EVALUATION OF WEED SUPPRESSION AND TERMINATION TIMINGS OF CEREAL RYE (SECALE CEREALE L.) AND CANOLA (BRASSICA NAPUS L.) AS WINTER COVER CROPS IN INDIANA

by

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ABSTRACT

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It is estimated that in the United States, agronomic weeds are responsible for about 50% of crop yield loss, costing nearly $27 billion each year. As interest in cover crops across the Midwest increases, so does the need to understand when to terminate cover crops for maximum weed control while still maintaining crop yield. Field experiments were conducted in 2017 and 2018 in Indiana to evaluate the effect of cover crop termination timings on weed control, and corn and soybean yield. Cereal rye (*Secale cereale* L.) and canola (*Brassica napus* L.) were subjected to early- or late- termination utilizing glyphosate-, saflufenacil- or glufosinate-based burndown herbicide programs. In corn, cereal rye and canola reduced early season weed biomass by 58 to 67% compared to fallow (no cover crop) plots. Cereal rye and canola reduced horseweed (*Erigeron canadensis* L.) and giant ragweed (*Ambrosia trifida* L.) emergence by 42 to 50% compared to fallow plots. Early- and late- terminated cereal rye reduced corn yields by 55 to 67% (5,173 to 7,116 kg ha^{-1}) compared to canola or fallow plots. In soybean, cereal rye and canola reduced early season weed biomass by 73 to 88% compared to fallow plots. Cereal rye and canola reduced horseweed emergence in 2017 and 2018 by 16 to 67 % compared to fallow plots. In 2017, both cover crop and termination timing influenced giant ragweed emergence. Early- and late-terminated cover crop plots reduced giant ragweed emergence by 50 to 76% compared to fallow plots. In 2018, cover crop termination timing influenced soybean yield. Late-terminated plots reduced yields by 48% compared to early-terminated plots. Results from this study suggest that

cereal rye and canola planted at these rates can be effective for weed suppression prior to corn and soybeans, however, yield loss in both corn and soybean is expected.

Reports from Indiana in 2015 suggested that growers planting canola as a cover crop were experiencing difficulties when terminating with glyphosate prior to corn and soybean production. This suggests the utilization of inadequate herbicide programs, or perhaps a seed contamination event containing glyphosate resistant canola. Field experiments were conducted in 2016 and 2017 to determine the most effective herbicide treatment for terminating glyphosate resistant canola in Indiana, and to quantify how these herbicide programs influence corn yield. Canola was planted in early September and herbicide treatments were applied in the spring three weeks before corn planting. Visual ratings of control and above-ground biomass reduction were collected 21 days after treatment (DAT). The highest control of canola occurred following the application of paraquat + saflufenacil + 2,4-D or metribuzin, resulting in 88 to 94% control. These control ratings are supported by applications with paraquat + saflufenacil + 2,4-D or metribuzin resulting in 88 to 97% biomass reduction. Auxin herbicides alone provided very poor control, less than 41% at both locations. In general, saflufenacil-containing herbicide treatments provided the highest control of canola compared to mesotrione or atrazine. Herbicide treatments had no effect on corn grain yield.

CHAPTER 1. LITERATURE REVIEW

1.1 Introduction

Cover crops can be linked back to ancient civilizations that depended on their use to improve soil health and increase food production. Native Americans utilized the "Three Sisters" method, where they planted corn (*Zea mays*), beans (*Phaseolus vulgaris*), and squash (*Cucurbita*) grown together, utilizing their synergistic effects (Groff, 2015). Although the use of cover crops is not a novel idea, adoption is increasing across the Midwest for soil health preservation. Government cost-shares are available for growers interested in cover crops, providing an opportunity to incorporate them into their existing farming system (NRCS 2017). Many growers that have planted cover crops have continued to do so in an attempt to improve overall soil health (Bechman 2017). It is widely accepted that cover crops provide above-ground residues (also known as green manures or living mulch) and belowground residues. These include vast root systems that help breakup soil compaction and provide organic matter when broken down by microorganisms (Abawi and Widmer 2000). These residues can reduce nutrient leaching through the soil profile, and topsoil runoff (Teasdale 1996). Although there is extensive literature on the benefits of cover crops, many studies are being conducted to better understand their functionality and optimize their use.

Cover crops utilized in the Midwest can be categorized as brassicas, grasses, legumes, and non-legumes (MCCC 2017). Common cover crop species in the Midwest include cereal rye (*Secale cereale* L.), rapeseed (*Brassica napus* L.), hairy vetch (*Vicia villosa* Roth), clover (*Trifolium* spp.), barley (*Hordeum vulgare* L.), and wheat (*Triticum aestivum* L.) (Teasdale and Mohler 1993; Johnson et al. 1998). The most common cover crops utilized in Indiana are fall-seeded cereals like rye, wheat, and annual ryegrass (CTIC 2014).

Surveys conducted by Sustainable Agriculture Research and Education (SARE) alongside Conservation Technology Information Center (CTIC) have provided information on how growers utilize cover crops, and made predictions on future cover crop adoption. In 2015, the survey showed a 25% increase in cover crop acreage compared to 2014, with a projected increase of 14% in 2016. Cereal rye was the most common cereal/grass species planted in 2016, with a total of 289,000 acres. As for canola, total acreage planted has increased from 2.7% in 2014 to 3.2% in 2015, with an estimated increase in 2016/2017. In 2018, the USDA and NRCS reported that over 900,000 acres were planted with cover crops in Indiana, the third most planted crop following corn and soybeans.

The utilization of cover crops in Indiana varies by cash crop selection, intended purpose, and tillage systems. Two types of cover crops can be planted in Indiana after harvest in the fall, cover crops that will winterkill (terminated by a hard freeze), or winter-hardy selections that can survive Indiana winters. Winterkill cover crops are popular for first time cover crop growers because they usually lack the additional termination step before cash crop planting in the spring (Myers et al. 2015). The advantage of winter-hardy cover crops is that they produce more above-ground biomass in the spring, providing more ground cover. Growers can terminate these crops by mowing, roller crimping, tillage, or by applying herbicides as a burndown. Most conventional growers utilize herbicides for cover crop termination before planting of the cash crop in the spring (Hager 2016).

Cover crop blends are gaining popularity among new and experienced growers. The 2015-2016 SARE survey reported that of the total respondents, more than 161,000 acres were planted to cover crop blends. Common blends in the Midwest usually incorporate a legume for nitrogen fixation, a cereal grain for rapid above-ground biomass production, and a brassica species for deeper soil penetration and forage. More than 180,000 acres of blends were predicted in 2016 (SARE 2015). Combinations of two to three cover crop species allows growers to fulfil multiple needs in between growing seasons.

1.2 History and Modern use of Cereal Rye

In the Midwest, cereal rye is the most widely used cover crop, with 289,068 acres planted by participants in a 2016 survey (SARE 2016). Cereal rye is a winter annual cover crop widely used throughout the Midwest because of its availability, cost efficiency, winter hardiness, high biomass production, and above-ground residue (Wilkins and Bellinder, 1996; SARE 2007). Cereal rye a winter annual cover crop typically sown in the fall after harvest, and terminated in the spring before planting a desired cash crop. It can be planted from late summer to mid-fall in the Midwest (SARE 2007). Many growers spray herbicides prior to planting, but terminating rye after flowering via mowing is also common (Mirsky et al. 2009). Most conventional farmers that use chemical termination utilize glyphosate for termination of cereal rye prior to cash crop planting. Volunteer cereal rye can occur when seed heads begin to mature before termination, or if tilled in before plants reach 20cm in height due to rapid regrowth. Regrowth is often an issue after mowing, thus many growers utilize a roller/crimper as an alternative to mowing and tillage (Mirsky et al. 2009). Adoption of cereal rye has been steadily increasing with both new and experienced cover crop growers.

1.3 History and Modern Use of Canola

Canola is a type of rapeseed developed in the 1970's through selective breeding. Unlike traditional rapeseed, the extracted oil has erucic acid levels below 2% which improves consumer safety (CCOC 2017). Much of the canola produced in the world comes from Canada, providing

$27 million dollars to their economy. States in Northern United States including North Dakota and Oklahoma grow nearly 89% of the canola produced in the country. In 2017, The United States harvested close to 2 million acres worth of canola for processing into oil and meal. Demand for canola continues to grow across the globe for its canola oil and source of high-quality feed (Canola Council 2017). The canola seed industry has invested in herbicide-resistant canola that provides additional modes of action for weed control for canola growers. The resistant varieties available on the market for growers include glufosinate, glyphosate, and imazamox resistant cultivars. These resistant varieties provide additional weed control options for farmers growing canola for its oil and meal production. While canola is valuable on its own as a monoculture crop, it can also be valuable in a cover crop rotation. In the Midwest, rapeseed/canola is promoted as a beneficial cover crop for its alleged allelopathic effects and nitrogen scavenging abilities. Innovative growers are planting canola for ground cover, weed control, and as an addition to their forage/grazing operations (SARE 2007). Canola is a part of the *Brassicaceae* family, in which many of the species have a thick taproot. The thick taproot helps break up compact soils while helping to prevent erosion. Winter-hybrid canola varieties are usually hardier, taller, develop greater biomass, and are more suppressive to weeds than traditional cultivars (Harker et al. 2003, Zand and Beckie 2002). Canola is most commonly terminated by tillage or herbicide application. Suggested herbicide programs include glyphosate, 2,4-D, dicamba, and other common corn herbicides such as atrazine or saflufenacil. In Tennessee, both glyphosate and glufosinate resistant varieties have been found in some cover crop blends, resulting in failed termination prior to a desired cash crop (McClure et al., 2017). Complete termination of canola is important, as rape volunteers can be a persistent problem in a desired cash crop if not terminated completely. Regrowth from persistent stems take only a few days to regenerate, and if allowed to go to seed, can remain dormant in the soil seed bank for years (Simard et al. 2002). Rapeseed/canola can provide great benefits for existing farming rotations. However, if used as a cover crop, it should be terminated completely utilizing the most effective herbicide programs so as to prevent canola from becoming a problematic weed in future years.

1.4 Cover Crop Contributions to Farming Systems

Cover crops have the potential to provide many benefits to agronomic cash crop systems. These benefits vary depending on the selected cover crop, management, and cash crop productivity (Liebl et al. 1992). For growers thinking about incorporating a cover crop into their rotation, it is important to understand that cover crops provide variable results depending on the environment from year to year. Cover crops can provide long-term benefits to soils, including but not limited to: increasing soil tilth, soil moisture capacity, microbial life, reducing nutrient runoff and soil erosion, supplying nitrogen, and providing some level of pest control (Clark et al. 2008, Teasdale 1996, Strock et al. 2004).

1.4.1 Improved soil physical properties

The pioneering purposes of cover crops after World War II were for soil erosion control, compaction reduction, and preventing fertilizer runoff (Groff, 2015). Winter cover crops provide canopy cover through normally fallow months, preventing movement of topsoil from strong winds or heavy rains, while the residues provide organic matter after termination (Kaspar et. al, 2001). Bulk density, a measure of water holding capacity and porosity, is an important factor in soil quality (Dam et al. 2004). Porosity can be increased by promoting infiltration rates by additional residues on the soil surface (Reeves, 1994). Cover crop residues and roots provide organic matter after termination. Soil microorganisms break down those plant residues, ultimately increasing bulk density (Kladivko, 1994).

Soil aggregation can be described by the size, density, and overall stability of soil aggregates, which ultimately determine overall susceptibility to erosion (Jury and Horton, 2004). Aggregate stability is important for reducing soil erosion and increased rooting potential. Soils with good aggregation also have increased water rentention and increased aeration (Clark, 2007). Cereal rye has a fibrous root system that can provide a path for water infiltration and reduce soil compaction (Liebl et al. 1992, Reeves, 1994). Forage radish has a thick taproot, providing 15-50cm of soil penetration. Some cover crops are better for reducing soil compaction, for example Chen and Weil (2009) reported that in heavily compacted soils, forage radish roots were not impacted by the presence of heavily compacted soils, compared to cereal rye roots that were severely reduced. In addition, cover crop roots provide structural support and increase soil aggregation (Chan, 2011).

1.4.2 Nutrient management

Phosphorous (P) and nitrogen (N) are two plant nutrients of great concern in the Eastern Corn Belt, that have the potential to leach from the soil into surrounding waterways. They are both crucial for high end of season yields in corn and soybean rotations. Cover crops can retain both nitrogen and phosphorus, thus reducing losses in the winter or early spring (Kaspar and Singer, 2011). Research shows that cereal rye is great scavenger of remaining soil N after corn harvest (Staver and Brinsfield, 1990). Cereal rye plants store soil nitrogen instead of leaching into drainage tiles and eventually, waterways. Non-leguminous cover crops have been reported to take up 12 to 117 kg N ha^{-1} a year, but more commonly 25 to 50 kg N ha^{-1} (Wagger and Mengel, 1988; Shennan, 1992). Cereal rye was shown to take up more N than other small grain cover crops in Maryland

(Brinsfield and Staver, 1998). Legume cover crops fix nitrogen as they grow, providing accessible nitrogen directly to the soil after termination. The fixed nitrogen mineralizes in the soil and becomes available(Rosecrance, 2000). Hairy vetch has been documented to provide 100 kg N ha^{-1} prior to corn as a best-case scenario (Ebelhar 1982), while clover can fix upwards of 50-200 kg N ha^{-1} depending on the species and the growing conditions (Torbert 1996).

1.5 Weed Suppression by Cover Crops

As mentioned previously, 28% of growers in a 2014 survey reported that they expect some level of weed control from cover crops (SARE & CTIC). Cover crops can provide weed suppression by inhibiting weed seed germination, or by slowing the growth of emerged weed seedlings. Cover crops limit light and nutrient availability through competition, delay weed seed germination by slowing soil warming, and reduce weed emergence by producing allelochemicals (Davis and Liebman 2003, Shearin et al. 2008, Teasdale 1993).

1.5.1 Competition

Cover crops can suppress emerged weeds by competing with weeds for light, water, nutrients, ultimately smothering weeds with above-ground residue (Weston 1996). Tall and fast growing cover crops, such as cereal grasses, are most competitive with weeds for light interception. Cereal rye, a common cover crop used in the Midwest, accumulates a large amount of above- and below-ground biomass, providing ideal residues for weed suppression (Liebert et al 2017). Cover crops provide the greatest weed control when they remain on the top of the soil as a residue (Teasdale et al., 1996; Wortman et al., 2013). This residue layer shades the soil surface, lowering or maintaining the soil temperature, therefore delaying germination of light and temperature sensitive weed species. These crops accomplish suppression by inhibiting small weed cotyledons or by preventing weed seed germination altogether (Teasdale, 1996). Residues of many cover crop species can provide effective weed control, but they must be managed carefully to not reduce crop yield (Johnson et al.1993). It is important to note that when a cover crop can provide enough biomass to inhibit light transmission, early season weed control is expected, although cover crops terminated in the spring may not provide complete weed control later in the growing season (Teasdale, 1996).

1.5.2 Allelopathy

Cereal rye and various rapeseed varieties release allelopathic compounds. Allelopathy is the secretion of secondary plant metabolites, which can discourage plant growth and inhibit germination (Creamer et al. 1996). Although research to on the effects of allelopathy on weed control has been done, results are highly variable. Teasdale (1996) demonstrated that allelopathic effects from cover crops are rarely consistent and/or reproducible in field studies. Brassicas provided 23 to 24 % control of weed management in a field study, but had no apparent advantages to other commonly utilized cover crops (Haramoto and Gallandt, 2005). Research also showed that rye and sorghum-sudangrass (*Sorghum bicolor* L.) hybrids, in addition to subterranean clover (*Trifolium subterraneum* L.) and rapeseed provided significant levels of weed control (Putnam and Tang 1986, Boydston and Hang 1995, Singh 2005). Cereal rye can effectively outcompete small-seeded, light sensitive annuals including redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), foxtail (*Setaria* spp.), horseweed, henbit (*Lamium amplexicaule* L.), and chickweed (*Stellaria media* L.). Sensitivity to cereal rye's allelopathic residues depend on weed species. Greenhouse experiments in 1994 resulted in horseweed germination inhibition up to 50% by greenhouse grown cereal rye roots, while little to no inhibition was seen on barnyardgrass (*Echinochloa crus-galli* L. P. Beauv.) (Przepiorkowski and Gorski, 1994). Results using winter cover crops for their allelopathic properties alone are variable and unpredictable; suggesting that further research and investigation is needed.

1.6 Challenges of Cover Crops

Although the benefits of using cover crops for sustainable agriculture and improving environmental quality are widely known, there are challenges to consider when incorporating them into existing rotations. The addition of an extra crop or blend of crops to these systems complicates the management of operations. For some growers, establishment and over wintering of cover crops into established corn and soybean fields can be an issue (Johnson et al. 1998, Wilson et al. 2013). As mentioned before, cereal rye provides many benefits, but there can be some adverse consequences associated with their addition to a cropping system. Cereal rye can affect corn growth and yield by immobilizing nitrogen, and from allelopathic remains in the plant residues on the soil surface (Johnson et al. 1998, Krueger et al. 2011). Cover crops have a negative impact on cash crop development by decreasing spring soil temperatures, slowing germination, and reducing emergence by light interception and increased soil shading from above-ground biomass. Corn germination is highly influenced by soil temperature (Schneider and Gupta, 1985). The longer the seed remains in cool soils before emergence, the more at risk it is to soil diseases and insects, and the greater the risk of non-uniform stands. Delayed germination influences total growing degree-days, which possibly reduces cash crop yields (Schneider and Gupta, 1985).

Water availability in the soil is influenced by the presence of cover crops (Liebl et al. 1992, Krueger at al. 2011). When weather warms up and plant growth is at its peak, cover crop transpiration may accelerate soil water loss. However, this could be beneficial in areas with high early spring rainfall and in soils where proper drainage is an issue (Kaspar and Singer, 2011). Despite promising water conservation during the fallow period, cover crops can reduce soil moisture levels on the surface and deeper water reserves which could severely affect cash crop growth and yields (Daigh et. al., 2014; Krueger et. al., 2011).

1.7 Justification of Research

According to Kansas State in 2016, if weeds were left uncontrolled, estimate costs upwards of $43 billion would be lost in corn and soybean rotations in United States and Canada. In 2013 a SARE/CTIC survey reported that the fourth highest reason for planting cover crops was to improve weed control. In a 2014 survey, 28% of farmers utilizing cover crops expected some level of weed control from the cover crop they incorporated into their cropping system (SARE). Cover crops can be an important tool in weed control by changing the environment of a cropping system to benefit a cash crop, but they can be problematic when incorporating them into an existing farming operation if not properly managed. Growers interested in utilizing cover crops commonly have questions regarding cover crop selection and termination.

In 2014, 48% of growers used herbicides to terminate their cover crops before planting their cash crop (SARE and CTIC). For growers that use winter-hardy varieties, successful termination in the spring before planting of the desired cash crop is crucial. Cover crops that escape termination have the potential to become a weed during the following growing season, and cover crop mismanagement has the potential to reduce cash crop yield (Tonitto et al 2005). While there are many benefits in using cover crops, just as many challenges exist to incorporate these crops into a farming system. There is a growing need to quantify yield loss from failed terminations, and to determine the most effective herbicide programs for terminating cover crops grown in the Midwest.

1.8 Summary and Objectives

While cover crops can help improve soil health, many growers question the weed control aspect of cover crops. The increased interest in cover crops in Indiana has raised questions regarding the potential for yield loss given a failed cover crop termination, as well as potentially introducing glyphosate resistant canola into corn and soybean fields. Conventional corn and soybean growers who use a chemical approach, terminate their existing cover crops with applications at different times in the spring. It is important to quantify how these different termination timings influence corn and soybean yield. Growers that use cover crops for weed control are in search of a better understanding of how the presence of these plants influence winter and summer weed emergence is needed. The objectives of this research are to: 1) evaluate suppression of winter and summer annual weeds from cereal rye and canola, 2) quantify how corn and soybean yields are influenced by cover crop termination timing, and, 3) determine the most effective herbicide programs for termination of glyphosate resistant canola in Indiana.

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CHAPTER 2. EFFECT OF CEREAL RYE AND CANOLA ON WINTER AND SUMMER ANNUAL WEED EMERGENCE IN CORN

2.1 Abstract

It is estimated that in the United States, agronomic weeds are responsible for about 50% of crop yield loss, costing nearly $27 billion each year (Soltani et al. 2017). As interest in cover crops across the Eastern Cornbelt increases, so does the need to understand when to terminate cover crops for maximum weed control while still maintaining crop yield. Field experiments were conducted in 2017 and 2018 in Indiana to evaluate how cover crop, herbicide treatment, and termination timing influence winter and summer annual weed suppression and impact corn yield. Each cover crop block included an early- and late- termination timing with a glyphosate or glufosinate based herbicide program. Cereal rye (*Secale cereale* L.) and canola (*Brassica napus* L.) reduced early season weed biomass by 58 to 67% compared to fallow (no cover crop) plots. Cereal rye and canola reduced horseweed (*Erigeron canadensis* L.) and giant ragweed (*Ambrosia trifida* L.) emergence by 42 to 50% compared to fallow plots. Early- and late- terminated cereal rye reduced corn yields by 55 to 67% (5,173 to 7,116 kg ha^{-1}) compared to canola or fallow plots. Results from this study suggest that cereal rye and canola planted at these rates can be effective for weed suppression prior to corn, however, yield loss can be expected in years with ideal growing conditions.

2.2 Introduction

In recent years, cover crops have increased in popularity across the Eastern Cornbelt. Winter and summer annual weed species can reduce corn and soybean yield (Creech 2007, Pimentel et al. 2005), and two of the most problematic weeds in Indiana include horseweed

(*Erigeron Canadensis* L.) and giant ragweed (*Ambrosia trifida* L.) (Gibson et al. 2005). For weed control, recommended cover crops include winter hardy varieties that produce substantial above-ground biomass. Cereal rye (*Secale cereale* L.), from the grass category and canola, (*Brassica napus* L.) a rapeseed in the brassica category, are two winter hardy varieties promoted in Indiana as beneficial cover crops.

One objective of this study was to evaluate how cereal rye and canola contribute to winter and summer annual weed suppression. Creech et al. (2008) reported that an annual ryegrass (*Lolium multiflorum* L.) as a cover crop did little to suppress winter annual weeds including henbit (*Lamium amplexicuale* L.) and purple deadnettle (*Lamium purpureum* L.). However, in late spring, Werle et al. (2017) reported that cereal rye provided >90% reduction of winter annual weed densities and biomass. Late-spring termination of cover crops results in more above-ground biomass than termination in early spring. Mirsky et al. (2011) reported that delaying termination of cereal rye by 9 days increased above-ground biomass by up to 40%. Early spring cover crop termination may not provide complete weed control later in the season, when many summer annuals germinate (Teasdale 1996). Webster et al. (2013) reported that cereal rye reduced Palmer amaranth (*Amaranthus palmeri* S. Watson) densities more than 40% in cotton, but crop yield loss was still observed due to later season weed emergence.

Giant ragweed is a large-seeded broadleaf in the Asteraceae family that germinates in Indiana from March through August, and grows rapidly to heights of 183 cm in soybeans to 274 cm in corn (Johnson et al. 2007). Each plant can produce up to 5,100 seeds, which can persist in the soil seedbank for years. Its summer annual life cycle requires POST applications following an effective pre-plant herbicide program, and it must be sprayed between 10 to 15 cm for maximum herbicide efficacy (Legleiter et al. 2015). This is a very small window as giant ragweed develops above-ground biomass rapidly. Giant ragweed has tolerance to some very long chain fatty acid inhibiting (group 15) herbicides, and resistance to both ALS (group 2) herbicides and glyphosate (group 9), further limiting herbicide options for giant ragweed control.

Horseweed is a member of the Asteraceae family, and considered both a winter and summer annual weed in Indiana. Horseweed is persistent in two ways: it can germinate in the fall and survive through winter as a rosette until early spring when it bolts, or in germination in the spring, finishing its life cycle as a summer annual (Regehr and Bazzaz 1979, Weaver 2001, Davis and Johnson 2008). Once horseweed bolts, it can survive multiple herbicide applications in the spring. Horseweed can produce anywhere from 200,000 to 500,000 seeds per plant (Kruger et al. 2009) and its small seeds germinate near the surface of the soil. Increased utilization of no-till crop production strategies, and the introduction of glyphosate resistant soybean in 1996, have increased horseweed prevalence across the Midwest (Davis 2008, CTIC 2004). Herbicide resistance in horseweed has been documented in 6 site of action groups including, bipyridiliums (group 22), ureas and amides (group 7), photosystem II inhibitors (groups 5 & 6), EPSP synthase inhibitors (group 9), and acetolactate synthase (ALS, group 2) inhibitors (Heap, 2019). Diversifying herbicide programs with multiple modes of action, crop rotation, and more than one herbicide application in a season have been documented to help with herbicide resistance (Davis et al. 2007, 2009a). Therefore, many growers trying to utilize non-GMO soybeans are restricted to limited herbicides options and tillage for weed control. Many are now exploring cover crops as another source of weed control.

The second objective in our study was to quantify how termination timing of cover crops impacts corn grain yield. Both cereal rye and canola can be problematic if not effectively terminated before cash crop planting. Cover crops can suppress cash crops by competing for light, water, nutrients, with above-ground residue (Weston 1996). Cereal rye is more efficient at immobilizing nitrogen compared to other cover crop species (Staver and Brinsfield 1998). This is beneficial in the fall to prevent nutrient leaching into rivers and lakes. Cereal rye continues to immobilize nitrogen in the spring that is needed for the following cash crop. Corn is sensitive to cold, moist soils in early spring (Schneider and Gupta 1985) and both cereal rye and canola's dense canopy reduces far red light from penetrating to the soil, potentially delaying soil drying and cash crop germination. While cereal rye termination is successful with glyphosate alone, cover crops from the Brassicaceae family are more tolerant to herbicide applications. More than one mode of action is recommended for control of Brassicaceae cover crop species. Additionally, reports in 2015 suggested that cover crop mixes with canola/rapeseed had glyphosate-resistant seed contamination, thus requiring more than just glyphosate as a burndown. A failed rapeseed termination allows regrowth and potential volunteers, which can be detrimental to cash crop yield. As a result, two objectives for this experiment were to evaluate how cover crop, termination timing, and herbicide treatment influence winter and summer annual weed suppression and corn grain yield.

2.3 Materials and Methods

2.3.1 Site description and field plot design

Field trials were initiated in 2016 and 2017 at the Throckmorton Purdue Agricultural Center near Lafayette, IN and at the Southeastern Purdue Agricultural Center near Butlerville, IN. The Lafayette location had a silty clay loam soil type with 3.0% organic matter and an average pH of 6.8. The Butlerville location had a silt loam soil type with 1.5% organic matter and an average pH of 6.4. Both sites had common winter annual weed species including horseweed, chickweed [*Stellaria media* (L.) Vill.], henbit (*Lamium amplexicaule* L.), and purple deadnettle (*Lamium* *purpureum* L.). Common summer annual weeds included giant ragweed, morningglory (*Ipomoea* spp.), and various grasses including yellow and giant foxtail [*Setaria pumila* (Poir.) Roem. & Schult., *Setaria faberi* Herrm.], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], goosegrass [*Eleusine indica* (L.) Gaertn.], and fall panicum (*Panicum dichotomiflorum* Michx.*)*. Giant ragweed was the predominant weed species at the Lafayette location, while horseweed was the predominant weed species at the Butlerville location. Trials were implemented utilizing a split plot design, with cover crop (cereal rye, canola, or none) as the whole plot factor, and termination timing and herbicide treatment as subplot factors. Plot dimensions at both sites were 3 wide by 8m in length. Monthly rainfall and mean air temperature at both sites during the 2016 to 2018 growing seasons can be found in Table 2.1.

2.3.2 Planting and crop management

Prior to trial initiation in the fall, applications of 840 g ai ha^{-1} of paraquat (Gramoxone SL. 2.0, Syngenta Crop Protection) were made in order to control any vegetation present. On September 21, 2016 and September 26, 2017 cereal rye and canola were no-till planted at both locations. A winter hardy, conventional canola variety (Baldur), was mixed with .03% glyphosate resistant canola (STAR 915W), in order to simulate seed contamination, and the mixture was planted at a rate of 6 kg ha^{-1} on 76 cm rows using a 4.5 m drill. Cereal rye was seeded at 90 kg ha^{-1} using 4.5 m drill for maximum weed suppression. Cover crop aboveground biomass growth can be found in Table 2.5. The following spring, cover crops were terminated with two burndown treatments at two termination timings. Herbicide treatments were applied at an early- or late-termination timing, relative to soybean planting date. Early- terminated occurred two weeks before soybean planting, and late termination occurred two weeks after soybean planting. Herbicide programs were selected for each cover crop species in order to achieve effective termination. A complete list of herbicides, treatment list, and timing of applications can be found in Tables 2.2 - 2.4. Corn was planted at the Lafayette site on May 30, 2017 and May 8, 2018, and at Butlerville on May 10, 2017 and May 14, 2018. Glyphosate- and glufosinate-resistant corn (SmartStax, DKC62-08RIB) was planted in 76 cm rows at a 5 cm depth at a seeding rate of 80,000 seeds ha^{-1}. Each plot consisted of 4 rows of corn. On July 2, 2017 and July 6, 2018 corn was side-dressed with liquid UAN (28-0-0) at the V6 growth stage at a rate of 168 kg N ha^{-1}. Plots were maintained weed-free via a post-emergence application of atrazine (1.1 kg ai ha^{-1}) + glyphosate (1.1 kg ai ha^{-1}) + dicamba (0.56 kg ai ha^{-1}) + topramezone (0.018 kg ai ha^{-1}) on July 15, 2017 and hand weeding. All treatments were applied with a CO2-pressurized backpack sprayer equipped with a 3-m boom and XR11002 nozzles calibrated to deliver 140 L ha^{-1} at 138 kPa. Dates of all major field operations can be found in Table 2.4.

2.3.3 Data collection

Winter and summer annual weed densities were recorded by counting individual plants within two 0.25 m^2 quadrat, one placed in the front and one in the back of each plot. Winter annual weed densities were recorded before cover crop termination each year, and summer annual weed emergence was recorded prior to a late season POST application. Weed above-ground biomass was collected in 0.25 m^2 quadrats placed in the front and back of the plot by clipping the plants at the soil surface and placing them in paper bags at initial cover crop termination and prior to the POST application. Cover crop biomass was recorded by clipping all plants at the soil surface within a 0.25 m^2 quadrat in each plot at termination timing and placing in paper bags. The paper bags that contained plant material were stored in a forced air driers set at 50 C for one week and dry weights were recorded. The center two corn rows within each plot were harvested, grain weighed, and corrected to 15.5% moisture.

2.3.4 Statistical analysis

Data were subjected to analysis of variance (ANOVA) using the PROC GLM and PROC GLIMMIX procedures in SAS (Version 9.3, SAS® Institute Inc., Cary, NC 27513). All data were checked for normality and tested for appropriate interactions. For normality, weed biomass was transformed using a square root transformation. Analysis of variance was used to test for significant main effects and interactions. Means were separated at the 0.05 level of significance using Tukey’s Honest Significant Difference (HSD) test. Above-ground weed biomass, horseweed density, giant ragweed density, and corn yield data were analyzed. Cover crop species, herbicide treatments, and termination timing were fixed effects. Replication was considered a random effect. Due to a significant interaction of year and termination timing ($P < 0.0001$), likely resulting from differences in early season rainfall and planting dates, data are separated by year.

2.4 Results and Discussion

2.4.1 Total weed biomass

Above-ground weed biomass was collected at an early-season timing (initial cover crop termination) and again at POST application, 28 days after the original treatment. The early-season weed density consisted of henbit, purple deadnettle, common chickweed and horseweed. The POST application collection contained more summer annual weed species including giant ragweed, morninglory, and various grasses including yellow and giant foxtail, large crabgrass, goosegrass, and fall panicum. Using a cover crop was significant in weed biomass reduction in 2017 and 2018 (Table 2.6). In both years, fallow (no cover crop) treatments had 14 to 20 more g m^{-2} of above-ground weed biomass compared to the plots with cereal rye and canola at the initial termination timing (Table 2.6). This equates to 58 to 67% in total weed biomass reduction with a cereal rye or canola cover crop compared to no cover crop. This early-season timing contained mostly winter annual weed species at both locations. Weed biomass collected at the POST application timing consisted of early emerging summer annual weeds that were primarily at the cotyledon stage. Cover crop plots reduced above-ground weed biomass by 20% in 2017 and by 37% in 2018 compared to plots with no cover crop.

2.4.2 Influence of cover crop and termination timing on horseweed density

A cover crop by termination timing interaction was observed with horseweed density in 2017 ($P = 0.0002$) (Table 2.7). In 2017, plots containing cereal rye and canola had 69 to 84 less horseweed plants m^{-2} than plots with no cover crop at the late termination timing (Table 2.7). This equates to 63 to 77% horseweed density reduction compared to the plots with no cover crop at the late termination timing. Looking at cover crop as a main effect, plots with no cover crop had up to 56 more horseweed plants m^{-2}, or 67% more horseweed than plots with cereal rye and canola. Differences in cover crop main effect ($P = 0.2381$) were not observed in 2018. Cover crops in 2017 had greater above-ground biomass than in 2018 due to heavy rains that delayed cover crop termination (Table 2.5). Above-ground biomass competition of cover crops is considered one of the most crucial aspects for weed control (Teasdale 1996), thus resulting in less early-season weed control in 2018.

Due to the fact that horseweed germinates through late June or July (Kruger et al. 2010), horseweed densities were evaluated prior to POST application. Cover crop as a main effect reduced horseweed density in both 2017 ($P= 0.0116$) and 2018 ($P = 0.0016$) (Table 2.7). Both cereal rye and canola plots reduced horseweed density compared to fallow plots by 22 plants m^{-2}, which equates to an 88% reduction (Table 2.7). Cover crop residues can reduce weeds by physical suppression acting as a mulch (Teasdale 2000), and this POST application timing utilizes physical suppression for extended weed control throughout the season. While there are less horseweed present in cover cropped plots, it is critical to have complete weed control to prevent weeds from going to seed and remaining a problem for future years.

Results from these data suggest that cereal rye and canola as a cover crop have the potential to reduce horseweed density. However, termination of cover crops is very weather dependent and it is critical to let the cover crop grow as long as possible without causing corn yield loss, if weed control is one of the objectives of using cover crops.

2.4.3 Influence of cover crop and termination timing on giant ragweed density

A cover crop by termination timing interaction was observed with giant ragweed density in 2017 ($P = 0.0139$) at our POST application timing (Table 2.8). Late- terminated fallow plots had the highest densities of giant ragweed. Evaluating cover crop as a main effect ($P = 0.0027$), giant ragweed was reduced in cereal rye and canola plots by 10 to 15 plants m^{-2} compared to plots with no cover crop (Table 2.8). This equates to a 43 to 65% reduction of giant ragweed in plots with a cover crop compared to fallow plots. Termination timing ($P = <0.0001$) as a main effect with cover crops terminated at the late- termination timing suppressed weeds by 50% compared to the early- termination timing (Table 2.8). This is due to more above-ground cover crop biomass providing a thicker mulch layer once terminated that remains on the soil surface, suppressing weed seed germination and subsequent growth. The main effect of cover crop was significant in 2018 as well ($P = 0.0101$), suppressing 42% of giant ragweed plants m^{-2} in cover crop plots compared to fallow plots (Table 2.8). Differences in termination timing were not observed in 2018, but herbicide treatment ($P = 0.0040$) was significant in giant ragweed control. The utilization of glyphosate suppressed 52% more giant ragweed plants m^{-2} than plots sprayed with glufosinate (Table 2.8).

Giant ragweed seeds tend to germinate in late June through the warmest summer months (Johnson et al. 2007), and at the first termination timing on May 12, 2017 and April 24, 2018 no significant density differences were observed. Later in the season at POST application timings, significant differences were observed underneath cover crop residues compared to fallow areas with bare soil, explaining why more differences in giant ragweed termination occurred later in the season.

2.4.4 Corn grain yield

A cover crop by termination timing interaction was observed in corn grain yield in 2018 ($P = <0.001$) (Table 2.9). Corn yield was highest in early- terminated fallow (no cover crop) plots, and lowest in late- terminated cereal rye plots. Late- terminated cereal rye reduced yields by 55 to 67% (5,173 to 7,116 kg ha^{-1}), compared to canola or fallow plots (Table 2.9). However, early- terminated cereal rye only reduced yields by 19% (2,995 kg ha^{-1}) compared to canola or fallow treatments. Fallow plots yielded 1,139 kg ha^{-1} more than canola plots, and 4,593 kg ha^{-1} more than cereal rye plots. These data suggest that both early- and late- terminated cereal rye compromises corn yield; however, in years with poor weather conditions, canola prior to corn has little impact on corn yields. In 2017, cover crop and termination timing influenced corn grain yield ($P = <0.0001$); however, there was no interaction between cover crop and termination timing ($P = 0.541$). Cereal rye plots reduced corn yields by 32% (3,393 kg ha^{-1}) compared to canola plots or fallow plots. Early terminated plots increased corn grain yield by 22% (1,910 kg ha^{-1}) or more compared to the late termination timing. Herbicide treatment had no influence on corn grain yield in 2018 or 2017 ($P = 0.6463$, 0.1534 respectively).

2.4.5 Summary

This research suggests that cereal rye and canola planted at these rates have potential to suppress winter and summer annual weed biomass and density. Early-season weed biomass was reduced in plots with cereal rye and canola compared to fallow plots. However, yield reductions in cereal rye and canola plots suggest that at these planting rates and these termination timings, that they should not be used prior to corn. Cereal rye was planted at 90 kg/ha^{-1}, the highest suggested rate in the Midwest Cover Crops Field Guide (MCCC 2014), resulting in very high above-ground biomass. Nonetheless, an integrated weed control approach that includes cover crop residues and effective herbicide programs can delay or reduce winter and summer annual weeds.

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Table 2.1. Monthly rainfall (mm) and average monthly temperatures (C) in comparison to the 30-yr average[a] in 2016, 2017, and 2018 at the Throckmorton Purdue Agricultural Center (TPAC) in Lafayette, IN and the Southeastern Purdue Agricultural Center (SEPAC) in Butlerville, IN.

	Rainfall				Temperature			
Month and Location	2016	2017	2018	30 y. Avg.	2016	2017	2018	30 y. Avg.
	mm				C			
TPAC								
January	-	92	30.5	46.74	-	-0.4	-6	1
February	-	39.9	84.1	40.1	-	4.1	-7.7	4
March	-	92	26.7	73.41	-	5.3	3.9	10
April	-	113.3	61.94	87.63	-	13.3	7.2	17
May	-	213.1	58.4	99.8	-	15.7	22.3	23
June	-	109.7	86.11	107.7	-	22.1	29.4	28
July	-	251.7	40.3	97.77	-	23.3	29.1	30
August	-	52.6	51.2	99.31	-	24.8	27.8	29
September	158.5	39.9	68.3	69.9	21.3	19.9	20.1	13
October	38.4	119.9	85.3	69.6	14.9	14.6	10.2	6
November	68.6	147.8	44.7	71.37	8.4	5.4	3.3	1
December	36.8	15.5	49.3	65.3	-1.8	-9.9	-12.1	-5
SEPAC								
January	-	96.3	59.44	75.4	-	3.1	-3.3	2.2
February	-	67.8	144.3	68.8	-	7.5	5	3.7
March	-	145.3	107	95.5	-	8.3	-2	6.1
April	-	146.3	102.1	111	-	16.3	5.1	14
May	-	173.5	31.6	119.9	-	17.6	28.3	19.9
June	-	176.8	23.4	97	-	21.5	30	27.5
July	-	99.3	128.8	112.3	-	24.1	30.6	27.2
August	-	53.3	12.7	112.4	-	22	32.8	28.1
September	94.23	73.7	136.4	73.4	21.6	20	23.3	24
October	106.7	115.3	22.86	81	16.8	14.6	21.1	15.8
November	44.7	165.6	35.4	97.28	9.5	7.3	7.2	9.7
December	71.37	172.5	99.8	86.36	0.4	0.3	10	3.4

[a] 30-yr averages (1981-2010) obtained from National Climatic Data Center (2019).

Table 2.2. Sources of chemicals used for termination of cover crops.

Herbicide[a]	Trade Name	Formulation[b]	Rate	Manufacturer	Address
			kg ai or ae ha^{-1}		
atrazine	Aatrex	4 L	1.1	Syngenta	Greensboro, NC
dicamba	Clarity	4 L	0.56	BASF	Research Triangle, NC
glufosinate	Liberty	280 SL	0.594	Bayer CropScience	Research Triangle Park, NC
glyphosate	Roundup PowerMax	4.5 L	1.120	Monsanto	St. Louis, MO
saflufenacil	Sharpen	2.85 L	0.025	BASF	Research Triangle, NC
mesotrione	Callisto	4 L	0.11	Syngenta	Greensboro, NC
topramezone	Impact	2.8 L	0.018	AMVAC	Newport Beach, CA

[a] AMS and MSO were included per label recommendation.
[b] Abbreviations: L, liquid.

Table 2.3. Herbicide treatments applied at two termination timings of cover crops in 2017 and 2018 at the Throckmorton Purdue Agricultural Center in Lafayette, Indiana and the Southeastern Purdue Agricultural Center in Butlerville, Indiana.

Termination Timing[a]	Cereal Rye	Canola	None[b]
2 WBP	Gly[c]	Safl	Gly
	Gluf	Gluf	Gluf
2 WAP	Gly	Gluf + meso + atraz	Gly
	Gluf	Gly + meso + atraz	Gluf

[a] Termination timings of cover crop prior to cash crop planting. Abbreviations: 2WBP, two weeks before planting cash crop; 2WAP, two weeks after planting cash crop.
[b] None indicates no cover crop planted, natural vegetation only.
[c] Herbicides applied. Abbreviations: Gly, glyphosate; Safl, saflufenacil; Gluf, glufosinate; Meso, mesotrione; and Atraz, atrazine.

Table 2.4. Dates of major field operations and herbicide applications in 2017 and 2018 at the Throckmorton Purdue Agricultural Center in Lafayette, Indiana and the Southeastern Purdue Agricultural Center in Butlerville, Indiana.

	Year and Date of Operation		
Location and Field Operation [a]	2016	2017	2018
Throckmorton Purdue Ag Center			
Corn seeding date	-	5/30	5/8
Dates of herbicide application:			
Early CC termination (2WBP)	-	5/12	4/26
Late CC termination (2WAP)	-	6/14	5/22
POST application	-	6/22	6/10
Cover crop seeding date	9/22	9/26	-
Southeastern Purdue Ag Center			
Corn seeding date	-	5/10	5/14
Dates of herbicide application:			
Early CC termination (2WBP)	-	4/24	4/30
Late CC termination (2WAP)	-	5/31	5/29
POST application	-	6/12	6/4
Cover crop seeding date	9/21	9/22	-

[a] Abbreviations: CC, cover crop; 2WBP, two weeks before corn grain planting; 2WAP, two weeks after corn grain planting; POST, post application of herbicide after initial burndown.

Table 2.5. Cover crop above-ground biomass (kg ha^{-1}) and height (cm) at the time of termination in Lafayette and Butlerville, Indiana.

	Lafayette				Butlerville			
	Dry Weight		Height		Dry Weight		Height	
Cover Crop[a]	2017	2018	2017	2018	2017	2018	2017	2018
	——kg ha^{-1}——		——cm——		——kg ha^{-1}——		——cm——	
Cereal Rye								
2 WBP	3134	2348	107	30	2124	2193	100	34
2 WAP	3920	3621	152	137	3158	2993	152	137
Canola								
2 WBP	2782	1583	100	26	2845	1429	94	31
2 WAP	3124	3110	132	91	3724	3814	126	86

[a] Abbreviations: 2 WBP, two weeks before corn grain planting; 2 WAP, two weeks after corn grain planting.

Table 2.6. Influence of cover crop on total weed biomass[a] collected prior to cover crop termination and our POST application at the Throckmorton Purdue Agricultural Center and the Butlerville Purdue Agricultural Center.

	2017 Total weed biomass		2018 Total weed biomass	
	Termination[b]	POST	Termination	POST
	g/m^{-2} [cd]			
Cover Crop				
Cereal Rye	2 a	2 a	3 a	1 a
Canola	4 a	3 ab	9 b	3 ab
None	18 b	4 b	25 b	4 b
P Value	0.0002	0.0476	0.0003	0.0339

[a] Total weed biomass includes winter and summer annual species present at time of collection.

[b] Termination indicates initial herbicide burndown either two weeks before or after planting corn grain.

[c] Means within a column followed by the same letter are not statistically different at the 0.05 probability level as determined by Tukey HSD.

[d] Data were square-root transformed and backtransformed for presentation.

Table 2.7. Influence of cover crop and termination timing on horseweed density prior to cover crop termination and our POST application at the Southeastern Purdue Agricultural Center in Butlerville, Indiana.

	Horseweed density			
	2017	2018	POST ‘17	POST ‘18
	Plants m^{-2}			
Cover crop				
Cereal Rye	32 a	82 a	3 a	6 a
Canola	27 a	65 a	16 b	12 a
None	83 b	106 a	25 c	25 b
P value	0.0011	0.2381	0.0116	0.0016
Termination timing[a]				
Early	42 a	85 a	17 a	16 a
Late	53 a	84 a	12 a	11 a
P value	0.0839	0.9345	0.0897	0.0906
Treatment[b]				
Glyphosate	51 a	86 a	16 a	15 a
Glufosinate	44 a	83 a	13 a	12 a
P value	0.3047	0.8373	0.2862	0.2630
Cover crop*termination timing				
Cereal rye*early	40 a	98 a	3 a	9 a
Cereal rye*late	25 a	67 a	3 a	3 a
Canola*early	30 a	57 a	21 b	14 ab
Canola*late	25 a	73 a	10 ab	11 a
None*early	57 a	98 a	27 b	26 b
None*late	109 b	115 a	23 b	24 b
P value	0.0002	0.2007	0.2738	0.8045

[a] Early: herbicide application applied 2 weeks before corn planting; Late: herbicide application applied 2 weeks after corn planting.

[b] Burndown application with glyphosate or glufosinate based program. Canola terminated at the late termination timing included mesotrione and atrazine with the glyphosate and glufosinate programs. A complete list of herbicides applied in Table 2.3.

Table 2.8. Influence of cover crop and termination timing on giant ragweed density prior to cover crop termination and our POST application at the Throckmorton Purdue Agricultural Center in Lafayette, Indiana.

	Giant ragweed density			
	2017	2018	POST ‘17	POST ‘18
	Plants m^{-2}			
Cover crop				
Cereal Rye	17 a	25 a	8 a	9 a
Canola	29 a	41 a	13 a	10 a
None	33 a	40 a	23 b	21 b
P value	0.0834	0.1333	0.0027	0.0101
Termination timing[a]				
Early	28 a	38 a	10 a	13 a
Late	24 a	32 a	20 b	13 a
P value	0.4064	0.3182	<0.0001	0.9019
Treatment[b]				
Glyphosate	27 a	35 a	16 a	17 a
Glufosinate	26 a	34 a	13 a	9 b
P value	0.8752	0.9607	0.0733	0.0040
Cover crop*termination timing				
Cereal rye*early	18 a	23 a	3 a	9 ab
Cereal rye*late	15 a	27 a	12 ab	8 a
Canola*early	35 a	29 a	11 ab	10 ab
Canola*late	23 a	33 a	15 b	11 ab
None*early	32 a	29 a	13 ab	21 b
None*late	34 a	31 a	32 c	21 b
P value	0.5805	0.3525	0.0139	0.8208

[a] Early: herbicide application applied 2 weeks before corn planting; Late: herbicide application applied 2 weeks after corn planting.

[b] Burndown application with glyphosate or glufosinate based program. Canola terminated at the late termination timing included mesotrione and atrazine with the glyphosate and glufosinate programs. A complete list of herbicides applied in Table 2.3.

Table 2.9. Influence of cover crop, termination timing and herbicide treatment on corn grain yield in 2017 and 2018 at the Throckmorton and Southeastern Purdue Agricultural Centers.

	Corn Grain Yield	
	November 7, 2017	October 31, 2018
	kg/ha^{-1}	
Cover crop		
Cereal Rye	7238 a	10497 a
Canola	9897 b	13951 b
None	10631 b	15090 c
P value	< 0.0001	<0.0001
Termination timing[a]		
Early	10397 a	14134 a
Late	8113 b	12224 b
P value	< 0.0001	< 0.0001
Herbicide treatment[b]		
Glyphosate	9330 a	13395 a
Glufosinate	9181 a	12964 a
P value	0.6463	0.1534
Cover crop*termination timing		
Cereal rye*early	8614 c	12557 c
Cereal rye*late	5861 d	8436 d
Canola*early	11001 ab	14294 ab
Canola*late	8793 c	13609 bc
None*early	11575 a	15552 a
None*late	9687 bc	14627 ab
P value	0.5471	< 0.001

[a] Early: herbicide application applied 2 weeks before corn planting; Late: herbicide application applied 2 weeks after corn planting.
[b] Burndown application with glyphosate or glufosinate based program. Canola terminated at the late termination timing included mesotrione and atrazine with the glyphosate and glufosinate programs. A complete list of herbicides applied in Table 2.3.

CHAPTER 3. EFFECT OF CEREAL RYE AND CANOLA BIOMASS ON WINTER AND SUMMER ANNUAL WEED EMERGENCE IN GLUFOSINATE-RESISTANT SOYBEAN

3.1 Abstract

Field experiments were conducted in 2017 and 2018 in Indiana to evaluate the effect of cover crop termination timings on winter and summer annual weed control and soybean yield. Cereal rye (*Secale cereale* L.) and canola (*Brassica napus* L.) were subjected to early- or late- termination (two weeks before or after planting) utilizing glyphosate-, saflufenacil- or glufosinate-based burndown herbicide programs on glufosinate-tolerant soybeans. Cover crop biomass was highest when terminated two weeks after planting soybean. Cereal rye and canola reduced early season weed biomass by 73 to 88% compared to fallow (no cover crop) plots. Cereal rye and canola reduced horseweed (*Erigeron canadensis* L.) emergence in 2017 and 2018 by 16 to 67 % compared to fallow plots. In 2017, both cover crop and termination timing influenced giant ragweed (*Ambrosia trifida*) emergence. Early- and late- terminated cover crop plots reduced giant ragweed emergence by 50 to 76% compared to fallow plots. Cover crop termination timing did not influence soybean yield.

3.2 Introduction

Herbicide resistant weeds continue to be problematic for soybean producers. Glufosinate-resistant soybeans were released for commercialization in 2009 and adoption has grown since glufosinate is an effective herbicide for glyphosate- and ALS-resistant weeds. (Wiesbrook et al. 2001, Beyers et al 2002). While glufosinate resistance has only been documented in Italian ryegrass [*Lolium perenne* ssp. *multiflorum* (Lam.) Husnot] on the west coast (Heap 2019, Avila-Garcia et al. 2011), utilizing diversified weed control methods are imperative to preventing herbicide-resistant weeds. Cover crop use has increased across the Eastern Cornbelt in recent years for their soil health benefits and potential weed control. There are currently four different categories of cover crops farmers can select from including brassicas, legumes, non-legumes, and grasses (MCCC 2014). For maximum weed control, winter hardy cover crops that produce substantial above-ground biomass are most commonly used. Cereal rye (*Secale cereale* L.), from the grass category and canola, (*Brassica napus* L.) a rapeseed in the brassica category, are two winter hardy varieties promoted in Indiana as beneficial cover crops.

In organic soybean production systems, the most commonly used methods for cover crop termination include tillage and roller crimping, providing successful termination prior to soybean planting (Mirsky et al. 2011). In soybean production, reduced or no tillage strategies limit weed control methods for control of difficult herbicide resistant weeds including horseweed. In Indiana, two of the most problematic weeds include horseweed (*Erigeron canadensis* L.) and giant ragweed (*Ambrosia trifida* L.), contributing to problems in both traditional tillage and reduced tillage crop production (Gibson et al. 2005, Nice et al. 2005). Horseweed is a member of the Asteraceae family, and considered both a winter and summer annual weed in Indiana. Horseweed is persistent in two ways: it can germinate in the fall and survive through the winter as a rosette until early spring when it bolts, or germinate in the spring, finishing its life cycle as a summer annual (Regehr and Bazzaz 1979, Weaver 2001, Davis and Johnson 2008). Once horseweed bolts, it can survive multiple herbicide applications in the spring. Horseweed can produce anywhere from 200,000 to 500,000 seeds per plant (Kruger et al. 2009) and its small seeds germinate near the surface of the soil. Increased utilization of no-till crop production strategies, and the introduction of glyphosate-resistant soybean in 1996, have increased horseweed prevalence across the Midwest (Davis 2008, CTIC 2004). Herbicide resistance in horseweed has been documented in 6 site of action groups including, bipyridiliums (group 22), ureas and amides (group 7), photosystem II inhibitors (groups 5 & 6), EPSP synthase inhibitors (group 9), and acetolactate synthase (ALS, group 2) inhibitors (Heap, 2019). Diversified weed management practices including multiple herbicide modes of action, crop rotation, and more than one herbicide application in a season have been documented to help with herbicide resistance (Davis et al. 2007, 2009a).

Giant ragweed is a large-seeded, summer annual broadleaf in the Asteraceae family that germinates in Indiana from March through August, and grows rapidly to heights of 183 cm in soybeans to 274 cm in corn (Johnson et al. 2007). Each plant can produce up to 5,100 seeds, which can persist in the soil seedbank for years. As few as one giant ragweed plant per 110 square feet has been shown to reduce soybean yields by up to 50% (Johnson et al. 2007). Giant ragweed requires POST applications following an effective pre-plant herbicide program. It must be sprayed between 10 to 15 cm for maximum herbicide efficacy (Legleiter et al. 2015), which is a very short window for producers as giant ragweed develops above-ground biomass rapidly. Giant ragweed populations have developed resistance to both ALS (group 2) herbicides and glyphosate (group 9), further limiting herbicide options for giant ragweed control in soybeans (Heap 2019).

While there are many benefits to cover crops, challenges exist when incorporating into an established cropping system. Cover crops have been reported to cause similar problems of weed pressure in the early season (Mirsky et al. 2014, Fisk et al. 2001), and can be troublesome to control if not effectively terminated before cash crop planting. Cover crops can suppress cash crops by competing for light, water, nutrients, with above-ground residue (Weston 1996). Cereal rye is more efficient at immobilizing nitrogen compared to other cover crop species (Brinsfield and Staver 1998). While this can be beneficial in preventing nutrient leaching into public waterways, it can immobilize nitrogen in the spring, reducing nitrogen availability for early season crop growth.

Soybean seeds take twice as long to germinate in temperatures below 24 C (Egli et al. 1973), and both cereal rye and canola's dense canopy reduces far red light from penetrating to the soil, potentially delaying soil warming and cash crop germination. Cover crops high mulch residues can also cause soybean lodging in no-tillage fields (Wells et al.2014). While chemical termination of cereal rye can be easily done with glyphosate alone (Price et al. 2009), cover crops from the Brassicaceae family are more tolerant to herbicide applications. More than one mode of action is recommended for control of Brassicaceae cover crop species. Additionally, reports in 2015 suggested that cover crop mixes with canola/rapeseed were contaminated with glyphosate-resistant seed, thus requiring more than just glyphosate as a burndown. A failed rapeseed termination allows regrowth and future volunteers, which can be detrimental to soybean yield. As a result, the two objectives for this experiment were to evaluate how cover crop, termination timing, and herbicide treatment influence on weed suppression and soybean grain yield.

3.3 Materials and Methods

3.3.1 Site description and field plot design

Field trials were initiated in 2016 and 2017 at the Throckmorton Purdue Agricultural Center near Lafayette, IN and at the Southeastern Purdue Agricultural Center near Butlerville, IN. The Lafayette location had a silty clay loam soil type with 3.0% organic matter and an average pH of 6.8. The Butlerville location had a silt loam soil type with 1.5% organic matter and an average pH of 6.4. Both sites had common winter annual weed species including horseweed, chickweed [*Stellaria media* (L.) Vill.], henbit (*Lamium amplexicaule* L.), and purple deadnettle (*Lamium purpureum* L.). Common summer annual weeds included giant ragweed, morningglory (*Ipomoea* spp.), and various grasses including yellow and giant foxtail [*Setaria pumila* (Poir.) Roem. & Schult., *Setaria faberi* Herrm.], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], goosegrass

[*Eleusine indica* (L.) Gaertn.], and fall panicum (*Panicum dichotomiflorum* Michx.*)* Giant ragweed was the predominant weed species at the Lafayette location, while horseweed was the predominant weed species at the Butlerville location. Trials were implemented utilizing a split plot design, with cover crop (cereal rye, canola, or none) as the whole plot factor, and termination timing and herbicide treatment as subplot factors. Plot dimensions at both sites were 3 wide by 8m in length. Monthly rainfall and mean air temperature at both sites during the 2016 to 2018 growing seasons can be found in Table 3.1.

3.3.2 Planting and crop management

Prior to trial initiation in the fall, applications of 840 g ai ha^{-1} of paraquat (Gramoxone SL. 2.0, Syngenta Crop Protection) were made in order to control any vegetation present. On September 21, 2016 and September 26, 2017 cereal rye and canola were no-till planted at both locations. A winter hardy, conventional canola variety (Baldur), was mixed with .03% glyphosate resistant canola (STAR 915W), in order to simulate seed contamination, and the mixture was planted at a rate of 6 kg ha^{-1} on 76 cm rows using a 4.5 m drill. Cereal rye was seeded at 90 kg ha^{-1} using 4.5 m drill for maximum weed suppression. Cover crop above-ground biomass growth can be found in Table 3.5. The following spring, cover crops were terminated with two burndown treatments at two termination timings. Herbicide treatments were applied at an early- or late-termination timing, relative to soybean planting date. Early- terminated occurred two weeks before soybean planting, and late termination occurred two weeks after soybean planting. Herbicide programs were selected for each cover crop species in order to achieve effective termination. A complete list of herbicides, rates, and timing of applications can be found in Tables 3.2, 3.3, and 3.4. Soybean was planted at the Lafayette site on May 30, 2017 and May 8, 2018, and at Butlerville on May 10, 2017 and May 14, 2018. Glufosinate-resistant soybean (LibertyLink, CZ2915LL) was planted in 38 cm rows at approximately 350,000 seeds ha^{-1}. Each plot consisted of 4 rows of soybean. Plots were maintained weed-free via a post-emergence application of glufosinate (0.594 kg ai ha^{-1}) + chloransulam-methyl (0.0353 kg ai ha^{-1}) + clethodim (0.136 kg ai ha^{-1}) on July 15, 2017 and hand weeding. All treatments were applied with a CO2-pressurized backpack sprayer equipped with a 3-m boom and XR11002 nozzles calibrated to deliver 140 L ha^{-1} at 138 kPa. Dates of all major field operations can be found in Table 3.4.

3.3.3 Data collection

Winter and summer annual weed densities were recorded by counting individual plants within two 0.25 m^2 quadrat, one placed in the front and one in the back of each plot. Winter annual weed densities were recorded before cover crop termination each year, and summer annual weed emergence was recorded prior to a late season POST application. Weed above-ground biomass was collected in 0.25 m^2 quadrats placed in the front and back of the plot by clipping the plants at the soil surface and placing them in paper bags at initial cover crop termination and prior to the POST application. Cover crop biomass was recorded by clipping all plants at the soil surface within a 0.25 m^2 quadrat in each plot at termination timing and placing in paper bags. The paper bags that contained plant material were stored in a forced air driers set at 50 C for one week and dry weights were recorded. The center two soybean rows within each plot were harvested, grain weighed, and corrected to 13% moisture.

3.3.4 Statistical analysis

Data were subjected to analysis of variance (ANOVA) using the PROC GLM and PROC GLIMMIX procedures in SAS (Version 9.3, SAS® Institute Inc., Cary, NC 27513). All data were checked for normality and tested for appropriate interactions. Analysis of variance was used to test for significant main effects and interactions. For normality, weed biomass was transformed using a square root transformation. Means were separated at the 0.05 level of significance using Tukey's Honest Significance Difference (HSD) test. Above-ground weed biomass, horseweed density, giant ragweed density, and soybean yield data were analyzed. Cover crop species, herbicide treatments, and termination timing were fixed effects. Replication was considered a random effect. Due to a significant interaction of year and termination timing ($P < 0.0001$), likely resulting from differences in early season rainfall and planting dates, data are separated by year.

3.4 Results and Discussion

3.4.1 Total weed biomass

Above-ground weed biomass was collected at an early-season timing (initial cover crop termination) and again at POST application, 28 days after the original treatment. The early-season weed density consisted of henbit, purple deadnettle, common chickweed and horseweed. The POST application collection contained more summer annual weed species including giant ragweed, morninglory, and various grasses including yellow and giant foxtail, large crabgrass, goosegrass, and fall panicum. Cover crop was significant in weed biomass reduction in 2017 and 2018 (Table 3.6). In 2017, plots with cereal rye and canola reduced above-ground weed biomass by 16 g m^{-2} compared to the fallow (no covercrop) treatments (Table 3.6). In 2018, plots with cereal rye and canola at both termination timings reduced above-ground weed biomass by 35 g m^{-2} compared to the fallow treatments (Table 3.6). This equates to 85 to 88% weed biomass reduction with a cereal rye or canola cover crop compared to no cover crop. This early-season timing contained mostly winter annual weed species at both locations. Weed biomass collected at the POST application timing consisted of early emerging summer annual weeds that were primarily at the cotyledon stage. In the POST collection timing, cover crop plots reduced above-ground weed biomass by 50% in 2017 and by 25% in 2018 compared to plots with no cover crop.

3.4.2 Influence of cover crop and termination timing on horseweed density

Cover crop as a main effect was significant in 2017 and 2018 (P = 0.0068, 0.0384 respectively). In 2017, plots with no cover crop had up to 44 more horseweed plants m^{-2}, or 70% more horseweed than plots with cereal rye and canola. In 2018, plots with no cover crop had up to 56 more horseweed plants m^{-2}, or 48% more horseweed than plots with cover crops.

Horseweed densities were evaluated prior to the POST application considering that horseweed germinates through late June or July (Kruger et al. 2010). Use of cover crops reduced horseweed density in both 2017 (P= 0.0035) and 2018 (P = 0.0396) (Table 3.7). Both cereal rye and canola plots reduced horseweed density compared to fallow plots from 4 to 14 plants m^{-2}, which equates to a 17 to 64% reduction (Table 3.7).

3.4.3 Influence of cover crop and termination timing on giant ragweed density

A cover crop by termination timing interaction was observed with giant ragweed density in 2017 at the initial termination and at the POST application timing (P = 0.0338, 0.0382 respectively) (Table 3.8.). At the initial termination, early- terminated cereal rye plots had the lowest densities of giant ragweed. At the POST evaluation timing, early- and late- terminated fallow plots had the highest densities of giant ragweed, with 10 to 18 more plants per $m\text{-}^{2}$ compared to cereal rye or canola plots. Giant ragweed was reduced in cereal rye and canola plots by 11 to 12 plants m^{-2} compared to plots with no cover crop (Table 3.8). This equates to a 73 to 80% reduction of giant ragweed in plots with a cover crop compared to fallow plots. Late- termination timing suppressed weeds by 42% compared to the early- termination timing (Table 3.8). This is due to more above-ground cover crop biomass providing a thicker mulch layer once terminated that remains on the soil surface, suppressing weed seed germination and subsequent growth. In 2018, use of cover crops suppressed 24 to 63% of giant ragweed plants m^{-2} in cover crop plots compared to fallow plots (Table 3.8). Differences in termination timing were not observed in 2018, however herbicide treatment (P = 0.0034) influenced giant ragweed control. The utilization of glyphosate controlled 33% more giant ragweed plants m^{-2} than plots sprayed with glufosinate (Table 3.8).

3.4.4 Soybean grain yield

In 2017, cover crop as a main effect influenced soybean grain yield (P = <0.0001), however, there was no interaction between cover crop and termination timing (P = 0.5288) (Table 3.9). Cereal rye plots reduced soybean yields by 17% (650 kg ha^{-1}) compared to fallow plots. A cover crop by termination timing interaction was observed in soybean grain yield in 2018 (P = <0.0018) (Table 3.9). Soybean yield was highest in early- terminated fallow (no cover crop) plots, and lowest in late- terminated fallow plots. Cover crop as a main effect was not significant (P = 0.6158), however, timing was significant (P = 0.0203). Late- terminated plots reduced yields by 52% compared early- terminated plots (Table 3.9). Cereal rye and canola plots did not reduce yields significantly compared to fallow plots in 2018. Herbicide treatment had no influence on soybean grain yield in 2018 or 2017 (P = 0.9133, 0.0203 respectively). These data suggest that cover crops can compromise soybean yield, but early termination can prevent yield loss.

3.4.5 Summary

This research suggests that cereal rye and canola have potential to suppress winter and summer annual weed biomass and density. Early-season weed biomass was reduced in plots with cereal rye and canola compared to fallow plots. Although differences in weed density were not influenced by termination timing, there was a delay in the number of days until 10-cm weeds were established. Similar results were reported by Montgomery et al. 2017, in dicamba tolerant soybeans, hairy vetch (*Vicia villosa* Roth) and wheat (*Triticum aestivum* L.) did not control Palmer amaranth compared to treatment or timing, but they did delay palmer growth to 10-cm in height by a few days. For winter annual weed control, timing of cover crop termination is not critical; however, for summer annual weed control, later termination timings reduce summer annual weed emergence. Nonetheless, an integrated weed control approach that includes cover crop residues and effective herbicide programs can delay or reduce winter and summer annual weeds. Cover crop residues can reduce weeds by physical suppression acting as a mulch (Teasdale 1996, 2000), and this POST application timing utilizes physical suppression for extended weed control throughout the season.

In 2018, ideal weather conditions provided greater yields than in 2017. In more favorable weather conditions, termination timing was significant, resulting in yield differences up to 48% compared to early- and late- terminated plots. However, in 2017, termination timing did not reduce soybean yields. Montgomery et al. 2017 also reported that soybean yields were not influenced by termination timing. In 2016 Kansas State University (Shoup et al. 2017) reported that no soybean yield differences were found between the check or cover crop treatments. Results from these data suggest that cereal rye and canola as a cover crop have the potential to reduce winter and summer annual weed density, however, depending on weather conditions, yield loss may occur.

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Table 3.1. Monthly rainfall (mm) and average monthly temperatures (C) in comparison to the 30-yr average[a] in 2016, 2017, and 2018 at the Throckmorton Purdue Agricultural Center (TPAC) in Lafayette, IN and the Southeastern Purdue Agricultural Center (SEPAC) in Butlerville, IN.

	Rainfall				Temperature			
Month and Location	2016	2017	2018	30 y. Avg.	2016	2017	2018	30 y. Avg.
	mm				C			
TPAC								
January	-	92	30.5	46.74	-	-0.4	-6	1
February	-	39.9	84.1	40.1	-	4.1	-7.7	4
March	-	92	26.7	73.41	-	5.3	3.9	10
April	-	113.3	61.94	87.63	-	13.3	7.2	17
May	-	213.1	58.4	99.8	-	15.7	22.3	23
June	-	109.7	86.11	107.7	-	22.1	29.4	28
July	-	251.7	40.3	97.77	-	23.3	29.1	30
August	-	52.6	51.2	99.31	-	24.8	27.8	29
September	158.5	39.9	68.3	69.9	21.3	19.9	20.1	13
October	38.4	119.9	85.3	69.6	14.9	14.6	10.2	6
November	68.6	147.8	44.7	71.37	8.4	5.4	3.3	1
December	36.8	15.5	49.3	65.3	-1.8	-9.9	-12.1	-5
SEPAC								
January	-	96.3	59.44	75.4	-	3.1	-3.3	2.2
February	-	67.8	144.3	68.8	-	7.5	5	3.7
March	-	145.3	107	95.5	-	8.3	-2	6.1
April	-	146.3	102.1	111	-	16.3	5.1	14
May	-	173.5	31.6	119.9	-	17.6	28.3	19.9
June	-	176.8	23.4	97	-	21.5	30	27.5
July	-	99.3	128.8	112.3	-	24.1	30.6	27.2
August	-	53.3	12.7	112.4	-	22	32.8	28.1
September	94.23	73.7	136.4	73.4	21.6	20	23.3	24
October	106.7	115.3	22.86	81	16.8	14.6	21.1	15.8
November	44.7	165.6	35.4	97.28	9.5	7.3	7.2	9.7
December	71.37	172.5	99.8	86.36	0.4	0.3	10	3.4

[a] 30-yr averages (1981-2010) obtained from National Climatic Data Center (2019).

Table 3.2. Sources of chemicals used in the termination of cover crops.

Herbicide[a]	Trade Name	Formulation	Rate	Manufacturer	Address
			kg ai or ae ha^{-1}		
chloransulam	FirstRate	84 DF	0.0353	Dow AgroSciences	Indianapolis, IN
glufosinate	Liberty	280 SL	0.594	Bayer CropScience	Research Triangle Park, NC
glyphosate	Roundup PowerMax	4.5 L	1.120	Monsanto	St. Louis, MO
saflufenacil	Sharpen	2.85 L	0.025	BASF	Research Triangle, NC
clethodim	Select Max	0.97 L	0.136	Valent	Walnut Creek, CA

[a] Abbreviations: L, liquid; WG, water-dispersible granule; DF, dry flowable; SC, soluble concentrate.

Table 3.3. Herbicide treatments applied at two termination timings of cover crops in 2017 and 2018 at the Throckmorton Purdue Agricultural Center in Lafayette, Indiana and the Southeastern Purdue Agricultural Center in Butlerville, Indiana.

Termination Timing[a]	Cereal Rye	Canola	None[b]
2 WBP	Gly[c]	Safl	Gly
	Gluf	Gluf	Gluf
2 WAP	Gluf	Gluf	Gluf + cleth
	Gluf + cleth	Gluf + chlor	Gluf + chlor

[a] Termination timings of cover crop prior to cash crop planting. Abbreviations: 2WBP, two weeks before planting cash crop; 2WAP, two weeks after planting cash crop.
[b] Fallow indicates no cover crop planted.
[c] Herbicides applied. Abbreviations: Gly, glyphosate; Safl, saflufenacil; Gluf, glufosinate; Cleth, clethodim; Chlor, chloransulam-methyl.

Table 3.4. Dates of major field operations and herbicide applications in 2017 and 2018 at the Throckmorton Purdue Agricultural Center in Lafayette, Indiana and the Southeastern Purdue Agricultural Center in Butlerville, Indiana.

	Year, Date of Operation, and Rainfall Following Herbicide Application		
Location and Field Operation	2016	2017	2018
Throckmorton Purdue Ag Center			
Soybean seeding date	-	5/30	5/8
Dates of herbicide application:			
Early CC termination (2WBP)	-	5/12	4/26
Late CC termination (2WAP)	-	6/14	5/22
POST application	-	6/22	6/10
Cover crop seeding date	9/22	9/26	-
Southeastern Purdue Ag Center			
Soybean seeding date	-	5/10	5/14
Dates of herbicide application:			
Early CC termination (2WBP)	-	4/24	4/30
Late CC termination (2WAP)	-	5/31	5/29
POST application	-	6/12	6/4
Cover crop seeding date	9/21	9/22	-

[a] Abbreviations: CC, cover crop; 2WBP, two weeks before soybean grain planting; 2WAP, two weeks after soybean grain planting; POST, post application of herbicide after X days after initial herbicide application.

Table 3.5. Cover crop above-ground biomass (kg ha^{-1}) and height (cm) at the time of termination in Lafayette and Butlerville, Indiana.

	Lafayette				Butlerville			
	Dry Weight		Height		Dry Weight		Height	
Cover Crop[a]	2017	2018	2017	2018	2017	2018	2017	2018
	kg ha^{-1}		cm		kg ha^{-1}		cm	
Cereal Rye								
2 WBP	3362	2292	110	36	2234	2231	98	41
2 WAP	2119	3710	147	122	3134	2842	138	121
Canola								
2 WBP	2719	1681	101	24	2719	1389	90	20
2 WAP	3099	3092	129	85	3693	2996	155	80

[a] Abbreviations: 2 WBP, two weeks before soybean grain planting; 2 WAP, two weeks after soyean grain planting.

Table 3.6. Influence of cover crop on total weed biomass[a] collected prior to cover crop termination and our POST application at the Throckmorton Purdue Agricultural Center and the Butlerville Purdue Agricultural Center.

	2017 Total weed biomass		2018 Total weed biomass	
	Termination[b]	POST	Termination	POST
	g/m^{-2} [cd]			
Cover Crop				
Cereal Rye	2 a	1 a	6 a	2 a
Canola	4 a	2 ab	12 a	3 ab
None	18 b	4 b	41 b	4 b
P Value	0.0001	0.0245	0.0003	0.0367

[a] Total weed biomass includes winter and summer annual species present at time of collection.

[b] Termination indicates initial herbicide burndown either two weeks before or after planting soybean grain.

[c] Means within a column followed by the same letter are not statistically different at the 0.05 probability level as determined by Tukey HSD.

[d] Data were square-root transformed and backtransformed for presentation.

Table 3.7. Influence of cover crop and termination timing on horseweed density prior to cover crop termination and our POST application at the Southeastern Purdue Agricultural Center in Butlerville, Indiana.

	Horseweed density			
	2017	2018	POST '17	POST '18
	Plants m^{-2}			
Cover crop				
Cereal Rye	22 a	61 a	8 a	12 a
Canola	34 a	67 a	14 a	20 ab
None	66 b	117 b	22 b	24 b
P value	0.0068	0.0384	0.0035	0.0396
Termination timing				
Early	37 a	86 a	17 a	23 a
Late	44 a	76 a	13 a	15 b
P value	0.3862	0.3704	0.0551	0.0129
Treatment				
Saflufenacil	43 a	79 a	16 a	20 a
Glufosinate	38 a	84 a	15 a	18 a
P value	0.5496	0.6569	0.7750	0.4653
Cover crop*termination timing				
Cereal rye*early	26 a	75 ab	9 a	15 ab
Cereal rye*late	19 a	47 a	7 a	9 b
Canola*early	33 a	79 ab	17 abc	24 ab
Canola*late	34 a	61 ab	12 ab	16 ab
None*early	53 ab	112 ab	25 c	29 b
None*late	79 b	121 b	20 bc	20 ab
P value	0.1639	0.3818	0.8439	0.8326

[a] Early: herbicide application applied 2 weeks before soybean planting; Late: herbicide application applied 2 weeks after soybean planting.

[b] Burndown application with saflufenacil or glufosinate based program. A complete list of herbicides applied in Table 3.3.

Table 3.8. Influence of cover crop and termination timing on giant ragweed density prior to cover crop termination and our POST application at the Throckmorton Purdue Agricultural Center in Lafayette, Indiana.

	Giant ragweed density			
	2017	2018	POST ‘17	POST ‘18
	Plants m^{-2}			
Cover crop				
Cereal Rye	10 a	11 a	3 a	9 a
Canola	14 a	15 a	14 b	16 ab
None	15 a	21 a	15 b	21 b
P value	0.3515	0.0659	0.0053	0.0097
Termination timing[a]				
Early	13 a	15 a	14 a	14 a
Late	13 a	17 a	8 b	17 a
P value	0.8165	0.4306	0.0044	0.1477
Treatment[b]				
Glyphosate	12 a	17 a	12 a	12 a
Glufosinate	14 a	14 a	10 a	18 b
P value	0.5073	0.2651	0.3344	0.0034
Cover crop*termination timing				
Cereal rye*early	5 a	13 a	4 a	4 a
Cereal rye*late	10 b	9 a	3 a	12 ab
Canola*early	16 b	9 a	11 b	14 ab
Canola*late	10 b	22 a	9 ab	18 b
None*early	18 b	23 a	17 c	22 b
None*late	13 b	21 a	21 c	20 b
P value	0.0338	0.0612	0.0382	0.1275

[a] Early: herbicide application applied 2 weeks before soybean planting; Late: herbicide application applied 2 weeks after soybean planting.

[b] Burndown application with glyphosate or glufosinate based program. Canola terminated at the late termination timing included mesotrione and atrazine with the glyphosate and glufosinate programs. A complete list of herbicides applied in Table 3.3.

Table 3.9. Influence of cover crop, termination timing and herbicide treatment on soybean grain yield in 2017 and 2018 at the Throckmorton and Southeastern Purdue Agricultural Centers.

	Soybean Grain Yield	
	November 7, 2017	October 31, 2018
	kg/ha^{-1}	
Cover crop		
Cereal Rye	3152 a	4183 a
Canola	3405 a	4312 a
None	3802 b	4302 a
P value	<0.0001	0.6158
Termination timing[a]		
Early	3488 a	4406 a
Late	3418 a	2125 b
P value	0.5288	0.0203
Herbicide treatment[b]		
Saflufenacil	3459 a	4235 a
Glufosinate	3447 a	4297 a
P value	0.9133	0.6035
Cover crop*termination timing		
Cereal rye*early	3246 ab	4248 ab
Cereal rye*late	3058 a	4117 b
Canola*early	3404 abc	4397 ab
Canola*late	3407 abc	4227 ab
None*early	3813 c	4745 a
None*late	3791 bc	3860 b
P value	0.7390	0.0018

[a] Early: herbicide application applied 2 weeks before soybean planting; Late: herbicide application applied 2 weeks after soybean planting.

[b] Burndown application with saflufenacil/glyphosate or glufosinate based program. A complete list of herbicides applied in Table 3.3.

CHAPTER 4. HERBICIDE PROGRAMS FOR TERMINATION OF GLYPHOSATE-RESISTANT CANOLA IN INDIANA

4.1 Abstract

Field experiments were conducted in 2016 and 2017 to determine the most effective herbicide programs for the termination of glyphosate resistant canola (*Brassica napus* L.) prior to corn. Canola was planted in early September and herbicide treatments were applied in the spring three weeks before corn planting. Visual ratings of control and above-ground biomass reduction were collected 21 days after treatment (DAT). The highest control of canola occurred following the application of paraquat + saflufenacil + 2,4-D or metribuzin, resulting in 88 to 94% control. These control ratings are supported by applications with paraquat + saflufenacil + 2,4-D or metribuzin resulting in 88 to 97% biomass reduction. Auxin herbicides alone provided very poor control, less than 41% at both locations. In general, saflufenacil-containing herbicide treatments provided the highest control of canola compared to mesotrione or atrazine. Herbicide treatments had no effect on corn grain yield.

4.2 Introduction

Cover crop acreage in Indiana has more than doubled in just a few years. From 461,081 acres planted to cover crop and winter cereal grains in 2014 to over 1,020,000 acres in 2017 (ISDA 2017). According to a 2014 SARE & CTIC survey, the fourth highest reason growers plant a cover crop is for weed suppression. For many growers utilizing cover crops for weed control, early spring termination using herbicides prior to corn and soybean planting is the preferred method. Previous research has shown that if not properly terminated, cover crops can inhibit desired cash crop germination and growth by inhibiting far-red light penetration, and by slowing down soil warming and drying (Teasdale et al. 2017 and Teasdale and Moehler 1993). Various rapeseed varieties are among the most commonly used cover crops when trying to achieve some level of weed control for their rapid above-ground biomass accumulation and alleged allelopathic properties (Blevins et al. 1990 and Boydston et al. 1995). However, rape volunteers can be a persistent problem in a desired cash crop if not terminated completely. Regrowth from persistent stems take only a few days to regenerate, and if allowed to go to seed, it can remain in the soil seed bank for years (Simard et al. 2002). Suggested herbicide programs include glyphosate, 2,4-D, dicamba, and other common corn herbicides such as atrazine or saflufenacil. In Tennessee, both glyphosate and glufosinate resistant varieties have been found in some cover crop blends, resulting in failed termination prior to a desired cash crop (McClure et al., 2017). Reports from Alabama and Georgia suggested that brassica cover crops are more difficult to terminate with herbicides than winter cereals (USDA 2016). Clark et al. (2007) reported that rapeseed proved difficult to terminate with glyphosate alone, requiring multiple applications for successful control. Rapeseed and other various mustard species require higher herbicide inputs in successful herbicide programs compared to cereal rye, which is known for successful termination with an application of glyphosate at the correct growth stage (Legleiter et al. 2012)

One of the most important things to consider when selecting canola or rapeseed as a cover crop is to use high quality seed not contaminated by a resistant variety or weed seed. The U.S. Canola Association and the Canadian Seed Growers' Association have strict standards for canola seed purity, but studies have provided evidence that contamination is always a possibility. Friesen et al. (2003) reported that of 27 seedlots, 14 failed the 99.75% cultivar purity guideline. Downey and Beckie (2002) reported 18 out of 70 pedigreed seedlots failed the purity guideline. They also reported that 3 varieties of 14 tested were greater than the 0.25% maximum contamination allowed for certification. Reports from Indiana in 2015 suggested that growers planting canola as a cover crop were experiencing difficulties when terminating with glyphosate prior to corn and soybean production. This suggests the utilization of inadequate herbicide programs, or perhaps a seed contamination event containing glyphosate resistant canola. The objectives of this study were to 1) determine the most effective herbicide treatment for terminating glyphosate resistant canola in Indiana and 2) to quantify how these herbicide programs influence corn yield.

4.3 Materials and Methods

4.3.1 Site description and field plot design

Field studies were established in 2016 at Throckmorton Purdue Agricultural Center in Lafayette, IN and at the Southeastern Purdue Agricultural Center near Butlerville, IN. The Lafayette site had a silty clay loam soil type with 3.0% organic matter and an average pH of 6.8, and the Butlerville location the soil type was a silt loam with 1.5% organic matter with an average pH of 6.4. Trials were implemented utilizing a random complete block design with four replicates. Plot dimensions at both sites were 3 by 8 m in size. Monthly rainfall and mean air temperature for the experiment at both sites during the 2016-2018 growing seasons can be found in Table 4.3.

4.3.2 Planting and crop management

Prior to trial initiation in the fall, applications of 840 g ai ha^{-1} of paraquat (Gramoxone SL. 2.0, Syngenta Crop Protection) were made in order to control any vegetation present. On September 21, 2016 and September 26, 2017, a winter hardy glyphosate resistant canola variety (STAR 915W) was no-till planted at a rate of 6 kg ha^{-1} on 76 cm rows using a 4.5 m drill. The following spring, fifteen herbicide treatments were applied three weeks prior to corn planting. A complete list of herbicides used in this study and treatment list can be found can be found in Table

4.1 and Table 4.2 respectively. Corn was planted at the Lafayette site on May 30, 2017 and May 8, 2018, and at Butlerville on May 10, 2017 and May 14, 2018. Glyphosate and glufosinate resistant corn (SmartStax, DKC62-08RIB) was planted in 76 cm rows at a 5 cm depth at a seeding rate of 80,000 seeds ha^{-1}. Each plot consisted of 4 rows of corn. On July 2, 2017 and July 6, 2018 corn was side-dressed with liquid UAN (28-0-0) at the V6 growth stage at a rate of 168 kg N ha^{-1}. Plots were maintained weed-free via a post-emergence application of glufosinate (0.74 kg ai ha^{-1}) + mesotrione (0.11 kg ai ha^{-1}) + atrazine (1.1 kg ai ha^{-1}) and hand weeding. All treatments were applied with a CO_2-pressurized backpack sprayer equipped with a 3 m boom and XR11002 nozzles calibrated to deliver 140 L ha^{-1} at 138 kPa.

4.3.3 Data collection

Canola control was visually estimated 21 days after treatment (DAT). Control ratings were made on a 0-100% scale, where 0 = no control and 100 = complete plant death. Above-ground canola biomass was collected in the spring prior to herbicide application, and at 21 DAT. Above-ground canola biomass was collected in two 0.25 m^2 quadrats, one placed in the front and on in the back of the plot by clipping the plants at the soil surface and placed in paper bags. The paper bags that contained plant material were stored in a forced air driers set at 50 C for one week and dry weights were recorded. Above-ground biomass reductions were adjusted as a percentage of the nontreated check for each herbicide treatment. The center two corn rows within each plot were harvested, grain weighed, and corrected to 15.5% moisture.

4.3.4 Statistical analysis

Data were subjected to ANOVA using the PROC GLM and PROC GLIMMIX procedures in SAS (version 9.3; SAS Institute; 100 SAS Campus Dr., Cary, NC 27513-2414). All data were checked for normality and tested for appropriate interactions. Analysis of variance was used to test for significant main effects and interactions. Means were separated at the 0.05 level of significance using Tukey's Honest Significant Difference (HSD) test. Treatment, year and location were considered fixed effects. Visual control data are presented separately by location due to a significant interaction effect between treatment and location ($P < 0.0001$). Percent biomass reduction data are presented separately by location due to significant effect between treatment and location ($P = 0.0048$). Due to a significant interaction of year and treatment ($P = <0.0001$), likely resulting from differences in early season rainfall and planting dates, data are separated by year.

4.4 Results and Discussion

4.4.1 Herbicide programs for termination of glyphosate resistant canola

Glyphosate resistant canola control varied greatly by herbicide treatments at both locations (Tables 4.5 and 4.6). At our Lafayette location, the combination of paraquat + saflufenacil + 2,4-D, or metribuzin resulted in 87 to 94% visual control. Removing paraquat from the mix resulted in 85 to 86% control. The remaining treatments provided 76% or less control. Similar trends were observed at the Butlerville location with the exception that the combination of 2,4-D + saflufenacil must also include metribuzin to provide control from 87 to 94% of glyphosate-resistant canola prior to corn.

Above-ground biomass reduction data supports our visual control ratings (Tables 4.7 and 4.7). At our Lafayette location, the combination of paraquat + saflufenacil + 2,4-D, or metribuzin resulted in 88 to 96% biomass reduction. Removing paraquat from the mix resulted in 74 to 89% biomass reduction. Similar trends were observed at the Butlerville location with the exception that the combination of paraquat + saflufenacil + metribuzin must also include 2,4-D to reduce above-ground canola biomass by 92 to 94% prior to corn. Auxin herbicides alone provided very poor control at both locations. Glyphosate-resistant canola was more susceptible to 2,4-D (38-41%

reduction) than dicamba (22% reduction). These results are similar to Palhano et al. (2018) who evaluated herbicide programs for termination of rapeseed. They reported that treatments with dicamba alone, glyphosate + 2,4-D, glyphosate + dicamba resulted in as little as 16% control of rapeseed four weeks after treatment. Their results suggest that rapeseed was more susceptible to 2,4-D than dicamba. Treatments of paraquat + metribuzin provided the greatest control (67% and 71%) four weeks after treatment in their experiment.

4.4.2 Corn grain yield

Herbicide treatment had no effect on yield in both 2017 and 2018, which indicates that adequate termination of canola within three weeks of a failed application can still provide adequate yields. After data collection, plots were maintained weed free using a POST application of glufosinate + atrazine + mesotrione application and hand weeding, thus eliminating further cover crop inhibition, and late season weed emergence and competition. The corn continued growing throughout the season uninhibited by any canola. Years presented separately due to a significant year effect. Yields were higher in 2018 than in 2017 due to heavy rains in the spring that delayed planting, followed by drought later in the season, further stunting grain production at both locations (Table 4.3).

4.4.3 Practical implications

The results from this experiment indicate that herbicide selection is critical for effective termination of canola in Indiana. Applicators should utilize saflufencil, metribuzin, 2,4-D and paraquat for greatest control of canola. Auxin herbicides alone do not provide adequate control, but if an auxin herbicide is desired, 2,4-D should be selected over dicamba. There were no differences in corn grain yield across treatments when canola was terminated properly within three weeks of termination failure, providing growers with a short window of opportunity if a failed termination has occurred. It is important to terminate canola and rapeseed completely due to its ability to regrow quickly and produce a large amount of seed, which could remain viable in the seedbank for years. Traditional rapeseed or canola are not cover crops suggested for new cover crop adopters, and while it has many benefits, it should be noted that it can be difficult to terminate even with the most intensive herbicide programs. Terminating early is very important to ensure complete cover crop kill prior to cash crop planting. For maximum biomass production, these cover crops were sprayed at bloom, which is not ideal for translocation of many herbicides. While less biomass is not ideal for weed suppression, it is recommended that canola is terminated before blooming to increase herbicide translocation, and therefore increase termination of the cover crop.

4.5 Literature Cited

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Table 4.1. Sources of chemicals used in the termination of glyphosate resistant canola.

Herbicide[a]	Trade Name	Formulation[b]	Manufacturer	Address
atrazine	Aatrex	4L	Syngenta	Greensboro, NC
paraquat	Gramoxone SL	2L	Syngenta	Greensboro, NC
glufosinate	Liberty	280 SC	Bayer CropScience	Research Triangle Park, NC
glyphosate	Roundup PowerMax	4.5 L	Monsanto	St. Louis, MO
dicamba	Clarity	4 L	BASF	Research Triangle, NC
2,4-D Amine	Weedar 64	3.8 L	Syngenta	Greensboro, NC
saflufenacil	Sharpen	2.85 L	BASF	Research Triangle, NC
metribuzin	Tricor 75 DF	75 DF	United Phosphorous	King of Prussia, PA
s-metolachlor + atrazine + mesotrione	Lexar EZ	3.74 L	Syngenta	Greensboro, NC
s-metolachlor + atrazine + mesotrione + bicyclopyrone	Acuron	3.44 L	Syngenta	Greensboro, NC

[a] AMS and MSO were included per label recommendation.
[b] Abbreviations: L, liquid; DF, dry flowable; SC, soluble concentrate.

Table 4.2. Description of herbicide treatments and rates used in the termination of glyphosate-resistant canola three weeks before planting.

Treatment[a,b]	Rate	Trade Name
	kg ag or ai ha^{-1}	
Nontreated Check (Gly)	1.1	Roundup PowerMax
Gly + saf	1.1 + 1.1	Roundup PowerMax + Sharpen
Gly + 2,4-D	1.1 + 1.1	Roundup PowerMax + Weedar 64
Gly + dic	1.1 + 0.56	Roundup PowerMax + Clarity
Para	1.12	Gramoxone SL
Para + safl + met	1.12 + 1.1 + 0.4	Gramoxone SL + Sharpen + Tricor
Para + safl + 2,4-D	1.12 + 1.1	Gramoxone SL + Sharpen + Weedar 64
Para + safl + 2,4-D + met	1.12 +1.1 + 0.4	Gramoxone SL + Sharpen + Weedar 64 + Tricor
2,4-D + safl	1.1 + 1.1	Weedar 64 + Sharpen
2,4-D + safl + met	1.1 + 1.1 + 0.4	Weedar 64 + Sharpen + Tricor
S-meto + atra + meso	1.46 + 1.46 + 0.188	Lexar EZ
S-meto + atraz + meso + safl	1.46 + 1.46 + 0.188 + 1.1	Lexar EZ + Sharpen
S-meto + atraz + meso + bicyclo	1.46 + 1.46 + 0.188 + 1.1	Acuron
S-meto + atraz + meso + bicyclo + safl	1.46 + 1.46 + 0.188 + 1.1	Acuron + Sharpen
S-meto + atraz + meso + bicyclo + safl + gluf	1.46 + 1.46 + 0.188 + 1.1	Acuron + Sharpen + Liberty

[a] Abbreviations: AMS; ammonium sulfate (WinField Solutions LLC., St. Paul, MN); gly, glyphosate; fb, followed by; dic, dicamba; saf, saflufenacil; para, paraquat; met, metribuzin; atraz, atrazine; S-meto, S-metolachlor; bicyclo, bicyclopyrone; meso, mesotrione; gluf, glufosinate; MSO, methylated seed oil (Premium MSO, Helena Chemical Company, Collierville, TN).
[b] All herbicide treatments contained AMS 2.5% (v/v), and treatments applied with Sharpen contained Premium MSO 1% (v/v).

Table 4.3. Monthly rainfall (mm) and average monthly temperatures (C) in comparison to the 30-yr average[a] in 2016, 2017, and 2018 at the Throckmorton Purdue Agricultural Center (TPAC) in Lafayette, IN and the Southeastern Purdue Agricultural Center (SEPAC) in Butlerville, IN.

	Rainfall				Temperature			
Month and Location	2016	2017	2018	30 y. Avg.	2016	2017	2018	30 y. Avg.
	mm				C			
TPAC								
January	-	92	30.5	46.74	-	-0.4	-6	1
February	-	39.9	84.1	40.1	-	4.1	-7.7	4
March	-	92	26.7	73.41	-	5.3	3.9	10
April	-	113.3	61.94	87.63	-	13.3	7.2	17
May	-	213.1	58.4	99.8	-	15.7	22.3	23
June	-	109.7	86.11	107.7	-	22.1	29.4	28
July	-	251.7	40.3	97.77	-	23.3	29.1	30
August	-	52.6	51.2	99.31	-	24.8	27.8	29
September	158.5	39.9	68.3	69.9	21.3	19.9	20.1	13
October	38.4	119.9	85.3	69.6	14.9	14.6	10.2	6
November	68.6	147.8	44.7	71.37	8.4	5.4	3.3	1
December	36.8	15.5	49.3	65.3	-1.8	-9.9	-12.1	-5
SEPAC								
January	-	96.3	59.44	75.4	-	3.1	-3.3	2.2
February	-	67.8	144.3	68.8	-	7.5	5	3.7
March	-	145.3	107	95.5	-	8.3	-2	6.1
April	-	146.3	102.1	111	-	16.3	5.1	14
May	-	173.5	31.6	119.9	-	17.6	28.3	19.9
June	-	176.8	23.4	97	-	21.5	30	27.5
July	-	99.3	128.8	112.3	-	24.1	30.6	27.2
August	-	53.3	12.7	112.4	-	22	32.8	28.1
September	94.23	73.7	136.4	73.4	21.6	20	23.3	24
October	106.7	115.3	22.86	81	16.8	14.6	21.1	15.8
November	44.7	165.6	35.4	97.28	9.5	7.3	7.2	9.7
December	71.37	172.5	99.8	86.36	0.4	0.3	10	3.4

[a] 30-yr averages (1981-2010) obtained from National Climatic Data Center (2019).

Table 4.4. Glyphosate resistant canola control (scale 0-100) at 21 days after herbicide treatment at the Throckmorton Purdue Agriculture Center in 2017 and 2018.

Treatment[a]	Control[b]
	%
Check (Gly)	0 h
Gly + safl	56 f
Gly + 2,4-D	26 g
Gly + dic	24 g
Para	58 de
Para + safl + met	87 a
Para + safl + 2,4-D	88 a
Para + safl + 2,4-D + met	94 a
2,4-D + safl	86 ab
2,4-D + safl + met	85 ab
S-meto + atraz + meso	63 ef
S-meto + atraz + meso + safl	71 cde
S-meto + atraz + meso + bicyclo	66 def
S-meto + atraz + meso + bicyclo + safl	76 cd
S-meto + atraz + meso + bicyclo + safl + gluf	75 cd

[a] Abbreviations: Gly, glyphosate; fb, followed by; dic, dicamba; saf, saflufenacil; para, paraquat; met, metribuzin; atraz, atrazine; S-meto, S-metolachlor; bicyclo, bicyclopyrone; meso, mesotrione; gluf, glufosinate; MSO, methylated seed oil.
[b] Means within columns with no common letter(s) are significantly different according to Tukey HSD at $P \leq 0.05$.

Table 4.5. Glyphosate resistant canola control (scale 0-100) at 21 days after herbicide treatment at the Southeast Purdue Agriculture Center in 2017 and 2018.

Treatment[a]	Control[b]
	%
Check (Gly)	0 e
Gly + safl	54 c
Gly + 2,4-D	24 d
Gly + dic	25 d
Para	57 c
Para + safl + met	88 a
Para + safl + 2,4-D	89 a
Para + safl + 2,4-D + met	94 a
2,4-D + safl	75 b
2,4-D + safl + met	87 a
S-meto + atraz + meso	69 b
S-meto + atraz + meso + safl	73 b
S-meto + atraz + meso + bicyclo	73 b
S-meto + atraz + meso + bicyclo + safl	71 b
S-meto + atraz + meso + bicyclo + safl + gluf	76 b

[a] Abbreviations: Gly, glyphosate; fb, followed by; dic, dicamba; saf, saflufenacil; para, paraquat; met, metribuzin; atraz, atrazine; S-meto, S-metolachlor; bicyclo, bicyclopyrone; meso, mesotrione; gluf, glufosinate; MSO, methylated seed oil.

[b] Means within columns with no common letter(s) are significantly different according to Tukey HSD at $P \leq 0.05$.

Table 4.6. Influence of herbicide treatments of the biomass reduction of glyphosate resistant canola 21 days after application at the Throckmorton Purdue Agriculture Center in 2017 and 2018.[a]

Treatment[b]	Biomass Reduction[cd]
	%
Check (Gly)	0 g
Gly + saf	40 e
Gly + 2,4-D	41 e
Gly + dic	22 f
Para	24 f
Para + safl + met	90 a
Para + safl + 2,4-D	88 ab
Para + safl + 2,4-D + met	96 a
2,4-D + safl	74 c
2,4-D + safl + met	89 ab
S-meto + atraz + meso	80 bc
S-meto + atraz + meso + safl	79 c
S-meto + atraz + meso + bicyclo	63 d
S-meto + atraz + meso + bicyclo + safl	79 c
S-meto + atraz + meso + bicyclo + safl + gluf	74 c

[a] All treatments were harvested on May 30, 2017 and May 14, 2018.

[b] Abbreviations: Gly, glyphosate; fb, followed by; dic, dicamba; saf, saflufenacil; para, paraquat; met, metribuzin; atraz, atrazine; S-meto, S-metolachlor; bicyclo, bicyclopyrone; meso, mesotrione; gluf, glufosinate; MSO, methylated seed oil.

[c] Means within columns with no common letter(s) are significantly different according to Tukey HSD at $P \leq 0.05$.

[d] Canola biomass reduction were adjusted as a percentage of the nontreated check for each herbicide treatment.

Table 4.7. Influence of herbicide treatments of the biomass reduction of glyphosate resistant canola 21 days after application at the Southeastern Purdue Agricultural Center in 2017 and 2018.[a]

Treatment[b]	Biomass Reduction[cd]
	%
Check (Gly)	0 f
Gly + saf	41 d
Gly + 2,4-D	38 d
Gly + dic	22 e
Para	23 e
Para + safl + met	84 b
Para + safl + 2,4-D	92 a
Para + safl + 2,4-D + met	97 a
2,4-D + safl	75 c
2,4-D + safl + met	94 a
S-meto + atraz + meso	77 bc
S-meto + atraz + meso + safl	76 bc
S-meto + atraz + meso + bicyclo	74 c
S-meto + atraz + meso + bicyclo + safl	80 bc
S-meto + atraz + meso + bicyclo + safl + gluf	75 c

[a] All treatments were harvested on May 30, 2017 and May 14, 2018.

[b] Abbreviations: Gly, glyphosate; fb, followed by; dic, dicamba; saf, saflufenacil; para, paraquat; met, metribuzin; atraz, atrazine; S-meto, S-metolachlor; bicyclo, bicyclopyrone; meso, mesotrione; gluf, glufosinate; MSO, methylated seed oil.

[c] Means within columns with no common letter(s) are significantly different according to Tukey HSD at $P \leq 0.05$.

[d] Canola biomass reduction were adjusted as a percentage of the nontreated check for each herbicide treatment.

Table 4.8. Influence of herbicide treatment on corn grain yield in 2017 and 2018 at the Throckmorton and Southeastern Purdue Agricultural Centers.

Treatment[a]	Corn grain yield[b]	
	October 24, 2017	November 7, 2018
	Kg ha^{-1}	
Check (Gly)	5,111 a	14,172 a
Gly + saf	6,694 a	15,194 a
Gly + 2,4-D	7,486 a	15,196 a
Gly + dic	6,866 a	15,049 a
Para	6,607 a	15,852 a
Para + safl + met	7,019 a	16,232 a
Para + safl + 2,4-D	6,803 a	15,355 a
Para + safl + 2,4-D + met	6,673 a	15,370 a
2,4-D + safl	6,284 a	16,120 a
2,4-D + safl + met	7,008 a	15,675 a
S-meto + atraz + meso	6,811 a	15,375 a
S-meto + atraz + meso + safl	6,830 a	15,485 a
S-meto + atraz + meso + bicyclo	6,500 a	15,614 a
S-meto + atraz + meso + bicyclo + safl	6,929 a	14,943 a
S-meto + atraz + meso + bicyclo + safl + gluf	6,450 a	15,552 a

[a] Abbreviations: Gly, glyphosate; fb, followed by; dic, dicamba; saf, saflufenacil; para, paraquat; met, metribuzin; atraz, atrazine; S-meto, S-metolachlor; bicyclo, bicyclopyrone; meso, mesotrione; gluf, glufosinate; MSO, methylated seed oil.

[b] Means within columns with no common letter(s) are significantly different according to Tukey HSD at $P \leq 0.05$.