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# INTEGRATING COVER CROPS IN NO-TILL CORN AND SOYBEAN TO DIVERSIFY HERBICIDE-RESISTANT WEED MANAGEMENT IN THE MID-ATLANTIC

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# ABSTRACT

Widespread adoption of genetically-engineered, herbicide-resistant (HR) crops have simplified crop rotation diversity and the use of single-tactic, herbicide-based weed management programs. These practices have resulted in an HR weed epidemic, where glyphosate-resistant weeds are especially problematic. Glyphosate-resistant weeds like horseweed [*Conyza canadensis* (L.)] and pigweeds (*Amaranthus spp.*) threaten grower productivity and long-term efficacy of common agronomic herbicides. Thus, integrated weed management (IWM) programs that implement both ecological- and herbicide-based tactics are needed in no-till annual grain systems to (1) manage current HR weeds, (2) reduce HR selection pressure for evolution of resistance to other herbicides, (3) preserve effective herbicide technology, (4) enhance environmental stewardship, (5) safeguard soil conservation gains, and (6) maintain farm profits and productivity. To address these goals, we established three field studies at two sites in the Mid-Atlantic and identified combinations of cover crop and herbicide tactics that achieve effective season-long annual weed management, minimize HR selection pressure, and increase sustainability by reducing herbicide inputs. The first two studies assessed the complementarity of cover crops treatments and herbicide programs in corn and soybean, where integrating a cover crop treatment combined with applying a spring, pre-plant burndown herbicide application as well as a POST-emergent application provided the most effective season-long annual weed control. The third study assessed cover crop treatments and varied management practices, such as planting and termination dates, on HR selection pressure reduction at the time of herbicide applications. While cover crops intercepted a portion of the burndown herbicide application from reaching the soil surface, weeds were effectively controlled by the cover crops before the application, thus reducing the HR selection pressure.

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# Prologue

Genetically-engineered, herbicide-resistant (HR) crops have become prevalent throughout the United States, simplifying weed management by catalyzing the use of single-tactic, herbicide-based weed management programs (Duke and Powels 2009; NRC 2010). Growers are more reliant on herbicides for weed control yet often apply few herbicide modes of action. Coupled with simplified crop rotations, selection pressure for HR weed species has significantly intensified in no-till production (Duke and Powels 2009; Mortensen et al. 2012). These practices have resulted in an HR weed epidemic, including widespread glyphosate- and multiple- herbicide resistance (Mortensen et al. 2012). We are interested in identifying ecologically and chemically based integrated weed management (IWM) tactics that can help mitigate the HR weed epidemic in the Mid-Atlantic.

Several glyphosate-resistant (GR) weeds are particularly troublesome in no-till production within the Mid-Atlantic region. In 2000, GR horseweed [*Conyza canadensis* (L.) Cronquist] was first reported in GR soybean in Delaware, the first confirmed case of a GR weed infesting a GR crop in the United States (VanGessel 2001). Horseweed is a facultative winter annual that germinates in both the fall and spring, but emergence patterns can vary by cropping system and region (Davis et al. 2010). There are few effective herbicides currently available for horseweed control in soybean (Heap and Duke 2017), which contributes to increased selection pressure on effective modes of action in conservation tillage systems (Buhler and Owen 1997). GR Palmer amaranth (*Amaranthus palmeri* S. Watson) and GR waterhemp [*A. tuberculatus* (Moq.) J.D. Sauer] are also becoming a significant management challenge in Mid-Atlantic no-till soybean systems. Both species are summer annuals and multiple-resistant biotypes are common, which increases the challenge of achieving effective herbicide-based weed control (Heap and Duke 2017).

The current HR epidemic threatens grower production practices and the long-term efficacy of many common agronomic herbicides. Changes in crop rotation and frequency of GR crop use could help address these problems, but economic production system constraints such as available equipment, grower budget, etc. make these changes difficult to enact in commodity grains (Harker et al. 2017). To address GR weed management, the herbicide-seed manufacturing industry has introduced stacked-trait HR crops bred to be resistant to glyphosate and an herbicide from an additional chemical family. However, these second-generation HR crops continue to reinforce current herbicide centric grower practices that increase HR weed selection pressure (Mortensen et al. 2012). Alternatively, IWM programs that incorporate both ecological- and herbicide-based tactics are needed in no-till systems to manage current HR weeds, reduce HR selection pressure for evolution of resistance to other herbicides, preserve effective herbicide technology, enhance environmental stewardship, safeguard soil conservation gains, and maintain farm profits and productivity (Mortensen et al. 2012; Heap and Duke 2017).

IWM utilizes knowledge of weed biology to design complementary and diverse weed control tactics comprised of biological, chemical, cultural, and mechanical methods (Swanton and Weise 1991). Optimizing cover crop management is a cultural tactic that can enhance weed control and reduce herbicide resistance selection pressure when employed as a component of IWM (Mortensen et al. 2012). Living cover crops and terminated cover crop residues/surface mulch affect weed population dynamics primarily via resource competition and niche pre-emption, although allelopathy can also contribute to weed control (Teasdale 1998; Vencill et al. 2012). Optimizing cover crop management can potentially reduce selection pressure for herbicide resistance by lowering the number of weeds exposed to herbicide active ingredients (Mortensen et al. 2012), and by reducing the number of large individuals exposed at the time of herbicide application. Having fewer and smaller weeds should increase weed control efficacy of herbicide-based tactics (Wallace et al. 2018), but further research is needed to investigate what cover crop management practices, including species selection and planting and termination dates, best manage weeds and reduce selection pressure for herbicide resistance.

Two trends support further investigation of cover cropping tactics for HR weed management. First, cover crops are increasingly integrated into annual crop production systems within the Mid-Atlantic region (Hamilton et al. 2017). Second, recent studies have shown that cover crops can serve as an IWM tool for GR weed management (Loux et al. 2017; Montgomery et al. 2018; Wiggins et al. 2016). In the Northeast region, fall-sown cover crops are often limited by the short growing season windows after late-harvested crops like corn grain and soybean. In these situations, potentially competitive cover crops are limited to winter-hardy species like cereal rye (*Secale cereale* L.) or other winter cereals. Alternatively, planting cover crops in the early fall facilitates a longer growing season window and permits use of winter-kill cover crops such as forage radish (*Raphanus sativus* L.). The length of the fall growing season window and the cover crop functional traits (winter-hardy versus winter-kill) in monocultures or mixtures will affect winter annual weed population responses differently (Lawley et al. 2012).

Spring cover crop management tactics can also influence weed populations. Minimizing the period between cover crop termination and cash crop planting can allow for greater cover crop biomass and enhanced summer annual weed suppression (Wells et al. 2014). Roller-crimping high-biomass cover crops creates a thick mulch that curtails weed seed germination cues. Further, cover crop residue maintained at the soil surface in no-till cropping systems can physically inhibit weed recruitment and growth (Ryan et al. 2011; Teasdale et al. 2005) and potentially increase seed predation by both invertebrate and vertebrate predators (Shearin et al., 2008; Gallandt et al., 2005). Surface mulch can also increase water infiltration, reduce evaporative losses of water during the growing season, and subsequently influence weed-crop competition (Wells et al. 2014).

The interaction between cover crop and herbicide-based weed control tactics within an IWM program needs further analysis and understanding. Spring pre-plant, burndown herbicide applications are generally used to terminate cover crops and emerged weeds in conventional no-till production systems (Duiker and Curran 2005). Cover crop tactics that reduce the density and size of winter annual weed populations at the time of a burndown herbicide application could reduce herbicide selection pressure and increase efficacy of herbicide-based tactics. It will also be necessary to understand the effect of cover crops on pre-plant burndown herbicide deposition patterns, which may affect control efficacy and herbicide resistance selection pressure on winter annual weeds. Currently, three-pass herbicide programs that include pre-plant, soil-applied PRE, and foliar-applied POST-emergent herbicides are recommended for HR summer annual weed control in no-till corn and soybean. High-biomass cover crops that also provide weed-suppressive surface mulches have the potential to decrease both the density and size of emerged weeds at the time of POST application, which would further lower HR selection pressure.

We are interested in identifying combinations of cover crop and herbicide tactics that achieve effective season-long annual weed management, minimize selection pressure for herbicide resistance, and increase long-term sustainability by reducing herbicide inputs. To address this objective, we completed field experiments designed to address both IWM goals and grower priorities. We visualized these considerations as radar plots (Prologue Figure 1), where the components were (1) cover crop performance, (2) winter annual weed control efficacy, (3) late summer weed community control efficacy, (4) cash crop performance, (5) herbicide strategy environmental stewardship, (6) winter annual weed HR selection pressure reduction, (7) summer annual weed HR selection pressure reduction, (8) potential cover crop interference of the burndown herbicide, (9) soil microbial activity, and (10) soil C:N. Three cover crop treatments – a no cover control, early-sowed cereal rye (*Secale cereale* L.), and early-sowed cereal rye + hairy vetch (*Vicia villosa* Roth) – were selected and plotted in the Epilogue, based on the discussion in the following two chapters. If herbicide program was significant, then the no cover control was plotted with regards to the spring, pre-plant burndown herbicide application (BD) program, while the latter treatments were plotted with regards to the BD + POST-emergent program. Cover crop treatments were ranked (1-3, or 0 if not applicable) Larger radar plots were associated with IWM programs that successfully incorporated ecologically- and herbicide-based tactics, while providing limited environmental trade-offs. To illustrate the radar plots, three field studies were conducted in the Mid-Atlantic, where cover crop treatments were planted in the fall preceding corn and soybean.

The first two studies, discussed further in the first chapter, assessed weed suppressive effects of cover crops with and without a range of standard herbicide inputs in corn and soybean systems. The objectives of these studies were to evaluate the (1) performance ability of cover crop treatments, (2) effect of living cover crops on winter annual weed control efficacy at the time of spring, pre-plant burndown herbicide application, (3) potential of optimal cover crops and herbicide strategies to achieve successful late-summer weed community control with fewer herbicide inputs, (4) effect of said strategies on cash crop performance, and (5) the herbicide strategy environmental stewardship and potential complementarity with effective weed control.

The third study, discussed further in the second chapter, assessed various adaptive cover crop facultative traits and management tactics in soybean. The objectives of this study were to evaluate the (1) effect of alternative cover crop tactics on winter annual weed population size at the time of a pre-plant burndown herbicide application; (2) effect of cover crop termination date summer annual weed population size at the time of POST-emergent herbicide application; and (3) effect of cover crops on herbicide deposition patterns in pre-plant burndown herbicide application.

Finally, potential environmental trade-offs between soil and cover crops for weed management, including soil microbial health, carbon-to-nitrogen content in cover crops and soil, and volumetric soil water content, were conducted in the third field study. Delaying cover crop termination may allow cover crops to deplete soil water, a negative trade-off that could prove problematic for the subsequent crop in drought conditions. However, delaying termination may also result in greater, persistent cover crop mulch that shields the soil surface from transpiration, a positive attribute that could help the subsequent crop in drought conditions. The potential environmental trade-offs are discussed further in the Epilogue.

In addition to the aforementioned objectives, the radar plots aim to achieve a central goal: how do we best implement cover crop-based IWM programs in no-till annual grains as a means of effectively and sustainably optimizing HR weed management on farms where herbicides are used?

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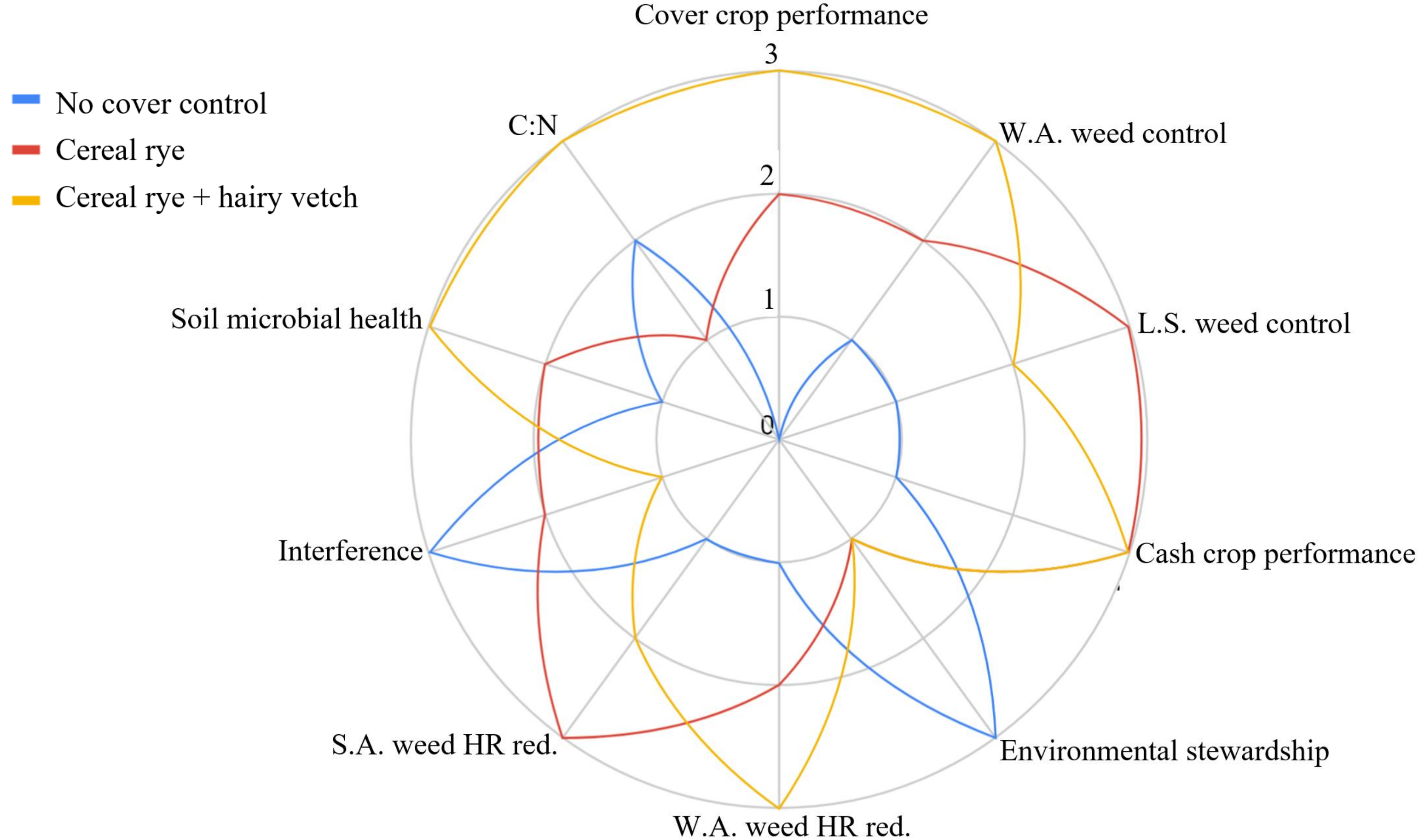
Epilogue Figure 1. The hypothesized radar plot of early-sown cereal rye, early-sown cereal rye + hairy vetch, and a no cover control. Plot components are as follows: (1) cover crop performance, (2) winter annual weed control efficacy (W.A. weed control), (3) late summer weed community control efficacy (L.S. weed control), (4) cash crop performance, (5) herbicide strategy environmental stewardship (Environmental stewardship), (6) winter annual weed HR selection pressure reduction (W.A. weed HR red.), (7) summer annual weed HR selection pressure reduction (S.A. weed HR red.), (8) potential cover crop interference of the burndown herbicide (Interference), (9) soil microbial health, and (10) carbon-to-nitrogen content in cover crops and soil (C:N). Cover crop treatments were ranked (1-3, or 0 if not applicable), where larger radar plots were associated with IWM programs that successfully incorporated ecologically- and herbicide-based tactics, while providing limited environmental trade-offs.



# Chapter 1

# Optimizing cover crop and herbicide inputs for weed management in no-till grain crops

## Introduction

Widespread adoption of genetically-engineered herbicide resistant (HR) crops have simplified weed management, as it has reduced the diversity of herbicide modes of action used and reinforced a trend away from the use of tillage as a component of an integrated weed management approach (Duke and Powels 2009; NRC 2010). Growers have become increasingly reliant on herbicide-based weed control while repeatedly applying fewer herbicide modes of action, resulting in an epidemic of HR weed species and areas infested by HR weeds – a pattern particularly striking for glyphosate resistance (Mortensen et al. 2012). The current HR weed outbreak threatens grower production practices as well as the efficacy and longevity of many important and common agronomic herbicides. Therefore, multi-tactic approaches for winter and summer annual weed management are needed for no-till production systems to remain productive and profitable, while safeguarding soil conservation gains.

Strict, continuous no-till production eliminates mechanical control as a weed management tool and can increase herbicide selection pressure for evolved resistance. Previous studies have documented decreased weed density and higher weed species diversity in no-till systems (Murphy et al. 2006), while others have documented increased weed densities (Légère et al. 2011). Increased weed density in conservation tillage systems has been linked to both low crop rotation diversity and simplified herbicide strategies (Légère et al. 2011; Murphy et al. 2006; Hoffman et al. 1998). Widespread adoption of glyphosate-resistant (GR) crops has facilitated simplified herbicide programs and crop rotations, which further increases selection pressure for HR weed species. Seventeen weed species have evolved resistance to glyphosate in the United States, thirteen of which have been found in GR crops (Heap and Duke 2017; Heap 2018). The herbicide-seed manufacturing industry has moved to address GR weeds with introduction of second-generation HR crops that are bred to be resistant to glyphosate and a second herbicide, such as dicamba, 2,4-D, glufosinate, etc., from another herbicide chemical family.

Second-generation HR crops reinforce grower practices that increase selection for herbicide resistance (Mortensen et al. 2012; Heap and Duke 2017). Integration of ecologically based weed control tactics within integrated weed management (IWM) programs offer an alternative path forward. IWM utilizes knowledge of weed biology to design complementary and diverse control tactics that draw on biological, chemical, cultural and mechanical methods (Swanton and Weise 1991). Improving utilization of ecologically based weed control tactics in IWM programs has potential to reduce selection for resistant weedy biotypes, preserve effective herbicide technology, enhance management of current HR weeds, and maintain cost-effective management options in no-till systems (Mortensen et al. 2012; Heap and Duke 2017).

Optimizing cover crop management is a cultural practice that can enhance weed suppression and has potential to reduce selection pressure for herbicide resistance in no-till production (Mortensen et al. 2012). Cover crops influence weed population dynamics by competing with weeds for light, water, space, and nutrients (Smith et al. 2015). Terminated cover crop residue left on the soil surface as a mulch in no-till crop production can also inhibit weed recruitment and growth rates (Ryan et al. 2011; Teasdale et al. 2005) and increase likelihood of weed seed predation (Shearin et al. 2008; Gallandt et al. 2005).

Cover crops are increasingly used by growers to achieve several important ecosystem services in addition to weed suppression (Hamilton et al. 2017). Surveys suggest that the principle motivation for cover crop use is to prevent soil erosion in winter fallow periods. Fall-sown small grain and legume cover crops have been shown to enhance weed suppression in subsequent corn and soybean crops, although suppression can be short-lived. Cover crops in no-till systems can help manage weeds, although supplementary control methods like herbicides are commonly needed (Gallagher et al. 2003).

Complementarity between cover crop and herbicide-based tactics in no-till systems has received relatively little attention. Ideally, cover crops would control weed populations throughout the growing season without requiring herbicide inputs. However, even with the most competitive cover crops, resumption of weedy plant growth in the late spring or early summer can result in unacceptably high weed infestations (Loux et al. 2017). The objective of our research was to identify combinations of cover crop and herbicide tactics that result in season-long weed control, high cash crop productivity, and limited herbicide environmental load. We evaluated alternative cover crop and herbicide tactics no-till corn and soybean production at two Mid-Atlantic locations, where we expected the highest performance in cover crop treatments with two-pass herbicide programs.

## Materials and Methods

We conducted corn and soybean field experiments at the Russell E. Larson Agricultural Research Center in Rock Springs, Pennsylvania (PA), and the Elbert N. & Ann V. Carvel Research and Education Center in Georgetown, Delaware (DE), in 2015-2016 (2016) and repeated in 2016-2017 (2017).

The PA location has silt loam soils and is located in USDA plant hardiness zone 6a, which experiences an annual average of 1,660 growing degree days (GDD; base 10 C) and 100 cm of rainfall. The corn experiment was in a Hagerstown silt loam (fine, mixed, semi-active Typic Hapludalfs), while the soybean experiment was in a Murrill channery silt loam (fine-loamy, mixed, semi-active, mesic Typic Hapludults) in 2016 and a Nolin silt loam (fine-silty, mixed, active, mesic Dystric Fluventic Eutrudepts) in 2017. The DE location is characterized by loamy sand soils and is located in zone 7a, with an annual average of 2,440 GDDs and 115 cm of rainfall. In the first year of the DE experiments (2016), the corn experiment was in a Rosedale loamy sand (loamy, siliceous, semi-active, mesic Arenic Hapludults) and in a Hurlock loamy sand (coarse-loamy, siliceous, semi-active, mesic Typic Endoaquults) and Klej loamy sand (mesic, coated Aquic Quartzipsamments) in the second year (2017). Soybean experiments were in a Hammonton loamy sand (coarse-loamy, siliceous, semi-active, mesic Aquic Hapludults) and Rosedale loamy sand in 2016 and a Hurlock loamy sand in 2017.

We arranged the experiments as a randomized complete block with split-plots and four replications. The main plot was the cover crop treatment, and the split-plot was the herbicide strategy. We selected cover crop treatments and herbicide strategies based on their feasibility and adaptability to Mid-Atlantic cropping systems and growing conditions. In PA, main plots were 12 m by 12 m and split-plots were 3 m by 12 m, while in DE the main plot size was 12 m by 8 m and split-plots were 3 m by 8 m.

Cover crop treatments preceding corn included a no cover control, cereal rye (*Secale cereal* L.) “Aroostook” + hairy vetch (*Vicia villosa* Roth) “Auburn early cover” mixture, and cereal rye + crimson clover (*Trifolium incarnatum* L.) “Dixie” mixture (Table 1-1). Cover crop treatments preceding soybean were a no cover control, cereal rye, and cereal rye + hairy vetch mixture (Table 1-1). Herbicide strategies included standard label rates (Table 1-2) of a burndown only control, a burndown + PRE-residual application, a burndown + POST-emergent application, and a burndown + PRE-residual + POST-emergent. We applied the PRE-residual 1-2 days after corn and soybean planting and the POST-emergent treatment at V3-V4 for both crops. Herbicides were applied at 187 L $ha^{-1}$ at 276 kPA using a tractor mounted sprayer equipped with TeeJet[1] AI11002VS spray tips.

We drill-seeded cover crops preceding corn with a Great Plains 1005 NT[2] no-till drill after small grain harvest (Table 1-3a), while cover crops preceding soybean followed corn silage harvest (Table 1-3a). Prior to cover crop planting, we harrowed the study sites preceding corn to promote volunteer small grain germination and applied glyphosate to all study sites at a rate of 1.26 kg ae $ha^{-1}$ to control emerged weeds and volunteer small grains. Each year, we terminated cover crops at the late boot stage of cereal rye (Zadoks 55) with a burndown herbicide application (Table 1-2) ten days prior to cash crop planting.

Cash crops grew under rain-fed conditions except for soybean in 2016 in DE, which implemented irrigation. Each site planted glufosinate-resistant corn 'DEKALB DKC48-56RIB[3]' and soybean 'Doebler's DB3217LL[4]' with a John Deere 7200 Conservation[5] planter. Corn was planted on 76 cm rows at 79,080 seeds $ha^{-1}$, with 45 kg $ha^{-1}$ N applied at planting. Soybeans were planted at 444,800 seeds $ha^{-1}$ on 76 cm rows in PA and in 2016 in DE and on 38 cm rows in 2017 in DE.

We established microplots (0.5 $m^2$) of horseweed (*Conyza canadensis* L.) and smooth pigweed (*Amaranthus hybridus* L.) in the fall in the center of each split plot at both sites. Horseweed microplot establishment immediately followed cover crop seeding and smooth pigweed microplots establishment was in late-October each year. We collected horseweed and smooth pigweed seed from local populations in late summer and seeded at a rate of 5,000 seeds $m^{-2}$ for horseweed and 500 seeds $m^{-2}$ for smooth pigweed. Weeds were gently mixed with sand and hand-seeded across the microplot; the sand aided in even seed distribution and reduce wind-blown dispersal out of the microplots.

Weed biomass collected at the time of burndown application took place in PA only. We assessed cover crop performance by harvesting aboveground cover crop biomass prior to termination in two 0.25 $m^2$ representative locations within each split plot. Sub-samples were sorted by species, oven-dried for a minimum of 96 hours at 60 C, weighed, and averaged prior to analysis. In late-August, we collected, dried, and weighed aboveground weed biomass from each microplot using the same methodology. We measured cash crop yields at the split-plot level by harvesting the middle two rows of each plot with a small plot combine.

We analyzed corn and soybean separately by site using analysis of variance (ANOVA) linear mixed effects models in R version 3.2.3[6]. Fixed effects included year, cover crop treatment, herbicide strategy, and their interactions. Block nested within year was a random factor. Response variables included (1) spring cover crop biomass (kg $ha^{-1}$); (2) winter annual weed biomass (kg $ha^{-1}$) prior to a pre-plant, burndown herbicide application; (3) late season weed biomass (kg $ha^{-1}$); and (4) cash crop yields (kg $ha^{-1}$). Shapiro-Wilk's Test, Levene's Test, and quantile-quantile plots tested assumptions of normality. Late season weed biomass required log transformation to meet the assumptions of normality. Tukey's adjusted P-Values separated means for significant main effects or interactions.

**Herbicide Strategy Environmental Stewardship.**

To quantify the environmental effects of alternative herbicide programs, each herbicide strategy was assigned an environmental impact rating based on a comprehensive literature review (Shaner 2014). For each herbicide strategy, ratings considered (1) frequency of herbicide applications per season, (2) soil leaching potential, (3) aerobic field half-life, and (4) $LC_{50}$. In this study, $LC_{50}$ represented the herbicide concentration in water that can kill 50% of an environmental Mid-Atlantic surrogate species found (rainbow trout; *Oncorhynchus mykiss* Walbaum) with a single exposure. The environmental impact rating was designed to assess trade-offs among herbicide strategies. Based on the literature review, each herbicide strategy was assigned a score for the considered parameters, as well as an overall average score, and plotted as a radar/spider plot (Smith et al. 2011). Scores ranged from 0-5, where a higher score indicated greater environmental stewardship and a lower environmental impact. The herbicide strategy environmental stewardship was quantified by consulting the *Herbicide Handbook* to obtain information on the half-life, leaching potential, and $LC_{50}$ (Shaner 2014).

First, the herbicide strategies required one (score = 5), two (score = 3), or three equipment passes (score = 1) in the field. Second, based on qualitative descriptions for leaching potential in the *Herbicide Handbook*, strategies were scored for soil leaching potential as low (score = 5), low-medium (score = 4), medium (score = 3), medium-high (score = 2), or high (score = 1) (Shaner 2014). Third, aerobic field half-life follows exponential decay, so the scoring system for this parameter was likewise exponential. Half-life scores were based on a range of 0-20 days (score = 5), 21-35 days (score = 4), 35-45 days (score = 3), 46-50 days (score = 2), and >50 days (score = 1). Fourth, $LC_{50}$ was based on the toxicity category signal words defined by the National Pesticide Information Center. Herbicides strategies were categorized as having negligible toxicity ($LC_{50}$: >16 mg/L; score = 5), very low toxicity ($LC_{50}$: >2.0-16.0 mg/L; score = 4), low toxicity ($LC_{50}$: >0.5-2.0 mg/L; score = 3), moderate toxicity ($LC_{50}$: >0.05-0.5 mg/L; score = 2), or high toxicity ($LC_{50}$: ≤0.05 mg/L; score = 1) (Signal Words 2008). All parameters were based on conditions found in the Mid-Atlantic and could vary by location, soil, and climate.

All active ingredients within each herbicide strategy were considered. However, the overall score for each strategy was based on the grand mean of all four parameter scores. In addition to the four herbicide strategies applied, the environmental stewardship of various, common PRE-residual herbicides in corn and soybean were also scored for comparison. For this latter assessment, only the PRE-residual herbicides are scored, omitting the effects of the burndown program as well as any POST application.

## Results and Discussion

### Corn

#### *Cover Crop Performance*

In PA, only study year influenced ($P < 0.001$) cover crop biomass production (Table 1-4). Mean biomass at spring termination was 2,299 and 7,243 kg $ha^{-1}$ in 2016 and 2017, respectively, in the cereal rye + crimson clover treatment. Mean biomass was 1,948 and 6,988 kg $ha^{-1}$ in the cereal rye + hairy vetch treatment in 2016 and 2017. Cover crop biomass production was greater in DE compared to PA (Table 1-4), which can be attributed to the warmer, coastal climate in southern Delaware. Study year ($P < 0.001$) and cover crop treatment ($P = 0.01$) influenced cover crop biomass production in DE. Mean biomass at spring termination was greater in the cereal rye

+ crimson clover treatment each year, and cover crop biomass production was greater in the second study year compared to the first across cover crop treatment levels.

***Winter Annual Weed Control***

We assessed winter annual weed suppression only in PA. The resident weed community included mouseear chickweed [*Cerastium fontanum* Baumg. *ssp. vulgare* (Hartm.) Greuter & Burdet], henbit (*Lamium amplexicaule* L.), annual ryegrass [*Lolium perenne L. ssp. multiflorum* (Lam.) Husnot], common evening primrose (*Oenothera biennis* L.), and common chickweed [*Stellaria media* (L.) Vill.]. Due to variable recruitment of horseweed in microplots, we measured winter annual weed suppression as total winter annual weed biomass at the time of a spring, pre-plant burndown application. A significant interaction between year and cover crop treatment ($P < 0.01$) was observed (Table 1-5). No differences among treatments occurred in the first study year, but each cover crop treatment reduced winter annual weed biomass compared to the no cover crop control in the second year. Winter annual weed production was higher in the second year due to a milder winter and spring. However, winter annual weed biomass in both cereal rye + crimson clover and cereal rye + hairy vetch was consistently low (< 45 kg $ha^{-1}$) across study years, despite varying levels of cover crop biomass production. Our results suggest the static ability of cover crops to manage winter annual weeds across variable years, so long as cover crops achieved roughly 2,000 kg $ha^{-1}$ or more at the time of burndown.

***Late Season Weed Control***

We assessed late season weed control in PA and DE in late August and included the resident weed community within microplots, such as common ragweed (*Ambrosia artemisiifolia* L.), Pennsylvania smartweed [*Persicaria pensylvanica* (L.) M. Gomez], horsenettle (*Solanum carolinense* L.), eastern black nightshade (*Solanum ptychanthum* Dunal), dandelion (*Taraxacum officinale* F.H. Wigg.), yellow nutsedge (*Cyperus esculentus* L.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and foxtail (*Setaria spp.*).

Analysis of late season weed biomass in PA detected a significant year by herbicide treatment interaction ($P < 0.001$; Table 1-6), but there was not a cover crop effect. Pooled across cover crop treatments, including the POST-emergent herbicide (BD + POST) in 2016 provided similar late season weed control (13 kg $ha^{-1}$) as the PRE-residual program (BD + PRE) (21 kg $ha^{-1}$) and the BD + PRE + POST program (17 kg $ha^{-1}$). Despite greater weed severity in 2017 due to a more favorable growing season, a two-pass herbicide program lowered weed biomass to below 10 kg $ha^{-1}$, and a three-pass program was negligibly better. Multiple-pass herbicide programs successfully controlled the late season weed community better than the BD only program in both 2016 (103 kg $ha^{-1}$) and 2017 (281 kg $ha^{-1}$).

Similarly, late season weed control in DE was pooled across cover crop treatment, which did not have a significant main effect, but was influenced by an interaction between year and herbicide program ($P < 0.001$; Table 1-6). In 2016, weed biomass in multiple-pass programs was at or below 3 kg $ha^{1}$. Like at the PA location, the 2017 growing season had greater weed severity (368 kg $ha^{-1}$) in the BD only program than in 2016 (79 kg $ha^{-1}$). However, in 2017, the BD + POST and BD + PRE + POST programs were equal (3 kg $ha^{-1}$) and consistently effective at controlling weeds late season. The BD + PRE herbicide program was less effective, with 31 kg $ha^{-1}$ late season weed biomass.

A primary objective of this experiment was to determine if cover cropping practices are a complementary weed control tactic in herbicide-based programs. Our ANOVA results suggest that cover crops did not significantly lower late season weed community levels (i.e. late season weed biomass) as extensively as the selected herbicide program (Figure 1-1a). For example, a cereal rye-legume mixture plus a two-pass burndown + POST-emergent program resulted in biologically similar levels of weed control compared to a three-pass herbicide program without cover crops. However, other research supports that fall-sown legume-based cover crop mixtures can produce surface mulch residues that enhance suppression of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson) in corn, and legume-based cover crops further suppress Palmer amaranth when employed in combination with a POST-emergent herbicide (Wiggins et al. 2015). We suspect that the weed community and severity in our field experiment was not sufficient to distinguish differences across herbicide programs in cover crop treatments.

***Herbicide Environmental Stewardship***

In corn, the BD program received an environmental stewardship score of 4.3 out of 5 (Table 1-9a; Figure 1-2a). Although the BD program received the highest environmental stewardship score, it was least effective in controlling late season weed populations. The BD + PRE program received a lower score (3.8) due to the second field pass for the PRE application. The BD + POST program received a score of 3.7. Although the BD + POST program was comparatively more effective for late season weed control, there was a trade-off associated with lower environmental stewardship due to the greater leaching potential of glufosinate. The BD +

PRE + POST received the lowest average score of 3.3 due to additional field passes and provided negligible late season weed control gains compared to two-pass programs. Other commonly used PRE-residual herbicides, such as acetochlor and dicamba, produced similar environmental stewardship scores as those used in this study, whereas atrazine and isoxaflutole use results in decreased environmental stewardship due to greater soil persistence. Our results show that achieving a balance between late season weed control and environmental stewardship is possible by integrating cover crops with two-pass herbicide programs.

***Cash Crop Performance***

In PA, we assessed corn performance by measuring stand counts (Table 1-7) and grain yield (Table 1-8). Corn populations were lower ($P < 0.01$) in the second year, which was likely a function of poor stand establishment due to the combination of wet conditions at planting and thicker cover crop residues relative to the previous year. Cereal rye + hairy vetch reduced corn populations compared to the control both years of the study and cereal rye + crimson clover reduced corn populations compared to the control in the second year ($P < 0.001$). Corn populations were not tested in DE. Cover crop and herbicide treatments did not affect corn yield in PA and DE (Table 1-8), though study year was a significant main effect ($P < 0.01$). These results suggest growing season conditions are a more important driver of corn grain yields relative to negative effects of cover crop residue on stand establishment.

## Soybean

### *Cover Crop Performance*

In PA, cover crop biomass differed across study year (P < 0.001) but not cover crop treatment (Table 1-4). Mean biomass at spring termination was 3,141 and 5,592 kg $ha^{-1}$ in 2016 and 2017, respectively, in the cereal rye treatment. Mean biomass was 3,064 and 5,496 kg $ha^{-1}$ in the cereal rye + hairy vetch treatment. Cover crop biomass in DE was not significant across study years or cover crop treatments. Mean biomass was 3,729 kg $ha^{-1}$ and 4,443 kg $ha^{-1}$ in 2016 and 2017, respectively, in the cereal rye treatment. Mean biomass was 4,115 kg $ha^{-1}$ and 4,001 kg $ha^{-1}$ in the cereal rye + hairy vetch treatment in these years.

### *Winter Annual Weed Control*

In PA, we included the resident weed community in evaluations of winter annual weed suppression and quantified populations of mouseear chickweed, henbit, and common evening primrose, and common chickweed. We pooled supplemented horseweed and these resident species for analysis and further pooled data across herbicide treatments to assess cover crop effects at the time of a spring, pre-plant burndown application. In PA, an interaction between study year and cover crop treatments occurred (Table 1-5). Under more favorable environmental conditions in 2017, we observed higher levels of winter annual weed recruitment in the no cover control (221 kg $ha^{-1}$) compared to 2016 (34 kg $ha^{-1}$), but also higher levels of cover crop biomass production in cover crop treatments compared to 2016. Winter annual weed biomass in cover crop treatments was lower than the control in 2017, but did not differ from the control in 2016. However, we saw similar levels of winter annual weed biomass (< 20 kg $ha^{-1}$) in both years of the experiment in the cereal rye and cereal rye + hairy vetch treatments. These results suggest that competitive interactions between cover crops and winter annual weeds produce similar net effects across varying levels of resource availability, similar to the results in corn.

### *Late Season Weed Control*

Year and herbicide program influenced late season weed biomass in PA ($P < 0.001$; Table 1-6), but cover crop treatment was not a significant main effect. In 2016, the two-pass BD + POST program provided the greatest late season weed control (258 kg $ha^{-1}$), compared to a PRE-residual program (BD + PRE) (484 kg $ha^{-1}$) or the insignificant additive effect of a BD + PRE + POST program (297 kg $ha^{-1}$). In 2017, late season weed biomass was lowest in the BD + POST program (5 kg $ha^{-1}$) and BD + PRE + POST program (1 kg $ha^{-1}$). Conversely, the BD + PRE program was less effective, with 41 kg $ha^{-1}$. Multiple-pass herbicide programs successfully controlled the late season weed community better than the BD only program in both 2016 (4,652 kg $ha^{-1}$) and 2017 (1,123 kg $ha^{-1}$).

A year and herbicide program interaction effect pooled over cover crop treatment ($P < 0.001$; Table 1-6; Figure 1-1b) influenced late season weed control in DE. Weed biomass decreased under a combination of cover crop treatment and BD + PRE program; however, this was the only instance where a cover crop program and herbicide treatment interaction occurred ($P < 0.01$). Late season weed biomass was lowest where a POST-emergent was applied as BD + POST and BD + PRE + POST in 2016 (1 and 5 kg $ha^{-1}$, respectively) and 2017 (1 and 2 kg $ha^{-1}$). Late season weed biomass was also low (18 and 42 kg $ha^{-1}$) each year in the BD + PRE treatment. Two- and three-pass programs were more effective than the BD only treatment in both 2016 (1,375 kg $ha^{-1}$) and 2017 (365 kg $ha^{-1}$).

Observed trends indicate that there is some evidence that integrating cover crops can help reduce herbicide inputs (Figure 1-1b), although the effects were not widespread throughout the study. Cover crops coupled with a two-pass burndown + PRE program or burndown + POST program resulted in biologically similar levels of weed control compared to a three-pass herbicide program without cover crops. Our results also indicate that cereal rye + hairy vetch mixtures are less weed suppressive than cereal rye monocultures despite similar levels of biomass production. Cover crops coupled with three-or four-pass herbicide programs successfully controlled *Amaranthus* weeds control in glyphosate- and glufosinate-resistant soybean (Loux et al. 2017). Similarly, our results suggest that summer annual weed control can be achieved by coupling cover crops with two-pass herbicide programs.

### *Herbicide Environmental Stewardship*

In soybean, the BD program received an average environmental stewardship score of 4.3 out of 5 (Table 1-9b; Figure 1-2b). Similar to the corn experiment, the BD program resulted in greater environmental stewardship compared to two- and three-pass herbicide programs but was ineffective in controlling late season weed populations. The BD + PRE program received a score of 3.7 due to the second field pass. The BD + POST program also received a score of 3.7, and finally the BD + PRE + POST, with the greatest number of field passes, received the lowest environmental stewardship score of 3.2. Use of other commonly used PRE-residual soybean herbicides, such as acetochlor, dicamba, and flumioxazin, would result in similar environmental stewardship scores as those used in this study. The results suggest that cover crops can help maintain crop protection goals while reducing the environmental impact of herbicide use.

### ***Cash Crop Performance***

In PA, a year and cover crop treatment interaction ($P < 0.01$; Table 1-7) influenced soybean populations. Soybean populations were higher in 2017 than 2016, and in each year, cereal rye and cereal rye + hairy vetch treatments reduced soybean populations compared to the no cover control. Lower soybean populations in cover crop treatments were likely a result of poorer establishment in thick cover crop residue. Soybean yield was affected by year and herbicide program ($P < 0.01$) but not cover crop treatment. Treatments with multi-pass herbicide programs resulted in higher soybean yield compared to BD only treatments, likely to due to decreased weed pressure. In DE, soybean yield increased in 2017 ($P < 0.001$), and yield was higher in treatments with multi-pass herbicide programs ($P < 0.05$) compared to BD only. These results suggest that soybean yield can be plastic, despite high cover crop residue interference during crop establishment.

## **Conclusions**

We were interested in assessing complementarity between cover crop and herbicide tactics in no-till corn and soybean systems. Optimizing cover crop use may (1) reduce herbicide inputs, which may increase environmental stewardship; (2) reduce selection pressure for resistance; and (3) minimize adverse effects on cash crop production.

Our results indicate that integration of cereal rye or cereal rye + legume reduces winter annual weed abundance at the time of a pre-plant burndown herbicide application. Cover cropping effects on summer annual weed suppression produced more variable results. In soybean, cereal rye and cereal rye + hairy vetch produced similar levels of biomass, but greater persistence of residue likely contributed to improved summer annual weed suppression observed in cereal rye treatments compared to the mixture. Based on our results, a complimentary two-pass herbicide program appears to provide the best control weeds across the growing season. Integrating a BD + POST program was most complimentary across cover crops, although the POST-emergent herbicide had greater leaching potential risk and, consequently, a lower environmental steward score compared to some PRE-residual herbicides. However, a two-pass herbicide program cannot only be as effective for weed management than a three-pass program, but two-pass programs can better environmental stewardship. Other studies have reported that multiple herbicide applications are necessary to meet crop protection requirements in corn and soybean production, regardless of cover crop management tactics (Didon et al. 2014; Loux et al. 2017).

Optimizing weed suppression with high-biomass cover crops will require negotiation of agronomic trade-offs. Although we did not directly measure residue levels, our results suggest that cover crop residue can create a short-term trade-off by decreasing crop population density early in the season; however, because crop yields were similar across cover crop treatments, we did not detect a long-term trade-off. Also, increasing the intensity and frequency of herbicide inputs may optimize weed control, but this can also result in trade-offs related to environmental stewardship. Further work is needed to determine to what extent cover cropping can improve environmental stewardship by enabling reduced herbicide inputs within a crop growing season or across a crop rotation. The extended benefits of reducing selection pressure for herbicide resistance and other ecosystem services provided by cover crops also require more thorough investigation.

## Sources of Materials

[1]Spraying Systems, Co., Glendale Heights, IL 60139

[2]Great Plains Manufacturing, Inc., Salina, KS 67401

[3]DEKALB Genetics Corporation, DeKalb, IL 60115

[4]Doebler's Pennsylvania Hybrids, Inc., Williamsport, PA 17701

[5]John Deere & Company, Moline, IL 61265

[6]R© statistical analysis software, The R Foundation for Statistical Computing, Vienna, Austria

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Table 1-1. Cover crop treatments and seeding rates for the corn and soybean experiments.

| Cover crop treatment | Seeding rate |
|---|---|
| *Corn* | kg $ha^{-1}$ |
| No cover control | — |
| Cereal rye + crimson clover | 34 + 22 |
| Cereal rye + hairy vetch | 34 + 34 |
| | |
| *Soybean* | |
| No cover control | — |
| Cereal rye | 135 |
| Cereal rye + hairy vetch | 101 + 22 |

Table 1-2. Herbicides used in pre-plant burndown (BD), soil-applied PRE-emergent (PRE) and POST-emergent (POST) treatments in corn and soybean experiments.

| Herbicide treatment | Active ingredient (Product) | Application rate |
|---|---|---|
| *Corn* | | |
| Burndown (BD) | glyphosate | 1.26 kg ae $ha^{-1}$ |
| | 2,4-D ester | 0.56 kg ae $ha^{-1}$ |
| PRE-residual | s-metolachlor | 1.7 kg ai $ha^{-1}$ |
| | mesotrione | 0.18 kg ai $ha^{-1}$ |
| POST-emergent | glufosinate | 0.59 kg ai $ha^{-1}$ |
| | ammonium sulfate | 3.36 kg $ha^{-1}$ |
| *Soybean* | | |
| Burndown (BD) | glyphosate | 1.26 kg ae $ha^{-1}$ |
| | 2,4-D ester | 0.56 kg ae $ha^{-1}$ |
| PRE-residual | s-metolachlor | 1.7 kg ai $ha^{-1}$ |
| | flumetsulam | 56 g ai $ha^{-1}$ |
| POST-emergent | glufosinate | 0.59 kg ai $ha^{-1}$ |
| | ammonium sulfate | 3.36 kg $ha^{-1}$ |

Table 1-3a. Field operations and data collection in corn experiment at Pennsylvania (PA) and Delaware (DE) locations in 2015-16 and 2016-17.

| | Pennsylvania | | Delaware | |
|---|---|---|---|---|
| Field operation / data collection | 2015-16 | 2016-17 | 2015-16 | 2016-17 |
| Cover crop planting | 9/1 | 9/1 | 9/17 | 9/15 |
| Fall N application (44 kg N $ha^{-1}$) | 9/11 | 9/13 | 9/23 | 9/21, 9/27 |
| Horseweed planting | 9/14 | 9/6 | 9/23 | 9/21 |
| Smooth pigweed planting | 12/21 | 12/13 | 11/24 | 12/6 |
| Percent ground cover assessment | 5/3 | 4/28 | 5/3 | 4/27 |
| Spring microplot weed data collection | 5/3 | 4/28 | 5/3 | 4/28 |
| Cover crop biomass | 5/3 | 5/4 | 4/26 | 4/28 |
| Cover crop burndown | 5/6 | 5/4 | 5/5 | 5/3 |
| Corn planting | 5/17 | 6/8 | 5/16 | 5/15 |
| PRE-residual application | 5/17 | 6/9 | 5/17 | 5/13 |
| Microplot counts | 5/31 | 6/20 | 5/18 | 5/30 |
| Microplot counts | 6/15 | 6/25 | 6/6 | 6/7 |
| POST application | 6/16 | 7/6 | 6/29 | 6/28 |
| Percent weed control rating | 7/6 | 7/20 | 9/7 | 7/27 |
| Summer weed microplot data & biomass | 8/13 | 8/29 | 8/17 | 7/27 |
| Corn harvest | 11/7 | 11/4 | 10/2 | 9/28 |

Table 1-3b. Field operations and data collection in soybean experiment at Pennsylvania (PA) and Delaware (DE) locations in 2015-16 and 2016-17.

| | Pennsylvania | | Delaware | |
|---|---|---|---|---|
| Field operation / data collection | 2015-16 | 2016-17 | 2015-16 | 2016-17 |
| Cover crop planting | 10/1 | 10/6 | 10/14 | 10/17 |
| Horseweed planting | 10/5 | 11/1 | 10/17 | 10/18 |
| Smooth pigweed planting | 12/21 | 12/13 | 11/24 | 12/6 |
| Spring green-up N application (44 kg N $ha^{-1}$) | 4/27 | 4/5 | 3/16 | 2/28 |
| Percent ground cover assessment | 5/9-5/10 | 5/8 | 5/10 | 5/18-5/19 |
| Spring microplot weed data collection | 5/9-5/10 | 5/8 | 5/10 | 5/18-5/19 |
| Cover crop biomass | 5/10 | 5/8 | 5/10 | 5/18-5/19 |
| Agrotain application (166 kg N $ha^{-1}$) | 5/9 | 5/7 | — | — |
| Cover crop pre-plant burndown application | 5/11 | 5/9 | 5/20 | 5/26 |
| Burndown weed survival counts | 5/25 | 5/31 | 5/31 | 5/30 |
| Soybean planting | 5/22 | 5/17 | 6/1 | 6/2 |
| Overall plot % cover crop and weeds control | 6/6 | 6/12 | 6/2 | 6/13 |
| PRE-residual application | 5/23 | 5/19 | 6/2 | 6/2 |
| $K_2O$ Application | — | 6/30 | — | — |
| Microplot weed data collection | 6/24 | 7/1 | 7/6 | 6/27 |
| POST application | 6/27 | 7/3 | 7/8 | 6/28 |
| Percent weed control rating | 7/11 | 7/24 | 7/27 | 7/17 |
| Summer weed microplot data & biomass | 8/11 | 8/30 | 8/17 | 8/2 |
| Soybean harvest | 11/1 | 11/15 | 10/27 | 10/2 |

Table 1-4. Mean aboveground cover crop biomass (kg ha$^{-1}$) at the time of a pre-plant spring burndown (BD) herbicide application in corn and soybean experiments at Pennsylvania and Delware study locations. Means are presented followed by the percentage of total contributed by each species in parentheses for treatments containing two-species mixtures. The second set of numbers in parentheses are standard errors of the mean. Data are pooled over herbicide treatment levels.

| | Pennsylvania | | | | Delaware | | | |
|---|---|---|---|---|---|---|---|---|
| | 2015-16 | | 2016-17 | | 2015-16 | | 2016-17 | |
| | kg ha$^{-1}$ | | | | | | | |
| *Corn* | | | | | | | | |
| Cereal rye + crimson clover | 2,299 (61/39) | (103) | 7,243 (82/18) | (541) | 4,699 (45/55) | (250) | 8,468 (8/92) | (451) |
| Cereal rye + hairy vetch | 1,948 (43/57) | (92) | 6,988 (82/18) | (784) | 4,154 (40/60) | (285) | 7,556 (9/91) | (219) |
| *Soybean* | | | | | | | | |
| Cereal rye | 3,141 | (144) | 5,592 | (376) | 3,729 | (116) | 4,443 | (306) |
| Cereal rye + hairy vetch | 3,064 (98/2) | (127) | 5,496 (88/12) | (462) | 4,115 (63/37) | (133) | 4,001 (68/32) | (347) |
| ANOVA | Wald $\chi^2$ | | | | | | | |
| *Corn* | | | | | | | | |
| Year (Y) | 65.5*** | | | | 74.9*** | | | |
| Cover crop (C) | 0.4 | | | | 6.5* | | | |
| Y × C | 0.01 | | | | 0.4 | | | |
| *Soybean* | | | | | | | | |
| Year (Y) | 44.8*** | | | | 1.4 | | | |
| Cover crop (C) | 0.1 | | | | 0.01 | | | |
| Y × C | 0.01 | | | | 2.9 | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance (Pr > $\chi^2$) of model terms shown as: NS, $P > 0.05$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Table 1-5. Mean aboveground winter annual weed biomass at the time of a pre-plant spring burndown (BD) herbicide application in corn and soybean experiments at the Pennsylvania location. Numbers in parentheses are standard errors of the mean. Means within crop followed by the same letter are not statistically different (P > 0.05). Data are pooled over herbicide treatment levels.

| | 2015-2016 | | | 2016-2017 | | |
|---|---|---|---|---|---|---|
| | | | kg ha$^{-1}$ | | | |
| *Corn* | | | | | | |
| No cover control | 85 | (21) | a | 494 | (163) | b |
| Cereal rye + crimson clover | 18 | (5) | a | 16 | (11) | a |
| Cereal rye + hairy vetch | 41 | (16) | a | 37 | (36) | a |
| *Soybean* | | | | | | |
| No cover control | 34 | (10) | a | 221 | (25) | b |
| Cereal rye | 11 | (5) | a | 3 | (3) | a |
| Cereal rye + hairy vetch | 16 | (14) | a | 3 | (2) | a |
| ANOVA | | | Wald $\chi^2$ | | | |
| *Corn* | | | | | | |
| Year (Y) | | | 10.1* | | | |
| Cover crop (C) | | | 25.8*** | | | |
| Y × C | | | 2.7** | | | |
| *Soybean* | | | | | | |
| Year (Y) | | | 92.7** | | | |
| Cover crop (C) | | | 52.7*** | | | |
| Y × C | | | 10.5*** | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance (Pr > $\chi^2$) of model terms shown as: NS, *P* > 0.05; *, *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.001.

Table 1-6. Year and herbicide program effects on late season aboveground weed biomass (kg ha$^{-1}$) in corn and soybean at Pennsylvania and Delaware locations. Data are log transformed with treatment means (se) pooled across cover crop treatment. Numbers in parentheses are standard errors of the mean.

| | Pennsylvania | | | | | | Delaware | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2015-2016 | | | 2016-2017 | | | 2015-2016 | | | 2016-2017 | | |
| | kg ha$^{-1}$ | | | | | | | | | | | |
| *Corn* | | | | | | | | | | | | |
| BD | 103 | (54) | b | 281 | (148) | c | 79 | (42) | b | 368 | (198) | c |
| BD + PRE | 21 | (11) | a | 8 | (4) | b | 1 | (1) | a | 31 | (17) | b |
| BD + POST | 13 | (7) | a | 6 | (3) | ab | 3 | (1) | a | 3 | (1) | a |
| BD + PRE + POST | 17 | (9) | a | 2 | (1) | a | 1 | (1) | a | 3 | (1) | a |
| *Soybean* | | | | | | | | | | | | |
| BD | 4,652 | (2,423) | b | 1,123 | (637) | c | 1,375 | (669) | c | 365 | (177) | c |
| BD + PRE | 484 | (252) | a | 41 | (21) | b | 18 | (9) | b | 42 | (20) | b |
| BD + POST | 258 | (134) | a | 5 | (2) | a | 1 | (0.5) | a | 5 | (2) | a |
| BD + PRE + POST | 297 | (155) | a | 1 | (1) | a | 1 | (0.5) | a | 2 | (1) | a |
| ANOVA | Wald $\chi^2$ | | | | | | | | | | | |
| *Corn* | | | | | | | | | | | | |
| Year (Y) | 2.4 | | | | | | 7.2** | | | | | |
| Cover Crop (C) | 2.6 | | | | | | 2.0 | | | | | |
| Herbicide (H) | 41.9*** | | | | | | 66.6*** | | | | | |
| Y × H | 10.5* | | | | | | 11.4** | | | | | |
| C × H | 7.1 | | | | | | 5.0 | | | | | |
| *Soybean* | | | | | | | | | | | | |
| Year (Y) | 30.1*** | | | | | | 0.3 | | | | | |
| Cover Crop (C) | 4.4 | | | | | | 2.9 | | | | | |
| Herbicide (H) | 64.0*** | | | | | | 107.0*** | | | | | |
| Y × H | 18.2*** | | | | | | 9.2* | | | | | |
| C × H | 12.4 | | | | | | 21.7** | | | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance (Pr > $\chi^2$) of model terms shown as: NS, $P > 0.05$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Table 1-7. Stand counts in corn and soybean at the Pennsylvania location. Data are treatment means. Numbers in parentheses are standard errors of the mean. Means followed by the same letter within each crop are not statistically different (P > 0.05). Data are pooled over herbicide treatments.

| | 2015-2016 | | | 2016-2017 | | |
|---|---|---|---|---|---|---|
| | plants ha$^{-1}$ | | | | | |
| *Corn* | | | | | | |
| No cover control | 80,155 | (1,334) | c | 76,757 | (1,138) | bc |
| Cereal rye + crimson clover | 76,603 | (2,080) | bc | 69,035 | (1,634) | a |
| Cereal rye + hairy vetch | 71,815 | (1,880) | ab | 68,726 | (1,087) | a |
| *Soybean* | | | | | | |
| No cover control | 283,399 | (11,572) | b | 397,376 | (3,908) | d |
| Cereal rye | 195,059 | (11,443) | a | 334,518 | (15,219) | c |
| Cereal rye + hairy vetch | 169,730 | (10,471) | a | 350,117 | (6,874) | c |
| ANOVA | Wald $\chi^2$ | | | | | |
| *Corn* | | | | | | |
| Year (Y) | 10.1** | | | | | |
| Cover crop (C) | 25.8*** | | | | | |
| Y × C | 2.7 | | | | | |
| *Soybean* | | | | | | |
| Year (Y) | 92.7*** | | | | | |
| Cover crop (C) | 52.7*** | | | | | |
| Y × C | 10.5** | | | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance (Pr > $\chi^2$) of model terms shown as: NS, *P* > 0.05; *, *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.001.

Table 1-8. Corn and soybean yield at the Pennsylvania and Delaware locations. Data are treatment means. Numbers in parentheses are standard errors of the mean. Data are pooled over cover crop treatment.

| | Pennsylvania | | | | Delaware | | | |
|---|---|---|---|---|---|---|---|---|
| | 2015-2016 | | 2016-2017 | | 2015-2016 | | 2016-2017 | |
| | kg ha$^{-1}$ | | | | | | | |
| *Corn* | | | | | | | | |
| BD | 13,753 | (198) | 12,780 | (365) | 7,111 | (455) | 11,400 | (206) |
| BD + PRE | 13,563 | (227) | 13,001 | (337) | 8,030 | (327) | 11,057 | (234) |
| BD + POST | 13,340 | (260) | 12,957 | (343) | 7,593 | (217) | 11,047 | (191) |
| BD + PRE + POST | 13,400 | (331) | 13,171 | (199) | 7,987 | (484) | 10,838 | (267) |
| *Soybean* | | | | | | | | |
| BD | 2,456 | (224) | 2,725 | (144) | 814 | (67) | 3,094 | (106) |
| BD + PRE | 3,494 | (104) | 3,180 | (129) | 1,077 | (77) | 3,543 | (178) |
| BD + POST | 3,754 | (126) | 3,267 | (121) | 1,046 | (75) | 3,557 | (292) |
| BD + PRE + POST | 3,621 | (136) | 3,410 | (118) | 1,281 | (176) | 3,570 | (203) |
| ANOVA | Wald $\chi^2$ | | | | | | | |
| *Corn* | | | | | | | | |
| Year (Y) | 7.1** | | | | 119.1*** | | | |
| Herbicide (H) | 0.3 | | | | 1.0 | | | |
| Y × H | 2.0 | | | | 7.2 | | | |
| *Soybean* | | | | | | | | |
| Year (Y) | 2.2 | | | | 160.1*** | | | |
| Herbicide (H) | 51.7*** | | | | 9.5* | | | |
| Y × H | 10.0* | | | | 0.9 | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance ($Pr > \chi^2$) of model terms shown as: NS, $P > 0.05$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Table 1-9a. Environmental stewardship score for each herbicide strategy in the corn experiment. Scores were quantified using the grand mean of the following factors: (1) the number of equipment passes in a field to make the application(s), (2) the leaching potential, (3) the half-life (as number of days), and (4) the $LC_{50}$ value (as mg $L^{-1}$). Environmental stewardship scores are additionally quantified for other corn PRE-residual herbicides common throughout the Mid-Atlantic. Scores are included in the right half of each category column and range as whole numbers from 0-5, where higher scores are higher environmental stewards. (Shaner, 2014).

| | Field passes | | Leaching potential | | Half-life | | $LC_{50}$ | |
|---|---|---|---|---|---|---|---|---|
| | Number | Score | Rating | Score | Days | Score | mg $L^{-1}$ | Score |
| *BD* | 1 | 5 | | | | | | |
| Glyphosate | | | low | 5 | 47 | 2 | 8-26 | 4 |
| 2,4-D | | | low | 5 | 7 | 5 | 1-15 | 3 |
| Average: 4.3 | | 5.0 | | 5.0 | | 3.5 | | 3.5 |
| *BD + PRE* | 2 | 3 | | | | | | |
| Glyphosate | | | low | 5 | 47 | 2 | 8-26 | 4 |
| 2,4-D | | | low | 5 | 7 | 5 | 1-15 | 3 |
| S-metolachlor | | | low | 5 | 43 | 3 | 4 | 4 |
| Mesotrione | | | low | 5 | 40 | 3 | >120 | 5 |
| Average: 3.8 | | 5.0 | | 5.0 | | 3.3 | | 4.0 |
| *BD + POST* | 2 | 3 | | | | | | |
| Glyphosate | | | low | 5 | 47 | 2 | 8-26 | 4 |
| 2,4-D | | | low | 5 | 7 | 5 | 1-15 | 3 |
| Glufosinate | | | high | 1 | 7 | 5 | >320 | 5 |
| Average: 3.7 | | 3.0 | | 3.7 | | 4.0 | | 4.0 |
| *BD + PRE + POST* | 3 | 1 | | | | | | |
| Glyphosate | | | low | 5 | 47 | 2 | 8-26 | 4 |
| 2,4-D | | | low | 5 | 7 | 5 | 1-15 | 3 |
| S-metolachlor | | | low | 5 | 43 | 3 | 4 | 4 |
| Mesotrione | | | low | 5 | 40 | 3 | >120 | 5 |
| Glufosinate | | | high | 1 | 7 | 5 | >320 | 5 |
| Average: 3.3 | | 1.0 | | 4.2 | | 3.6 | | 4.2 |
| *PRE-residuals* | — | — | | | | | | |
| Acetochlor | | | low | 5 | 14 | 5 | 0.45 | 2 |
| Atrazine | | | low | 5 | >60 | 1 | 10 | 4 |
| Dicamba | | | medium | 3 | 15 | 5 | 1000 | 5 |
| Isoxaflutole | | | low | 5 | >60 | 1 | non-toxic | 5 |
| Mesotrione | | | low | 5 | 40 | 3 | >120 | 5 |
| S-metolachlor | | | low | 5 | 43 | 3 | 4 | 4 |

Table 1-9b. Environmental stewardship score for each herbicide strategy in the soybean experiment. Scores were quantified using the grand mean of the following factors: (1) the number of equipment passes in a field to make the application(s), (2) the leaching potential, (3) the half-life (as number of days), and (4) the $LC_{50}$ value (as mg $L^{-1}$). Environmental stewardship scores are additionally quantified for other corn PRE-residual herbicides common throughout the Mid-Atlantic. Scores are included in the right half of each category column and range as whole numbers from 0-5, where higher scores are higher environmental stewards. (Shaner, 2014).

| | Field passes | | Leaching potential | | Half-life | | $LC_{50}$ | |
|---|---|---|---|---|---|---|---|---|
| | Number | Score | Rating | Score | Days | Score | mg $L^{-1}$ | Score |
| *BD* | 1 | 5 | | | | | | |
| Glyphosate | | | low | 5 | 47 | 2 | 8-26 | 4 |
| 2,4-D | | | low | 5 | 7 | 5 | 1-15 | 3 |
| Average: 4.3 | | 5.0 | | 5.0 | | 3.5 | | 3.5 |
| *BD + PRE* | 2 | 3 | | | | | | |
| Glyphosate | | | low | 5 | 47 | 2 | 8-26 | 4 |
| 2,4-D | | | low | 5 | 7 | 5 | 1-15 | 3 |
| S-metolachlor | | | low | 5 | 43 | 3 | 4 | 4 |
| Flumetsulam | | | low | 5 | 60 | 1 | >300 | 5 |
| Average: 3.7 | | 3.0 | | 5.0 | | 2.8 | | 4.0 |
| *BD + POST* | 2 | 3 | | | | | | |
| Glyphosate | | | low | 5 | 47 | 2 | 8-26 | 4 |
| 2,4-D | | | low | 5 | 7 | 5 | 1-15 | 3 |
| Glufosinate | | | high | 1 | 7 | 5 | >320 | 5 |
| Average: 3.7 | | 3.0 | | 3.7 | | 4.0 | | 4.0 |
| *BD + PRE + POST* | 3 | 1 | | | | | | |
| Glyphosate | | | low | 5 | 47 | 2 | 8-26 | 4 |
| 2,4-D | | | low | 5 | 7 | 5 | 1-15 | 3 |
| S-metolachlor | | | low | 5 | 43 | 3 | 4 | 4 |
| Flumetsulam | | | low | 5 | 60 | 1 | >300 | 5 |
| Glufosinate | | | high | 1 | 7 | 5 | >320 | 5 |
| Average: 3.2 | | 1.0 | | 4.2 | | 3.2 | | 4.2 |
| *PRE-residuals* | — | — | | | | | | |
| Acetochlor | | | low | 5 | 14 | 5 | 0.45 | 2 |
| Dicamba | | | medium | 3 | 15 | 5 | 1000 | 5 |
| Flumioxazin | | | low | 5 | 18 | 5 | 2 | 3 |
| Metribuzin | | | low-med. | 4 | 35 | 3 | 76 | 5 |
| Sulfentrazone | | | medium | 3 | >60 | 1 | >130 | 5 |
| Flumetsulam | | | low | 5 | 60 | 1 | >300 | 5 |
| S-metolachlor | | | low | 5 | 43 | 3 | 4 | 4 |

Figure 1-1a. Cover crop and herbicide treatment effects on total late season aboveground weed biomass (kg ha$^{-1}$) in corn at Pennsylvania and Delaware locations. Data are log-transformed treatment means (se) pooled across years, and cover crop by herbicide interaction significance (P < 0.05) is included in the upper righthand corner.

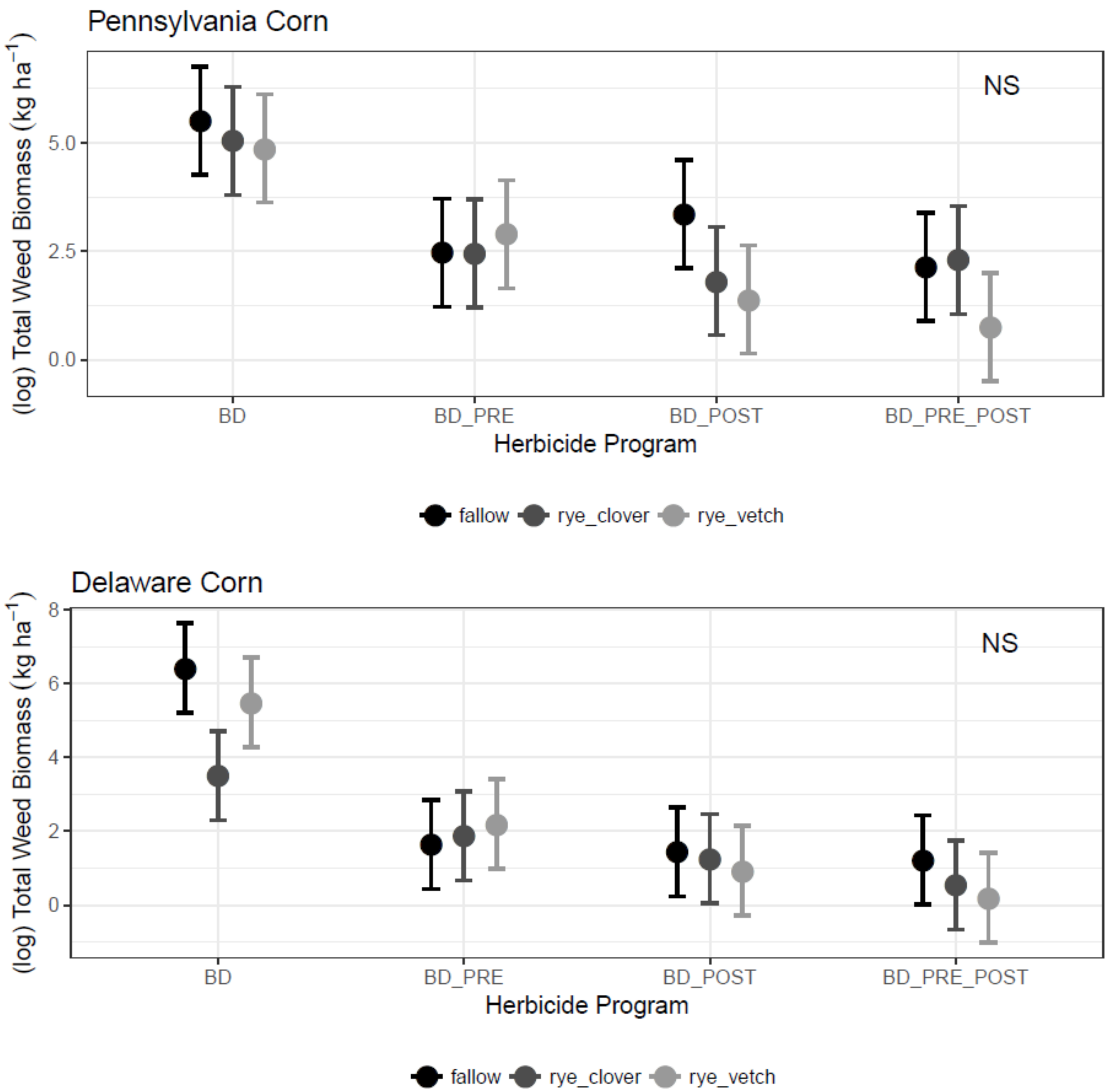


Figure 1-1b. Cover crop and herbicide treatment effects on total late season aboveground weed biomass (kg $ha^{-1}$) in soybean at Pennsylvania and Delaware locations. Data are log-transformed treatment means (se) pooled across years, and cover crop by herbicide interaction significance (P < 0.05) is included in the upper righthand corner.

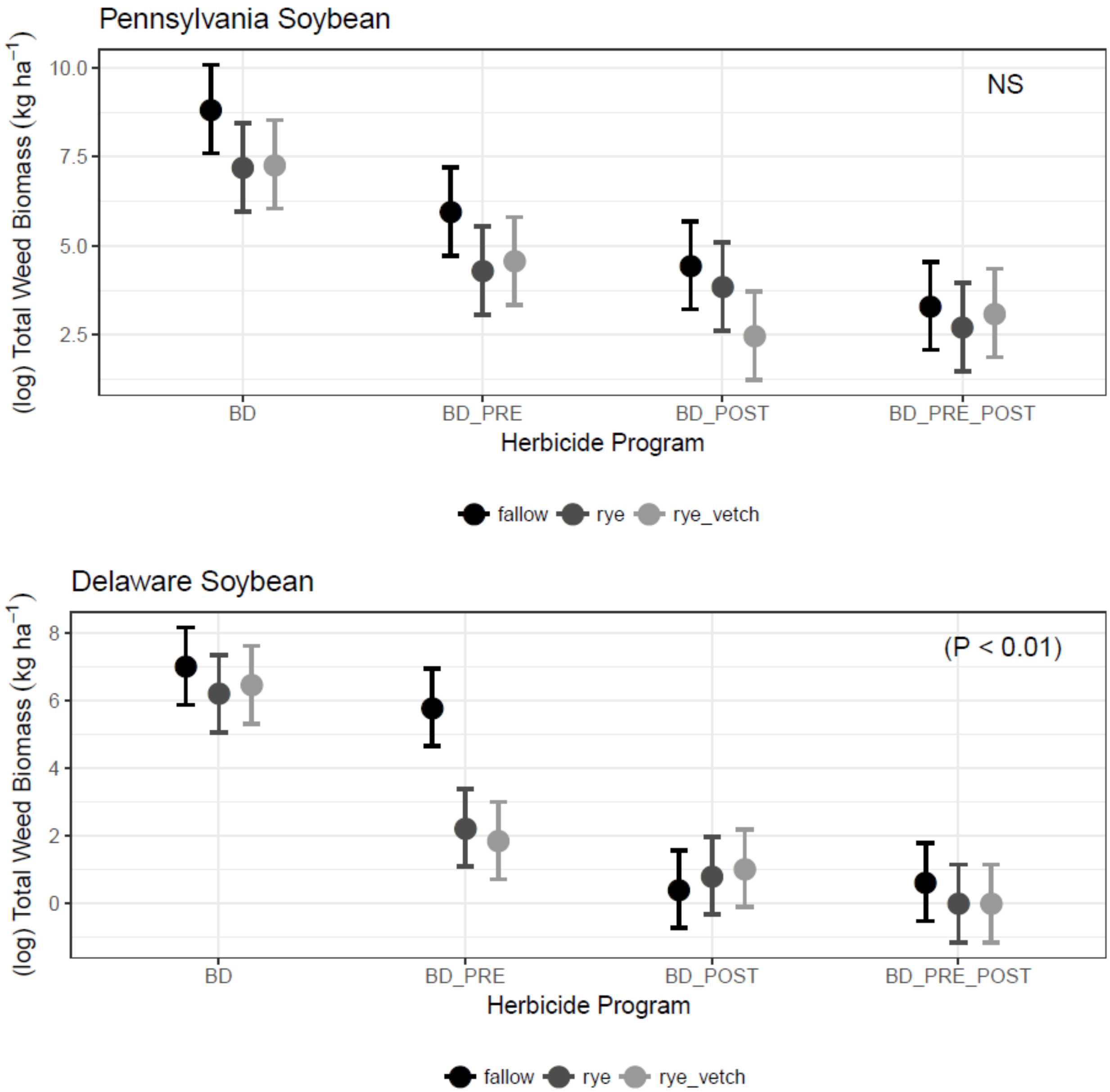


Figure 1-2a. Environmental stewardship for herbicide strategies in corn (**A**) were rated on a scale of 0-5. Within each herbicide strategy, scores were derived from the number of equipment passes in a field to make the application(s), the leaching potential of the most detrimental herbicide, the half-life (as number of days) of the most persistent herbicide, and the $LC_{50}$ (as mg $L^{-1}$) value for the most toxic herbicide. Environmental stewardship was also considered for both applied PRE-residuals, as well as other corn PRE-residual herbicides common throughout the Mid-Atlantic (**B**) (Shaner, 2014).

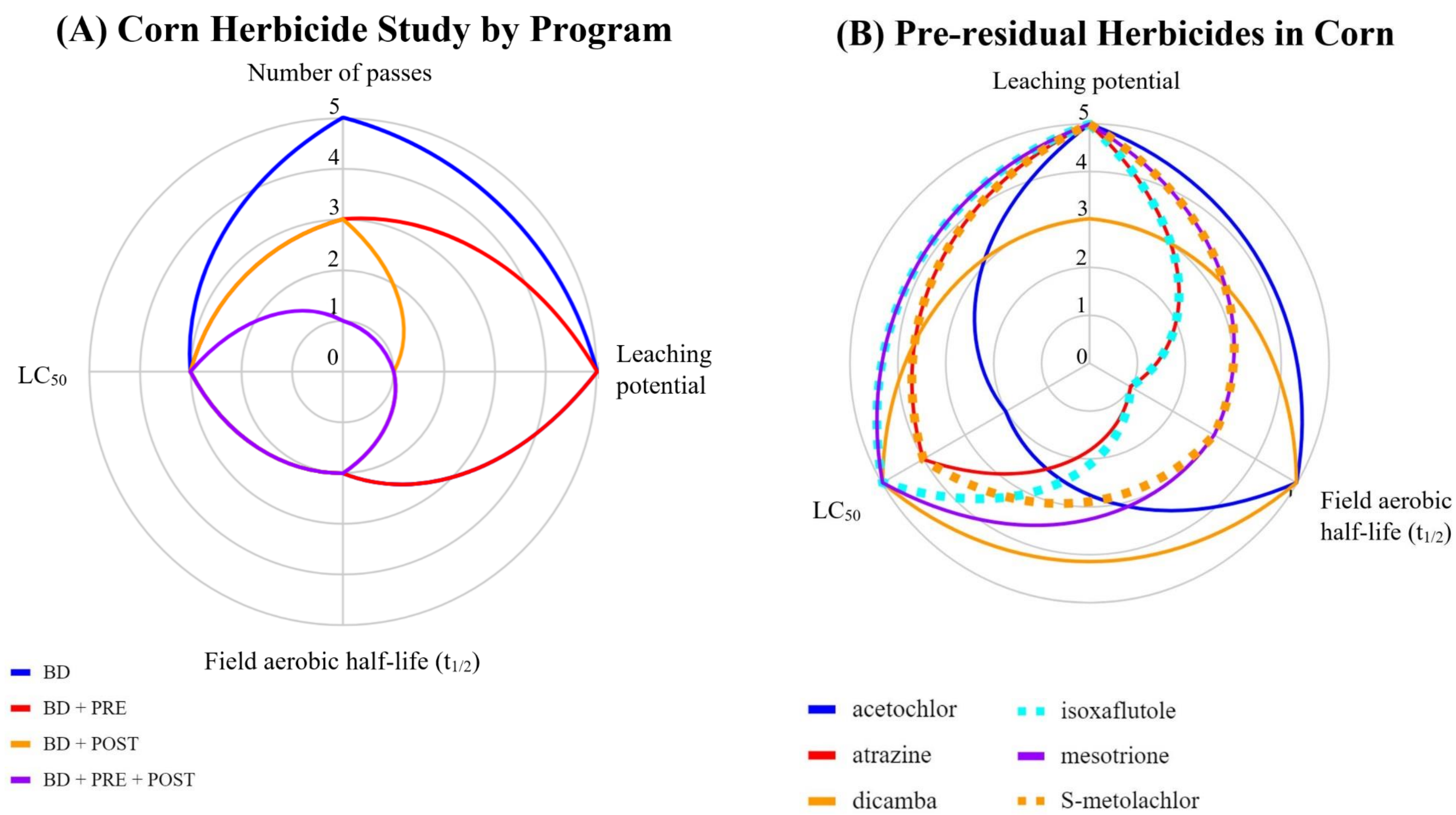
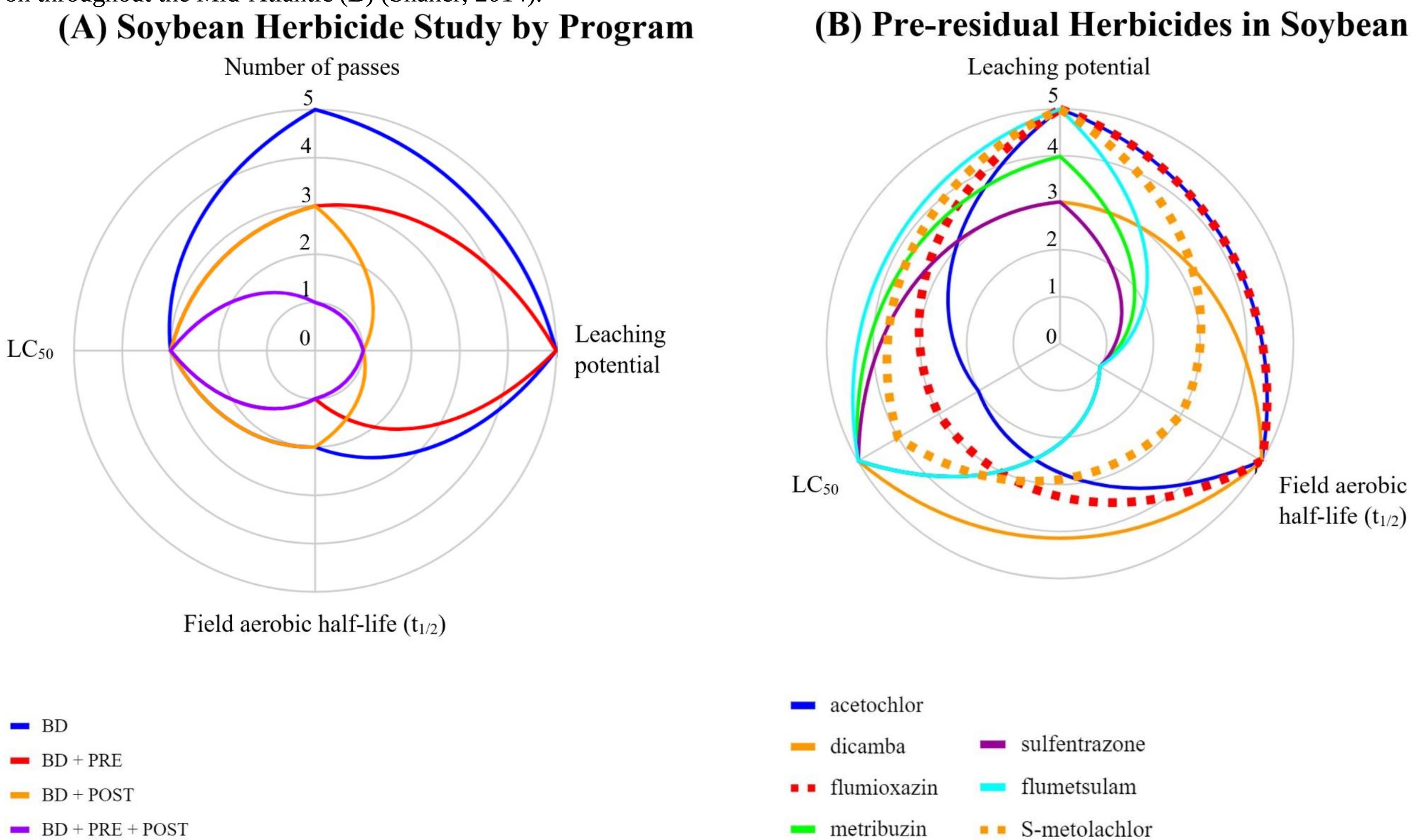


Figure 1-2b. Environmental stewardship for the herbicide strategies in soybean (**A**) were rated on a scale of 0-5. Within each herbicide strategy, scores were derived from the number of equipment passes in a field to make the application(s), the leaching potential of the most detrimental herbicide, the half-life (as number of days) of the most persistent herbicide, and the $LC_{50}$ (as mg $L^{-1}$) value for the most toxic herbicide. Environmental stewardship was also considered for both applied PRE-residuals, as well as other soybean PRE-residual herbicides common throughout the Mid-Atlantic (**B**) (Shaner, 2014).
on throughout the Mid-Atlantic (**B**) (Shaner, 2014).



# Chapter 2

## Reducing herbicide resistance selection pressure with cover crop-based integrated weed management programs in no-till soybean

### Introduction

Herbicide-resistant (HR) crops have facilitated use of single-tactic, herbicide-based weed management programs, which has significantly increased selection pressure for HR weed species (Duke and Powles 2009; Mortensen et al. 2012). High adoption levels of glyphosate-resistant (GR) soybean (93%) and GR corn (82%) have expanded the frequency of use and area treated with glyphosate (Fernandez-Cornejo et al. 2014). In 2000, GR horseweed [*Conyza canadensis* (L.) Cronquist] was first reported in GR soybean in Delaware, the first confirmed case of a GR weed infesting a GR crop in the United States (VanGessel, 2001). In total, seventeen weed species have evolved resistance to glyphosate in the United States, thirteen of which have been found in GR crops (Heap and Duke 2017). While changes in rotation and frequency of GR crop use could help address this problem, economic and systems constraints in commodity grain production make such changes difficult to realize (Harker et al. 2017). Multi-tactic integrated weed management (IWM) programs are needed to manage current HR weeds and reduce HR selection pressure (Heap and Duke 2017; Mortensen et al. 2012).

Horseweed is a facultative winter annual weed that has become a persistent problem in conservation tillage systems (Buhler and Owen 1997). Horseweed germinates in both the fall and spring, but emergence patterns can vary by production region and systems (Davis et al. 2010). Currently, there are few effective herbicides for horseweed control in no-till soybean production (Heap and Duke 2017). In the Mid-Atlantic region, GR Palmer amaranth (*Amaranthus palmeri*

S. Watson) and GR waterhemp [*A. tuberculatus* (Moq.) J.D. Sauer] have been identified and pose a significant management challenge in no-till soybean systems. These summer annual *Amaranthus* species are among the most economically damaging GR weeds worldwide (Culpepper et al. 2006). Herbicide-based control of these species is particularly challenging because of the prevalence of multiple-resistant biotypes of Palmer amaranth and common waterhemp (Heap and Duke 2017). Multiple-resistance occurs when a weed biotype evolves resistance to more than one herbicide site of action.

Cover crop use is increasing in the Mid-Atlantic region (Hamilton et al. 2017), and recent studies have demonstrated that cover cropping can be employed as an IWM tool to manage GR weeds (Loux et al. 2017; Montgomery et al. 2018; Wiggins et al. 2016). Living cover crops and terminated cover crop surface mulch primarily influence weed population dynamics via resource competition and niche pre-emption, though additional weed suppressive mechanisms such as allelopathy can also contribute to regulation of weed populations (Teasdale 1998; Vencill et al. 2012). As a result, cover crops can potentially reduce (1) selection for herbicide resistance by reducing the proportion of the population exposed to the selection pressure of herbicides (Mortensen et al. 2012), and (2) the number of large individuals at time of herbicide application due to resource pre-emption, which may increase weed control efficacy of herbicide-based tactics (Wallace et al. 2018).

In the Northeast region, cover crop management tactics are constrained by growing season length in annual grain rotations. Many growers have difficulty establishing cover crops following late-harvested crops such as corn grain and soybean. In this scenario, cover crop options are limited to use of winter-hardy species like cereal rye, hairy vetch (*Vicia villosa* Roth), and clover spp. (*Trifolium spp*.). Grower use of cereal rye alone or grass-legume mixtures is likely determined by N-demand of the subsequent cash crop but will also influence weed population dynamics. Further, growers may be constrained by the higher cost of legume cover crop seed compared to cheaper cereal rye seed cost. In contrast, integration of cover crops after winter or summer cereal facilitates a longer growing season window and permits use of winter-kill species such as forage radish (*Raphanus sativus* L.) and spring oat (*Avena sativa* L.), which produces cover crop biomass in the fall capable of suppressing fall-emerging winter annual weeds (Lawley et al. 2012). Resource acquisition in the fall and the residue that remains from winter-kill cover crop species may also indirectly suppress spring-emerging weeds (Lawley et al. 2012). The length of the fall growing season window and the functional traits (e.g. winter-hardy vs. winter-kill) of cover crop monocultures or mixtures are important factors that will determine weed population responses.

Cover crop management in late-spring can also influence weed population responses. Minimizing the period between cover crop termination and cash crop establishment has the potential to enhance suppression of summer annual weeds due to greater cover crop biomass production (Nord et al. 2012). Roller-crimping high-biomass cover crops produces a thick mulch that attenuates weed seed germination cues and acts as a physical barrier to establishment of germinated weeds (Mirsky et al. 2013). Cover crop surface mulch may also indirectly influence weed-crop competition by increasing water infiltration and reducing evaporative losses of water during the growing season (Wells et al. 2014).

In conventional no-till production systems, pre-plant, burndown herbicide applications are used to terminate the cover crop and emergent weed populations (Duiker and Curran 2005). Further research is needed to determine cover crop tactics that reduce size of winter annual weed populations, such as horseweed, at the time of a pre-plant herbicide application, to reduce the selection intensity for herbicide resistance evolution. If delaying cover crop termination to allow for greater biomass accumulation becomes a more common practice, it will also be necessary to understand the effect of cover crops on the deposition patterns of pre-plant burndown herbicides, which could influence both weed control efficacy and herbicide selection pressure intensity on emerged weed populations. Further research is needed to identify cover cropping tactics that reduce selection for herbicide resistance reduction and can be employed as a proactive IWM approach in no-till grain production (Owen 2016).

The objectives of this research were to evaluate the (1) effect of alternative cover crop tactics on winter annual weed population size at the time of a pre-plant burndown herbicide application; (2) effect of cover crop termination date on summer annual weed population size at the time of POST-emergent herbicide application; and (3) effect of cover crops on herbicide deposition patterns in pre-plant burndown herbicide application.

## Materials and Methods

We conducted two field experiments at the Russell E. Larson Agricultural Research Center in Rock Springs, Pennsylvania (PA) in 2015-2016 (2016) and the Elbert N. & Ann V. Carvel Research and Education Center in Georgetown, Delaware (DE) in 2015-2016 (2016) and repeated in 2016-2017 (2017).

The PA location has Hagerstown silt loam (fine, mixed, semi-active Typic Hapludalfs) soils and is in USDA plant hardiness zone 6a, with an annual average of 1,660 growing degree days (GDD; base 10 C) and 100 cm of precipitation. The DE location has loamy sand soils and is in zone 7a, with an annual average of 2,440 GDDs and 115 cm of precipitation. In the first year of the study (2016), the soil was a Rosedale loamy sand (loamy, siliceous, semi-active, mesic

Arenic Hapludults), and in the second year (2017) the soil was a Klej loamy sand (mesic, coated Aquic Quartzipsamments).

Each experiment was arranged as a randomized complete block with a split-plot design and four replications. The main plot was cover crop treatment and the split-plot was termination timing. Main plots were 6 m by 9 m, and split-plots were 3 m by 9 m. We selected cover crop treatments and termination timings based on agronomic and environmental constraints in Mid-Atlantic annual grain crop systems.

We seeded cover crop treatments (Table 2-1) with a Great Plains 1005 NT[2] no-till drill in early September (early) or early October (late) following a small grain to examine the impact of establishment date on cover crop performance and weed suppression throughout fall and spring (Table 2-2). The experimental site was rotary-harrowed prior to seeding to promote emergence of volunteer small grains, followed by an application of glyphosate (1.26 kg ae $ha^{-1}$) before each respective cover crop seeding date to control emerged vegetation. Cover crop treatments included a no cover control (early in PA and DE and late in DE only), spring oat (early), cereal rye “Aroostook” (early and late), cereal rye + crimson clover “Dixie” (early and late), cereal rye + hairy vetch “Auburn early cover” (early and late), and cereal rye + forage radish (early) (Table 1-1).

We established horseweed microplots (0.5 $m^2$) at a seeding rate of 5,000 seeds near the center of each split-plot following the early cover crop seeding date, and we established separate smooth pigweed (*A. hybridus* L.) microplots (0.5 $m^2$) at a seeding rate of 500 seeds near the center of each split-plot in the late fall. Seeds were gently mixed with a fine sand and evenly distributed across the microplot. In addition to even distribution, the sand helped weigh down the seeds to prevent dispersal at time of sowing.

We terminated cover crops the following spring at either an early (late boot stage of cereal rye or Zadoks 55) or late (full heading of cereal rye or Zadoks 69) date with 1.26 kg ae $ha^{-1}$ glyphosate + 0.56 kg ae $ha^{-1}$ 2,4-D 10 d prior to soybean planting. Herbicides were applied using a tractor mounted boom sprayer equipped with TeeJet[1] AI11002VS spray tips at 187 L $ha^{-1}$. We planted glufosinate-resistant soybean 'Doebler's DB3217LL[4]' in 76 cm rows at 444,800 seeds $ha^{-1}$ using a John Deere 7200 planter[5]. At the V3-V4 stage, we broadcast applied glufosinate at the V3-V4 soybean stage at 0.59 kg ai $ha^{-1}$, which represents a recommended POST-emergent application timing in no-till soybean production.

In the late fall, approximately 10 weeks after the early cover crop planting date (10 WAP), we collected aboveground cover crop and weed biomass at two 0.25 $m^2$ representative locations within each split-plot, sorted the composited sub-samples species, and oven-dried the sub-samples for a minimum of 96 h at 60 C. Ground cover (%) was also visually assessed 10 WAP in each 0.25 $m^2$ quadrat by cover crop and weed species, surface mulch from the preceding crop, and bare soil. The metrics taken 10 WAP were measured again using the same methodology just prior to spring, pre-plant burndown applications. We assessed horseweed (PA only) and other winter annual weeds (plt 0.5 $m^{-2}$) in (1) late fall (10 WAP), (2) at the pre-plant, spring burndown application timing, and (3) at the POST-emergent herbicide application timing. Smooth pigweed (PA only) and other summer annual weeds (in DE; plt 0.5 $m^{-2}$) was assessed at the POST-emergent application timing. Additionally, we examined late summer (Aug) weed biomass by harvested all aboveground weed biomass in representative locations at the split-plot level.

The effect of cover crops on herbicide deposition patterns at the time of a spring, pre-plant burndown application was assessed at the PA location in 2016 and 2017 within companion field experiments that utilized a subset of the same cover crop treatments (species and seeding rates) and were managed using the same methodology and field operation dates. Cover crop treatments used for evaluation of herbicide deposition patterns included a no cover control, cereal rye, cereal rye + crimson clover, and cereal rye + hairy vetch. In each cover crop treatment plot, two water-sensitive spray cards[6] were placed on the ground surface beneath the cover crop canopy and in the interrow between seeded cover crops at the time of the pre-plant burndown application. To avoid adverse moisture effects, the cover crop canopy was opened prior to card placement to increase air circulation. Spray cards were positioned just before herbicide application and the canopy was reclosed. Spray cards were removed promptly following application, allowed to air dry, and then stored until post-processing. Spray deposition was quantified in the laboratory by taking a photograph of each spray card using a Samsung F1.7 lens camera[7]. The digital images were then cropped to a uniform area of 30 $cm^{-2}$ and analyzed using SnapCard[8] software. Water sensitive spray cards change color from yellow to dark maroon when contacted by water droplets. SnapCard[8] software quantifies spray card deposition as percent of the card area turned dark maroon.

Analysis of variance (ANOVA) was conducted using linear mixed effects models in R version 3.2.3[9] to evaluate cover crop treatment effects by study location on response variables, including (1) fall cover crop and winter annual weed biomass (kg $ha^{-1}$); (2) fall ground cover (%) of cover crops and winter annual weeds; (3) spring cover crop and winter annual weed biomass (kg $ha^{-1}$) prior to a pre-plant, burndown herbicide application (BD); (4) ground cover (%) of cover crop treatments and winter annual weeds prior to BD; (5) weed community density (plt $m^{-2}$) in the fall, prior to BD, and prior to a POST-emergent application; and (6) and spray card coverage (%) at BD. Fixed effects included cover crop treatment, year (DE only) and their interaction (DE only) for fall and spring-burndown performance metrics. Evaluation of weed density at the POST- timing included cover crop treatment, termination timing, year (DE only) and their interaction as fixed effects. Block was included as a random factor in PA and DE. Assumptions of normality were assessed with the Shapiro-Wilk's Test and quantile-quantile plots. Percent ground cover and spray card coverage were arcsine square root transformed to achieve normality. Weed density was analyzed using a generalized linear mixed effects model with a negative binomial distribution. Means were separated with Tukey's adjusted *P*-values for significant main effects or interactions.

## Results and Discussion

### Fall Cover Crop Performance

In PA, cover crop treatments affected ($P < 0.001$) aboveground biomass and ground cover (%) in late fall (Table 2-3). Early-seeded cover crop treatments resulted in greater biomass and ground cover than late-planted cover crops. Within early-planted treatments, cereal rye + forage radish produced higher levels of fall biomass and ground cover than cereal rye + hairy vetch but was similar to other treatments. Cereal rye and forage radish produced similar biomass levels in mixture, but forage radish contributed 75% to the total ground cover. Use of spring oat did not result in greater biomass production than cereal rye in grass + legume mixtures. Late-planted cereal rye, cereal rye + crimson clover, and cereal rye + hairy vetch did not differ in aboveground biomass or ground cover at the late fall assessment.

In DE, there was a significant interaction between year and cover crop treatment for cover crop biomass ($P < 0.001$) and percent ground cover ($P < 0.01$) (Table 2-3). Cover crop biomass production and ground cover was greater in the second year due to more favorable growing conditions. In the first year, fall biomass did not differ among cover crop treatments but early-seeded cover crop treatments resulted in higher ground cover (%) than late-planted treatments. In the second year, higher biomass levels occurred in the early-seeded treatments compared to late-seeded treatments. Within early-seeded treatments, spring oat + hairy vetch did not differ from other treatments in the first year, but resulted in greater biomass than cereal rye seeded alone or in mixture with a legume in the second year.

**Spring Cover Crop Performance**

In PA, cover crop treatment main effect was significant for biomass ($P < 0.01$) and percent ground cover ($P < 0.001$) (Table 2-4). The timing of seeding (early, late) did not affect spring biomass production or ground cover in treatments including cereal rye alone or in mixture with a legume. It is generally thought that seeding dates later than early September in central PA result in poor legume establishment, but species composition in grass-legume mixtures were similar in early- and late-seeded treatments at the PA location. Cover crop mixtures that included both a winter-hardy and winter-kill species produced variable results. Early-seeded spring oat + hairy vetch produced the lowest biomass at the time of spring burndown, though percent ground cover produced by hairy vetch (84%) was comparable or greater than other treatments. Conversely, spring biomass levels of early-seeded cereal rye + forage radish were comparable to other cereal rye-based treatments, but percent ground cover was lower than other cover crop treatments due to winter mortality and residue breakdown of forage radish. These results suggest that use of winter-kill + winter-hardy mixtures produce trade-offs between different functional traits (biomass vs. ground cover) in fall and spring that are thought to enhance weed suppression.

In DE, a significant interaction between year and cover crop treatment occurred in the analysis of cover crop biomass ($P < 0.01$) and percent ground cover ($P < 0.01$; Table 2-4). Biomass production was approximately an order of magnitude higher in the second study year due to more favorable growing conditions. Like the PA location, late-sown cover crops produced similar levels of biomass and ground cover compared to early-sown cover crops at the time of spring burndown. No treatment effects on biomass production were observed in the first study year, but cereal rye alone (early and late) or in mixture with forage radish produced lower levels of ground cover. Similar cover treatment effects on ground cover were observed in the second study year.

Termination timing influenced cover crop biomass at the PA location ($P < 0.001$; data not shown), where as expected, delaying spring termination resulted in greater spring biomass accumulation. On average, cover crop biomass increased by 1,359 kg $ha^{-1}$ between termination dates, with spring oat + hairy vetch (early) exhibiting the lowest additional growth (353 kg $ha^{-1}$) and cereal rye + hairy vetch (late) with the greatest (2,625 kg $ha^{-1}$). Termination timing also affected cover crop biomass production ($P < 0.05$) at the DE location, with biomass generally increasing as termination was delayed.

**Population Responses of Winter Annual Weeds**

Recruitment of horseweed populations in seeded microplots was sufficient for evaluating cover crop treatment effects at the PA location (Table 2-5). In late-fall, horseweed density in early-sown cover crop treatments did not differ from the control, but density in late-sown cover crop treatments were significantly lower than the control. (Figure 2-1). With the exception of cereal rye + crimson clover (early), mean horseweed density was generally lower than the no cover control, but high variability in horseweed recruitment across treatment replicates was observed. Lower horseweed density in late-sown treatments than early-sown treatments is likely attributable to the later fall burndown application, which likely eliminated emerged horseweed seedlings.

Horseweed populations declined from fall to spring in all cover crop treatments, indicating that overwintering horseweed plants are susceptible to mortality regardless of residue effects (Table 2-5; Figure 2-1). Cover crop effects ($P < 0.01$) on horseweed density were lower at the time of the spring, pre-plant herbicide application. Relative to the control, mean horseweed population reductions ranged from 20 to > 90% across evaluated cover crop treatments at the time of exposure to spring, pre-plant burndown herbicides (Figure 2-2). Cover crops alone can lower selection intensity at the time of spring pre-plant herbicide application, and applying a fall burndown prior to cover crop seeding, coupled with the potential for overwinter mortality (Buhler and Owen 1997), can further proactively manage winter annual weed populations and lower selection intensity.

Horseweed density was low (< 10 plt $m^{-2}$) across cover crop treatments, including the no cover crop control, at the time of a POST-emergent application. Although each combination of cover crop and herbicide-tactics produced similar horseweed control efficacy by mid-growing season, horseweed mortality resulted from a single “hammer,” and the number of horseweed individuals exposed to herbicide selection was measurably greater in the no cover crop control.

Horseweed recruitment was poor in DE, so we assessed overall winter annual weed density within the horseweed microplot. The resident weed community included mouseear chickweed [*Cerastium fontanum* Baumg. *ssp. vulgare* (Hartm.) Greuter & Burdet], henbit (*Lamium amplexicaule* L.), annual ryegrass [*Lolium perenne L. ssp. multiflorum* (Lam.) Husnot], common evening primrose (*Oenothera biennis* L.), common chickweed [*Stellaria media* (L.) Vill.], and field pansy (*Viola bicolor* Pursh). A significant year by cover crop interaction ($P < 0.001$) occurred in analysis of winter annual weed density in DE. Winter annual weed density was higher in the fall of 2016 compared to 2015 (Table 2-6). At the cover crop main effect level, early-sown and late-sown cover crop treatments did not affect winter annual weed density relative to the respective control treatments, but late-sown treatments resulted in lower winter annual weed density compared to early-sown treatments in the fall of 2015. Early-sown cover crop treatments produced greater biomass and percent ground cover by the late fall than late-sown treatments, although the late-sown treatments ultimately controlled winter annual weed density to a greater degree. This is likely a result of the fall herbicide application prior to each respective cover crop sowing date. While the fall herbicide application before the early sowing date was likely too early to target most fall-emerged winter annual weeds, the herbicide application prior to the late sowing date likely targeted more winter annual weeds. Thus, winter annual weed control in late-sown treatments resulted from not only cover crop effects but also the herbicide effects.

In the fall of 2016, late-seeded cereal rye controlled winter annual weed density better than other late-sown treatments; cereal rye (late) also yielded higher fall biomass than cereal rye + crimson clover (late) and cereal rye + hairy vetch (late). Cases did arise where treatments with cover crops did have higher weed densities than the control, notably cereal rye + hairy vetch (early) and spring oat + hairy vetch (early) in the fall of 2015 and 2016, and late-sown cereal rye + crimson clover and cereal rye + hairy vetch. This is possibly a result of the crop rotation in DE, where this particular study followed a rye crop and could have created a situation of soil N immobilization that inhibited the cover crop growth and subsequent winter annual weed control.

Winter annual density experienced overwinter mortality in all cover crop treatments in the 2016 season, but winter annual weed density increased from fall to spring in the no cover control treatments and late-sown rye. Treatments with higher weed densities in the fall had lower densities in the spring, except for late-sown cereal rye in 2017. The absence of cover crop competition in the control treatments resulted in significantly higher winter annual weed density, which resulted in selection pressure on pre-plant burndown herbicides compared the use of a complementary cover crop tactic.

**Summer Annual Weed Resistance Reduction**

Smooth pigweed establishment prior to the spring, pre-plant burndown application was negligible across all treatments at the PA location (Table 2-7). At the POST-emergent application, early- and late- sown cereal rye and cereal rye + forage radish resulted in lower smooth pigweed densities than oat + vetch but did not differ from the control (Figure 2-5). Delaying termination timing, which resulted in higher cover crop biomass, further reduced smooth pigweed populations ($P < 0.05$). On average, smooth pigweed density declined by 5 plt $m^{-2}$ between termination dates, except for early-sown oat + hairy vetch, which resulted in increased smooth pigweed density at the later termination date. In comparison, early- and late-sown cereal rye + hairy vetch resulted in the largest population decline from early to late termination dates of all cover crop treatments (20 and 15.5 plt $m^{-2}$, respectively). These results suggest that hairy vetch residue alone in the spring oat + hairy vetch treatment was less effective at suppressing smooth pigweed recruitment than when paired with cereal rye. Further, treatments with greater mean cereal rye biomass at termination produced resulted in greater than 50% smooth pigweed population reductions at the time of a POST-emergent application relative to the no cover control (Figure 2-6). In comparison, early-sown spring oat + hairy vetch and cereal rye + hairy vetch resulted in higher smooth pigweed density than the no cover control at the time of a POST-emergent application, possibly a result of the quick decomposition of hairy vetch compared to a cover crop species with higher lignin, such as cereal rye (Ruffo and Bollero 2003). The decomposition rate of hairy vetch may decrease the ratio of soil C:N early in the growing season and create a trade-off of N mineralization that could benefit summer annual weeds.

In DE, mean summer annual weed density was lower in treatments with cover crops ($P < 0.001$) at the spring pre-plant burndown application. Summer annual weed densities at the time of a POST-emergent application were not affected by cover crop treatment or termination date. Summer annual weed recruitment remained low (10 plants $m^{-2}$) across all treatments, which may have obscured treatment effects (Table 2-7; Figure 2-7). Early-sown spring oat + hairy vetch produced similar patterns to the PA location, with nearly 50% higher summer annual weed density observed in comparison to the control treatments (Figure 2-8).

Hairy vetch and other legume species have low carbon to nitrogen ratios, and decomposition releases nitrogen that rapidly converts to nitrate, which can favor germination of pigweed species (Mohler et al. 2018). Other studies have shown that cereal rye effectively suppresses *Amaranthus* species, including Palmer amaranth and tall waterhemp (Loux et al. 2017). Terminating cover crops as close to planting as possible can reduce Palmer amaranth populations (Montgomery et al. 2018). The results from our studies were consistent with Montgomery et al. (2018) in that cover crops have the potential to reduce *Amaranthus* spp. and summer annual weed density at the time of herbicide exposure, thereby reducing selection pressure for resistance. However, these results suggest that, in some cases, grass-legume mixtures can create conditions favorable for summer annual weed recruitment, consequently increasing herbicide selection pressure.

**Herbicide Interception by Cover Crops**

Cover crop biomass in corn was significant across year at both sites ($P < 0.001$) (Table 2-8). In PA, cereal rye + crimson clover produced 2,299 and 7,243 kg $ha^{-1}$ in 2016 and 2017, respectively, and cereal rye + hairy vetch produced 1,948 and 6,988 kg $ha^{-1}$ in those years. In DE, cereal rye + crimson clover produced 4,699 and 8,468 kg $ha^{-1}$ in 2016 and 2017, and cereal rye + hairy vetch produced 4,154 and 7,556 kg $ha^{-1}$ in those years. Cover crop biomass in soybean was significant across years in PA ($P < 0.001$), but there were no significant effects in DE. In PA, cereal rye produced 3,141 kg $ha^{-1}$ in 2016 and 5,592 kg $ha^{-1}$ in 2017, and cereal rye + hairy vetch produced 3,064 and 5,496 kg $ha^{-1}$ in those years. In DE, cereal rye produced 3,729 kg $ha^{-1}$ in 2016 and 4,443 kg $ha^{-1}$ in 2017, and cereal rye + hairy vetch produced 4,115 and 4,001 kg $ha^{-1}$ in those years.

Year and cover crops influenced weed response in corn ($P < 0.01$) and soybean ($P < 0.001$) in PA (Table 2-9). Growing conditions in 2017 were more favorable for both cover crops and weeds. In corn, winter annual weed biomass in the no cover control was 85 kg $ha^{-1}$ in 2016 and 494 kg $ha^{-1}$ in 2017. In soybean, winter annual weed biomass was 34 and 221 kg $ha^{-1}$ in those years. Across both cropping systems, winter annual weed biomass was lower in treatments with cover crops (Figure 2-9). Further, although weed biomass in the control was roughly six times higher in 2017 in corn and soybean, weed biomass in a cover crop was held constant.

In the corn experiment, cover crop treatment had a significant effect ($P < 0.001$) on herbicide spray coverage (%) (Table 2-10). In the no cover control, mean spray coverage was

23%, whereas cereal rye + crimson clover and cereal rye + hairy vetch treatments resulted in significantly lower (2%) spray coverage. In soybean experiments, the study year and cover crop treatment affected both burndown herbicide spray coverage (%) and mean weed biomass beneath the cover crop canopy ($P < 0.001$). In 2016, both the cereal rye and cereal rye + hairy vetch treatments exhibited lower herbicide spray coverage, 24% and 17% respectively, at the soil surface compared to the no cover control (33%). Similar patterns occurred in 2017, where cereal rye (13%) and cereal rye + hairy vetch (10%) resulted in lower spray coverage than the no cover control (19%).

In no-till production, pre-plant burndown herbicides are used to terminate cover crops and to control emerged winter annual and early emerging summer annual weeds. Our results demonstrate lower herbicide coverage penetrating the cover crop canopy in treatments with higher cover crop biomass and cover, which results in lower rate of burndown active ingredient reaching the soil surface (Table 2-9; Figure 2-9). Weeds at the soil surface not controlled by the cover crop prior to burndown application may not receive a high enough herbicide concentration to be effectively controlled. While smaller spray droplets may increase herbicide penetration through the cover crop canopy, application risks such as off-target drift should be considered. However, the combination of actively growing cover crops prior to termination and the resulting surface mulch residue after termination has the potential to achieve acceptable levels of winter annual weed suppression, which would further reduce the herbicide selection intensity at the pre-plant burndown application timing.

**Conclusions**

Our results suggest that fall-sown cover crops can reduce the selection pressure exerted by herbicide-based weed control programs for winter and summer annual weed species, including problematic resistant species like horseweed and smooth pigweed. Smooth pigweed served as a surrogate for GR Palmer amaranth and waterhemp, which have more aggressive growth and may be more challenging to control. Consequently, inferences extended to these species should be viewed cautiously. In other regions, cover cropping tactics can improve suppression and control of Palmer amaranth. Minimizing the window between cover crop termination timing and crop planting, as well as high levels of cereal rye residue, can enhance Palmer amaranth suppression and reduce reliance on herbicides (Montgomery et al. 2018). Our study also demonstrates that cover crops influence deposition of pre-plant, burndown herbicide applications by intercepting some of the herbicide, which reduced herbicide selection pressure at this application timing but may also have produced a negative trade-off related to reduced weed control efficacy beneath the cover crop canopy. Further research should examine this potential negative relationship more closely, focusing on specific weed species as well as herbicide sites of action. In particular, certain herbicides such as contact herbicides may be more prone to reduced weed control efficacy in the presence of cover crops, necessitating alternative herbicide selection.

**Sources of Materials**

[1]Spraying Systems, Co., Glendale Heights, IL 60139

[2]Great Plains Manufacturing, Inc., Salina, KS 67401

[4]Doebler's Pennsylvania Hybrids, Inc., Williamsport, PA 17701

[5]John Deere & Company, Moline, IL 61265

[6]Syngenta AG, Basel, Switzerland

[7]Samsung Group, Seoul, South Korea

[8]Government of Western Australia, South Perth, WA 6151

[9]R© statistical analysis software, The R Foundation for Statistical Computing, Vienna, Austria

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Table 2-1. Cover crop treatments and seeding rates used in experiments. Treatments were established at the "early-sown" timing in early September or at the "late-sown" timing in early October.

| Cover crop treatment | Early-sown | Late-sown | Seeding rate |
|---|---|---|---|
| | | | ———kg $ha^{-1}$——— |
| No cover control | X | X[†] | — |
| Spring oat + hairy vetch | X | | 34 + 34 |
| Cereal rye | X | X | 135 |
| Cereal rye + crimson clover | X | X | 34 + 22 |
| Cereal rye + hairy vetch | X | X | 34 + 34 |
| Cereal rye + forage radish | X | | 101 + 6 |

[†]Established in Delaware only

Table 2-2. Field operations and data collection at the Pennsylvania location in 2015-2016 (PA16) and Delaware location in 2015-16 (DE16) and 2016-17 (DE17).

| Field operation / data collection | PA16 | DE16 | DE17 |
|---|---|---|---|
| Early cover crop planting | 9/1 | 10/14 | 10/17 |
| Horseweed planting | 9/14 | 10/17 | 10/18 |
| Smooth pigweed planting | 12/21 | 11/24 | 12/6 |
| Spring green-up N application (44 kg N $ha^{-1}$) | 4/27 | 3/16 | 2/28 |
| Percent ground cover assessment | 5/3 | 5/10 | 5/19 |
| Spring microplot weed data collection | 5/3 | 5/10 | 5/19 |
| Cover crop biomass | 5/3 | 5/10 | 5/19 |
| Cover crop pre-plant burndown application | 5/6 | 5/20 | 5/26 |
| Soybean planting | 5/22 | 6/1 | 6/2 |
| Microplot weed data collection | 6/24 | 7/6 | 6/27 |
| POST application | 6/27 | 7/8 | 6/28 |
| Percent weed control rating | 7/11 | 7/27 | 7/17 |
| Soybean harvest | 11/1 | 10/27 | 10/2 |

Table 2-3. Cover crop treatment effect on fall aboveground biomass (kg $ha^{-1}$) production and ground cover (%) at Pennsylvania in 2015-16 (PA16) and Delaware location in 2015-16 (DE16) and 2016-2017 (DE17). Data were collected in the late fall, approximately 10 weeks after planting of early seeded cover crops. Means are presented followed by the percentage of total contributed by each species in parentheses for treatments containing two-species mixtures. Means within a column followed by the same letter are not statistically different (P > 0.05).

| | Aboveground fall biomass | | | | | | Fall ground cover | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PA16 | | DE16 | | DE17 | | PA16 | | DE16 | | DE17 | |
| | kg $ha^{-1}$ | | | | | | % | | | | | |
| Oat + vetch (early) | 2,287 (81/19) | bc | 121 (74/26) | a | 628 (71/29) | d | 78 (60/40) | b | 31 (52/48) | d | 19 (53/47) | abc |
| Rye (early) | 2,446 | bc | 75 | a | 434 | c | 77 | b | 29 | cd | 14 | ab |
| Rye + clover (early) | 2,231 (74/26) | bc | 67 (46/54) | a | 384 (32/68) | c | 83 (43/57) | bc | 29 (38/62) | cd | 17 (18/82) | ab |
| Rye + radish (early) | 2,619 (44/56) | c | 105 (53/47) | a | 467 (68/32) | cd | 88 (25/75) | c | 33 (48/52) | d | 15 (53/47) | ab |
| Rye + vetch (early) | 1,972 (78/22) | b | 65 (38/62) | a | 340 (33/67) | bc | 78 (62/38) | b | 32 (28/72) | d | 24 (12/88) | bcd |
| Rye (late) | 141 | a | 26 | a | 193 | ab | 21 | a | 14 | ab | 10 | a |
| Rye + clover (late) | 85 (67/33) | a | 27 (33/67) | a | 114 (57/43) | a | 19 (47/53) | a | 16 (38/62) | ab | 12 (25/75) | a |
| Rye + vetch (late) | 65 (74/26) | a | 14 (71/29) | a | 62 (77/23) | a | 13 (62/38) | a | 13 (38/62) | ab | 9 (44/56) | a |
| ANOVA | Wald $\chi^2$ | | | | | | | | | | | |
| Year (Y) | — | | 63.2*** | | | | — | | 33.3*** | | | |
| Cover crop (C) | 157.0*** | | 69.8*** | | | | 150.7*** | | 84.2*** | | | |
| Y × C | — | | 51.0*** | | | | — | | 23.5** | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance (Pr > $\chi^2$) of model terms shown as: NS, *P* > 0.05; *, *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.001.

Table 2-4. Cover crop treatment effect on spring aboveground biomass (kg $ha^{-1}$) production and ground cover (%) prior to pre-plant burndown application at Pennsylvania in 2015-16 (PA16) and Delaware location in 2015-16 (DE16) and 2016-2017 (DE17). Data were collected in the late fall, approximately 10 weeks after planting of early seeded cover crops. Means are presented followed by the percentage of total contributed by each species in parentheses for treatments containing two-species mixtures. Means within a column followed by the same letter are not statistically different (P > 0.05).

| | Aboveground spring biomass | | | | | | Spring ground cover | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PA16 | | DE16 | | DE17 | | PA16 | | DE16 | | DE17 | |
| | kg $ha^{-1}$ | | | | | | % | | | | | |
| Oat + vetch (early) | 2,544 (0/100) | a | 492 (0/100) | a | 4,493 (0/100) | de | 84 (0/100) | d | 70 (0/100) | de | 81 (0/100) | e |
| Rye (early) | 4,952 | b | 352 | a | 2,475 | bc | 57 | ab | 10 | a | 8 | a |
| Rye + clover (early) | 4,243 (81/19) | ab | 555 (39/61) | ab | 5,438 (32/68) | e | 68 (63/37) | bc | 42 (2/98) | bc | 64 (5/95) | cde |
| Rye + radish (early) | 3,354 (100/0) | ab | 331 (100/0) | a | 2,568 (100/0) | cd | 44 (100/0) | a | 9 (100/0) | a | 8 (100/0) | a |
| Rye + vetch (early) | 4,379 (60/40) | ab | 459 (32/68) | a | 4,395 (6/94) | cde | 100 (26/74) | e | 66 (2/98) | de | 78 (1/99) | e |
| Rye (late) | 4,913 | b | 381 | a | 4,118 | cde | 68 | bc | 9 | a | 13 | ab |
| Rye + clover (late) | 4,475 (85/15) | b | 459 (37/63) | a | 4,590 (34/66) | e | 77 (55/45) | cd | 54 (2/98) | cd | 69 (4/96) | de |
| Rye + vetch (late) | 4,506 (83/17) | b | 391 (60/40) | a | 4,098 (31/69) | cde | 78 (51/49) | cd | 41 (5/95) | bc | 75 (1/99) | de |
| ANOVA | Wald $\chi^2$ | | | | | | | | | | | |
| Year (Y) | — | | 140.2*** | | | | — | | 5.3* | | | |
| Cover crop (C) | 23.0** | | 22.1** | | | | 110.8*** | | 176.2*** | | | |
| Y × C | — | | 20.7** | | | | — | | 22.4** | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance (Pr > $\chi^2$) of model terms shown as: NS, $P > 0.05$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Table 2-5. Cover crop treatment effects on mean horseweed density at Pennsylvania. Weed density was collected in the late-fall (Fall), at the time of spring pre-plant burndown herbicide application (Burndown), and at the time of POST-emergent application (POST) at the V3-V4 soybean stage. Numbers in parentheses are standard errors of the mean. Data are pooled over termination timing. Means within a column followed by the same letter are not statistically different (P > 0.05).

| | Fall | | | Burndown | | | POST | | |
|---|---|---|---|---|---|---|---|---|---|
| | plants $m^{-2}$ | | | | | | | | |
| No cover control (early) | 340 | (110) | C | 181 | (64) | b | 1 | (0.4) | ab |
| No cover control (late) | — | — | — | — | — | — | — | — | — |
| Oat + vetch (early) | 214 | (79) | C | 17 | (12) | ab | 1 | (1) | ab |
| Rye (early) | 261 | (59) | C | 60 | (23) | ab | 5 | (2) | ab |
| Rye + clover (early) | 345 | (49) | C | 114 | (27) | ab | 3 | (2) | ab |
| Rye + radish (early) | 159 | (57) | Bc | 11 | (7) | a | 1 | (0.3) | ab |
| Rye + vetch (early) | 264 | (27) | C | 19 | (12) | ab | 0.3 | (0.3) | a |
| Rye (late) | 19 | (3) | A | 14 | (5) | a | 1 | (1) | ab |
| Rye + clover (late) | 26 | (5) | A | 18 | (8) | ab | 3 | (1) | ab |
| Rye + vetch (late) | 41 | (11) | Ab | 26 | (11) | ab | 7 | (4) | b |
| ANOVA | Wald $\chi^2$ | | | | | | | | |
| Year (Y) | — | | | — | | | — | | |
| Cover crop (C) | 64.7*** | | | 25.1** | | | 19.2* | | |
| Y × C | — | | | — | | | — | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance ($Pr > \chi^2$) of model terms shown as: NS, $P > 0.05$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Table 2-6. Cover crop treatment effects on mean winter annual weed density in Delaware. Weed density was collected in the late-fall (Fall) and at the time of spring pre-plant burndown herbicide application (Burndown). Numbers in parentheses are standard errors of the mean. Data are pooled over termination timing. Means within a column followed by the same letter are not statistically different (P > 0.05).

| | 2015-2016 | | | | | | 2016-2017 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fall | | | Burndown | | | Fall | | | Burndown | | |
| | plants $m^{-2}$ | | | | | | | | | | | |
| No cover control (early) | 145 | (31) | de | 196 | (25) | de | 18 | (6) | bc | 381 | (242) | a |
| No cover control (late) | 32 | (19) | abc | 131 | (13) | cde | 3 | (2) | c | 277 | (169) | abcde |
| Oat + vetch (early) | 160 | (93) | cde | 335 | (75) | e | 3 | (2) | c | 15 | (6) | bc |
| Rye (early) | 144 | (54) | cde | 190 | (47) | de | 10 | (6) | cd | 80 | (14) | abcd |
| Rye + clover (early) | 113 | (44) | bcde | 104 | (22) | cde | 9 | (4) | cd | 55 | (22) | abcd |
| Rye + radish (early) | 68 | (26) | abcd | 126 | (23) | cde | 14 | (7) | bc | 71 | (13) | abcd |
| Rye + vetch (early) | 246 | (177) | de | 246 | (75) | de | 8 | (4) | cd | 22 | (11) | bc |
| Rye (late) | 16 | (7) | a | 116 | (27) | cde | 0 | (0) | abc | 439 | (338) | a |
| Rye + clover (late) | 18 | (6) | ab | 208 | (36) | de | 0 | (0) | abc | 164 | (116) | ab |
| Rye + vetch (late) | 20 | (12) | ab | 233 | (78) | de | 0 | (0) | abc | 30 | (13) | bcde |
| ANOVA | Wald $\chi^2$ | | | | | | | | | | | |
| Year (Y) | 60.8*** | | | | | | | | | | | |
| Cover crop (C) | 26.2*** | | | | | | | | | | | |
| Y × C | 66.0*** | | | | | | | | | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance (Pr > $\chi^2$) of model terms shown as: NS, *P* > 0.05; *, *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.001.

Table 2-7. Cover crop treatment effects on smooth pigweed density at Pennsylvania and summer annual weed density in Delaware. Weed density was collected at the time of spring pre-plant burndown herbicide application (Burndown) and at the time of POST-emergent application at the V3-V4 soybean stage (POST). Numbers in parentheses are standard errors of the mean. Data are pooled across years. Means with a column followed by the same letter are not statistically different (P > 0.05).

| | Pennsylvania | | | | | | Delaware | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Burndown | | | POST | | | Burndown | | | POST | | |
| | plants $m^{-2}$ | | | | | | | | | | | |
| No cover control (early) | 2 | (1) | a | 13 | (3) | ac | 5 | (3) | ab | 8 | (2) | a |
| No cover control (late) | — | — | — | — | — | — | 13 | (4) | a | 8 | (2) | a |
| Oat + vetch (early) | 0 | (0) | a | 41 | (9) | c | 0 | (0) | ab | 9 | (3) | a |
| Rye (early) | 0 | (0) | a | 6 | (1) | ab | 0.3 | (0.3) | b | 3 | (1) | a |
| Rye + clover (early) | 0 | (0) | a | 14 | (4) | ac | 0 | (0) | ab | 2 | (1) | a |
| Rye + radish (early) | 2 | (1) | a | 5 | (2) | a | 1 | (1) | ab | 4 | (2) | a |
| Rye + vetch (early) | 0 | (0) | a | 24 | (7) | bc | 0.3 | (0.3) | b | 5 | (2) | a |
| Rye (late) | 2 | (1) | a | 4 | (1) | a | 2 | (2) | ab | 4 | (1) | a |
| Rye + clover (late) | 2 | (1) | a | 10 | (2) | ab | 1 | (1) | ab | 3 | (1) | a |
| Rye + vetch (late) | 1 | (1) | a | 12 | (4) | abc | 2 | (1) | ab | 3 | (1) | a |
| ANOVA | Wald $\chi^2$ | | | | | | | | | | | |
| Cover crop (C) | 126.2*** | | | 39.5*** | | | 956.2*** | | | 16.1 | | |
| Termination (T) | — | | | 6.5* | | | — | | | 0.002 | | |
| C × T | — | | | 7.4 | | | — | | | 2.3 | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance (Pr > $\chi^2$) of model terms shown as: NS, $P > 0.05$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Table 2-8. Mean aboveground cover crop biomass at the time of a pre-plant spring burndown (BD) herbicide application in corn and soybean experiments pertinent to spray card assessment at Pennsylvania in 2015-2016 (PA16) and 2016-2017 (PA17), and Delware in 2015-2016 (DE16) and 2016-2017 (DE17). Means are presented followed by the percentage of total contributed by each species in parentheses for treatments containing two-species mixtures. Numbers in the second set of parentheses are standard errors of the mean. Data are pooled over herbicide treatment levels. Means with a column followed by the same letter are not statistically different (P > 0.05).

| | PA16 | | PA17 | | DE16 | | DE17 | |
|---|---|---|---|---|---|---|---|---|
| | kg ha$^{-1}$ | | | | | | | |
| *Corn* | | | | | | | | |
| Rye + crimson clover | 2,299 (61/39) (103) | a | 7,243 (82/18) (541) | b | 4,699 (45/55) (250) | a | 8,468 (8/92) (451) | b |
| Rye + hairy vetch | 1,948 (43/57) (92) | a | 6,988 (82/18) (784) | b | 4,154 (40/60) (285) | a | 7,556 (9/91) (219) | b |
| *Soybean* | | | | | | | | |
| Rye | 3,141 (144) | a | 5,592 (127) | b | 3,729 (116) | a | 4,443 (306) | a |
| Rye + hairy vetch | 3,064 (98/2) (376) | a | 5,496 (88/12) (462) | b | 4,115 (63/37) (133) | a | 4,001 (68/32) (347) | a |
| ANOVA | Wald $\chi^2$ | | | | | | | |
| *Corn* | | | | | | | | |
| Year (Y) | 65.5*** | | | | 74.9*** | | | |
| Cover crop (C) | 0.4 | | | | 6.5* | | | |
| Y × C | 0.01 | | | | 0.4 | | | |
| *Soybean* | | | | | | | | |
| Year (Y) | 44.8*** | | | | 1.4 | | | |
| Cover crop (C) | 0.1 | | | | 0.01 | | | |
| Y × C | 0.01 | | | | 2.9 | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance (Pr > $\chi^2$) of model terms shown as: NS, *P* > 0.05; *, *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.001.

Table 2-9. Mean aboveground cover crop cover at the time of a pre-plant spring burndown (BD) herbicide application in corn and soybean experiments pertinent to spray card assessment at Pennsylvania in 2015-2016 (PA16) and 2016-2017 (PA17), and Delware in 2015-2016 (DE16) and 2016-2017 (DE17). Means are presented followed by the percentage of total contributed by each species in parentheses for treatments containing two-species mixtures. Numbers in the second set of parentheses are standard errors of the mean. Data are pooled over herbicide treatment levels. Means with a column followed by the same letter are not statistically different (P > 0.05).

| | PA16 | | PA17 | | DE16 | | DE17 | |
|---|---|---|---|---|---|---|---|---|
| | % | | | | | | | |
| *Corn* | | | | | | | | |
| Rye + crimson clover | 76 (35/65) (2) | a | 94 (63/37) (1) | b | 60 (13/87) (4) | a | 71 (1/99) (3) | ab |
| Rye + hairy vetch | 96 (20/80) (1) | b | 99 (51/49) (1) | c | 70 (9/91) (5) | ab | 80 (1/99) (1) | b |
| *Soybean* | | | | | | | | |
| Rye | 52 (2) | a | 71 (2) | b | 6 (0.2) | a | 10 (1) | a |
| Rye + hairy vetch | 54 (68/32) (2) | a | 82 (70/30) (2) | c | 42 (4/96) (4) | b | 56 (13/87) (6) | c |
| ANOVA | Wald $\chi^2$ | | | | | | | |
| *Corn* | | | | | | | | |
| Year (Y) | 19.8*** | | | | 5.6* | | | |
| Cover crop (C) | 54.4*** | | | | 8.5** | | | |
| Y × C | 9.9** | | | | 0.2 | | | |
| *Soybean* | | | | | | | | |
| Year (Y) | 70.7*** | | | | 2.9 | | | |
| Cover crop (C) | 13.7*** | | | | 59.7* | | | |
| Y × C | 11.1*** | | | | 2.8 | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance (Pr > $\chi^2$) of model terms shown as: NS, *P* > 0.05; *, *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.001.

Table 2-10. Mean aboveground winter annual weed biomass at the time of a pre-plant spring burndown (BD) herbicide application in corn and soybean experiments pertinent to spray card assessment at the Pennsylvania location. Numbers in parentheses are standard errors of the mean. Data are pooled over herbicide treatment levels. Means with a column followed by the same letter are not statistically different (P > 0.05).

| | 2015-2016 | | | 2016-2017 | | |
|---|---|---|---|---|---|---|
| | kg ha$^{-1}$ | | | | | |
| *Corn* | | | | | | |
| No cover control | 85 | (21) | a | 494 | (163) | b |
| Rye + crimson clover | 18 | (5) | a | 16 | (11) | a |
| Rye + hairy vetch | 41 | (16) | a | 37 | (36) | a |
| *Soybean* | | | | | | |
| No cover control | 34 | (10) | a | 221 | (25) | b |
| Rye | 11 | (5) | a | 3 | (3) | a |
| Rye + hairy vetch | 16 | (14) | a | 3 | (2) | a |
| ANOVA | Wald $\chi^2$ | | | | | |
| *Corn* | | | | | | |
| Year (Y) | 10.1* | | | | | |
| Cover crop (C) | 25.8*** | | | | | |
| Y × C | 2.7** | | | | | |
| *Soybean* | | | | | | |
| Year (Y) | 92.7** | | | | | |
| Cover crop (C) | 52.7*** | | | | | |
| Y × C | 10.5*** | | | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance ($Pr > \chi^2$) of model terms shown as: NS, $P > 0.05$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Table 2-11. Cover crop treatment effects on pre-plant burndown herbicide spray coverage beneath the cover crop canopy in 2015-2016 and 2016-2017. Calculated rates of glyphosate and 2,4-D reaching the soil surface, compared to the full rate in the no cover control, are included. Numbers in parentheses are standard errors of the mean. Means within a column followed by the same letter are not statistically different (P > 0.05).

| | 2015-2016 | | | | | 2016-2017 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Percent coverage | | | Glyphosate | 2,4-D | Percent coverage | | | Glyphosate | 2,4-D |
| | % | | | kg ha$^{-1}$ | | % | | | kg ha$^{-1}$ | |
| *Soybean* | | | | | | | | | | |
| No cover control | 33 | (1) | d | 1.26 | 0.56 | 19 | (2) | bc | 1.26 | 0.56 |
| Rye | 24 | (1) | c | 0.90 | 0.40 | 13 | (1) | ab | 0.86 | 0.38 |
| Rye + hairy vetch | 17 | (1) | b | 0.63 | 0.28 | 10 | (1) | a | 0.63 | 0.28 |
| *Corn* | | | | | | | | | | |
| No cover control | | | | | | 23 | (1) | b | 1.26 | 0.56 |
| Rye + crimson clover | | | | | | 2 | (1) | a | 0.13 | 0.50 |
| Rye + hairy vetch | | | | | | 2 | (0.2) | a | 0.09 | 0.52 |
| ANOVA | Wald $\chi^2$ | | | | | | | | | |
| *Soybean* | | | | | | | | | | |
| Year (Y) | 26.8*** | | | | | | | | | |
| Cover crop (C) | 41.4*** | | | | | | | | | |
| Y × C | 5.8 | | | | | | | | | |
| *Corn* | | | | | | | | | | |
| Cover crop | 86.0*** | | | | | | | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance (Pr > $\chi^2$) of model terms shown as: NS, *P* > 0.05; *, *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.001.

Figure 2-1. Log horseweed density (plt m$^{-2}$) at the Pennsylvania site over time (late fall, at spring pre-plant burndown herbicide application, and at POST-emergent herbicide application at the V3-V4 soybean stage). Cover crop treatments were either early-sown (E) or late-sown(L). Data are means averaged across treatment replications (± SE; *n* = 4) and presented by cover crop treatment and termination timing (early, late).

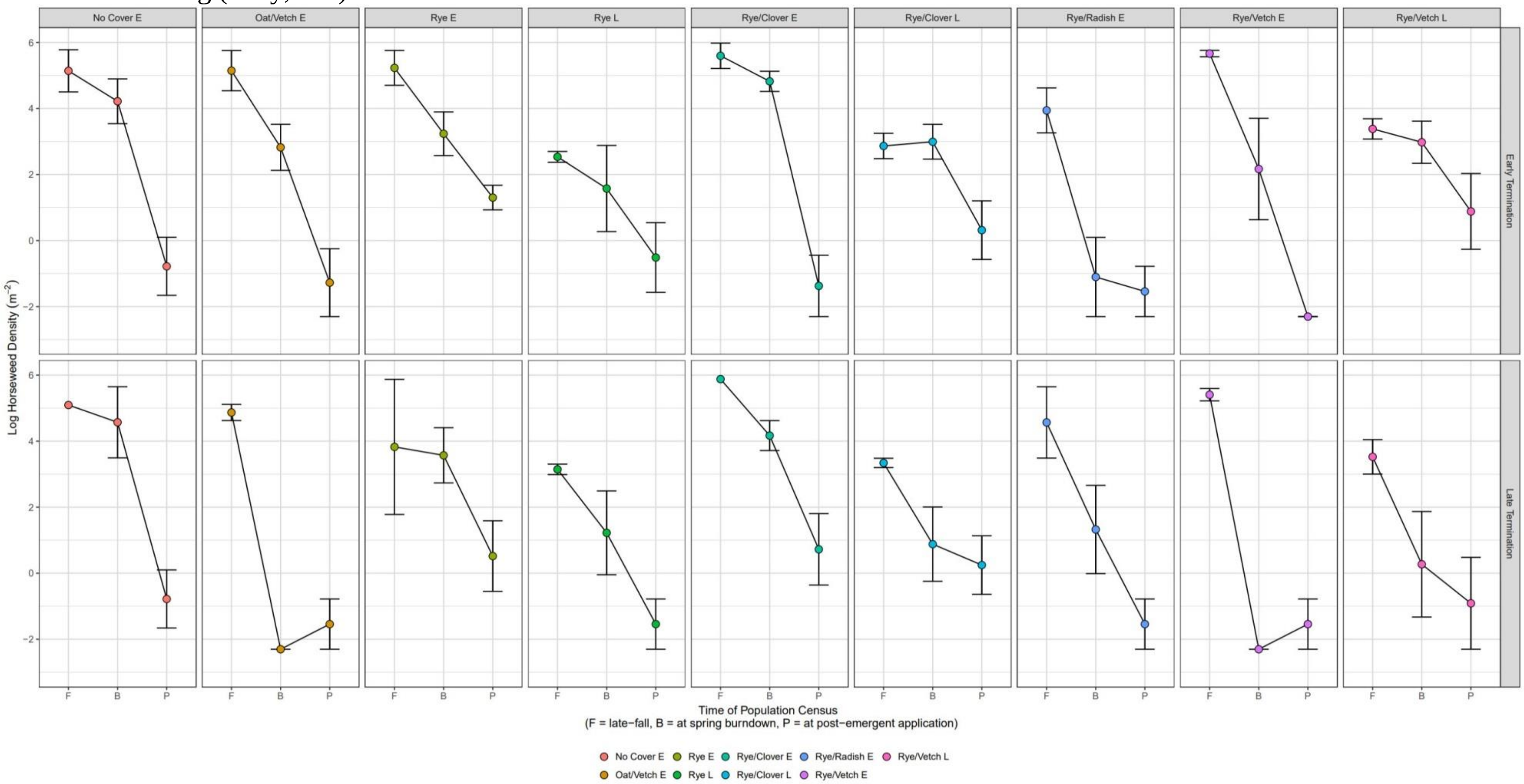


Figure 2-2. Effect of cover crop treatment on horseweed density at Pennsylvania at the time of pre-plant burndown herbicide application (Burndown) compared to the no cover control. Data are plotted as [1 – (treatment density / no cover control density) × 1] = percent (%) population decline. Data are pooled across termination timing and replicates (± SE; *n* = 8).

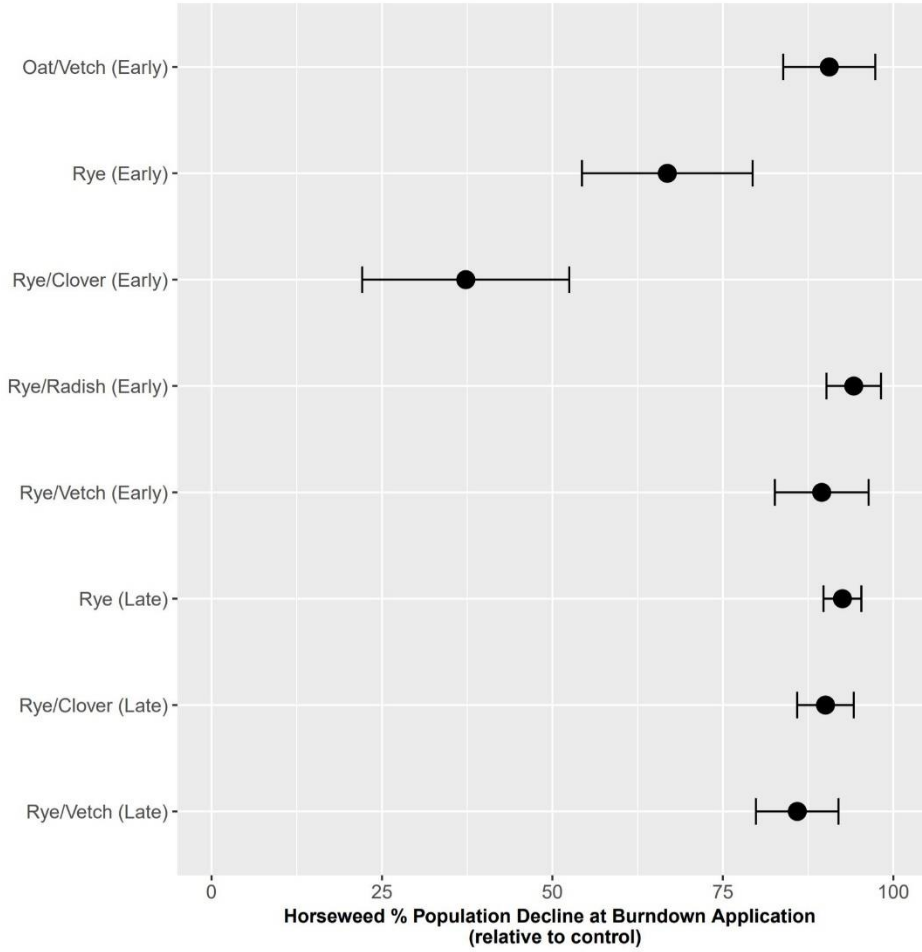


Figure 2-3. Log winter annual weed density (plt m$^{-2}$) at the Delaware site over time (late fall and at spring pre-plant burndown herbicide application). Cover crop treatments were either early-sown (E) or late-sown (L). Data are means averaged across treatment replications (± SE; $n$ = 4) and presented by cover crop treatment and termination timing (early, late). Data are pooled across year.

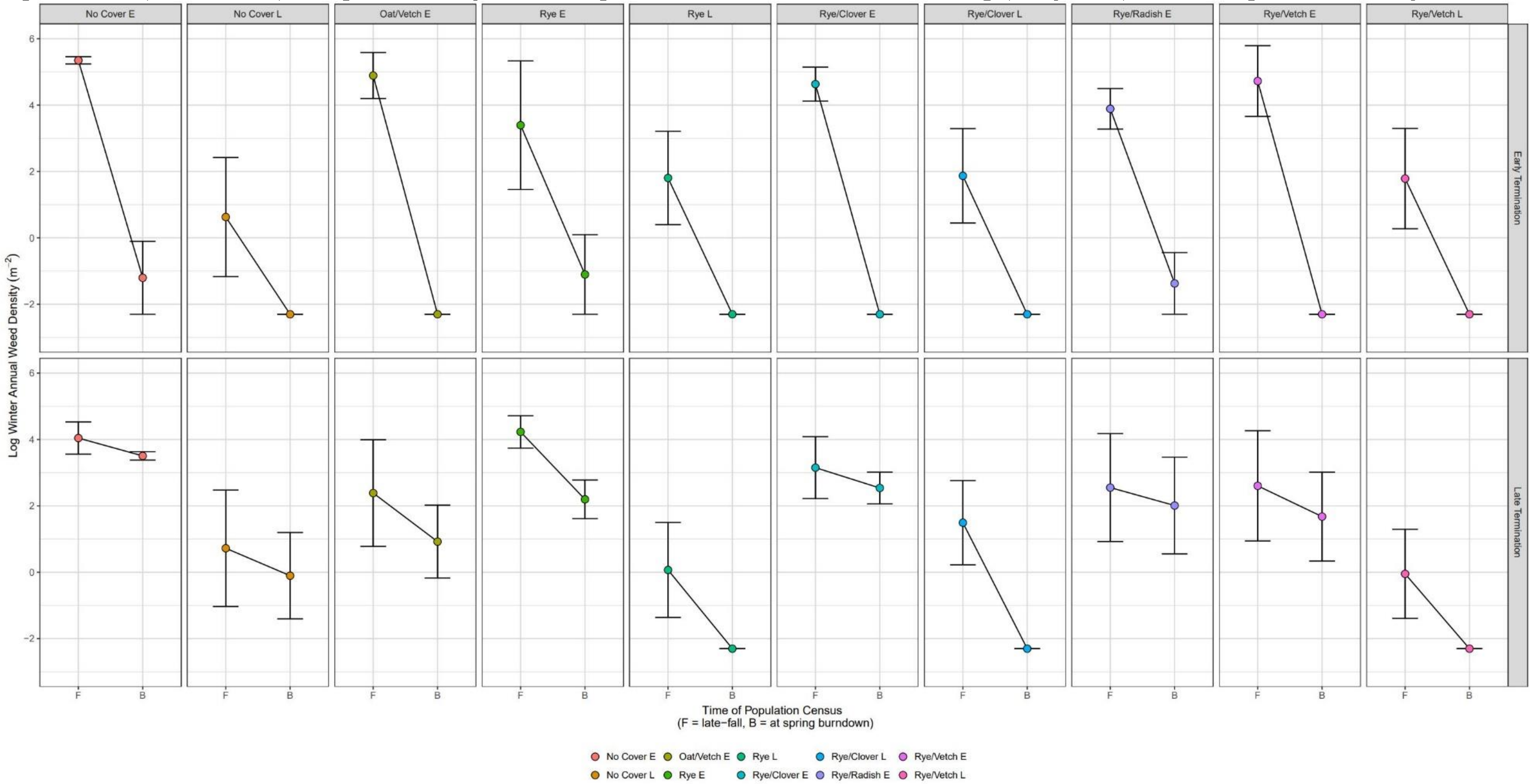


Figure 2-4. Effect of cover crop treatment on winter annual weed density in Delaware at the time of pre-plant burndown herbicide application (Burndown) compared to the no cover control. Data are plotted as [1 – (treatment density / no cover control density) × 1] = percent (%) population decline. Data are pooled across termination timing and year and treatment replicates (± SE; *n* = 8).

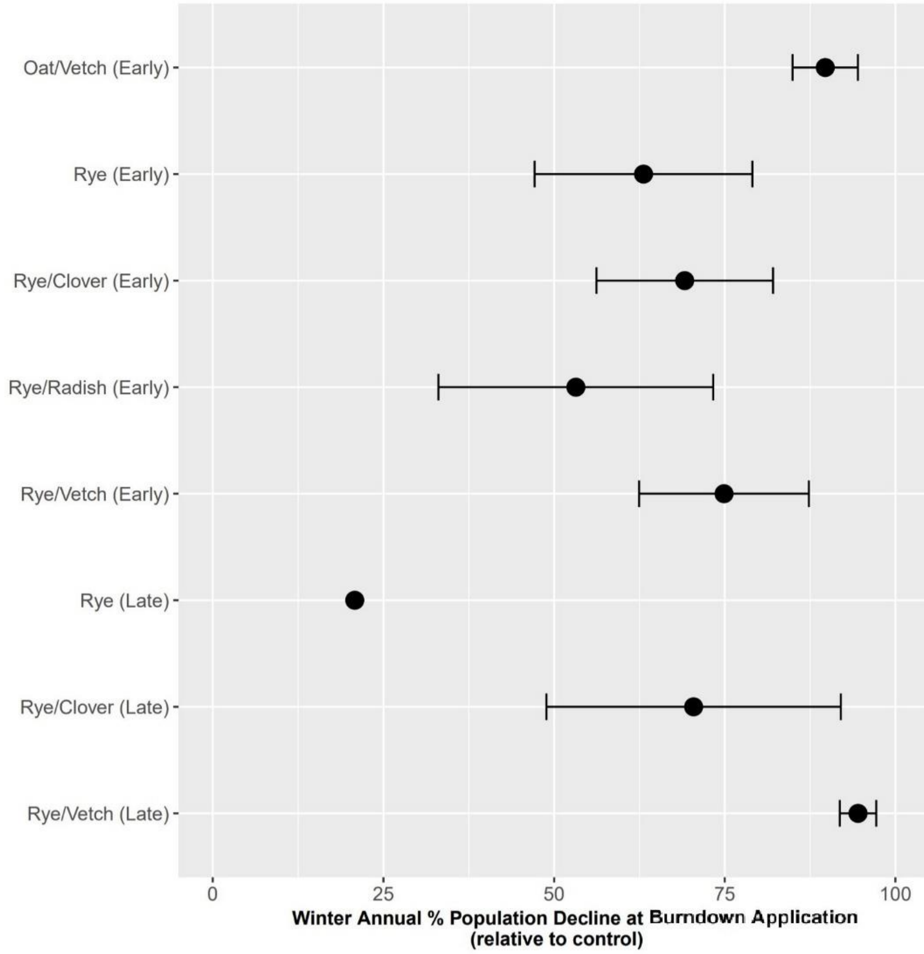


Figure 2-5. Log smooth pigweed density (plt $m^{-2}$) at the Pennsylvania site at POST-emergent herbicide application at the V3-V4 soybean stage. Cover crop treatments were either early-sown (Early) or late-sown (Late). Data are means averaged across treatment replications (± SE; *n* = 4) and presented by cover crop treatment and termination timing (early, late).

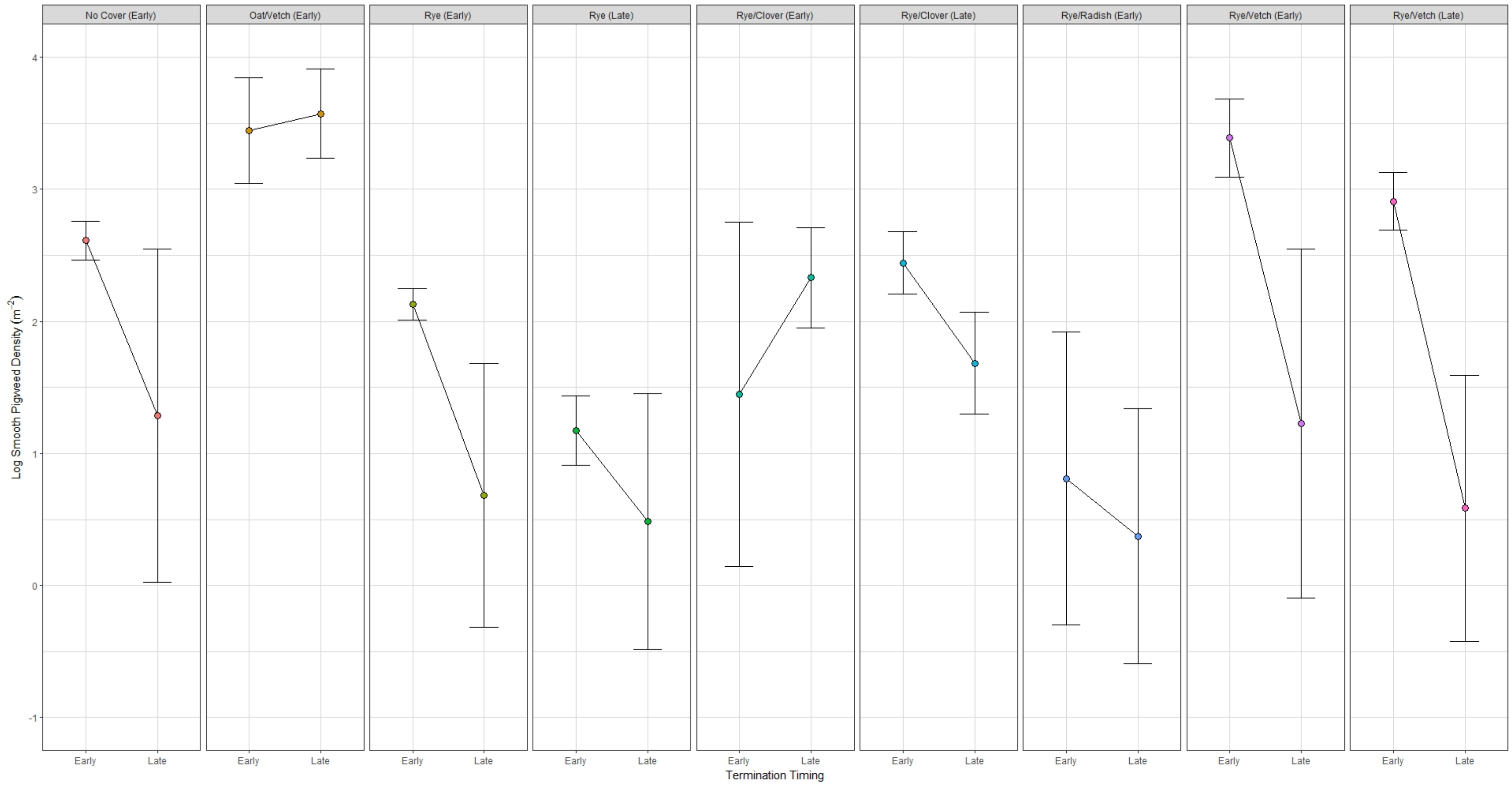


Figure 2-6. Effect of cover crop treatment on smooth pigweed density at Pennsylvania at the time of POST-emergent herbicide application at the V3-V4 soybean stage (POST) compared to the no cover control. Data are plotted as [1 – (treatment density / no cover control density) × 1] = percent (%) population decline. Data are pooled across termination timing and treatment replicates (± SE; *n* = 8).

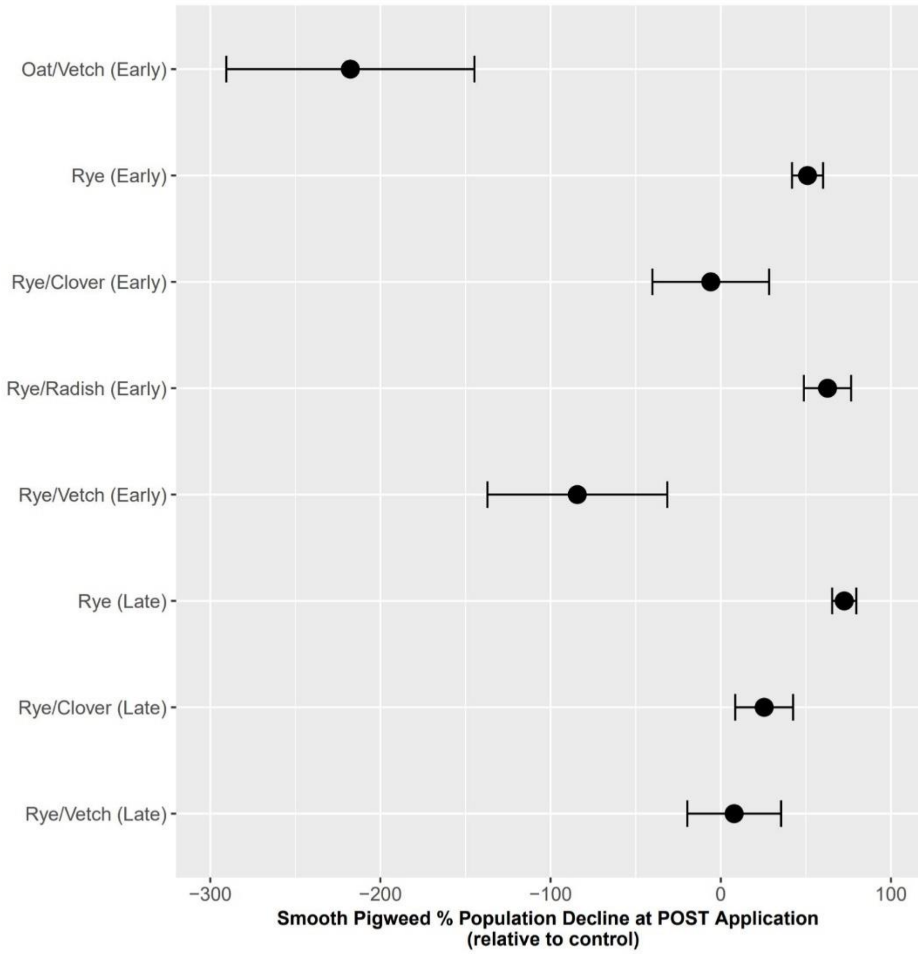


Figure 2-7. Log summer annual weed density (plt $m^{-2}$) at the Delaware site at POST-emergent herbicide application at the V3-V4 soybean stage). Cover crop treatments were either early planted (Early) or late planted (Late). Data are means averaged across treatment replications (± SE; *n* = 4) and presented by cover crop treatment and termination timing (early, late). Data are pooled across year.

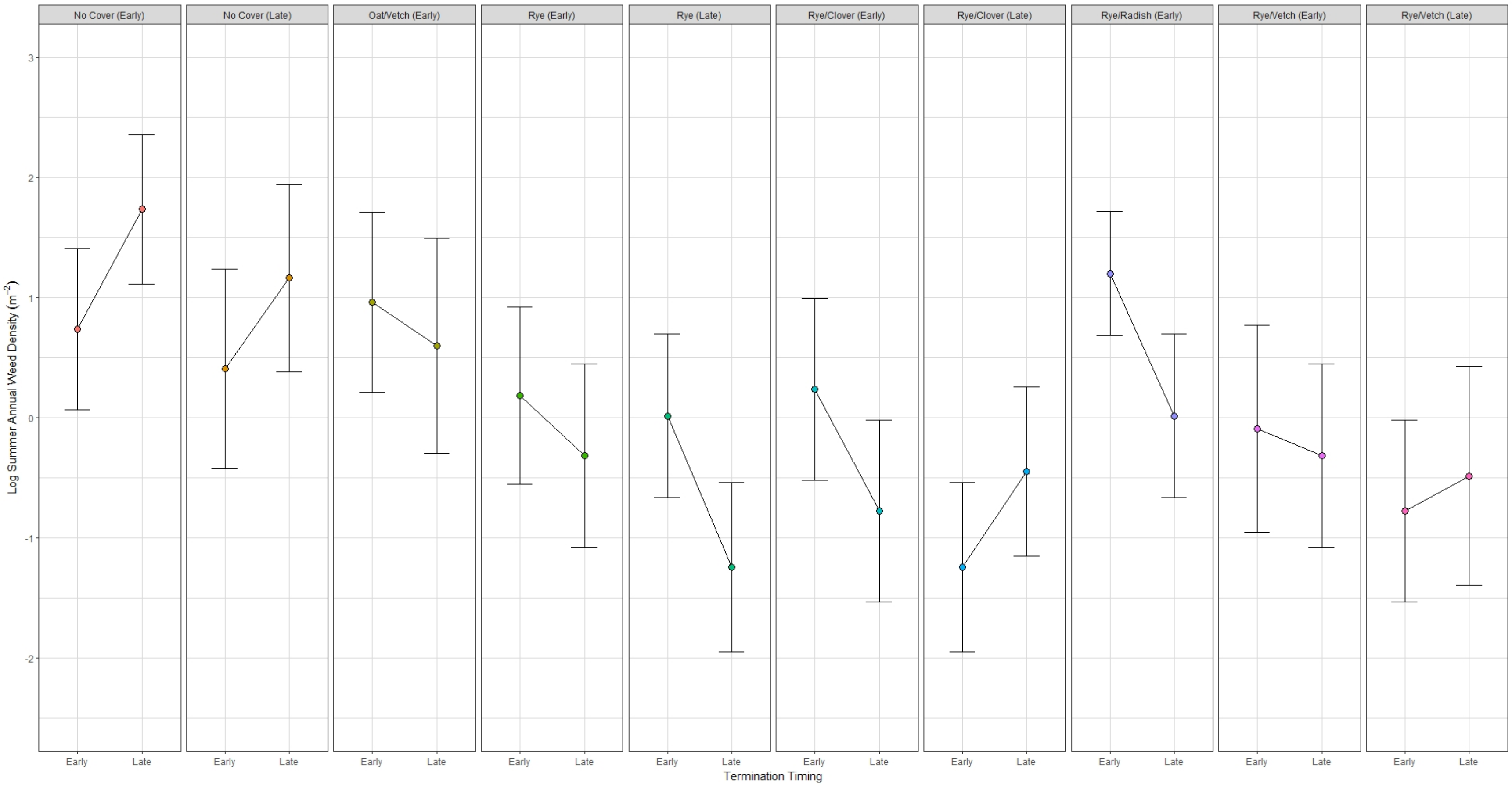


Figure 2-8. Effect of cover crop treatment on summer annual weed density in Delaware at the time of POST-emergent herbicide application at the V3-V4 soybean stage (POST) compared to the no cover control. Data are plotted as [1 – (treatment density / no cover control density) × 1] = percent (%) population decline. Data are pooled across termination timing and treatment replications (± SE; *n* = 8)

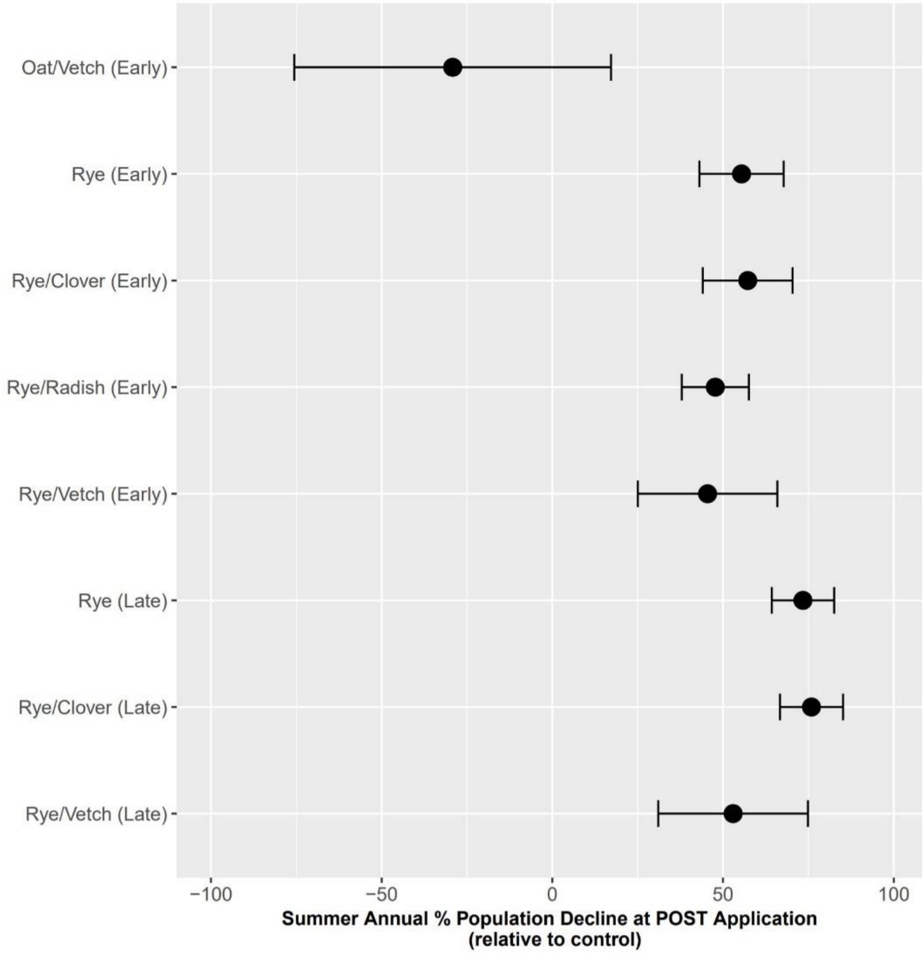
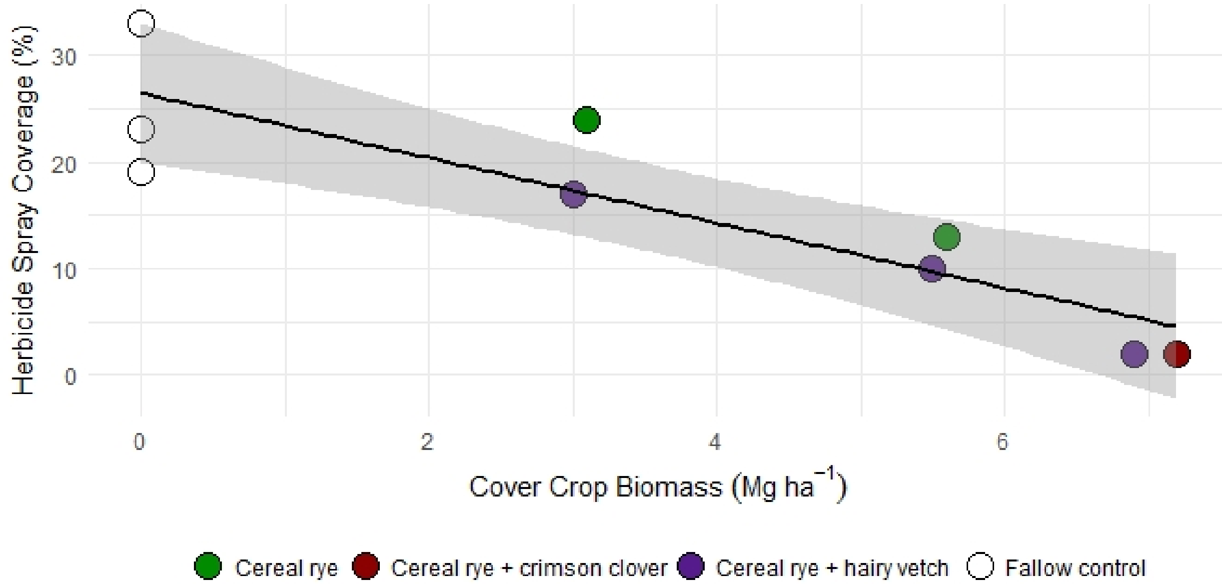
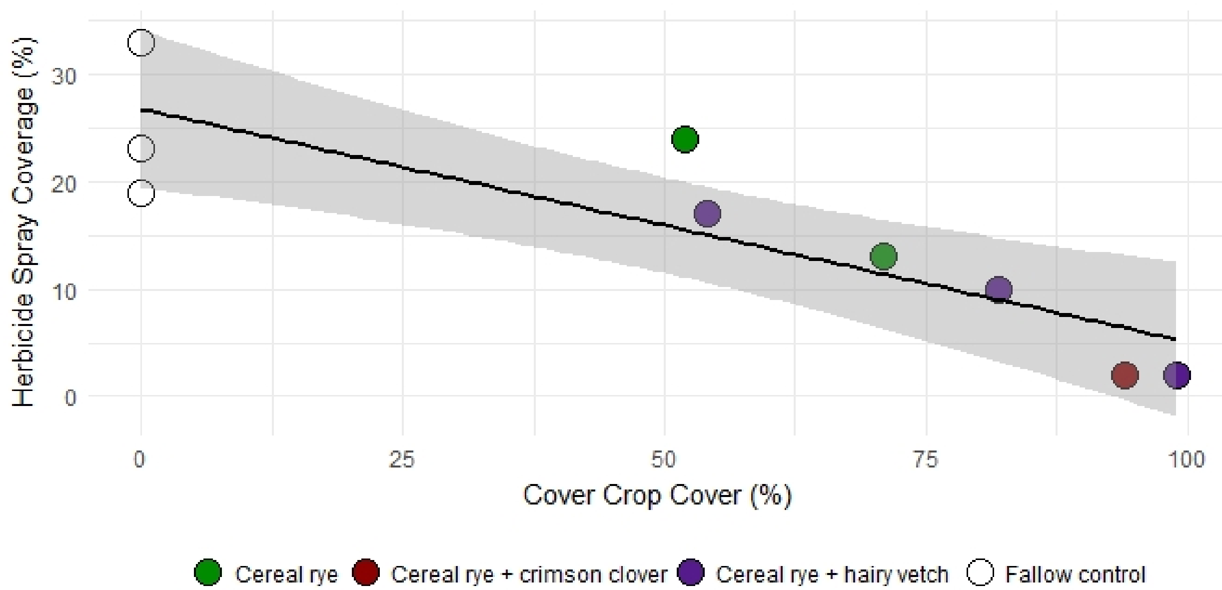


Figure 2-9. Herbicide spray coverage (%) within corn and soybean at the time of spring, pre-plant herbicide application as a function of cover crop biomass (Mg ha$^{-1}$) and cover crop ground cover (%). Data are plotted using a linear model and pooled across year, crop, and treatment replications.



Appendix Table 1. Fall horseweed production (as kg $ha^{-1}$) and percent ground cover (as %) at Pennsylvania (PA16) and winter annual production and percent ground cover in Delaware in 2015-2016 (DE16) and 2016-2017 (DE17). Data were collected in the late fall, roughly 10 weeks after study initiation. Means with a column followed by the same letter are not statistically different (P > 0.05).

| | PA16 | | | | DE16 | | DE17 | |
|---|---|---|---|---|---|---|---|---|
| | —kg $ha^{-1}$— | | —————— | | % | | | |
| No cover control (early) | 1,565 | c | 72 | b | 15 | abc | 42 | e |
| No cover control (late) | — | — | — | — | 1 | a | 38 | de |
| Oat + vetch (early) | 492 | b | 8 | a | 3 | a | 19 | abcd |
| Rye (early) | 10 | a | 11 | a | 3 | ab | 14 | abc |
| Rye + clover (early) | 16 | a | 5 | a | 5 | ab | 14 | abc |
| Rye + radish (early) | 0 | a | 3 | a | 3 | a | 11 | abc |
| Rye + vetch (early) | 9 | a | 9 | a | 4 | ab | 13 | abc |
| Rye (late) | 0 | a | 1 | a | 1 | a | 25 | bcde |
| Rye + clover (late) | 1 | a | 0 | a | 1 | a | 18 | abcd |
| Rye + vetch (late) | 1 | a | 3 | a | 0.4 | a | 27 | cde |
| ANOVA | Wald $\chi^2$ | | | | | | | |
| Year (Y) | — | | — | | 59.0*** | | | |
| Cover crop (C) | 155.7*** | | 164.9*** | | 40.1*** | | | |
| Y × C | — | | — | | 27.9*** | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance ($Pr > \chi^2$) of model terms shown as: NS, $P > 0.05$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Appendix Table 2. Effects of cover crop treatment at the time of spring pre-plant burndown herbicide application. Horseweed production (as kg $ha^{-1}$) and percent ground cover (as %) at Pennsylvania (PA16) and winter annual production and percent ground cover in Delaware in 2015-2016 (DE16) and 2016-2017 (DE17). Means with a column followed by the same letter are not statistically different (P > 0.05).

| | PA16 | | | | DE16 | | DE17 | |
|---|---|---|---|---|---|---|---|---|
| | —kg $ha^{-1}$— | | —% | | | | | |
| No cover control (early) | 837 | c | 29 | c | 25 | bc | 53 | d |
| No cover control (late) | — | — | — | — | 11 | abc | 50 | d |
| Oat + vetch (early) | 513 | abc | 6 | ab | 0.1 | a | 3 | a |
| Rye (early) | 109 | abc | 6 | ab | 2 | a | 20 | abc |
| Rye + clover (early) | 778 | bc | 15 | b | 2 | a | 10 | abc |
| Rye + radish (early) | 451 | abc | 6 | ab | 3 | a | 29 | c |
| Rye + vetch (early) | 71 | ab | 0 | a | 0.3 | a | 2 | a |
| Rye (late) | 30 | ab | 3 | a | 0.7 | a | 26 | bc |
| Rye + clover (late) | 25 | a | 4 | ab | 0 | a | 10 | abc |
| Rye + vetch (late) | 25 | a | 4 | ab | 0.1 | a | 7 | ab |
| ANOVA | ----Wald $\chi^2$---- | | | | | | | |
| Year (Y) | — | | — | | 30.9*** | | | |
| Cover crop (C) | 28.0*** | | 66.0*** | | 106.7*** | | | |
| Termination (T) | 3.5 | | 0.9 | | 1.0 | | | |
| Y × C | — | | — | | 48.2*** | | | |
| C × T | 7.3 | | 13.9 | | 7.7 | | | |

Evaluation of fixed effects are based on Likelihood Ratio Tests (Wald $\chi^2$) using random effects as null model. Significance (Pr > $\chi^2$) of model terms shown as: NS, *P* > 0.05; *, *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.001.

# Epilogue

## Introduction

Fall-planted cover crop treatments successfully control winter annual weeds in no-till corn and soybean, lessening herbicide-resistant (HR) selection pressure by reducing weed population fitness and decreasing sole reliance on a spring, pre-plant burndown herbicide application. Further, complimentary combinations of cover crop treatments and herbicide programs can successfully control summer annual weeds and reduce HR selection pressure, while maintaining environmental stewardship and crop production. The following sections contain examples of cropping systems radar plots, noteworthy field events, and practical suggestions for effective ecologically- and herbicidally-based IWM tactics in no-till annual grains. I will conclude with summaries of my research efforts and vision for future research in this area.

## Radar Plots

Three selected cover crop treatments – a no cover control, late-seeded cereal rye (*Secale cereale* L.), and late-seeded cereal rye + hairy vetch (*Vicia villosa* Roth) were evaluated using radar or spider plots (Figure E-1). The radar plots were intended to model the complexity of the cropping systems in an effort to visually assess the effects of ecologically and chemically based IWM in no-till cropping systems. In this document, the radar plot components derived from the aforementioned results and discussion from previous chapters, but the radar plots were not created using statistical analysis. This model also takes into account components of our cropping systems that we were unable to include in this document, such as the soil health components, so much of these radar plots are hypothesized and would vary by location, cover crops, year, and components considered. However, modeling the complexity of cropping system components can help us better visualize the various effects of our cropping system inputs.

Out modeled example used Pennsylvania data in soybean. Plot components were as follows: (1) cover crop performance, (2) winter annual weed control efficacy, (3) late summer weed community control efficacy, (4) cash crop performance, (5) herbicide strategy environmental stewardship, (6) winter annual weed HR selection pressure reduction, (7) summer annual weed HR selection pressure reduction, (8) potential cover crop interference of the burndown herbicide, (9) soil microbial health, and (10) carbon-to-nitrogen content in cover crops and soil. Cover crop treatments were ranked (1-3, or 0 if not applicable), where larger radar plots were associated with IWM programs that successfully incorporated ecologically- and herbicide-based tactics, while providing limited environmental trade-offs.

The first five components derived from the objectives of the first chapter. First, cover crop performance for the no cover control was rated as 0 (not applicable). Cereal rye and cereal rye + hairy vetch did not differ from each other, so both were given ratings of 3 (Table 1-4). Second, winter annual weed control was lowest in the no cover control (score = 1), and both cereal rye and cereal rye + hairy vetch successfully reduced aboveground winter annual weed biomass at the time of BD (score = 3; Table 1-5). Third, there was not a cover crop main effect for late season weed community control efficacy, so this component was rated based on the herbicide program. The BD + POST program (score = 3) reduced aboveground late season weed biomass by a 1.5 order of magnitude in 2016 and a 4.5 order of magnitude in 2017 compared to the BD control (score = 1; Table 1-6). Fourth, cash crop performance was also considered at the herbicide program level (Table 1-8). The no cover control (score =1), assessed with the BD control program, was the lowest yielding. The cereal rye and cereal rye + hairy vetch programs (scores = 3), assessed with the BD + POST program, were higher yielding. Fifth, although the BD program was least effective for weed control, the single-pass program had the highest environmental stewardship average score at 4.3 (score = 3; Table 1-9b), whereas the BD + POST program scored 3.7. The BD + PRE + POST treatment had the lowest environmental stewardship score, so the moderate BD + POST was given a radar plot component score of 2.

The remaining components pertained to the objectives in the second chapter. The sixth component, winter annual weed HR selection pressure reduction, was based on the mean horseweed density at BD. The no cover control (score = 1) had the highest density compared to the late-sown cereal rye (score = 3) and the late-sown cereal rye + hairy vetch (score = 2; Table 2-5). Next, summer annual weed HR selection pressure reduction was similar in the no cover control and rye + hairy vetch treatments (scores = 2), although other treatments had higher smooth pigweed densities than the control. Conversely, the cereal rye (late) was lower than the aforementioned treatments (score = 3; Table 2-7; Figure 2-5). The potential cover crop interference of the burndown herbicide was highest in the cereal rye + hairy vetch treatment (score = 1), moderate in the cereal rye treatment (score = 2), and, in the absence of cover crops, not an issue in the no cover control (score = 3). Lastly, soil microbial health and carbon-to-nitrogen content in cover crops and soil have not yet been scored, since data analysis is still forthcoming for these components. However, we predict that microbial activity will be highest in a legume-based cover crop (score = 3) and lowest in the absence of cover crops (score = 1). High-residue cover crops like cereal rye (score = 2) could create a negative trade-off by withholding nutrients from the following crop. Hairy vetch (score = 3) quickly decomposes, narrowing the C:N ratio. Averaged over all components, the late-sown cereal rye + hairy vetch (score = 2.5) is a slightly better performing IWM program than the cereal rye alone (score = 2.4), and both are recommended over the no cover control (score = 1.4).

## Experimental Notes

The second field season, 2016-2017 (2017), at the Pennsylvania location was omitted from the second chapter due to difficulties establishing cover crop treatments. Extensive slug and belowground predation decimated treatments established at the early planting date, a replant attempt, and the late planting date. In a nearby field, the corn herbicide study (see Chapter 1) displayed successful cover crop establishment; we planted both studies on the same day and under identical seeding rates and methods, seed varieties and sources, and field conditions. The ease of cover crop establishment in one study compared to the failure to establish cover crops in a nearby study highlight two challenges associated with researching and integrating fall-planted cover crops. First, rotating research fields at each location each year can feature varied histories that present unique, sometimes unpredictable, challenges to the studies. Second, cover crops can be successfully established throughout the fall. However, if problems arise when establishing cover crops in the fall, whether for research or in actual practice, it may be difficult to properly diagnose the problem and successfully replant before temperatures become unfavorable. Thoroughly understanding the field history and proactively addressing planting challenges can increase the likelihood of successful cover crop establishment in difficult situations.

Further, there were challenges associated with conducting the studies at two locations in separate states. Thorough communication was required to ensure all field processes and data collection were performed correctly. While winters at the Pennsylvania location were cold enough to kill forage radish (*Raphanus sativus* L.) and spring oat (*Avena sativa* L.), the winters at the Delaware location were mild at both years, causing concern that both cover crop species would overwinter and set seed, becoming unintended plants themselves. Both locations also struggled to achieve successful weed germination in the established microplots. Both horseweed [*Conyza canadensis* (L.) Cronquist] and smooth pigweed (*Amaranthus hybridus* L.) seed were collected from local populations, and greenhouse germination tests using identical seeding methods as those used in the field confirmed >90% germination rates for both species. However, germination rates in the field varied by year, location, and study. Thus, alternative methods that increase the chance for successful weed germination are suggested for similar, future studies.

Spray cards are relatively easy to include in a field study by providing inexpensive and extensive data in a short amount of time. The cards are also easy to analyze with SnapCard software. However, achieving successful spray coverage and analysis requires haste in the field and proper analysis. For example, high humidity inadvertently marks the cards, even affecting the entire card in many cases. Broadleaf cover crops like hairy vetch harbor humidity beneath the thick canopy, so opening the canopy for at least an hour prior to card placement helps release humidity. Once cards are placed and the opened cover crop canopies are replaced, apply the herbicide immediately to limit both unwanted moisture from returning and from the wind moving cards. Thick cover crop biomass can also house animals that eat, move across, or otherwise damage and disturb spray cards in a short amount of time. Thus, remove cards from plots shortly after application and allowed to dry elsewhere. Finally, SnapCard is a simple, effective, and quick software designed specifically to measure percent cover on spray cards. However, it is a simple smartphone application that does not outsource collected data to other formats. To ensure uniformity when measuring coverage, we recommend that smartphones are placed in a stable platform.

We conducted three soil tests as part of the environmental trade-offs portion of this study: volumetric water content, soil microbial health, and carbon-to-nitrogen ratio. Volumetric water content was measured in 2015-2016 (2016) at both the Pennsylvania and Delaware locations, where we were interested in which cover crop treatments may deplete water content. Further, we wanted to know if delaying cover crop termination created a negative trade-off for the following crop. Soil probes were placed at 10 and 20 cm depths in the soil profile of each split plot of the soybean study discussed in Chapter 2. Volumetric water content was measured weekly throughout the growing season. Unfortunately, there were numerous equipment issues at both locations, and the volumetric water content test was omitted from the 2017 protocol. The raw data for this test is included in the Appendices.

We assessed a portion of the soil microbial health, where we were interested in effects the different cover crop treatments and cropping system inputs. The Solvita 24-hour "$CO_2$ burst" test served as a soil health metric by determining the amount of microbial activity occurring within each cover cropping management practice. We took soil samples for the test in November when cover crops were at their peak fall growth, at spring green-up, and at the V3-V4 stages of corn and soybean. Sampling over time aims to show the effects of the cover crops throughout the entire life cycle. We predict that soil microbial activity in the spring will be highest where a winter-kill species is decomposing while a broadleaf species is at the peak growth rate. We further predict that diverse cover crop treatments, particularly with legume species, will have higher microbial activity than other treatments, indicating a positive association between high cover crop production and soil health. We also quantified soil health via carbon-to-nitrogen content in cover crops and soil, using soil samples taken at the same stages as those used for the Solvita test. Comparing C:N ratios across the cover crop treatments and the soil of each treatment determined if certain treatments or cover cropping management practices, such as delaying termination date, could harbor a negative environmental trade-off by sequestering excessive nutrients from the soil and resources available for the subsequent cash crop. We further predict that legume cover crops, which decompose quicker than grass species, could quickly reduce the C:N ratio in the soil, create a favorable environment for weed species, and serve as a potential negative trade-off. Raw data for both tests are included in the Appendices.

## IWM Practical Solutions

We assessed complementarity between cover crop and herbicide IWM tactics in no-till corn and soybean systems. Our results suggest that a complimentary two-pass, BD + POST herbicide program in a cover crop treatment can best control both winter and summer annual weeds while striving for environmental stewardship. Further, high-performing cover crops can lower crop density, although proper weed control throughout the growing season can ensure crop recovery at the time of harvest.

Our results further imply that fall-sown cover crops can serve as an IWM tactic that can reduce the selection pressure exerted by herbicide-based weed control programs for both winter and summer annual weeds. Cover crops can also intercept a portion of the spring, pre-plant burndown herbicide applications, further reducing herbicide selection pressure at this timing. However, if cover crops and the proportion of the burndown herbicide reaching the surface do not control weeds, there may be a negative trade-off for herbicide resistance at the POST-emergent application. No cropping system is absent of trade-offs. However, when considering a wide array of cropping system components, a cereal rye or cereal rye + legume mixture can serve as well-rounded IWM components.

## Future Research Recommendations

Further research in this area is needed on environmental trade-offs associated with cover crops. Although we measured soil microbial activity and cover crop-to-soil C:N ratio, soil health has countless considerations. We were unable to measure volumetric water content due to equipment failure at both locations. As climate change becomes an ever growing concern, understanding the effects of various cover crop treatments on volumetric water content is vital. Also, we limited our use of spray cards in our field studies. Continuing to explore spray deposition beneath the cover crop canopy could help determine the most efficient combination of cover crop treatment with herbicide programs. Testing cover crop treatments different from ours, various spray nozzles and spray settings, and comparing active ingredients could provide promising results, particularly from an Extension standpoint. Finally, we were unable to test Palmer amaranth (*Amaranthus palmeri* S. Watson) and/or water waterhemp [*A. tuberculatus* (Moq.) J.D. Sauer] at our locations. Further research in the Mid-Atlantic could help predict how cover crops could help slow migration of these weed species in this region.

Epilogue Figure 1. Early-sown cereal rye, early-sown cereal rye + hairy vetch, and a no cover control. Plot components are as follows: (1) cover crop performance, (2) winter annual weed control efficacy (W.A. weed control), (3) late summer weed community control efficacy (L.S. weed control), (4) cash crop performance, (5) herbicide strategy environmental stewardship (Environmental stewardship), (6) winter annual weed HR selection pressure reduction (W.A. weed HR red.), (7) summer annual weed HR selection pressure reduction (S.A. weed HR red.), (8) potential cover crop interference of the burndown herbicide (Interference), (9) soil microbial health, and (10) carbon-to-nitrogen content in cover crops and soil (C:N). Cover crop treatments were ranked (1-3, or 0 if not applicable), where larger radar plots were associated with IWM programs that successfully incorporated ecologically- and herbicide-based tactics, while providing limited environmental trade-offs.