding (Table 5.10). Terminating cover crops containing cereal rye after planting were more likely to have yield reductions compared to earlier terminated treatments.

In 2019, soybean yield at TPAC was 28% lower in the early terminated crimson clover compared to all other treatments (Table 5.10, P =0.0311). Lower soybean yields in early terminated plots in 2019 is likely a result of delayed soybean planting due to high spring precipitation resulting in higher weed pressure in those plots, as evaluated by collecting the POST weed biomass.

In 2018 soybean yield at SEPAC was influenced by termination timing ($P<0.0001$). Delaying termination to at, or after soybean planting reduced soybean yields 14 and 41% compared to the earliest timing (Table 5.10). Producer interest in delaying termination timing of cover crops to plant into a living cover crop has increased in recent years (CTIC 2017). However, reductions in soybean yield up to 41% can occur when termination of a cover crop is delayed as observed in this study in 2018. Previous reductions in cash-crop yield due to cover crops has been observed (Eckert 1988; Liebl et al. 1992). Reddy (2001) reported yield reduction in soybean yield due to stand loss ranging from 2 to 20% when cover crops were terminated two to three weeks prior to soybean planting. However, we report that terminating crimson clover at or after planting does not cause yield reductions in soybean yield and like Ruffo et al. (2004) reported with rye, yield reduction prior to soybean planting were rare, only occurring at TPAC in 2019 (Table 5.10). Nutrient analysis was conducted on cover crop biomass in 2019 due to the reductions in yield in 2018. Carbon increased by at least 41% from the before planting timing to the at or after soybean planting termination timings (data not shown). Additionally, nitrogen taken up by the cover crop was higher at the TPAC location by at least 68% at the later termination timings (data not shown). In one of the six site-years delayed termination increased soybean yield at DPAC in 2019, however, cover crops at this site were winter-killed (Table 5.10). This research provides evidence that cover crops alone did not cause yield reductions, however, when used in combination with a delayed termination they can result in yield reductions from 14 to 41%. Cover crops used in label-mandated buffer areas should be terminated before soybean planting to avoid reductions in yield. The effect of cover crops and termination timing on soybean yield within buffer areas has not previously been reported.

Haramoto and Pearce (2019) reported similar results in Kentucky as cover crop composition, termination timing, and herbicide interactions where variable in suppressing weeds over 4 site-years. Haramoto and Pearce (2019) demonstrated that residual herbicides are generally beneficial to use in cover crops to suppress weeds in summer annual cash crops. We provide additional evidence of the benefit of residual herbicides in cover crops and evaluate the effect of cover crops, termination timing, and herbicide strategy on a species level of four problematic broadleaf species and grasses as a whole. Cover crops with high biomass production were effective in reducing grass and waterhemp densities. Grass densities were reduced when termination was delayed to after planting by 41 to 98% at all site-years. In 2019 giant ragweed densities were reduced by 78% when termination was delayed to after planting compared to before soybean planting, but were not reduced in 2018. Waterhemp densities were reduced by as much as 93% at DPAC in 2019 when termination was delayed to after soybean planting compared to the earliest termination timing. Cover crops were beneficial in reducing horseweed densities at two of five site-years. Horseweed densities were reduced by cover crops alone at one of five site-years with cereal rye and mix reducing horseweed densities by 93% compared to crimson clover which resulted in higher horseweed densities.

Caution should be used when delaying cover crop termination due to potential reductions in cash-crop yield. We show that cereal rye with termination delayed to at, or after planting would be beneficial within buffer areas for control of waterhemp, and grass densities. However, yield reductions were observed of up to 41% when cover crops termination was delayed to after soybean planting. Use of cover crops within buffer areas mandated by 2,4-D herbicide labels has not previously been evaluated. We show that cover crops will be useful in suppressing grass, waterhemp, and sometimes horseweed densities within buffer areas, but will not be effective in suppressing giant ragweed.

2,4-D and residual herbicides should be used with cover crops, and can reduce the number of weeds exposed to POST applications of glyphosate and 2,4-D (Dewerff et al. 2015). We showed that the addition of 2,4-D and, or a residual provided 68% more control of horseweed control at 5 of 6 sites, and at least 26% more control of giant ragweed compared to glyphosate alone. Waterhemp densities were reduced by 34% due to the addition of 2,4-D and a residual to terminate at the latest termination SEPAC in 2019. Early summer weed biomass supports the assessments of reduced weed densities as early summer weed biomass was also reduced by 36% compared to early termination of glyphosate or glyphosate plus 2,4-D when termination was delayed to after planting and glyphosate was used in combination with 2,4-D and a residual herbicide (data not shown).

Future research on weed control with cover crops should focus on the impact on soybean yields when terminated near, or after planting in various environments. Additionally, interactions between cover crop and residual herbicide strategies used will have important management implications when managing for problematic herbicide-resistant weed species.

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Table 5.1: Date of cover crop planting, termination times, planting, POST application, and harvest at all three of the trial locations.[a,b]

	TPAC		SEPAC		DPAC	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Cover Crop Planted	9/26/2017	10/03/2018	9/22/2017	10/3 & 18/2018[c]	10/27/2017	10/22/2018
BP Termination	4/26/2018	4/23/2019	4/30/2018	5/8/2019	5/5/2018	5/6/2019
Planting	5/10/2018	6/3/2019	5/14/2018	6/4/2019	5/17/2018	6/7/2019
AFP Termination	5/23/2018	6/11/2019	5/29/2018	6/12/2019	6/2/2018	6/21/2019
Blanket POST Application	6/16/2018	6/26/2019	6/5/2018	7/09/2019	6/14/2018	7/13/2019
Harvest	10/24/2018	10/14/2019	10/25/2018	11/25/2019	10/22/2018	11/05/2019

[a] Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), BP=Before Planting; and AFP=After Planting.
[b]The before planting termination was much longer than originally intended due to adverse weather condition in the spring of 2019 causing an extended delay in planting time.
[c]Cereal rye at SEPAC in 2019 was reseeded due to poor emergence resulting in two cover crop planting dates.

Table 5.2: Herbicides used and rates which were applied for the three cover crop termination timings & the blanket POST application.[a,b,c]

Site & timing	Active ingredient	Rate (kg ha^{-1})	Formulation	Manufacturer	Address
Used at all sites for termination	Glyphosate + 2,4-D	1.12 + 1.08	Enlist Duo®	Corteva	Leverkusen, Germany
Used at all sites for termination & blanket POST	Glyphosate	1.28	Roundup Powermax®	Bayer	Leverkusen, Germany
All TPAC terminations, and blanket POST at SEPAC & TPAC	Cloransulam-methyl	0.009/0.027/0.044 [a]	FirstRate®	Corteva	Zionsville, IN
Residual at DPAC BP and ATP	Sulfentrazone + imazethapyr	0.32 + 0.065	Authority® Assist	FMC	Market Street, PA
Residual at SEPAC BP and ATP	Flumioxazin + chlorimuron-ethyl	0.085 + 0.029	Valor® XLT	Valent	Walnut Creek, CA
Residual at DPAC & SEPAC AFP	Acetochlor	1.49	Warrant®	Bayer	Leverkusen, Germany
Blanket POST at DPAC	Fomesafen	0.2	Flexstar®	Syngenta	Greensboro, NC
Blanket POST at SEPAC (2019 only)	Glyphosate + fomesafen	1.13 + 0.24	Flexstar GT 3.5®	Syngenta	Greensboro, NC

[a] Three different rates of cloransulam-methyl were used in this experiment. The 0.044 kg ha^{-1} was used at the two earliest terminations at TPAC, the 0.027 kg ha^{-1} rate was used as the blanket POST application at SEPAC, and the 0.009 kg ha^{-1} rate was used at the late termination timing & the blanket POST applications at TPAC. This was done in order to follow maximum use rates determined from the label.

[b] Fomesafen was added to the blanket POST application in 2019 at the SEPAC location due to waterhemp being much more prevalent than the previous year.

[c] Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), BP=Before Planting,ATP=At Planting, and AFP=After Planting.

Table 5.3: Key weed species at each of the trial locations that were collected for biomass and recorded for density.[a,b,c]

TPAC	SEPAC	DPAC
Grasses[b]	Grasses	Grasses
Morningglory (*Iopomea spp*.)	Morningglory	Morningglory
Horseweed (*Erigeron canadensis L*.)	Horseweed	Horseweed
Giant ragweed (*Ambrosia trifida L*.)	Common ragweed (*Ambrosia artemisiifolia L*.)	Waterhemp
Common lambsquarters (*Chenopodium album L*.)	Common cocklebur (*Xanthium stumarium L.*)	
Velvetleaf (*Abutilon theophrasti Medik*.)	Waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer), 2019 only]	

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340).
[b] Grass species and approximate composition at the two sites; TPAC: large crabgrass (*Digitaria sanguinalis (L.)* (2%), smooth crabgrass (*Digitaria ischaemum (Schreb.) Schreb. ex Muhl*.) (3%), fall panicum (*Panicum dichotomiflorum Michx.)* (15%), barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv) (17%), and foxtail species (*Setaria spp*.) (67%), SEPAC: barnyardgrass (2%), large crabgrass (2%), annual bluegrass (*Poa annua L*.) (8%), fall panicum (34%), and foxtail species (54%), DPAC: smooth crabgrass (1%), large crabgrass (4%), foxtail species (18%), barnyardgrass (32%), and fall panicum (45%).
[c]Waterhemp was added at the SEPAC location in 2019 because the trial was moved to an area where waterhemp was more prevalent.

Table 5.4: Influence of cover crop and termination timing on cover crop biomass prior to termination in the spring at three sites in Indiana.[a,b,c]

Site	Year	Cover crop	Termination timing			
			BP	ATP	AFP	Pooled
			kg ha^{-1}			
TPAC	2018	Crimson clover	488 c	1346 bc	3095 ab	1643 b
		Cereal rye	3358 a	5127 a	6281 a	4922 a
		Mix	3804 a	4148 a	6149 a	4700 a
		Pooled	2550 b	3540 a	5175 a	
	2019	Crimson clover	0 c	0 c	0 c	0 b
		Cereal rye	1548 b	5956 a	5484 a	4329 a
		Mix	1631 b	6327 a	5682 a	4547 a
		Pooled	1060 b	4094 a	3722 a	
SEPAC	2018	Crimson clover	922	3016	3435	2458 b
		Cereal rye	3405	6692	6944	5680 a
		Mix	3597	5751	7293	5509 a
		Pooled	2614 b	5238 a	5829 a	-
	2019	Crimson clover	17 b	0 b	0 b	6 b
		Cereal rye	3166 a	5919 a	5759 a	4948 a
		Mix	3111 a	6669 a	6747 a	5509 a
		Pooled	2614	5238	5829	
DPAC	2018	Crimson clover	0	60	200	87 b
		Cereal rye	1470	3076	4420	2989 a
		Mix	700	1691	2369	1587 a
		Pooled	725 b	1601 a	2322 a	-

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), BP=Before Planting, ATP=At Planting and AFP=After Planting.

[b]Data were log-transformed before analysis, however untransformed mean values are presented based on the interpretation of the transformed data.

[c]Means followed by the same letter within site-year and pooled data not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

Table 5.5: Influence of cover crop and termination timing on weed biomass prior to cover crop termination in the spring at three sites in Indiana.[a,b,c,d,e]

Year	Site	Cover crop	Termination timing			
			BP	ATP	AFP	Pooled
			kg ha^{-1}			
TPAC	2018	Crimson clover	1061	-[e]	761	911 a
		Cereal rye	17	-	22	20 c
		Mix	134	-	32	83 b
		Pooled	404 a	-	272 b	
	2019	Crimson clover	116 bc	1563 a	2436a	1372 a
		Cereal rye	15 d	82 bc	157 bc	85 c
		Mix	29 cd	118 bcd	160 b	102 b
		Pooled	53	588	918	
SEPAC	2018	Crimson clover	413	662	307	461
		Cereal rye	168	128	26	107
		Mix	168	177	45	130
		Pooled	250 a	323 a	126 b	-
	2019	Crimson clover	220 b	533 ab	576 a	443 a
		Cereal rye	21 c	46 c	15 c	27 b
		Mix	13 c	11 c	6 c	10 b
		Pooled	85	196	199	
DPAC	2018	Crimson clover	12 b	113 b	985 a	370
		Cereal rye	10 b	65 b	27 b	34
		Mix	40 b	21 b	102 b	54
		Pooled	20 a	66 b	372 c	

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), BP=Before Planting, ATP=At Planting, and AFP=After Planting.
[b]Data were log-transformed before analysis, however untransformed mean values are presented based on the interpretation of the transformed data.
[c]Means followed by the same letter within site-year and pooled data are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.
[d]Weeds that made up more than approximately 5% of the density combined for biomass measurements included: TPAC: chickweed (*Stellaria media* (L.) Vill.) (50%), henbit (*Lamium amplexicuale* L.) (17%), giant ragweed (18%), SEPAC: fall panicum (5%), cressleaf groundsel (*Packera glabella* (Poir.) C. Jeffrey) (6%), bittercrest (*Cardamine hirsuta*)(7%), horseweed (9%), field speedwell (*Veronica agrestis* L.)(15%), and annual bluegrass (Poa annua L.)(30%), DPAC: fall panicum (6%), field speedwell (11%), horseweed (28%), and waterhemp (32%).
[e]Missing data from ATP timing at TPAC in 2018.

Table 5.6: Influence of cover crop, termination timing, and herbicide strategy on early-summer horseweed density prior to a POST application at three sites in Indiana in 2018 and 2019.[a,b,c]

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
				Plants m^{-2}			
TPAC	2018	Gly	Crimson clover	0.88	0.50	0.63	0.67 a
			Cereal rye	0.13	0.13	0.25	0.17 ab
			Mix	0.50	0.13	0.00	0.21 ab
		Gly + 2,4-D	Crimson clover	0.00	0.13	0.00	0.04 b
			Cereal rye	0.13	0.13	0.38	0.21 ab
			Mix	0.00	0.13	0.13	0.08 b
		Gly + 2,4-D + residual	Crimson clover	0.25	0.13	0.13	0.17 b
			Cereal rye	0.00	0.00	0.00	0.00 b
			Mix	0.00	0.00	0.13	0.04 b
		Pooled	Crimson clover	0.38	0.25	0.25	0.29
			Cereal rye	0.13	0.08	0.21	0.13
			Mix	0.17	0.08	0.08	0.11
		Gly	Pooled	0.50	0.25	0.29	0.35 a
		Gly + 2,4-D		0.04	0.13	0.17	0.11 b
		Gly + 2,4-D + residual		0.08	0.04	0.08	0.07 b
		Pooled	Pooled	0.21	0.14	0.18	
TPAC	2019	Gly	Crimson clover	0.00	0.00	0.00	0.00
			Cereal rye	0.00	0.00	0.00	0.00
			Mix	0.50	0.00	0.00	0.17
		Gly + 2,4-D	Crimson clover	0.50	0.00	0.00	0.17
			Cereal rye	0.00	0.00	0.00	0.00
			Mix	0.50	0.00	0.00	0.17
		Gly + 2,4-D + residual	Crimson clover	0.00	0.00	0.00	0.00
			Cereal rye	0.00	0.00	0.00	0.00
			Mix	0.50	0.00	0.00	0.17
		Pooled	Crimson clover	0.17	0.00	0.00	0.06
			Cereal rye	0.00	0.00	0.00	0.00
			Mix	0.50	0.00	0.00	0.17

Table 5.6 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
TPAC	2019	Gly	Pooled	0.17	0.00	0.00	0.06
		Gly + 2,4-D		0.33	0.00	0.00	0.11
		Gly + 2,4-D + residual		0.17	0.00	0.00	0.06
		Pooled	Pooled	0.22 a	0.00 b	0.00 b	
SEPAC	2018	Gly	Crimson clover	133	20	25	59
			Cereal rye	7	3	4	4
			Mix	3	3	1	2
		Gly + 2,4-D	Crimson clover	8	9	19	12
			Cereal rye	2	1	2	1
			Mix	1	0	3	1
		Gly + 2,4-D + residual	Crimson clover	15	4	36	18
			Cereal rye	1	0	4	1
			Mix	0	0	1	0
		Pooled	Crimson clover	52	11	27	30 a
			Cereal rye	7	1	3	2 b
			Mix	1	1	1	1 b
		Gly	Pooled	48 a	8 a-c	10 ab	22 a
		Gly + 2,4-D		3 bc	3 bc	8 a-c	5 b
		Gly + 2,4-D + residual		5 bc	1 c	13 a-c	7 b
		Pooled	Pooled	19 ab	4 b	10 a	
SEPAC	2019	Gly	Crimson clover	8	33	48	30
			Cereal rye	15	4	12	10
			Mix	12	14	5	10
		Gly + 2,4-D	Crimson clover	28	0	1	10
			Cereal rye	11	0	0	4
			Mix	4	0	0	1
		Gly + 2,4-D + residual	Crimson clover	3	0	0	1
			Cereal rye	1	0	0	0
			Mix	0	0	1	0
		Pooled	Crimson clover	13	11	16	13
			Cereal rye	15	1	4	5
			Mix	5	5	2	4
		Gly	Pooled	11 a	17 a	22 a	17 a
		Gly + 2,4-D		14 a	0 b	0 b	5 b
		Gly + 2,4-D + residual		1 b	0 b	0 b	0 b

Table 5.6 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
SEPAC	2019	Pooled	Pooled	9 a	6 a	7 a	
DPAC	2018	Gly	Crimson clover	33	31	113	59
			Cereal rye	1	4	4	3
			Mix	5	11	7	7
		Gly + 2,4-D	Crimson clover	33	8	8	18
			Cereal rye	1	1	1	1
			Mix	17	4	2	7
		Gly + 2,4-D + residual	Crimson clover	1	3	9	4
			Cereal rye	0	2	0	1
			Mix	2	1	1	1
		Pooled	Crimson clover	22	14	50	28
			Cereal rye	1	2	2	1
			Mix	8	5	3	5
		Gly	Pooled	13	15	41	23 a
		Gly + 2,4-D		17	4	3	8 b
		Gly + 2,4-D + residual		1	2	3	2 c
		Pooled	Pooled	10	7	16	
DPAC	2019	Gly	Pooled	12	41	33	28 a
		Gly + 2,4-D		14	12	4	10 b
		Gly + 2,4-D + residual		4	5	1	3 b
		Pooled	Pooled	10	19	13	

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), Gly=Glyphosate, BP=Before Planting, ATP=At Planting, and AFP=After Planting.
[b]Data were log-transformed before analysis, however untransformed mean values are presented based on the interpretation of the transformed data.

[c]Means followed by the same letter within site-year and pooled data are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

Table 5.7: Influence of cover crop, termination timing, and herbicide strategy on early-summer grass density prior to a POST application at three sites in Indiana in 2018 and 2019.[a,b,c,d]

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
				Plants m^{-2}			
TPAC	2018	Gly	Crimson clover	32	18	21	24
			Cereal rye	9	26	2	12
			Mix	90	5	135	77
		Gly + 2,4-D	Crimson clover	32	38	9	26
			Cereal rye	23	10	4	12
			Mix	34	47	3	28
		Gly + 2,4-D + residual	Crimson clover	31	20	12	21
			Cereal rye	15	5	1	7
			Mix	19	4	10	11
		Pooled	Crimson clover	32	25	14	24 a
			Cereal rye	16	13	3	11 b
			Mix	47	19	49	38 ab
		Gly	Pooled	44	16	53	38
		Gly + 2,4-D		30	31	5	22
		Gly + 2,4-D + residual		22	9	8	13
		Pooled	Pooled	32 a	19 b	22 ab	
TPAC	2019	Gly	Crimson clover	32	12	11	18
			Cereal rye	38	20	8	22
			Mix	8	25	7	13
		Gly + 2,4-D	Crimson clover	34	9	1	14
			Cereal rye	39	11	3	17
			Mix	14	11	13	12
		Gly + 2,4-D + residual	Crimson clover	28	7	1	12
			Cereal rye	38	2	1	14
			Mix	20	4	31	18
		Pooled	Crimson clover	31	9	4	15
			Cereal rye	38	11	4	18
			Mix	14	13	17	14
		Gly	Pooled	26	19	9	18
		Gly + 2,4-D		29	10	5	15
		Gly + 2,4-D + residual		28	4	11	14
		Pooled	Pooled	28 a	11 b	8 b	

Table 5.7 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
SEPAC	2018	Gly	Crimson clover	204 ab	162 a-c	0 c	122
			Cereal rye	79 ab	21 a-c	2 a-c	34
			Mix	11 a	15 ab	10 a-c	12
		Gly + 2,4-D	Crimson clover	205 ab	27 ab	1 a-c	78
			Cereal rye	48 ab	4 ab	0 a-c	17
			Mix	25 ab	2 ab	1 a-c	9
		Gly + 2,4-D + residual	Crimson clover	16 ab	1 ab	5 a-c	7
			Cereal rye	8 ab	16 a-c	0 a-c	8
			Mix	3 ab	1 bc	0 a-c	1
		Pooled	Crimson clover	142 a	63 bc	2 ef	69 a
			Cereal rye	79 ab	14 d-e	1 f	20 ab
			Mix	13 b-d	6 d-e	4 ef	8 b
		Gly	Pooled	98 a	66 ab	4 d	56 a
		Gly + 2,4-D		93 a	11 bc	1 d	35 a
		Gly + 2,4-D + residual		9 bc	6 cd	2 d	6 b
		Pooled	Pooled	67 a	28 b	2 c	
SEPAC	2019	Gly	Crimson clover	63	7	1	24 b
			Cereal rye	48	20	20	29 ab
			Mix	73	30	43	49 ab
		Gly + 2,4-D	Crimson clover	73	41	18	44 a
			Cereal rye	75	57	24	52 ab
			Mix	60	29	20	36 ab
		Gly + 2,4-D + residual	Crimson clover	25	36	39	33 ab
			Cereal rye	58	17	16	30 ab
			Mix	28	6	14	16 a
		Pooled	Crimson clover	54	28	19	34
			Cereal rye	48	31	20	37
			Mix	53	22	25	33
		Gly	Pooled	61 a	19 a	21 b	34 b
		Gly + 2,4-D		69 a	42 b	21 b	44 a
		Gly + 2,4-D + residual		37 a	19 b	23 b	26 b
		Pooled	Pooled	56 a	27 b	21 c	

Table 5.7 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
DPAC	2018	Gly	Crimson clover	116 ab	125 a-e	0 c	80 a
			Cereal rye	11 a-g	10 b-g	0 e-g	7 b
			Mix	25 a-d	2 a-g	0 c-g	9 ab
		Gly + 2,4-D	Crimson clover	103 a	6 a-g	2 a-g	44 ab
			Cereal rye	11 a-f	1 gf	0 g	4 b
			Mix	51 a-c	4 d-g	0 gf	18 ab
		Gly + 2,4-D + residual	Crimson clover	55 a-g	11 a-g	1 c-g	19 ab
			Cereal rye	23 a-g	3 gf	0 g	9 b
			Mix	8 a-g	1 gf	0 gf	3 b
		Pooled	Crimson clover	91	47	1	49
			Cereal rye	15	4	0	6
			Mix	28	2	0	10
		Gly	Pooled	50	46	0	32 a
		Gly + 2,4-D		55	3	1	21 b
		Gly + 2,4-D + residual		29	5	1	11 ab
		Pooled	Pooled	45 a	18 b	0 c	
DPAC	2019	Gly	Pooled	33	3	2	13 ab
		Gly + 2,4-D		47	6	1	19 a
		Gly + 2,4-D + residual		11	2	1	5 b
		Pooled	Pooled	30 a	4 b	1 b	

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), BP=Before Planting, ATP=At Planting, and AFP=After Planting.
[b]Data were log-transformed before analysis, however untransformed mean values are presented based on the interpretation of the transformed data.
[c]Means followed by the same letter within site year are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$), unless pooled. . No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.
[d] Grass species and approximate composition at the three sites; TPAC: large crabgrass (2%), smooth crabgrass (3%), fall panicum (15%), barnyardgrass (17%), and foxtail species (67%), DPAC: smooth crabgrass (1%), large crabgrass (4%), foxtail species (18%), barnyardgrass (32%), and fall panicum (45%). SEPAC: barnyardgrass (2%), large crabgrass (2%), annual bluegrass (8%), fall panicum (34%), and foxtail species (54%).

Table 5.8: Influence of cover crop and termination timing on early-summer giant ragweed density prior to application of a POST at the Throckmorton Purdue Agricultural Center (TPAC, 8343 US-231, Lafayette, IN 47909).[a,b,c]

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
				Plants m^{-2}			
TPAC	2018	Gly	Crimson clover	9	17	40	22
			Cereal rye	18	135	65	73
			Mix	64	7	88	53
		Gly + 2,4-D	Crimson clover	11	12	18	14
			Cereal rye	26	79	23	43
			Mix	19	50	14	28
		Gly + 2,4-D + residual	Crimson clover	2	10	18	10
			Cereal rye	6	18	3	9
			Mix	14	11	8	11
		Pooled	Crimson clover	7	13	25	15
			Cereal rye	18	77	30	41
			Mix	32	23	37	30
		Gly	Pooled	30	53	64	49 a
		Gly + 2,4-D		19	47	18	28 ab
		Gly + 2,4-D + residual		7	13	10	10 b
		Pooled	Pooled	19	38	31	
TPAC	2019	Gly	Crimson clover	246	148	71	155
			Cereal rye	292	127	32	150
			Mix	271	131	120	174
		Gly + 2,4-D	Crimson clover	260	201	45	168
			Cereal rye	251	98	17	122
			Mix	276	84	73	144
		Gly + 2,4-D + residual	Crimson clover	223	105	29	119
			Cereal rye	186	40	9	78
			Mix	265	111	101	159
		Pooled	Crimson clover	243	151	48	147
			Cereal rye	292	88	19	117
			Mix	271	108	98	159
		Gly	Pooled	270	135	74	160 a
		Gly + 2,4-D		262	127	45	145 ab
		Gly + 2,4-D + residual		224	85	46	118 b
		Pooled	Pooled	252 a	116 b	55 b	

[a]Abbreviations: Gly=Glyphosate, BP=Before Planting, ATP=At Planting and AFP=After Planting.
[b]Data were log-transformed before analysis, however untransformed mean values are presented based on the interpretation of the transformed data.
[c]Means followed by the same letter within year and factor are not different according to Tukey's honest significant difference (HSD) test (*P* ≤0.05).. No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

Table 5.9: Influence of the interactions between termination time and herbicide strategy and cover crop and termination timing on early-summer waterhemp density prior to a POST application at two sites in Indiana.[a,b,c]

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
				Plants m^{-2}			
SEPAC	2019	Gly	Crimson clover	253	440	714	469
			Cereal rye	740	357	279	458
			Mix	432	250	369	350
		Gly + 2,4-D	Crimson clover	204	224	390	273
			Cereal rye	300	269	205	258
			Mix	245	268	220	244
		Gly + 2,4-D + residual	Crimson clover	95	171	174	147
			Cereal rye	174	219	25	139
			Mix	87	150	38	91
		Pooled	Crimson clover	184	278	426	296
			Cereal rye	740	282	169	285
			Mix	254	222	209	228
		Gly	Pooled	475 a	349 ab	454 ab	426 a
		Gly + 2,4-D		249 ab	254 ab	272 ab	258 b
		Gly + 2,4-D + residual		119 b	180 b	79 c	126 c
		Pooled	Pooled	281 a	261 ab	268 b	
DPAC	2018	Gly	Crimson clover	135	62	2	66
			Cereal rye	85	24	0	36
			Mix	66	27	0	31
		Gly + 2,4-D	Crimson clover	115	20	2	54
			Cereal rye	77	1	0	26
			Mix	50	12	0	21
		Gly + 2,4-D + residual	Crimson clover	15	8	1	8
			Cereal rye	19	0	0	6
			Mix	7	2	0	3
		Pooled	Crimson clover	88	30	1	42 a
			Cereal rye	60	8	0	23 b
			Mix	41	13	0	18 ab
		Gly	Pooled	95 a	37 ab	1 de	44 a
		Gly + 2,4-D		81 a	11 b-d	0 c-e	32 a
		Gly + 2,4-D + residual		13 bc	3 c-e	0 e	5
		Pooled	Pooled	63 a	17 b	0 c	

Table 5.9 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
DPAC	2019	Gly	Pooled	196	111	24	110 a
		Gly + 2,4-D		266	57	10	120 a
		Gly + 2,4-D + residual		21	3	1	8 b
		Pooled	Pooled	161 a	57 b	12 c	

[a]Abbreviations: SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), Gly=Glyphosate, BP=Before Planting, ATP=At Planting, and AFP=After Planting.
[b]Data were log-transformed before analysis, however untransformed mean values are presented based on the interpretation of the transformed data.
[c]Means followed by the same letter within site-year and pooled data are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

Table 5.10: Influence of cover crop, termination time and herbicide strategy on soybean yield at the at three sites in Indiana in 2018 and 2019.[a,b]

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
				kg ha^{-1}			
TPAC	2018	Gly	Crimson clover	4614 ab	4282 a-c	4573 ab	4490
			Cereal rye	4577 ab	4955 a	3013 cd	4182
			Mix	4548 a-c	3449 a-d	3761 a-d	3919
		Gly + 2,4-D	Crimson clover	4599 ab	4577 ab	4564 ab	4580
			Cereal rye	4801 a	4592 ab	2975 cd	4123
			Mix	4887 a	3893 a-d	2973 cd	3918
		Gly + 2,4-D + residual	Crimson clover	4685 a	4281 a-c	4370 a-c	4446
			Cereal rye	4451 a-c	4400 a-c	3140 b-d	3997
			Mix	4507 ab	3884 a-d	2711 cd	3701
		Pooled	Crimson clover	4633 a	4380 a	4503 a	4505 a
			Cereal rye	4577 a	4649 a	3043 b	4101 ab
			Mix	4648 a	3742 ab	3148 b	3846 b
		Gly	Pooled	4580	4229	3783	4197
		Gly + 2,4-D		4762	4354	3504	4207
		Gly + 2,4-D + residual		4548	4188	3407	4048
		Pooled	Pooled	4630 a	4257 a	3565 b	0
TPAC	2019	Gly	Crimson clover	3083	4917	4427	4143
			Cereal rye	4036	4644	4787	4489
			Mix	4074	4957	4511	4514
		Gly + 2,4-D	Crimson clover	2920	4837	4636	4131
			Cereal rye	4264	4745	4742	4584
			Mix	3922	4948	4619	4496
		Gly + 2,4-D + residual	Crimson clover	2740	4075	4220	3678
			Cereal rye	4210	4648	4730	4529
			Mix	4110	4529	4539	4393
		Pooled	Crimson clover	2914 b	4610 a	4428 a	3984 b
			Cereal rye	4036 a	4679 a	4753 a	4534 a
			Mix	4036 a	4811 a	4556 a	4468 a
		Gly	Pooled	3731	4839	4575	4382 a
		Gly + 2,4-D		3702	4843	4665	4404 a
		Gly + 2,4-D + residual		3687	4418	4496	4200 a
		Pooled	Pooled	3707 b	4700 a	4579 a	

Table 5.10 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
SEPAC	2018	Gly	Crimson clover	2872	3705	2723	3100
			Cereal rye	5153	3952	2918	4008
			Mix	4359	3437	2312	3369
		Gly + 2,4-D	Crimson clover	3704	3233	2381	3106
			Cereal rye	4771	3806	2628	3735
			Mix	4476	3699	3013	3729
		Gly + 2,4-D + residual	Crimson clover	3736	3348	1739	2941
			Cereal rye	4284	3720	2082	3362
			Mix	4254	3561	2492	3436
		Pooled	Crimson clover	3437	3429	2281	3049
			Cereal rye	5153	3826	2543	3702
			Mix	4363	3565	2606	3511
		Gly	Pooled	4128	3698	2651	3492
		Gly + 2,4-D		4317	3579	2674	3523
		Gly + 2,4-D + residual		4091	3543	2104	3246
		Pooled	Pooled	4179 a	3607 b	2476 c	
SEPAC	2019	Gly	Crimson clover	2238 ab	2538 ab	2685 ab	2487
			Cereal rye	2777 ab	2943 a	3278 a	2999
			Mix	2010 ab	1777 ab	2602 ab	2130
		Gly + 2,4-D	Crimson clover	2591 ab	892 b	2710 ab	2064
			Cereal rye	3346 a	3298 a	3114 a	3253
			Mix	1972 ab	1901 ab	2481 ab	2118
		Gly + 2,4-D + residual	Crimson clover	3051 a	1832 ab	2654 ab	2512
			Cereal rye	3082 a	3048 a	2960 a	3030
			Mix	1625 ab	1817 ab	2451 ab	1964
		Pooled	Crimson clover	2626	1754	2683	2354 b
			Cereal rye	2777	3096	3117	3094 a
			Mix	1869	1832	2511	2071 b
		Gly	Pooled	2342	2419	2855	2538
		Gly + 2,4-D		2636	2030	2768	2478
		Gly + 2,4-D + residual		2586	2232	2688	2502
		Pooled	Pooled	2521	2227	2770	

Table 5.10 Continued

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
DPAC	2018	Gly	Crimson clover	3172	3071	2781	3008 a
			Cereal rye	3474	3022	2867	3121 a
			Mix	3294	3348	3005	3216 a
		Gly + 2,4-D	Crimson clover	2846	3239	2562	2946 a
			Cereal rye	3285	3075	2652	3004 a
			Mix	3705	3536	3079	3440 a
		Gly + 2,4-D + residual	Crimson clover	3113	3385	2640	2988 a
			Cereal rye	3083	2971	2325	2793 a
			Mix	3769	3462	2979	3404 a
		Pooled	Crimson clover	3044	3232	2674	3011
			Cereal rye	3281	3023	2614	2973
			Mix	3589	3449	3021	3353
		Gly	Pooled	3313	3147	2884	3115
		Gly + 2,4-D		3279	3283	2804	3141
		Gly + 2,4-D + residual		3322	3273	2647	3058
		Pooled	Pooled	3305 a	3234 a	2785 b	
DPAC	2019	Gly	Pooled	2862	3527	4129	3506
		Gly + 2,4-D		3183	3613	4166	3654
		Gly + 2,4-D + residual		3260	3910	3915	3695
		Pooled	Pooled	3101 b	3683 ab	4070 a	

[a]Abbreviations: TPAC= Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC=South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340), Gly=Glyphosate, BP=Before Planting, ATP=AT Planting, and AFP=After Planting.
[b]Means followed by the same letter within site-year and pooled data are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

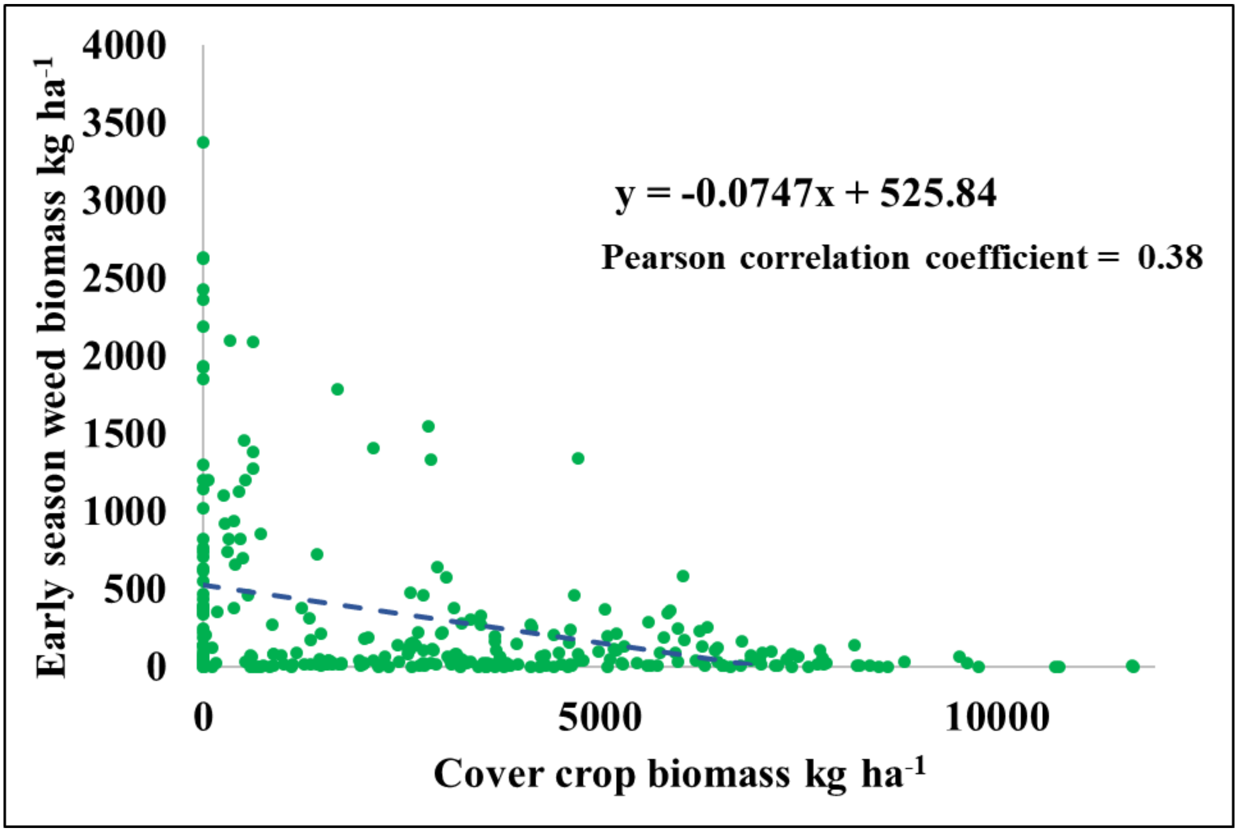

Figure 5.1: Correlation of early season (April and May) weed biomass by cover crop biomass across three sites in Indiana in 2018 and 2019. Sites included the Throckmorton Purdue Agricultural Center (TPAC, 8343 US-231, Lafayette, IN 47909), the South East Purdue Agricultural Center (SEPAC, 4425 County Rd 350 N Butlerville, IN 47223), and the Davis Purdue Agriculture Center (DPAC, 6230 N State Rd 1 Farmland, IN 47340-9340). Pearson correlation coefficient was 0.38 with a P<0.0001.

APPENDIX A- CHAPTER 2

Table A.1: Influence of year on dicot and monocot weed densities at SEPAC, and TPAC's total weed density, dicot density and monocot density from 2013 to 2019 in late-April prior to spring weed control methods.[a,b,c]

Year	SEPAC			TPAC
	Total weed species	Dicot weed species	Monocot weed species	Dicot weed species
	Plants m^{-2}			
2013	52 b	27 a	26 c	9 bcd
2014	46 bc	12 bc	35 bc	15 b
2015	27 c	5 c	22 c	1 d
2016	27 c	2 c	24 c	4 cd
2017	54 b	10 c	44 ab	12 bc
2018	81 a	23 ab	58 a	38 a
2019	45 bc	12 bc	33 bc	18 a

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

[b]Means followed by the same letter within column are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).

[c]Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown 2014, 2016, and 2018.

Table A.2: Influence of year on total, dicot, and monocot weed species richness at SEPAC, and dicot weed species richness at TPAC from 2013 to 2019 in late-April prior to spring weed control methods.[a,b,c]

Year	SEPAC			TPAC
	Total species	Dicot weed species	Monocot weed species	Dicot weed species
	Species richness m^{-2}			
2013	6 ab	4 b	2 a	2.92 ab
2014	7 a	6 b	1 b	3.63 a
2015	4 cd	3 bc	1 b	1.21 d
2016	3 d	2 c	1 b	2.00 cd
2017	3 d	2 c	1 b	1.92 d
2018	5 bc	4 b	1 b	2.13 bcd
2019	6 ab	4 b	2 a	3.04 ab

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).
[b]Means followed by the same letter within column are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$)
[c]Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown 2014, 2016, and 2018.

Table A.3: Influence of year on total and dicot weed species richness at SEPAC, and dicot weed species richness at TPAC from 2013 to 2019 in late-April prior to spring weed control methods.[a,b]

Herbicide strategy	SEPAC		TPAC
	Total weed species	Dicot weed species	Dicot weed species
	Species richness m^{-2}		
Diversified Gly	5.3 ab	4.0 a	2.0 b
2,4-D Reliant	4.8 ab	3.5 a	2.7 a
Div 2,4-D	5.4 a	4.1 a	2.6 ab
Fully Div	4.2 b	3.0 a	2.3 ab

[a]Abbreviations: Gly=glyphosate, Div=Diversified, TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

[b]Means followed by the same letter within column are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$)

Table A.4: Influence of year on dicot weed species richness at the South East Purdue Agriculture Center (SEPAC, 4425 County Rd 350 N Butlerville, IN 47223).from 2013 to 2019 in early-summer (mid-June).[a,b]

Year	Dicot weed species
	Species Richness m^{-2}
2013	6.8 a
2014	4.2 b
2015	1.3 c
2016	2.1 c
2017	1.1 c
2018	3.9 b
2019	3.8 b

[a]Means followed by the same letter are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).
[b]Corn was grown in 2013, 2015. 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

Table A.5: Influence of year on total, dicot, and monocot weed densities at the South East Purdue Agriculture Center (SEPAC, 4425 County Rd 350 N Butlerville, IN 47223) from 2013 to 2019 on soil seedbank.[a,b]

Year	All weed species	Dicot weed species	Monocot weed species
	——Plants 3000 cm^{-3}——		
2013	389 bc	161 a	229 b
2014	137 cd	57 b	80 b
2015	265 cd	156 a	109 b
2016	89 d	43 b	46 b
2017	125 cd	33 b	91 b
2018	606 ab	61 b	536 a
2019	787 a	135 a	653 a

[a]Means followed by the same letter within column are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).
[b]Corn was grown in 2013, 2015, 2017 and 2019, and soybeans were grown in 2014, 2016, and 2018.

Table A.6: Influence of year on total, dicot, and monocot weed species richness at SEPAC and dicot species richness at TPAC 2013 to 2019 on soil seedbank.[a,b,c]

Year	SEPAC			TPAC
	All weed species	Dicot weed species	Monocot weed species	Dicot weed species
	———Species richness 3000 cm^{-3}———			
2013	13.6 c	9.7 b	3.9 bc	2.1 ab
2014	11.5 d	7.5 cd	4.0 bc	1.0 b
2015	12.1 cd	8.9 bc	3.2 cd	1.5 ab
2016	8.8 e	6.0 d	2.8 d	1.5 ab
2017	10.8 d	6.5 d	4.3 b	1.7 ab
2018	16.9 b	7.8 cb	6.5 a	2.4 a
2019	19.3 a	12.9 a	6.4 a	2.0 ab

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).
[b]Means followed by the same letter within column are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).
[c]Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

Table A.7: Influence of herbicide strategy on total and monocot weed species richness at SEPAC and dicot species richness at TPAC 2013 to 2019 on soil seedbank.[a,b]

	SEPAC		TPAC
Herbicide strategy	All weed species	Monocot weed species	Dicot weed species
	——Species richness 3000 cm^{-3}——		
Diversified Gly	12.9 ab	4.5 a	1.6 ab
2,4-D Reliant	14.0 a	4.6 a	2.2 a
Div 2,4-D	13.6 ab	4.6 a	1.8 ab
Fully Div	12.6 b	4.0 a	1.2 b

[a]Abbreviations: Gly=glyphosate, Div=Diversified, TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

[b]Means followed by the same letter within columns are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).

Table A.8: ANOVA table for the influence of herbicide strategy on yield from 2013 to 2019.[a,b]

Year	TPAC	SEPAC
	P	
2013	0.4967	0.3361
2014	0.2889	0.8389
2015	<0.0001	0.0155
2016	0.4349	0.7449
2017	<0.0001	<0.0001
2018	0.9365	0.2589
2019	0.0133	0.928

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

[b]Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

Table A.9: Crop Yield from 2013 to 2019 from SEPAC near Butlerville, IN and TPAC near Lafayette, IN.[a,b]

Site	Herbicide Strategy	Year and Crop						
		2013	2014	2015	2016	2017	2018	2019
		Corn	Soybean	Corn	Soybean	Corn	Soybean	Corn
		kg ha^{-1}						
SEPAC	Diversified Gly.	6287 A	4888 A	12010 AB	4607 A	13263 B	3509 A	4813 A
	2,4-D Reliant	6063 A	5076 A	10438 B	4744 A	12923 BC	3667 A	5001 A
	Div 2,4-D	5117 A	4891 A	10582 AB	4756 A	11741 C	3190 A	5229 A
	Fully Div	5977 A	5049 A	12385 A	4974 A	15070 A	3673 A	.
TPAC	Diversified Gly	15799 a	4662 a	17149 a	5198 a	16499 a	4593 a	16027 ab
	2,4-D Reliant	15039 a	4391 a	13679 b	4997 a	13129 b	4490 a	15782 ab
	Div 2,4-D	15259 a	4792 a	13765 b	4775 a	13679 b	4605 a	15036 b
	Fully Div	15436 a	4380 a	17462 a	5042 a	16455 a	4538 a	16988 a

[a]Abbreviations: Gly= glyphosate, Div=Diversified, TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).
[b]Means followed by the same letter within year and location are not different according to Tukey's honest significant difference (HSD) test (*P* ≤ 0.05).

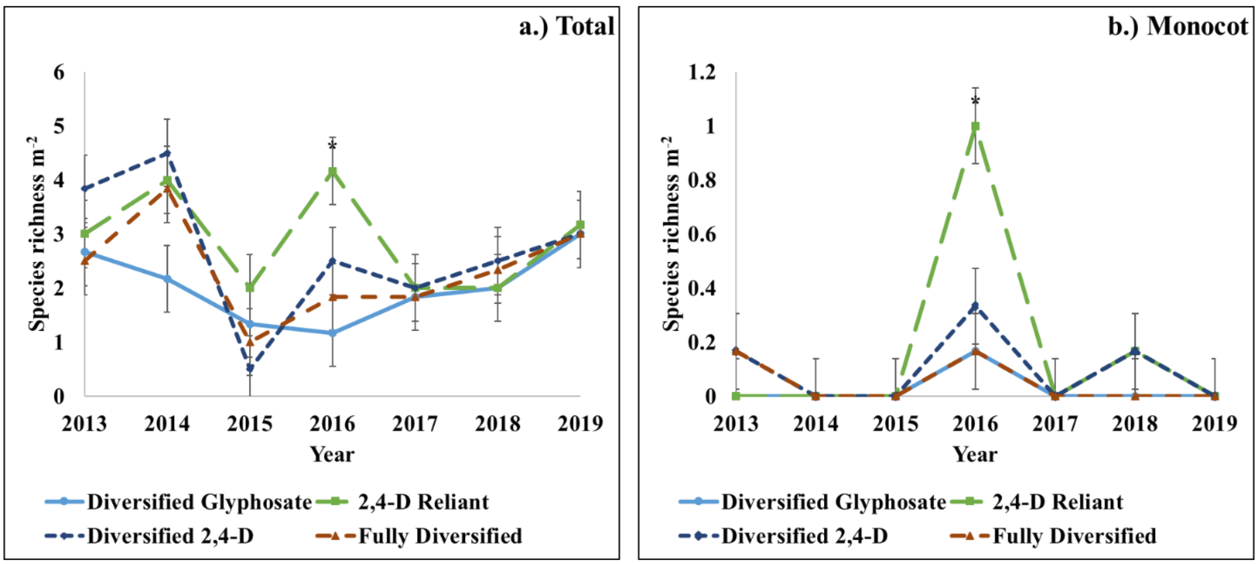

Figure A.1: a.) Total, and b.) monocot, species richness at the Throckmorton Purdue Agricultural Center (TPAC, 8343 US-231, Lafayette, IN 47909) in April. Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy prior to spring weed control. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

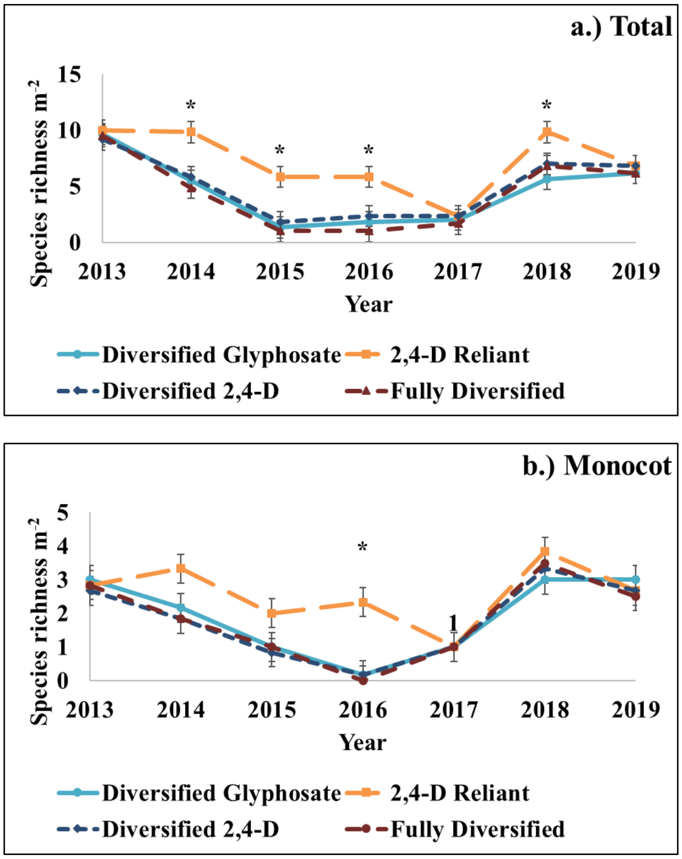

Figure A.2: a.) Total and b.) monocot weed species richness from the South East Purdue Agriculture Center (SEPAC, 4425 County Rd 350 N Butlerville, IN 47223) in mid-June. Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy in early-summer. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

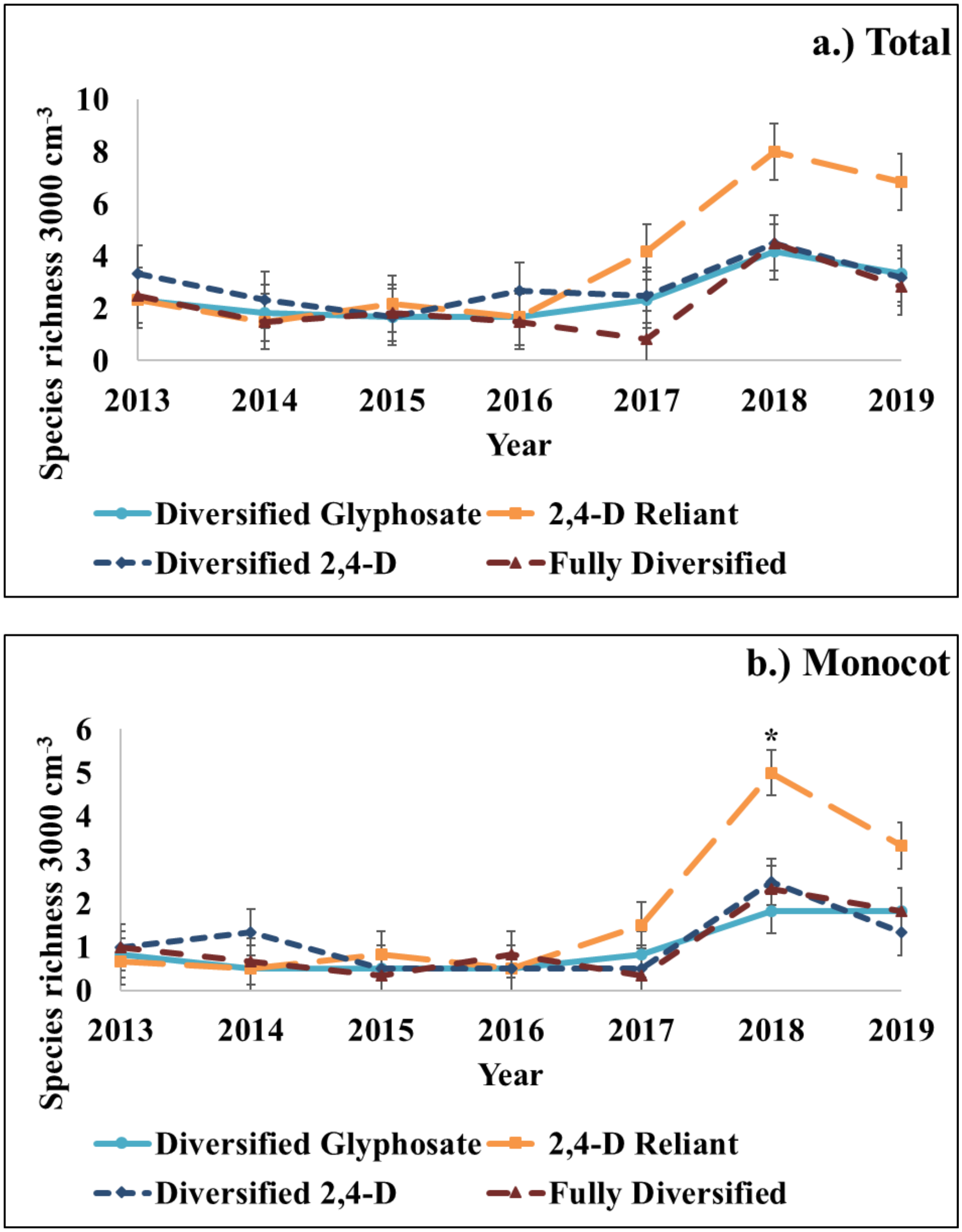

Figure A.3: a.) Total and b.) monocot weed species richness from the Throckmorton Purdue Agricultural Center (TPAC, 8343 US-231, Lafayette, IN 47909). Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy on soil seedbank. Corn was grown in 2013, 2015, 2017, and 2019 and soybeans were grown in 2014, 2016, and 2018.

APPENDIX B- CHAPTER 3

Table B.1: Influence of year on in-field total and dicot densities from 2013 to 2019 in late-April prior to spring weed control at the Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909).[a,b]

Year	Total weed species	Dicot weed species
	Plants m^{-2}	
2013	9 cd	8 cd
2014	18 b	18 b
2015	4 d	4 d
2016	8 cd	4 d
2017	13 bc	13 bc
2018	40 a	40 a
2019	14 bc	14 bc

[a]Means followed by the same letter within columns are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).
[b]Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

Table B.2: Influence of year on in-field total, dicot, and monocot weed species richness from 2013 to 2019 in late-April prior to spring weed control pooled across herbicide strategies.[a,b,c]

Year	SEPAC			TPAC		
	Total weed species	Dicot weed species	Monocot weed species	Total weed species	Dicot weed species	Monocot weed species
	——Species richness m^{-2}——					
2013	4.5 cd	3.5 cd	1 b	3.0 abc	3.0 bc	0.2 b
2014	9.0 a	7.5 a	1.5 ab	4.0 a	4.0 a	0.0 c
2015	4 d	3 d	1 b	2.0 d	2.0 d	0.0 c
2016	4 cd	3.5 d	1 b	3.0 bc	2.5 bcd	0.4 a
2017	3.5 d	2.5 d	1 b	2.0 d	2.0 d	0.0 c
2018	5.5 c	4.5 bc	1 b	2.0 cd	2.0 cd	0.0 c
2019	7 b	5.5 b	1.5 a	3.0 abc	3.0 ab	0.0 c

[a]Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

.[b]Means followed by the same letter within columns are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).

[c]Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

Table B.3: Influence of year on in-field total and monocot density pooled from 2013 to 2019 in mid-June at early-summer evaluations at the South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).[a,b]

Year	Total weed species	Monocot weed species
	——Plants m^{-2} ——	
2013	74 a	49 a
2014	57 a	44 a
2015	6 b	5 b
2016	6 b	4 b
2017	7 b	5 b
2018	80 a	67 a
2019	62 a	43 a

[a]Means followed by the same letter within columns are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).
[b]Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

Table B.4: Influence of year on in-field dicot species richness from 2013 to 2019 in mid-June at early-summer evaluations at the South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).[a,b]

Year	Dicot weed species
	Species richness m^{-2}
2013	5.8 a
2014	4.7 ab
2015	1.1 ef
2016	2.2 de
2017	0.9 f
2018	3.1 dc
2019	3.8 bc

[a]Means followed by the same letter within columns are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).
[b]Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

Table B.5: Influence of herbicide strategies on soil seedbank total, monocot, and dicot weed species richness at SEPAC and total and dicot species richness at TPAC from 2013 to 2019.[a,b,c]

Year	SEPAC			TPAC	
	Total weed species	Dicot weed species	Monocot weed species	Total weed species	Dicot weed species
	Species richness 3000 cm^{-3}				
2013	12.9 c	9.0 b	3.9 b	5.4 ab	4.8 a
2014	10.2 d	7.0 cd	3.3 b	3.7 bc	2.5 b
2015	12.3 c	9.3 b	3.1 b	4.0 bc	2.9 b
2016	7.9 e	5.8 d	2.1 c	3.4 c	2.3 b
2017	9.6 de	6.2 d	3.4 b	3.4 c	2.5 b
2018	15.4b	8.0 bc	5.7 a	6.7 a	3.2 b
2019	17.9 a	11.8 a	6.2 a	4.6 bc	2.8 b

[a] Abbreviations TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

[b]Means followed by the same letter with columns are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).

[c]Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

Table B.6: ANOVA table for the influence of herbicide strategy on yield from 2013 to 2019.[a,b]

Year	TPAC	SEPAC
	———————*P*———————	
2013	0.114	0.7122
2014	0.9598	0.427
2015	0.1735	0.7251
2016	0.8532	0.0593
2017	0.6344	0.1651
2018	0.1881	0.4899
2019	0.6354	0.3215

[a] Abbreviations: TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).

[b]Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

Table B.7: Yield data from 2013 to 2019. Soybean yield in even years and corn yield in odd years.[a,b]

Site	Herbicide Strategy	Year and Crop						
		2013 Corn	2014 Soybean	2015 Corn	2016 Soybean	2017 Corn	2018 Soybean	2019 Corn
		kg ha^{-1}						
SEPAC	Diversified Gly	7353 A	4072 A	11761 A	4333 AB	14911 A	3566 A	7957 A
	Dicamba Reliant	6880 A	4311 A	12130 A	4141 B	13086 A	3568 A	7338 A
	Div Dicamba	6953 A	4233 A	11471 A	4501 A	12564 A	3222 A	7154 A
	Fully Div	7317 A	4212 A	11679 A	4240 AB	14477 A	3611 A	.
TPAC	Diversified Gly	15189 a	4616 a	16461 a	4370 a	16008 a	4344 a	15473 a
	Dicamba Reliant	15245 a	4738 a	14468 a	4650 a	15209 a	4349 a	14624 a
	Div Dicamba	15462 a	4679 a	14675 a	4656 a	15019 a	4229 a	15688 a
	Fully Div	16273 a	4594 a	16070 a	4633 a	15522 a	3740 a	15031 a

[a]Abbreviations: Gly= glyphosate, Div=Diversified, TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223).
[b]Means followed by the same letter within year and location are not different according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$).

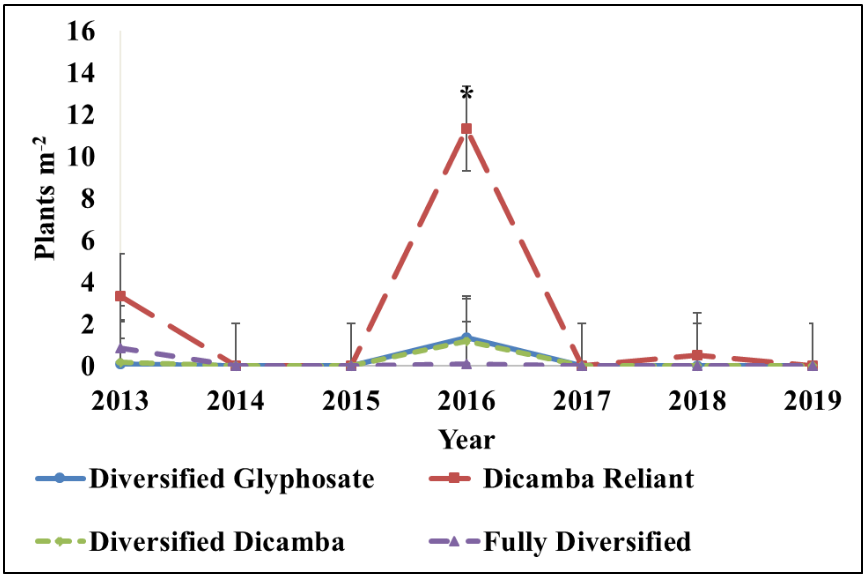

Figure B.1: Monocot densities at the Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) in late-April. Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy prior to spring weed control. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

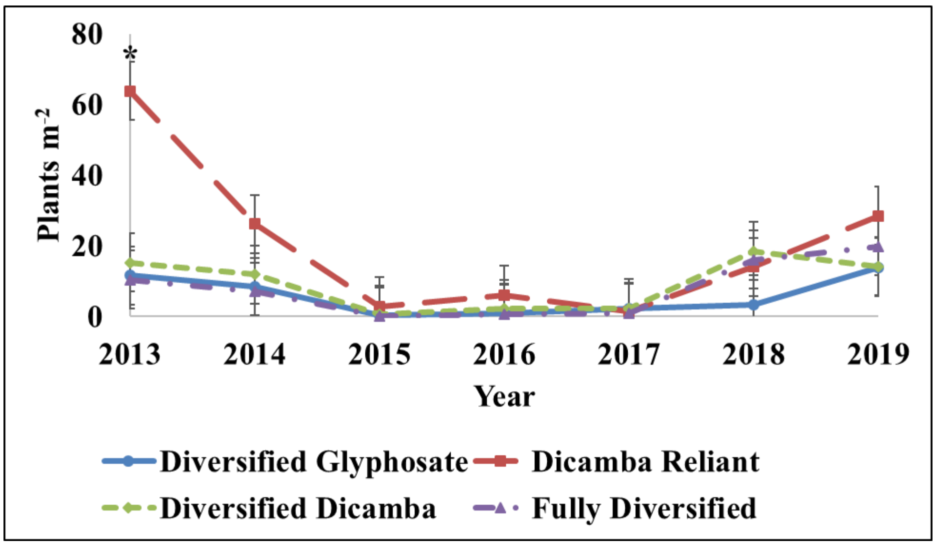

Figure B.2: In-field dicot densities at the South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223) in mid-June. Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test *(P* ≤ 0.05) within year as influenced by an interaction between year and herbicide strategy at early-summer evaluations. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

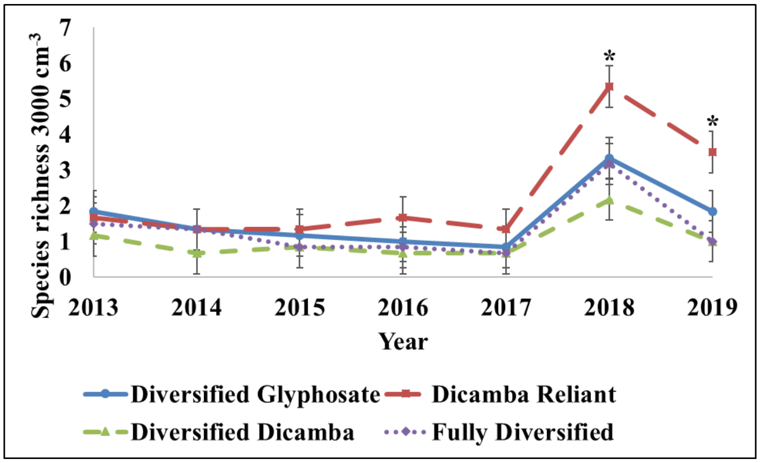

Figure B.3: Monocot species richness within the soil seedbank from the Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909). Standard error bars shown. Asterisk represents differences in mean separation according to Tukey's honest significant difference (HSD) test ($P \leq 0.05$) within year as influenced by an interaction between year and herbicide strategy. Corn was grown in 2013, 2015, 2017, and 2019, and soybeans were grown in 2014, 2016, and 2018.

APPENDIX C- CHAPTER 4

Table C.1: ANOVA table for the influence of cover crop and termination time on cover crop and weed biomass prior to cover crop termination. Weed biomass consisted of a variety of winter annual species.[a,b]

Site	Year	Variable	Cover crop	Termination timing	Cover crop x termination timing
				P	
TPAC	2018	Cover crop biomass	0.0007	<0.0001	0.3968
		Weed biomass	<0.0001	0.0036	0.0738
	2019	Cover crop biomass	0.0002	<0.0001	<0.0001
		Weed biomass	0.0565	<0.0001	0.0072
SEPAC	2018	Cover crop biomass	0.0007	<0.0001	0.0433
		Weed biomass	0.0069	<0.0001	0.6278
	2019	Cover crop biomass	<0.0001	<0.0001	0.464
		Weed biomass	<0.0001	0.7942	0.3173
DPAC	2018	Cover crop biomass	0.0129	<0.0001	0.0238
		Weed biomass	0.0004	<0.0001	<0.0001
	2019	Cover crop biomass	.	.	.
		Weed biomass	.	.	.

[a]Abbrieviations:TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340).

[b]Weeds that made up more than approximately 5% of the density combined for biomass measurements included: TPAC: chickweed (*Stellaria media* (L.) Vill.) (52%), and henbit (*Lamium amplexicuale* L.) (18%), giant ragweed (21%), SEPAC: buttercup (*Ranaunculaceae arvensis* L.) (6%), (chickweed (7%), bittercrest (*Cardamine hirsuta*) (7%), foxtail spp. (10%), horseweed (11%), field speedwell (*Veronica agrestis* L.) (17%), and annual bluegrass (Poa annua L.) (20%), DPAC: chickweed (6%), fall panicum (6%), field speedwell (16%), foxtail spp. (18%), horseweed (19%), and waterhemp (26%).

Table C.2: ANOVA table for the influence of cover crop, termination timing, and herbicide strategy and the interaction of the three on weed densities and soybean yield at Throckmorton Purdue Agricultural Center (TPAC: 8343 US-231, Lafayette, IN 47909).[a]

Factors & interactions	2018				2019			
	Grass density	Horseweed density	Giant ragweed density	Soybean yield	Grass density	Horseweed density	Giant ragweed density	Soybean yield
	P							
Cover Crop	0.0127	0.0778	0.6572	0.8585	0.7036	.	0.3552	0.0347
Termination	0.009	0.6569	0.1787	0.0001	0.0024	.	<0.0001	0.1703
Herbicide	0.0253	<0.0001	<0.0001	0.0026	0.076	.	0.0012	<0.0001
Cover Crop x Termination	0.9042	0.1639	0.6053	0.2641	0.8369	.	0.289	0.9341
Cover Crop x Herbicide	0.1671	0.0077	0.4409	0.5028	0.9761	.	0.6601	0.4812
Termination x Herbicide	0.1434	0.4333	0.1112	0.3412	0.0122	.	0.0204	0.001
Cover Crop x Termination x Herbicide	0.5883	0.0635	0.8216	0.4046	0.9065	.	0.2331	0.0422

[a]Grass species and approximate composition included large crabgrass (2%), smooth crabgrass (3%), fall panicum (15%), barnyardgrass (17%), and foxtail species (67%).

Table C.3: ANOVA table for the influence of cover crop, termination timing, and herbicide strategy and the interaction of the three on weed densities and soybean yield at the South East Purdue Agriculture Center (SEPAC: 4425 County Rd 350 N Butlerville, IN 47223).[a,b]

Factors & interactions	2018			2019			
	Grass density	Horseweed density	Soybean yield	Grass density	Horseweed density	Waterhemp density	Soybean yield
	———	———	———	*P*	———	———	———
Cover Crop	0.0069	<0.0001	0.8984	0.1155	0.0287	0.9507	0.2148
Termination	<0.0001	0.0659	<0.0001	<0.0001	0.2889	0.0449	0.3528
Herbicide	0.0319	<0.0001	0.2319	0.0004	<0.0001	<0.0001	0.1948
Cover Crop x Termination	0.0292	0.6362	0.1372	0.5935	0.2212	0.0049	0.3283
Cover Crop x Herbicide	0.5087	0.0688	0.8467	0.4545	0.3194	0.0643	0.6342
Termination x Herbicide	0.6973	0.04	0.5332	0.5475	0.0945	<0.0001	0.755
Cover Crop x Termination x Herbicide	0.8417	0.7565	0.7136	0.311	0.23	0.0085	0.3275

[a]Grass species and approximate composition included barnyardgrass (2%), large crabgrass (2%), annual bluegrass (8%), fall panicum (34%), and foxtail species (54%).
[b]Watterhemp was only present in 2019

Table C.4: ANOVA table for the influence of cover crop, termination timing, and herbicide strategy and the interaction of the three on weed densities and soybean yield at the Davis Purdue Agriculture Center (DPAC: 6230 N State Rd 1 Farmland, IN 47340-9340). Cover crop in 2019 winter killed so no cover crop interactions are presented for 2019. [a]

Factors & interactions	2018				2019			
	Grass density	Horseweed density	Waterhemp density	Soybean yield	Grass density	Horseweed density	Waterhemp density	Soybean yield
	P							
Cover Crop	<0.0001	0.0034	<0.0001	0.2337	.	.	.	.
Termination	<0.0001	0.0275	<0.0001	0.0003	0.0042	0.3422	0.0007	0.8034
Herbicide	0.5048	<0.0001	<0.0001	0.5947	0.0029	<0.0001	<0.0001	0.9288
Cover Crop x Termination	0.0105	0.0402	0.4373	0.0051	.	.	.	.
Cover Crop x Herbicide	0.9009	0.0439	0.9305	0.0004	.	.	.	.
Termination x Herbicide	0.0651	0.5403	0.0011	0.6798	0.1332	0.1411	0.0185	0.164
Cover Crop x Termination x Herbicide	0.1408	0.5048	0.3074	0.0664	.	.	.	.

[a]Grass species and approximate composition included smooth crabgrass (1%), large crabgrass (4%), foxtail species (18%), barnyardgrass (32%), and fall panicum (45%).

APPENDIX D- CHAPTER 5

Table D.1: ANOVA table for the influence of cover crop, termination timing, and the interaction of the two on cover crop and weed biomass prior to the termination of the cover crop. Weed biomass consisted of a variety of winter annual species.[a,b,c]

Site	Year	Variable	Cover crop	Termination timing	Cover crop x termination timing
				P	
TPAC	2018	Cover crop biomass	<0.0001	<0.0001	0.0433
		Weed biomass	<0.0001	0.0186	0.0719
	2019	Cover crop biomass	<0.0001	<0.0001	<0.0001
		Weed biomass	0.0489	<0.0001	<0.0001
SEPAC	2018	Cover crop biomass	<0.0001	<0.0001	0.173
		Weed biomass	0.3534	<0.0001	0.4748
	2019	Cover crop biomass	0.0003	0.09	0.0183
		Weed biomass	0.0031	0.1108	0.0122
DPAC	2018	Cover crop biomass	0.0039	<0.0001	0.9658
		Weed biomass	0.1646	<0.0001	<0.0001
	2019	Cover crop biomass	.	.	.
		Weed biomass	.	.	.

[a]Abbreviations TPAC=Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909), SEPAC= South East Purdue Agriculture Center (4425 County Rd 350 N Butlerville, IN 47223), and DPAC= Davis Purdue Agriculture Center (6230 N State Rd 1 Farmland, IN 47340-9340).
[b]DPAC in 2019 excluded due to cover crop winter-kill:
[c]Weeds that made up more than approximately 5% of the density combined for biomass measurements included: TPAC: chickweed (*Stellaria media* (L.) Vill.) (50%), henbit (*Lamium amplexicuale* L.) (17%), giant ragweed (18%), SEPAC: fall panicum (5%), cressleaf groundsel (*Packera glabella* (Poir.) C. Jeffrey) (6%), bittercrest (*Cardamine hirsuta*)(7%), horseweed (9%), field speedwell (*Veronica agrestis* L.)(15%), and annual bluegrass (Poa annua L.)(30%), DPAC: fall panicum (6%), field speedwell (11%), horseweed (28%), and waterhemp (32%).

Table D.2: ANOVA table for the influence of cover crop, termination timing, and herbicide strategy and the interaction of the three on weed densities and soybean yield at Throckmorton Purdue Agricultural Center (TPAC: 8343 US-231, Lafayette, IN 47909). [a]

Factors & interactions	2018				2019			
	Grass density	Horseweed density	Giant ragweed density	Soybean yield	Grass density	Horseweed density	Giant ragweed density	Soybean yield
	P							
Cover Crop	0.0295	0.1381	0.7131	0.0043	0.9358	0.1803	0.5032	0.0036
Termination	0.0009	0.9159	0.9516	<0.0001	0.0001	0.022	<0.0001	<0.0001
Herbicide	0.0603	0.0023	0.0073	0.1337	0.1065	0.7794	0.0018	0.033
Cover Crop x Termination	0.3662	0.9307	0.3238	0.0029	0.3056	0.1471	0.4595	0.0311
Cover Crop x Herbicide	0.7486	0.0382	0.8278	0.9206	0.1096	0.9089	0.5597	0.1543
Termination x Herbicide	0.4296	0.6811	0.4458	0.1376	0.0795	0.9089	0.4051	0.258
Cover Crop x Termination x Herbicide	0.25	0.819	0.831	0.008	0.5272	0.9795	0.979	0.8687

[a]Grass species and approximate composition included large crabgrass (2%, smooth crabgrass (3%), fall panicum (15%), barnyardgrass (17%), and foxtail species (67%).

Table D.3: ANOVA table for the influence of cover crop, termination timing, and herbicide strategy and the interaction of the three on weed densities and soybean yield at the South East Purdue Agriculture Center (SEPAC: 4425 County Rd 350 N Butlerville, IN 47223).[a,b]

Factors & interactions	2018			2019				
	Grass density	Horseweed density	Soybean yield	Grass density	Horseweed density	Waterhemp density	Waterhemp biomass	Soybean yield
	P							
Cover Crop	0.0088	<0.0001	0.051	0.5277	0.2308	0.6541	0.1056	0.0014
Termination	<0.0001	0.0385	<0.0001	<0.0001	0.0614	0.0203	<0.0001	0.1239
Herbicide	<0.0001	<0.0001	0.0881	0.0017	<0.0001	<0.0001	<0.0001	0.8708
Cover Crop x Termination	0.0011	0.3669	0.0652	0.5831	0.7081	0.9095	<0.0001	0.4261
Cover Crop x Herbicide	0.1352	0.4294	0.2164	0.0006	0.755	0.5725	0.0381	0.0791
Termination x Herbicide	<0.0001	0.0367	0.4005	0.064	0.0014	0.0002	0.0701	0.1681
Cover Crop x Termination x Herbicide	0.0019	0.4067	0.1942	0.6345	0.197	0.2579	0.6903	0.0275

[a]Grass species and approximate composition included barnyardgrass (2%), large crabgrass (2%), annual bluegrass (8%), fall panicum (34%), and foxtail species (54%).
[b]Waterhemp was only present in 2019.

Table D.4: ANOVA table for the influence of cover crop, termination timing, and herbicide strategy and the interaction of the three on weed densities and soybean yield at the Davis Purdue Agriculture Center (DPAC: 6230 N State Rd 1 Farmland, IN 47340-9340). Cover crop in 2019 winter killed so no cover crop interactions are presented for 2019. [a]

Factors & Interactions	2018				2019			
	Grass density	Horseweed density	Waterhemp density	Soybean yield	Grass density	Horseweed density	Waterhemp density	Soybean yield
	P							
Cover Crop	0.658	0.2571	0.0364	0.209	.	.	.	.
Termination	<0.0001	0.7683	<0.0001	0.0043	0.0128	0.2616	<0.0001	0.0555
Herbicide	0.0109	<0.0001	0.0001	0.9184	0.0196	0.0003	<0.0001	0.3205
Cover Crop x Termination	0.2394	0.4881	0.4808	0.5318	.	.	.	.
Cover Crop x Herbicide	0.0196	0.2769	0.8648	0.0347	.	.	.	.
Termination x Herbicide	0.0008	0.0704	0.0064	0.3478	0.2948	0.3571	0.0742	0.2426
Cover Crop x Termination x Herbicide	0.019	0.842	0.8877	0.7658	.	.	.	.

[a]Grass species and approximate composition included smooth crabgrass (1%), large crabgrass (4%), foxtail species (18%), barnyardgrass (32%), and fall panicum (45%).