EVALUATION OF COVER CROPS AS A COMPONENT OF A WEED MANAGEMENT SYSTEM IN CORN AND SOYBEAN

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By

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The undersigned, appointed by the Dean of the Graduate School,

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A candidate for the degree of Master of Science

And hereby certify that in their opinion it is worthy of acceptance.

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CHAPTER I

Literature Review

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Justification. In recent years cover crops have become increasingly common in the Midwestern United States. Several species, such as annual ryegrass (*Lolium multiflorum*), barley (*Hordeum vulgare*), oat (*Avena sativa* L.), rye (*Secale cereal*), wheat (*Triticum aestivum*), hairy vetch (*Vicia vilossa* Roth.), and various clovers (*Trifolium* spp.) have been identified for their utility as cover crops and are being widely recommended (Johnson et al. 1998; Kuo et al. 1997; Teasdale and Mohler 1993; Weston 1990). It is commonly understood that cover crops have several agronomic benefits such as reducing soil erosion, reducing water runoff, improving water infiltration, increasing soil moisture retention, increasing soil tilth, and increasing organic carbon and nitrogen (Mallory et al. 1998; Sainju and Singh 1997; Teasdale 1996; Varco et al. 1999; Yenish et al. 1996). Although there are several soil and nutrient-related aspects of cover crops that have been thoroughly investigated, there are still questions that need to be addressed regarding their utility in a typical Midwest corn and soybean rotation and especially how cover crops fit into a weed management program. In 2014, the Sustainable Agriculture Research and Education (SARE) program in conjunction with the Conservation Technology Information Center (CTIC) surveyed 1,924 farmers concerning their cover crop usage in 2013 and 2014. The fourth highest reason farmers gave for planting cover crops was to achieve some level of weed control (SARE and CTIC 2014). The majority of previous research that has reported on the effects of cover crops on weed density has been conducted in organic production systems where the cover crop is terminated with a mower or roller/crimper, and has focused primarily on a few species such as cereal rye (*Secale cereal L.)* and hairy vetch (*Vicia villosa* Roth) (Shumway et al. 2011). In their recent survey, SARE (2014) reported that over 48% of farmers use herbicides to terminate their cover crops prior to planting their corn or soybean cash crop. Thus, there is a need to determine the level of weed control that cover crops can provide throughout the growing season following termination with a herbicide application. Also, if a cover crop is not completely or effectively terminated before planting a cash crop such as corn and soybean, the cover crop has the potential to become a weed in the following cash crop. Therefore there is a need to determine the best herbicide program for terminating the various cover crop species that are now being promoted and used in the Midwest.

In order for a cover crop to provide the desired and proven agronomic and weed control benefits, an adequate level of above and below ground biomass must be present. Teasdale and Moehler (1993) found that as the amount of above ground biomass increases from cover crops, the potential for summer annual weed control will increase. Therefore, uninhibited establishment and growth following a previous corn or soybean crop is critical in order to achieve these potential benefits. As a result of a shift towards no-tillage systems, many growers are now reliant on non-selective pre-plant and soil residual herbicides to achieve weed free planting environments. This is an important consideration when planting a cover crop because some residual herbicides have long soil half-lives (Curran 2001). Specifically, pendimethalin and fomesafen can have half-lives of 100 to 101 days in clay soils, respectively (Shaner 2014). Herbicides with half-lives of this magnitude have the potential to carryover into the establishment period of a subsequent cover crop. Nearly all soil residual herbicides have restrictive labels that limit the crops that can be planted following certain herbicide applications, but these restrictions are for situations where the intention is to graze or harvest the crop for animal or human consumption. In most cover crop situations, the goal is not to feed or graze, but instead to achieve satisfactory ground cover throughout the winter. Thus, the grower is assuming the risk of potential crop failure if the herbicide carryover is substantial enough to reduce stand density or biomass of the cover crop. Rogers et al. (1986) found that certain cotton herbicides can reduce subsequent wheat stand densities up to 89% depending on the soil type. A comprehensive analysis of commonly used corn and soybean residual herbicides is needed to determine their effect on the vigor and potential stand density reduction of fall seeded cover crops.

The objectives of this research are to: 1) determine what contribution eight different cover crop species make to winter and summer annual weed control following termination, 2) determine the most effective herbicide or herbicide combination for terminating eight different cover crop species prior to planting of a cash crop, 3) determine what corn and soybean herbicide programs have the potential to carryover to eight different fall seeded cover crop species and decrease stand density or biomass.

Weed Control. According to a recent SARE survey (2014), 28% of farmers using cover crops expect some level of weed control from the cover crop they plant. Hayden et al. (2012) reported that cereal rye (*Secale cereal L.)* and hairy vetch (*Vicia villosa* Roth) reduced winter annual weed biomass by 95 to 98% and 71 to 91%, respectively. Cover crops can reduce weed density by interacting as living plants or as plant residue following cover crop termination but living cover crops have a higher suppressive potential at all weed life cycle stages than non-living cover crop residues (Teasdale et al. 2007). Live cover crops will absorb higher ratios of red: far-red light resulting in inhibition of phytochrome mediated germination, in contrast cover crop residues have a minimal effect on this ratio (Teasdale and Moehler 1993). Thus, it is widely accepted that certain cover crop species can have a substantial suppressive impact on winter annual weeds. In the United States, crop production losses from weed competition are estimated to be as high as $33 billion annually (Pimentel et al. 2005). In a corn and soybean production system, summer annual weeds contribute the majority of this economic loss because of their overlapping lifecycles. Therefore the ability of cover crops to suppress summer annual weeds is of greater concern in these systems. Webster et al. (2013) found that cereal rye reduced palmer amaranth densities from 40 to 88% between cotton rows in a strip tillage system, but the aggressive growth of palmer amaranth within the cotton row still prevented the cotton from producing lint. These findings correlate with those of Teasdale and Moehler (1993) that the suppressive potential of a cover crop declines as the amount of residue decreases or if there are areas where the residue is not present. Cover crop residues have the ability to suppress weed growth by releasing allelopathic volatile chemicals (Olofsdotter et al. 2002), by changing microclimatic conditions, and/or through the creation of a physical barrier (Teasdale and Moehler 2000). In a production system where the cover crop residue must be eliminated or removed in the crop row in order to plant the cash crop, a banded herbicide application is still needed to control the weeds that are present. The level of weed control that can be achieved through cover crops is largely dependent on the species due to the fact that some cover crops produce more biomass than others (Teasdale and Moehler 1993). Cover crop species that have a faster rate of decomposition will also result in a lower level of weed control later in the season as opposed to ones that decompose more slowly (Teasdale and Moehler 1993). Thus, the level that cover crop residue can suppress weeds is typically higher earlier compared to later in the season (Teasdale et al. 2007).

SARE and CTIC (2014) also reported that 48% of cover crop users rely on herbicides to terminate their cover crop prior to planting their corn or soybean cash crop. Davis (2010) showed that the use of a cover crop roller-crimper resulted in a 26 and 56% reduction in residual weed biomass within the vetch and rye systems, respectively, compared to the burndown treatment. The allelopathic potential of cereal rye is mainly a result of the contribution of phytotoxic benzoxazinones, which are compounds that accumulate in the tissue at varying degrees depending on environment, growth stage, and cultivar (Tabaglio et al. 2013). Also, decomposing cereal rye residues have been shown to release higher levels of these compounds than living tissue (Tabaglio et al. 2013). When a cover crop such as cereal rye is terminated using a roller crimper, the stems are broken and forced to the soil surface resulting in a higher level of these phytotoxic compounds being released close to the rooting zone of various weed species. Although rolling a cover crop has proven to effectively suppress weeds, it is not usually economically viable for large farming operations when compared to using herbicides to terminate the cover crop. A roller/crimper system will range in widths of 10-40’ and speed is limited to the terrain whereas commercial sprayers that are being used today range from 80-120’ and can travel much faster. Most of the research conducted to date has focused on cover crop species such as cereal rye and hairy vetch and often in organic-based systems where the use of herbicides is prohibited. Therefore, there is a need to determine the level of weed control that can be expected following termination of several of the most common cover crop species that are being recommended throughout the Midwest.

Termination. SARE and CTIC (2014) reported that 48% of cover crop users rely on herbicides to terminate their cover crop prior to planting a corn or soybean cash crop. If not properly terminated, cover crops have the potential to become weeds in the following production crop and can slow soil drying and warming in the spring. Several cover crop species, such as annual ryegrass, barley (*Hordeum vulgare*), oat (*Avena sativa* L.), rye (*Secale cereal*), wheat (*Triticum aestivum*), hairy vetch (*Vicia vilossa* Roth.), and various clovers (*Trifolium* spp.) have been identified for their utility as cover crops (Johnson et al. 1998; Kuo et al. 1997; Teasdale and Mohler 1993; Weston 1990). Thus, it is important to identify herbicide programs that will effectively control these cover crop species prior to corn or soybean planting. One commonly recommended cover crop that may require special attention when it comes to termination is annual or Italian ryegrass (*Lolium perenne* L. *ssp.*) *multiflorum).* Relative to other cover crop species, annual ryegrass has several desirable benefits including partial recovery of residual nitrogen, low seed cost, rapid establishment, cold tolerance, and disease tolerance (Reddy 2001; Shipley et al. 1992; Weston 1990). However, following an annual ryegrass cover crop, corn and soybean yield were reduced as much as 18 and 29%, respectively, compared to where no cover crop had been planted (Vyn et al. 1999; Reddy 2001). Also, in situations where annual ryegrass is not properly controlled it can reduce wheat yields as much as 92% (Hashem et al. 1998).

Most spring pre-plant herbicide programs in Missouri contain glyphosate because of its broad-spectrum activity, short plant back interval, and price. Lins et al. (2007) evaluated three different rates of glyphosate (415, 830, 1660 g ae/ha) on annual ryegrass at late tiller, second node, boot, and early flowering stages and found that the level of control was maximized at the highest rate applied at boot or early flowering stages. Although control was maximized at the highest rate of glyphosate, a sequential herbicide application or addition of a graminicide tank-mix will be needed for adequate stand removal (Hoskins et al. 2005). Currently no known glyphosate resistant populations of annual ryegrass exist in Missouri, but Arkansas, Mississippi, Oregon, and Tennessee have each discovered populations with resistance to glyphosate (Heap 2015). Across the United States there are several multiple resistant populations of annual ryegrass that exist. Specifically, there is a multiple resistant population of annual ryegrass in Oregon that is resistant to both glyphosate and glufosinate (only known case of glufosinate resistance), and several other cases of ACCase inhibitor and ALS inhibitor resistance also exist (Heap 2015). Although most annual ryegrass that is planted as a cover crop is susceptible to glyphosate, plants missed during a pre-plant herbicide application have the potential to set seed which can then be spread through harvest equipment to other fields. From this data it is important to realize that annual ryegrass has proven difficult to control with glyphosate even in susceptible populations, but it has also proven to quickly develop resistance not only to glyphosate but several other sites of action. It is important to understand what herbicide programs are most effective at controlling all of the various species that are being recommended as cover crops, and especially those that have proven difficult to control such as annual ryegrass.

Carryover. When planting a cover crop, an important thing to consider is the herbicide application history within that particular field. Widespread adoption of no-tillage systems has changed weed control tactics from a tillage emphasis to the need for non-selective pre-plant and residual herbicides in order to plant into weed free fields and keep them weed-free for several weeks after planting In addition, residual herbicides can be applied post-emergence (POST) in corn, soybean and cotton production. This practice has become much more common in soybean production in recent years in an attempt to eliminate late-season flushes of waterhemp or Palmer amaranth, which are two of the most troublesome glyphosate-resistant weeds in the U.S. More specifically, the amount of acres being treated with herbicides in the diphenyl ether chemical family has increased from 1.4 to 24.6% from 2006 to 2012, respectively (USDA 2015). By their very nature, residual herbicides have the potential to carry over and injure sensitive rotational crops. Tharp and Kells (2000) found that 40 days after treatment (DAT), EPTC, pendimethalin, and metolachlor reduced the stand densities of annual ryegrass by 12, 46, and 94%, respectively when compared to the non-treated control. Riddle et al. (2013) reported an 18% visual injury 39 days after planting (DAP) in a spring planted Austrian winter pea crop, one year after application of a 2x labeled rate (280 g ha^{-1}) of mesotrione.

Soil properties such as pH and organic matter content have been shown to play a major role in the degradation of soil-applied herbicides. Loux and Reese (1993) found that imazaquin persisted in the soil at higher rates as soil pH decreased between soils. In soils with organic matter at or above 3%, carryover potential increases, but at organic matter content below 3%, carryover is not as likely (Curran 2001). Other factors such as the amount of rainfall after the time of application have a major contribution to the speed at which a herbicide degrades in the soil. Specifically, pendimethalin has been shown to degrade faster with increasing amounts of rainfall and therefore cause less injury to subsequent crops (Zimdahl et al. 1984; Tharp and Kells 2000). It is important to understand how certain soil applied herbicides will respond to different soil pH and organic matter content in regards to carryover to a subsequent cover crop. Having a better understanding of this will allow cover crop users to make a more educated decisions when selecting which to use following a soil applied herbicide application in their previous soybean or corn crop.

Current label restrictions and plant back guidelines apply to crops that are intended to be grazed or harvested for hay, but these specific guidelines do not apply to cover crops that are simply intended to act as a ground cover through the winter fallow. Therefore, commonly used corn and soybean soil residual herbicides need to be investigated to determine their potential to reduce stand densities and biomass of subsequent cover crop species.

Summary and Objectives. In recent years, cover crops have increased in popularity throughout the Midwest due to their potential agronomic benefits and as a result of economic incentives offered by the Natural Resources Conservation Service. Although cover crops have been more commonly investigated for their impact on soil health and environmental impact, there is still a need to determine how they fit into a corn and soybean rotation. Understanding cover crops from the perspective of weed management is crucial to understanding how they fit into a corn and soybean rotation. The objectives of this research are to: 1) determine at what level eight cover crop species control winter and summer annual weeds following termination using herbicides, 2) determine the best herbicide for effectively terminating eight cover crop species prior to planting of a cash crop, and 3) determine what corn and soybean herbicide programs have the potential to carryover to a fall seeded cover crop and decrease stand density or biomass.

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Chapter II

Carryover of Common Corn and Soybean Herbicides to Various Cover Crop Species

Cody D. Cornelius and Kevin W. Bradley

Abstract

The recent interest in cover crops as component of Midwest corn and soybean production systems has led to the need for additional research, including the effects of residual corn and soybean herbicide treatments on fall cover crop establishment. Field studies were conducted in 2013, 2014, and 2015 in Columbia, Missouri to investigate the effects of common residual herbicides applied in corn and soybean on establishment of winter wheat, tillage radish, cereal rye, crimson clover, winter oat, Austrian winter pea, Italian ryegrass, and hairy vetch. Cover crops were evaluated for stand and biomass reduction 28 days after emergence (DAE). Rainfall from herbicide application to cover crop seeding date was much greater in 2014 and 2015, which resulted in less carryover in these years compared to 2013. When averaged across all herbicides evaluated in these experiments, the general order of sensitivity of cover crops to herbicide carryover, from greatest to least was Austrian winter pea = crimson clover > tillage radish > Italian ryegrass > hairy vetch> wheat > winter oat > cereal rye. Cereal rye had the fewest instances of biomass or stand reduction with only four out of the 29 herbicides adversely effecting establishment. Pyroxasulfone consistently reduced Italian ryegrass and winter oat biomass at least 67% in both the corn and soybean experiments. In the soybean

experiment imazethapyr and fomesafen-containing products resulted in severe stand and biomass reduction in both years while flumetsulam-containing products resulted in the greatest carryover symptoms in the corn experiment. Results from these experiments suggest that several commonly used corn and soybean herbicides have the potential to hinder cover crop establishment, but the severity of damage will depend on weather, cover crop species, and the specific herbicide combination.

Introduction

According to a survey of cover crop users in the U.S., the 2nd biggest challenge to adoption of cover crops is successful establishment in a corn or soybean production system (SARE 2014). Additionally, certain residual herbicides applied in a corn and soybean rotation have the potential to carryover in the soil and inhibit successful establishment of fall-seeded cover crops (Curran et al. 1996). In recent years, the adoption of no-tillage systems has changed weed control tactics from a tillage emphasis to the need for non-selective pre-plant and residual herbicides in order to plant into weed-free fields and keep them weed free for several weeks after planting. In addition, overreliance on glyphosate has resulted in an increase in glyphosate- and multiple-herbicide resistant weeds (Heap 2016), leading many growers to apply additional residual, soil-applied herbicides in order to achieve adequate weed control (Hager et al. 2003; Riggins and Tranel 2012). For example, the use of diphenyl ether and dinitroaniline herbicides increased by approximately 24% in the U.S. from 2006 to 2012 while the percent of soybean acres that received at least one pre-emergence residual herbicide application increased by approximately 19% from 2001 to 2006 (USDA 2015).

Soil characteristics such as pH, organic matter, cation exchange capacity (CEC) and soil texture have been shown to play a major role in the degradation of soil-applied herbicides. Soil persistence of herbicides like imazaquin and imazethapyr has been found to be greater as soil pH decreases as a result of greater adsorption resulting in less herbicide availability for microbial degradation (Loux and Reese 1993; Cantwell et al. 1989). In soils with greater than 3% organic matter, herbicide carryover potential increases (Curran 2001). Soil texture also plays a role in the likelihood of herbicide carryover; Westra et al. (2014) found that the half-life (DT_{50}) of pyroxasulfone ranged from 104 to 134 days compared to 46 to 48 days in a fine clay loam and fine sandy loam soil, respectively. In addition, Kerr et al. (2004) found that herbicide persistence is more likely when soil CEC levels are higher. Environmental factors such as the amount of rainfall and temperature after application also play a major role in herbicide degradation. For example, Bauer and Calvet (1999) found that the dissipation rate of simazine, atrazine, diuron, and sulcotrione was higher as soil moisture increased while Zimdahl et al. (1984) and Tharp and Kells (2000) showed that pendimethalin degraded faster with increasing amounts of rainfall and caused less injury to subsequent crops. In addition, Westra et al. (2014) observed that, regardless of sand or clay content, pyroxasulfone and *S*-metolachlor dissipation rate was positively correlated with the amount of irrigation. In reduced tillage systems, results are mixed as to whether a greater incidence of herbicide carryover is observed, but most researchers indicate that climatic variables such as rainfall and temperature have a greater impact on herbicide carryover than residue management (Kells et al. 1990; Locke and Bryson 1997).

Few studies have reported on the potential carryover effects of common soil residual herbicides applied in corn and soybean to fall-seeded cover crops. In one Michigan study, pendimethalin and metolachlor were found to reduce stand densities of Italian ryegrass [*Lolium perenne* L. *ssp. multiflorum (Lam.) Husnot*] by 46 and 94%, respectively, 40 days after treatment (DAT) (Tharp and Kells 2000). Hanson and Thill (2001) found that imazethapyr applied to Lentil (*Lens culinaris* L.) and Austrian winter pea (*Pisum sativum* L.) reduced the biomass of a subsequently planted wheat (*Triticum aestivum* L.) crop by 35 to 51% (Hanson and Thill 2001). Walsh et al. (1993a) evaluated chlorimuron, clomazone, imazaquin, imazethapyr, and metribuzin plus chlorimuron applied in soybean for their potential to carryover to subsequently planted winter wheat, cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), and grain sorghum (*Sorghum bicolor* L.) and reported winter wheat injury of 25% five months after an application of clomazone, spring planted cotton injury as high as 33% following imazaquin, and corn and grain sorghum injury from 7 to 24% following metribuzin + chlorimuron, imazaquin, clomazone, or imazethapyr. Walsh et al. (1993b) also found that a 2X rate of clomazone reduced spring-planted winter oat (*Avena sativa* L.) biomass by 44% while imazaquin and imazethapyr did not show significant carryover symptoms. Overall, few studies have reported on the effects of within-season applications of residual herbicides on fall-seeded cover crops, and many of those conducted have not investigated some of the species that are currently being promoted and/or investigated for inclusion in current corn and soybean production systems. Therefore, the objectives of this research were to determine the potential of common corn and soybean residual herbicides to reduce stand densities and biomass of subsequent fall-seeded cover crop species.

Materials and Methods

General Trial Information. Field experiments were conducted in 2013 and repeated in 2014, and 2015 in Boone County at the University of Missouri Bradford Research Center near Columbia, Missouri (38˚53'53.22"N, 92˚22'14.42"W). The soil was a Mexico silt loam (fine, smectic, mesic, Aeric Vertic Epiaqualfs) with 2.3% organic matter and a pH of 6.5 in 2013, 2.1% organic matter and pH of 6.4 in 2014, and 2.2% organic matter and pH of 6.3 in 2015. Corn and soybeans were planted into a no-till seedbed in rows spaced 76-cm apart at a rate of 71,661 and 444,789 seeds ha-1, respectively. Following removal of the previous corn or soybean crop for forage, seven winter annual cover crops were planted at the following seeding rates on September 11, 12, and 10 in 2013, 2014, and 2015, respectively: winter wheat at 135 kg ha^{-1}, cereal rye (*Secale cereale* L.) at 123 kg ha^{-1}, Italian ryegrass at 28 kg ha^{-1}, winter oat at 78 kg ha^{-1}, crimson clover (*Trifolium incarnatum* L.) at 34 kg ha^{-1}, Austrian winter pea at 56 kg ha^{-1}, hairy vetch (*Vicia villosa* Roth) at 34 kg ha^{-1}, and tillage radish (*Raphanus sativus* L.) at 9 kg ha^{-1}. All cover crops were planted with a 750 no-till drill (Deere & Company, 1 John Deere Place, Moline, IL 61265). Corn herbicides were applied once corn reached the V2 stage of growth. Soybean herbicides were applied post-emergence (POST) once the soybeans reached V2-V3 stage of growth except for flumioxazin, sulfentrazone, metribuzin, sulfentrazone + cloransulam, and chlorimuron, which were applied pre-emergence (PRE) based on crop safety requirements. Herbicides were applied using a CO_2-pressurized backpack sprayer equipped with XR 8002 flat fan nozzle tips (TeeJet®, Spraying Systems Co., P.O. Box 7900, Wheaton, IL. 60187) delivering 140 Lha-1 at 117 kPa. All treatments were arranged in a split-plot design with four replications. Whole plots consisted of herbicide treatments while subplots were cover crop species. Individual plots were 3 x 3 m in size. Dates of major field operations and specific rainfall between herbicide application and cover crop planting dated are shown in Table 2.1. Monthly rainfall totals and average temperatures for each year are presented in Table 2.2. A list of all herbicide formulations evaluated and their respective application timing can be found in Table 2.3.

Treatment Evaluation and Data Collection. All cover crop species were evaluated for stand and biomass reduction 28 days after emergence (DAE). Stand counts were performed by counting all emerged plants within two, 1/3 m^2 quadrats within each subplot. In a similar manner, above ground biomass was collected within one, 1/3 m^2 quadrat from each subplot. Biomass samples were weighed after being dried at 49° C for 96 hrs. Percent stand and biomass reductions were calculated by determining the differences between the treated and non-treated plots and dividing by the non-treated plot values.

Statistical Analysis. All stand and biomass reduction data were analyzed in SAS (SAS 9.3, SAS® Institute Inc. Cary, NC) using the PROC GLIMMIX procedure. Herbicide treatment and cover crop species were considered as fixed effects in the model while environment and replication were considered random effects. Significant interactions were present between years, likely due to the considerable differences in rainfall (Table 2.1), therefore results are presented by year. Means were separated using Fisher's protected LSD at α=0.05.

Results and Discussion

Carryover of Soybean Herbicides. In general, herbicide degradation is more rapid with adequate soil moisture and warm temperatures (Zimdahl 2007). In 2013 and 2015, there was a significant cover crop species by herbicide treatment interaction for biomass and stand reduction, but this interaction was not significant in 2014 (Table 2.4). This can be attributed to substantially more rainfall from the time of herbicide application to cover crop planting in 2014. In 2014, this experiment received at least 268 and 186 mm more rainfall compared to 2013 and 2015, respectively, from the time of the herbicide applications to the cover crop planting date (Table 2.1).

Winter wheat biomass was reduced in 2013 following imazethapyr, pyroxasulfone, and fomesafen + *S*-metolachlor, but no significant carryover was observed in 2015 (Table 2.5 and 2.6). Imazethapyr, pyroxasulfone, and fomesafen + *S*-metolachlor resulted in a 26 to 41% winter wheat biomass reduction. In addition, when averaged across all herbicide treatments, winter wheat biomass was reduced by 28% in 2014 (Table 2.7).

Tillage radish stand and biomass were reduced following fomesafen, imazethapyr, and fomesafen + *S*-metolachlor in 2013 and 2015 (Table 2.5 and 2.6). In 2013, imazethapyr and fomesafen + *S*-metolachlor resulted in 62 to 76% tillage radish biomass reduction, while fomesafen resulted in lower biomass reduction (51%) relative to imazethapyr, but a similar level as that provided by fomesafen + *S*-metolachlor. Additionally, sulfentrazone + cloransulam reduced tillage radish biomass by 26% in 2013, but no stand or biomass reduction were observed following this herbicide treatment in 2015 most likely due to the higher rainfall in 2015 compared to 2013 (Table 2.1 and 2.2). Throughout both experiments, certain herbicides resulted in cover crop biomass reduction but no significant stand reduction, as was the case with sulfentrazone + cloransulam in 2013. This response is not uncommon, and is most likely a result of herbicides that allowed for seedling emergence, but as the seedlings develop and roots absorb herbicide residues, herbicide injury can occur and result in biomass reduction. In 2015, fomesafen, imazethapyr, and fomesafen + *S*-metolachlor resulted in 33 to 43% tillage radish biomass reduction. Tillage radish stand reduction was the greatest following fomesafen at 41%, but remained similar to imazethapyr and acetochlor; fomesafen + *S*-metolachlor also resulted in 19% stand reduction. The consistent carryover of fomesafen-containing products and imazethapyr to tillage radish can be correlated with their extended half-life in clay soils (Mueller et al. 2014; Shaner 2014; Loux and Reese 1993; Cantwell et al. 1989) and the sensitivity of this cover crop to low residue levels of this herbicide.

Cereal rye was not negatively impacted by any herbicide treatment in more than one year (Table 2.5 and 2.6). These results are similar to those reported by Smith et al. (2015) that cereal rye was not impacted by commonly used soybean herbicides across two years in Wisconsin and Indiana. However, in 2013 cereal rye biomass was reduced by at least 24% following flumioxazin and cloransulam. In 2015, sulfentrazone reduced cereal rye biomass by 33%. In 2014, when averaged across all herbicide treatments, cereal rye biomass and stand density were reduced by 17 and 11%, respectively (Table 2.7). At near neutral pH, cloransulam has been shown to have a half-life as long as 200 days, which would help to explain the observed carryover to cereal rye (Shaner et al. 2014).

Crimson clover stand or biomass were reduced following fomesafen and acetochlor in 2013 and 2015 (Table 2.5 and 2.6). In 2013, crimson clover stand density was reduced by 23% following acetochlor. Biomass was reduced similarly by at least 29% following metribuzin, *S*-metolachlor, and acetochlor in 2013. In 2015, biomass was also reduced between 31 and 38% following sulfentrazone + cloransulam, fomesafen, imazethapyr, chlorimuron + thifensulfuron, and acetochlor in 2015. The consistent carryover observed from fomesafen can be attributed to the extended half-life of this herbicide. Acetochlor carryover to crimson clover is consistent with the eight month rotational restriction listed on the herbicide label (Anonymous 2016b).

Winter oat stand density or biomass were reduced in 2013 and 2015 following imazethapyr and pyroxasulfone (Table 2.5 and 2.6). Imazethapyr reduced winter oat biomass by 42 and 52% in 2013 and 2015, respectively, but stand density was not impacted in either year. Pyroxasulfone reduced winter oat stand density by 45% in 2015 and reduced biomass by 68% in 2015. In 2015, winter oat biomass was also reduced by at least 31% following flumioxazin, acetochlor, and chlorimuron, while stand density was reduced 22 and 19% following fomesafen and sulfentrazone. When averaged across all cover crops, pyroxasulfone and imazethapyr resulted in a 32 and 25% reduction in stand density, respectively (Table 2.8). This consistent trend of pyroxasulfone carryover coincides with the results of Westra et al. (2014) who showed a pyroxasulfone half-life of 104 to 134 days in soils with high clay content.

Flumioxazin, metribuzin, fomesafen, and acetochlor reduced Austrian winter pea stand density or biomass in 2013 and 2015 (Table 2.5 and 2.6). In 2013, flumioxazin, metribuzin, fomesafen, cloransulam, S-metolachlor, pyroxasulfone and acetochlor reduced Austrian winter pea biomass by at least 26%, but stand density was unaffected by all herbicides except flumioxazin. In 2015, sulfentrazone, flumioxazin, metribuzin, fomesafen, and acetochlor reduced Austrian winter pea biomass between 28 and 37% while stand density was unaffected. Flumioxazin and sulfentrazone have been reported to have half-lives as long as 21 and 71 days, respectively, under field conditions (Mueller et al. 2014). In addition, flumioxazin, metribuzin, and fomesafen require at least a four month rotational restriction before planting Austrian winter peas (Anonymous 2016c; 2016d; 2016e).

Italian ryegrass stand density and biomass were reduced by at least 57 and 67%, respectively, in response to previous applications of pyroxasulfone in 2013 and 2015 (Table 2.5 and 2.6). Bond et al. (2014) reported that 0.16 kg ai ha^{-1} pyroxasulfone provided 93% control of Italian ryegrass 180 d following a fall application. Therefore, the substantial reductions in Italian ryegrass stand and biomass can be attributed to the extended half-life and high level of sensitivity of this species to pyroxasulfone. In 2013, *S*-metolachlor also reduced Italian ryegrass biomass by 27%, but no significant carryover injury was observed in 2015 following an in-season application of this herbicide. In 2015, sulfentrazone reduced stand density and biomass by 19 and 33%, respectively, but no significant carryover injury was observed in 2013 following a pre-emergent application of this herbicide.

In 2013, hairy vetch biomass was reduced 31 to 49% following metribuzin, *S*-metolachlor, acetochlor, and pyroxasulfone, while flumioxazin reduced biomass by 24%; however, no herbicide resulted in carryover symptoms in 2015 (Table 2.5 and 2.6). In addition, hairy vetch only exhibited a 7 and 6% reduction in biomass and stand density, respectively, across all herbicides in 2014 (Table 2.8). Hairy vetch proved to be one of the cover crop species least affected by herbicide carryover in these experiments.

Carryover of Corn Herbicides. In 2013, there was a cover crop species by herbicide treatment interaction, but not in 2014 or 2015 (Table 2.4). However, a significant cover crop species interaction existed in 2014 for stand and biomass reduction and for stand reduction in 2015. Additionally, there was a significant herbicide treatment interaction for stand and biomass reduction in 2014 and 2015, respectively. Rainfall from herbicide application to cover crop planting date was 362 and 331 cm in 2014 and 2015, respectively, but only 96 cm in 2013 (Table 2.1). This deficiency in rainfall helps to explain the cover crop by herbicide interaction observed in 2013.

Following nicosulfuron, winter wheat stand density and biomass were reduced by 27 and 54%, respectively, while no other herbicides reduced winter wheat stand density in 2013 (Table 2.9). The observed winter wheat stand and biomass reduction following nicosulfuron is consistent with the four month rotational restriction stated on the herbicide label (Anonymous 2016a). In addition, when averaged across all herbicide treatments, winter wheat stand density was reduced by 16 and 10% in 2014 and 2015, respectively (Table 2.10). Winter wheat biomass was reduced similarly following atrazine, topramazone, isoxaflutole, flumetsulam, rimsulfuron, and clopyralid + acetochlor + flumetsulam + atrazine in 2013.

Flumetsulam reduced tillage radish stand density by 55%, while flumetsulam and clopyralid + acetochlor + flumetsulam + atrazine resulted in 80 and 56% biomass reduction, respectively (Table 2.9). The flumetsulam herbicide label lists a 26 month rotational restriction to canola (*Brassica napus*), which is likely to have a similar herbicidal sensitivity as tillage radish (*Brassica sativum*) (Anonymous 2016g). Shaner et al. (2014) also reported that across 23 soils, the half-life for flumetsulam ranged from 2 weeks to 4 months, with 80% of soils having a 2 month half-life. Topramazone, isoxaflutole, and rimsulfuron also reduced tillage radish biomass by 33 to 36% in 2013, but had no negative effect on stand density.

Similar to the soybean experiment, cereal rye showed very few herbicide carryover symptoms (Table 2.9). Biomass and stand reduction did not exceed 13% when averaged across all herbicide treatments in 2015 (Table 2.10). However, isoxaflutole reduced cereal rye biomass by 38% in 2013. Smith et al. (2015) also reported that cereal rye was not impacted by commonly used corn herbicides in a two-year study.

Clopyralid reduced crimson clover biomass and stand by 82 and 57%, respectively (Table 2.9). Nicosulfuron and clopyralid + acetochlor + flumetsulam + atrazine also reduced crimson clover biomass by 56 and 50%, respectively, while atrazine, tembotrione, and isoxaflutole reduced biomass between 35 and 38%. The observed carryover from clopyralid can be associated with the 12 to 70 day soil half-life

(Shaner et al. 2014), and the sensitivity of the clover species to this synthetic auxin herbicide.

Winter oat biomass and stand was reduced by 67 and 81%, respectively, following in-season applications of pyroxasulfone (Table 2.9). When averaged across all cover crop species, pyroxasulfone also resulted in a 32% stand reduction in 2014 (Table 2.8). Topramazone also reduced winter oat biomass by 36%, which was comparable to that observed following pyroxasulfone. However, topramazone resulted in a 27% winter oat stand reduction, which was a lower level of stand reduction relative to pyroxasulfone.

Austrian winter pea stand was not affected by any herbicides, but mesotrione and clopyralid reduced biomass by 42 and 36%, respectively (Table 2.9). Shaner et al. (2014) lists Austrian winter pea as susceptible to clopyralid with a rotational restriction of 18 months and states that the soil half-life for clopyralid is dependant on soil and climactic conditions.

As reported in the soybean experiment, pyroxasulfone resulted in the highest level of Italian ryegrass stand and biomass reduction (95%) (Table 2.9). Atrazine, topramazone, rimsulfuron, nicosulfuron, glyphosate + mesotrione + *S*-metolachlor + atrazine, and tembotrione + thiencarbazone resulted in 37 to 51% Italian ryegrass biomass reduction, but these levels of reduction were less detrimental than pyroxasulfone. In addition to biomass reduction, rimsulfuron and glyphosate + mesotrione + *S*-metolachlor + atrazine also resulted in stand reductions of 25 and 39%, respectively.

Hairy vetch stand and biomass were reduced by 26 and 33% following glyphosate + mesotrione + *S*-metolachlor + atrazine (Table 2.9). Although no other herbicide treatment reduced hairy vetch stand, mesotrione, clopyralid, flumetsulam, and clopyralid + acetochlor + flumetsulam + atrazine resulted in a 35 to 58% biomass reduction. Each herbicide treatment that contained clopyralid or flumetsulam as stand-alone treatments or in combination with other herbicides resulted in biomass reduction of hairy vetch. Therefore, herbicide applications containing either active ingredient should be avoided when establishing hairy vetch as a cover crop.

In conclusion, all herbicides evaluated, excluding lactofen, resulted in at least one instance of biomass or stand reduction. However, for each cover crop evaluated there were herbicide treatments that did not result in biomass or stand reduction. Certain cover crops such as Italian ryegrass, tillage radish, winter oat, and crimson clover exhibited the highest levels of stand and biomass reduction in both experiments. In contrast, cereal rye was only impacted by five out of the 29 total herbicide treatments evaluated. Additionally, none of the soybean herbicide treatments caused a stand or biomass reduction in consecutive years and isoxaflutole was the only corn herbicide to significantly reduce cereal rye biomass. Previous research has shown that cereal rye has several agronomic benefits such as reducing soil erosion, suppressing weed emergence, and increasing soil organic matter (Kuo et al. 1997; Sainju and Singh 1997; Webster et al. 2013). The fact that cereal rye can be effectively established following several corn and soybean herbicides should be considered as an additional benefit of the use of this species. These results indicate that certain residual herbicides have the potential to reduce stand and biomass of fall-seeded cover crops, but herbicide carryover is heavily dependent on rainfall after herbicide application. Additional research is needed to determine how much time and rainfall are needed prior to cover crop establishment following specific herbicide applications.

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Table 2.1 Dates of major field operations and rainfall following herbicide application in 2013, 2014 and 2015 at the University of Missouri Bradford Research Farm in Boone County Missouri and at the Moberly Missouri site in Randolph County Missouri.

	Year, Date of Operation, and Rainfall following herbicide application		
Field operation	2013	2014	2015
Corn Experiment[a]			
Corn Seeding Date	6/12	5/19	6/16
Dates of herbicide application			
V2	6/26	6/11	6/30
Cover Crop Seeding Date	9/11	9/11	9/13
Rainfall from herbicide application to cover crop seeding date	96 cm	362 cm	331 cm
Soybean Experiment			
Soybean Seeding Date	6/12	6/3	7/14
Dates of herbicide application			
PRE	6/13	6/6	7/14
V2-V3	7/2	6/17	7/28
Cover Crop Seeding Date	9/11	9/11	9/13
Rainfall from herbicide application to cover crop seeding date			
PRE	131 cm	404 cm	218 cm
POST V2-V3	90 cm	358 cm	127 cm

[a] Abbreviations: V2, two leaves; PRE, pre-emergence; POST, post-emergence.

Table 2.2. Monthly rainfall (mm) and average monthly temperatures (C) in comparison to the 30-yr average in 2012,2013, 2014 and 2015 at the Bradford Research Center in Boone County MO.

	Rainfall					Temperature				
Month	2012	2013	2014	2015	30 y. Avg.	2012	2013	2014	2015	30 y. Avg.
	mm					C				
January	26	61	23	24	56	1	1	-4	0	-1
February	55	98	35	36	63	3	1	-4	-4	2
March	113	84	31	39	81	14	4	5	8	8
April	171	188	210	84	114	14	12	13	14	14
May	25	249	78	144	138	21	18	19	19	18
June	39	52	129	192	132	24	23	23	24	24
July	18	62	37	213	115	29	24	23	25	26
August	49	48	75	80	114	25	24	25	23	25
September	46	62	156	29	109	20	22	19	20	21
October	68	72	259	25	85	13	14	14	14	14
November	25	37	34	--	105	8	6	4	--	8
December	42	43	56	--	64	4	-1	3	--	1

[a] 30-yr averages (1981-2010) obtained from National Climatic Data Center (2011).

Table 2.3. Sources of herbicides used in the experiments.

Herbicide	Trade name	Formulation	Rate	Manufacturer	Address
			kg ai or ae ha^{-1}		
Soybean Experiment					
Sulfentrazone	Spartan	4 L[a]	0.28	FMC Corporation	Philadelphia, PA
Flumioxazin	Valor	51 WG	0.089	Valent	Walnut Creek, CA
Metribuzin	Sencor	75 DF	0.42	Bayer CropScience	Research Triangle Park, NC
Sulf + Clor	Authority First	70 DF	0.28 + 0.036	FMC Corporation	Philadelphia, PA
Chlorimuron	Classic	25 DF	0.0263	DuPont	Wilmington, DE
Fomesafen	Flexstar	1.88 L	0.33	Syngenta	Greensboro, NC
Lactofen	Cobra	2 EC	0.22	Valent	Walnut Creek, CA
Imazethapyr	Pursuit	2 EC	0.07	BASF	Research Triangle Park, NC
Cloransulam	FirstRate	84 DF	0.0353	Dow AgroSciences	Indianapolis, IN
Chlor+ Thif	Synchrony XP	28.4 WG	0.0057 + 0.0018	DuPont	Wilmington, DE
S-metolachlor	Dual II Magnum	7.64 EC	1.43	Syngenta	Greensboro, NC
Acetochlor	Warrant	3 L	1.26	Monsanto	St. Louis, MO
Pyroxasulfone	Zidua	85 WG	0.18	BASF	Research Triangle, NC
S-met + Fom	Prefix	5.92 EC	1.22 + 0.266	Syngenta	Greensboro, NC
Corn Experiment					
Atrazine	Aatrex	4 L	2.24	Syngenta	Greensboro, NC
Mesotrione	Callisto	4 L	0.11	Syngenta	Greensboro, NC
Tembotrione	Laudis	3.5 L	0.092	Bayer CropScience	Research Triangle Park, NC
Topramazone	Impact	2.8 L	0.018	AMVAC	Newport Beach, CA
Isoxaflutole	Balance Flexx	2 SC	0.088	Bayer CropScience	Research Triangle Park, NC
Clopyralid	Stinger	3 L	0.21	Dow AgroSciences	Indianapolis, IN
Flumetsulam	Python	80 WG	0.056	Dow AgroSciences	Indianapolis, IN
Rimsulfuron	Resolve	25 DF	0.018	DuPont	Wilmington, DE
Nicosulfuron	Accent Q	54.5 WG	0.034	DuPont	Wilmington, DE
Acet + Clop + Flum	Surestart	47.24 L	0.92 + 0.093 + 0.029	Dow AgroSciences	Indianapolis, IN
S-met + Gly + Meso	Halex GT	4.4 SC	1.17 + 1.17 + .117	Syngenta	Greensboro, NC

Thien+ Tembo	Capreno	3.45 SC	0.015 + 0.076	Bayer CropScience	Research Triangle Park, NC
Pyroxasulfone	Zidua	85 WG	0.18	BASF	Research Triangle, NC
Crop Oil Concentrate	Relay	100L	1.4 L ha^{-1}	Van Diest Supply Co.	Webster City, IA
Ammonium Sulfate	N-Pak AMS	3.4 L	2.9	Winfield Solutions	St. Paul, MN
Non-Ionic Surfactant	Astute	100 L	0.35 L ha^{-1}	MFA	Columbia, MO

[a] Abbreviations: Sulf, sulfentrazone; Clor, cloransulam; Chlor, chlorimuron; Thif, thifensulfuron; S-met, *s*-metolachlor, Fom, fomesafen; Acet, acetochlor, Clop, clopyralid; Flum, flumetsulam; Gly, glyphosate; Meso, mesotrione, Thien, thiencarbazone; Tembo, tembotrione; L, liquid; WG, water-dispersable granule; DF, dry flowable; EC, emulsifiable concentrate; SC, soluble concentrate;

Table 2.4. Summary of effects of cover crop species and herbicide treatments on cover crop biomass and stand density reduction 28 days after emergence (DAE) in the corn and soybean experiments.

	Biomass Reduction			Stand Reduction		
Variables	2013	2014	2015	2013	2014	2015
Corn experiment	----------P-value[b]----------					
Cover crop species	<0.0001	0.0348	0.2164	0.0006	0.0180	<0.0001
Herbicide treatment	0.0248	0.6737	0.0389	<0.0001	0.0001	0.7387
Herbicide treatment*cover crop	<0.0001	0.1402	0.9098	<0.0001	0.9737	0.9859
Soybean experiment						
Cover crop species	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Herbicide treatment	<0.0001	<0.0001	<0.0001	0.1123	0.7602	<0.0001
Herbicide treatment*cover crop	<0.0001	0.9476	0.0007	0.0190	0.9983	0.0002

Table 2.5. Influence of soybean herbicides on stand and biomass reduction 28 days after emergence in Columbia, Missouri in 2013.

	Winter Wheat		Tillage Radish		Cereal Rye		Crimson Clover		Winter Oat		Austrian Winter Pea		Italian Ryegrass		Hairy Vetch	
Herbicide	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass
	---% Reduction---															
Sulfentrazone	33	11	6	0	17	5	4	19	3	0	7	3	9	0	9	13
Flumioxazin	27	10	6	15	18	24	14	29	3	0	8	38	19	2	6	24
Metribuzin	43	13	2	3	23	23	11	13	9	7	23	32	20	4	11	40
Sulfentrazone + cloransulam	13	9	18	26	3	10	6	7	14	0	2	8	5	0	7	9
Chlorimuron	27	13	7	9	14	7	2	4	13	0	18	0	17	4	14	8
Fomesafen	22	13	28	51	5	16	27	8	8	5	17	26	11	0	1	19
Lactofen	7	12	6	6	14	11	7	5	12	14	12	10	6	10	9	6
Imazethapyr	11	30	41	76	17	17	0	1	12	42	13	14	14	7	16	17
Cloransulam	15	18	2	8	9	29	9	0	6	13	7	26	6	8	17	14
Chlorimuron + thifensulfuron	19	19	3	0	16	20	8	9	14	13	8	20	17	0	6	16
S-metolachlor	38	18	5	4	18	12	20	43	13	7	21	43	14	27	15	31
Acetochlor	22	12	6	10	15	15	23	32	14	9	0	27	32	15	11	49
Pyroxasulfone	20	26	2	9	17	15	13	13	33	14	4	27	57	67	0	46
Fomesafen + *S*-metolachlor	21	41	32	62	19	31	15	3	6	4	8	15	12	11	15	11
LSD (0.05):	22	23	22	23	22	23	22	23	22	23	22	23	22	23	22	23

Table 2.6. Influence of soybean herbicides on stand and biomass reduction 28 days after emergence in Columbia, Missouri in 2015.

	Winter Wheat		Tillage Radish		Cereal Rye		Crimson Clover		Winter Oat		Austrian Winter Pea		Italian Ryegrass		Hairy Vetch	
Herbicide	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass
	--------% Reduction--------															
Sulfentrazone	13	9	19	13	13	33	8	17	19	25	3	28	19	33	14	6
Flumioxazin	8	6	19	4	3	16	17	25	13	32	4	30	18	13	12	18
Metribuzin	0	7	13	13	0	2	14	21	2	15	15	30	13	8	1	1
Sulfentrazone + cloransulam	1	2	4	1	11	9	12	38	9	23	0	17	18	2	0	4
Chlorimuron	1	5	20	19	4	0	2	22	13	40	0	15	3	11	7	0
Fomesafen	3	3	41	33	4	8	10	32	22	15	12	31	8	12	3	0
Lactofen	2	1	6	0	6	5	1	15	6	6	0	22	6	2	0	4
Imazethapyr	1	3	32	39	4	20	7	38	17	52	7	25	14	2	8	0
Cloransulam	3	0	5	0	1	0	3	19	17	9	0	10	0	0	12	0
Chlorimuron + thifensulfuron	0	5	10	0	6	11	5	31	15	12	2	13	15	18	5	8
S-metolachlor	6	3	12	7	12	24	3	18	14	22	0	14	17	25	9	4
Acetochlor	4	1	24	12	2	24	5	38	7	31	0	37	6	22	7	15
Pyroxasulfone	4	6	3	1	9	23	13	17	45	68	5	17	68	82	7	2
Fomesafen + *S*-metolachlor	4	0	19	43	8	0	3	17	17	23	0	12	20	14	2	4
LSD (0.05):	17	26	17	26	17	26	17	26	17	26	17	26	17	26	17	26

Table 2.7. Cover crop stand and biomass reduction 28 days after emergence when averaged across all herbicide treatments in the 2014 and 2015 in corn and soybean experiments in Columbia, Missouri.

	Soybean experiment		Corn experiment		
	2014				2015
Cover crop	Biomass	Stand	Biomass	Stand	Stand
	% Reduction				
Cereal rye	17	11	10	13	13
Crimson clover	30	22	10	9	12
Winter oat	15	18	17	15	21
Austrian winter pea	30	5	15	8	19
Tillage radish	29	14	17	14	6
Italian ryegrass	9	5	21	6	14
Hairy vetch	8	6	12	12	6
Winter wheat	28	16	14	16	10
LSD (0.05):	9	7	7	8	5

Table 2.8. Influence of soybean herbicides on the stand reduction of all cover crop species 28 days after emergence at Columbia, Missouri in 2014.

Herbicide	% Reduction
Sulfentrazone	31
Flumioxazin	24
Metribuzin	23
Sulfentrazone+ cloransulam	21
Chlorimuron	26
Fomesafen	21
Lactofen	3
Imazethapyr	25
Cloransulam	19
Chlorimuron+ thifensulfuron	13
S-metolachlor	15
Acetochlor	10
Pyroxasulfone	32
Fomesafen + *S*-metolachlor	28
LSD (0.05):	9

Table 2.9. Influence of corn herbicides on stand and biomass reduction 28 days after emergence at Columbia, Missouri in 2013.

	Winter Wheat		Tillage Radish		Cereal Rye		Crimson Clover		Winter Oat		Austrian Winter Pea		Italian Ryegrass		Hairy Vetch	
Herbicide	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass
	--% Reduction--															
Atrazine	16	37	11	22	11	26	9	35	20	29	18	8	14	37	15	1
Mesotrione	12	29	15	30	17	8	15	32	19	3	20	42	14	28	11	35
Tembotrione	13	15	5	16	14	28	0	38	13	11	6	9	9	19	3	12
Topramazone	18	51	7	36	13	14	11	30	27	36	20	25	13	46	3	19
Isoxaflutole	21	43	8	36	14	38	7	36	12	24	5	22	15	22	11	0
Clopyralid	16	1	20	7	16	12	57	82	23	24	21	36	12	0	23	39
Flumetsulam	11	45	55	80	6	18	9	30	18	9	13	30	10	6	5	58
Rimsulfuron	17	28	6	33	6	23	9	20	11	13	13	0	25	46	11	32
Nicosulfuron	27	54	11	24	13	14	13	56	26	29	11	11	22	48	13	27
Clop + Acet + Flum + Atra	16	40	4	56	6	23	15	50	9	22	9	29	8	31	17	49
Gly + Mes + *S*-meto + Atra	19	16	18	31	14	8	4	26	14	6	18	31	39	51	26	33
Tembotrione + thiencarbazone	12	19	16	18	10	5	7	16	29	21	11	4	19	50	17	17
Pyroxasulfone	18	24	22	7	23	11	19	28	81	67	14	1	95	95	12	5
LSD (0.05):	23	32	23	32	23	32	23	32	23	32	23	32	23	32	23	32

[a] Abbreviations: clop, clopyralid; aceto, acetochlor; flum, flumetsulam; atra, atrazine; gly, glyphosate; mes, mesotrione; *s*-meto, *s*-metolachlor;

Table 2.10. Influence of corn herbicides on the stand and biomass reduction of all cover crop species 28 DAE[a] at Columbia, MO in 2014 and 2015.

Herbicide	Biomass	Stand
	2015	2014
	----------------------% Reduction----------------------	
Atrazine	14	15
Mesotrione	11	5
Tembotrione	17	12
Topramazone	16	11
Isoxaflutole	12	12
Clopyralid	16	16
Flumetsulam	8	7
Rimsulfuron	18	14
Nicosulfuron	12	26
Acetochlor + clopyralid + flumetsulam + atrazine	20	6
Glyphosate + *s*-metolachlor + glyphosate + mesotrione	23	9
Thiencarbazone + tembotrione	13	12
Pyroxasulfone	11	6
LSD (0.05):	9	8

[a] Abbreviations: DAE, days after emergence

Chapter III

Herbicide Programs for the Termination of Various Cover Crop Species

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Abstract

The recent interest in cover crops as a component of Midwest corn and soybean production systems has led to a greater need to understand the most effective herbicide program for cover crop termination prior to planting corn or soybean. Previous research has shown that certain cover crop species can significantly reduce subsequent cash crop yields if not properly terminated. Two field experiments were conducted in 2013, 2014 and 2015 to determine the most effective herbicide program for the termination of winter wheat, cereal rye, crimson clover, Austrian winter pea, Italian ryegrass, and hairy vetch. Cover crops were planted in early September and herbicide treatments were applied at different timings from early to late in the spring. Visual control and above-ground biomass reduction was determined 28 days after application (DAA). The most consistent control of broadleaf cover crops occurred following treatment with glyphosate + 2,4-D, dicamba, or saflufenacil. In general, glyphosate-containing herbicide treatments provided the most consistent control of grass species compared to paraquat and glufosinate. Across all timings, 1.4 kg ae ha^{-1} glyphosate + 0.136 kg ai ha^{-1} clethodim provided at least 98% control of Italian ryegrass while 1.4 kg ha^{-1} glyphosate provided between 87 and 94% control of cereal rye and winter wheat. Biomass reduction (BR) was greater following earlier applications, but certain treatments still provided adequate control at

mid or late application timings. Thus, growers seeking to maximize cover crop residue can delay termination without sacrificing effective control.

Introduction

If not properly terminated, cover crops have the potential to become weeds in the following crop and can also slow soil drying and warming in the spring (Eckert 1988). In addition, inadequate termination of cover crops can result in reductions in corn or soybean yield by inhibiting crop emergence. Cereal rye and cereal rye-legume mixtures have been reported to reduce corn and soybean yields up to 12% due to irregular or low final plant populations (Eckert 1988; Mitchell and Teel 1977). Thelan et al. (2004) concluded that cereal rye growing with soybean reduced yield by as much as 27%, and attributed this yield loss to water stress caused by the cereal rye.

Several cover crop species, such as Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot), barley (*Hordeum vulgare* L.), winter oat (*Avena sativa* L.), cereal rye (*Secale cereal* L.), winter wheat (*Triticum aestivum* L.), hairy vetch (*Vicia villosa* L.), Austrian winter pea (*Pisum sativum* L.) and various clover species (*Trifolium* spp.) have been investigated for their utility as cover crops (Johnson et al. 1998; Kuo et al. 1997; Teasdale and Mohler 1993; Weston 1990). Johnson et al. (1998) reported that cereal rye can reduce subsequent corn yields as much as 1.6 mg ha^{-1}, but oats did not significantly reduce corn yields because they did not overwinter in Iowa. Kuo et al. (1997) found that Italian ryegrass and cereal rye increased soil organic matter at a higher rate than leguminous cover crops such as hairy vetch and Austrian winter pea due to higher biomass production. Specific interactions between cover crops and various soil properties and cash crop yields have been thoroughly investigated within the literature.

However, little research has been conducted to investigate management considerations for how cover crops fit into Midwest crop production systems. Specifically, it is important to identify herbicide programs that will effectively control these cover crop species prior to corn or soybean planting.

One commonly recommended cover crop that may require special attention when it comes to termination is Italian ryegrass. Relative to other cover crop species, Italian ryegrass has several desirable benefits including partial recovery of residual nitrogen, low seed cost, rapid establishment, and cold and disease tolerance (Reddy 2001; Shipley et al. 1992; Weston 1990). However, following an Italian ryegrass cover crop, corn and soybean yield were reduced as much as 18 and 29%, respectively, compared to where no cover crop had been planted (Vyn et al. 1999; Reddy 2001). Many spring pre-plant herbicide programs in the Midwest contain glyphosate because of its broad-spectrum activity, short plant back interval, and price. Lins et al. (2007) evaluated three different rates of glyphosate (415, 830, 1660 g ae/ha) for the control of Italian ryegrass at four different stages of growth and found that the highest rate applied at the boot or early flower growth stage provided 70 to 99% control. Hoskins et al. (2005) reported that mid- to late-March applications of ACCase inhibiting herbicides such as diclofop, clodinafop, and tralkoxydim provided 91% or greater control of Italian ryegrass. Currently glyphosate-resistant populations of Italian ryegrass have been identified in Arkansas, Mississippi, Oregon, and Tennessee (Heap 2015). Across the United States there are several multiple resistant populations of Italian ryegrass that exist. Specifically, there is a multiple resistant population of Italian ryegrass in Oregon that is resistant to both glyphosate and glufosinate, and several populations with resistance to ACCase and ALS-inhibiting herbicides (Heap 2015). Italian ryegrass plants that are not effectively controlled have the potential to set seed which can then be spread through harvest equipment to other fields. It is important to understand what herbicide programs are most effective at controlling all of the various species that are being recommended as cover crops, and especially those that have proven difficult to control such as Italian ryegrass. The objectives of this research are to determine the effects of different herbicide treatments and application timings on the termination of various cover crops in the spring.

Materials and Methods

General Trial Information. Two separate field experiments were conducted in 2013 and repeated in 2014 and 2015 in Boone County, Missouri at the University of Missouri Bradford Research Center (38°53'N, 92°12'W). In both experiments the soil was a Mexico silt loam (fine, smectic, mesic Aeric Vertic Epiaqualfs) with 2.3% organic matter and a pH of 6.5 in 2013, 2.1% organic matter and pH of 6.4 in 2014, and 2.2% organic matter and pH of 6.3 in 2015. Cover crops were planted on September 11, 10, and 12 in 2013, 2014 and 2015, respectively, using a no-till drill with rows spaced 19 cm apart. Monthly rainfall totals and average monthly temperature for each year are presented in Table 3.1.

The first field experiment investigated the effects of 9 different herbicide programs on the termination of wheat, cereal rye, Italian ryegrass, crimson clover (*Trifolium incarnatum* L.), Austrian winter pea, hairy vetch, and tillage radish (*Raphanus sativus* L.). Termination data on tillage radish was not collected due to the fact that tillage radish did not overwinter in any year of the study. All herbicide treatments were applied at an early and late termination timing (Table 3.2). Throughout the Midwest there are typically small windows for completing spring fieldwork due to the wet conditions that persist during April and May. Therefore, an early and late herbicide application timing was made to simulate seasons that allow for early April or early May burndown applications based of field conditions. The height of each cover crop at the time of application can be found in Table 3.3. The experimental design was a randomized complete block in a split-plot arrangement of treatments. Whole plots consisted of cover crop species and subplots were herbicide treatments. Individual plots were 3 x 5 m and each treatment was replicated 3 times.

The second field experiment evaluated the effects of 18 different herbicide programs on the termination of Italian ryegrass. All herbicide treatments were applied at an early, middle and late timing (Table 3.4), which were based on the height of Italian ryegrass at the time of application. The target heights were 15 cm for the early application, 35 cm for the middle application, and 75 cm for the late application. The height of Italian ryegrass at each application timing can be found in Table 3.5. The experimental design was a randomized complete block and all herbicide treatments were replicated four times.

Data Collection. In both experiments, visible estimates of control were evaluated 28 days after application (DAA) on a scale of 0 to 100%, where 0 was equal to no control and 100 was equivalent to complete cover crop death. Cover crop biomass was also determined by clipping all plants within a 0.33-m^2 quadrat in each plot 28 DAA. Fresh weights of the harvested plants were recorded immediately after clipping and biomass reduction (BR) was calculated as a percentage of the non-treated control.

Statistical Analysis. Visible control and biomass reduction data were analyzed using the PROC GLIMMIX procedure in SAS (Version 9.3, SAS® Instute Inc., Cary, NC 27513). Environments and replications (nested within environments) were considered random effects, and herbicide treatments, application timing and cover crop species were considered fixed effects. Considering year as a random effect in the model allows inferences about treatments over a wide range of environments (Blouin et al. 2011; Carmer et al. 1989). Individual treatment differences were separated using Fisher's Protected LSD at $P \leq 0.05$.

Results and Discussion

Multi-Species Experiment. Across all herbicide treatments and cover crop species there were significant differences in control and BR between the early and late application timing (Tables 3.5 and 3.6). There was a significant interaction of cover crop species-by-herbicide program-by-timing for visual control ($P = 0.035$) as well as BR ($P = 0.002$). When averaged across all herbicide treatments and all cover crop species, the early and late application timings resulted in 83 and 80% visual control and 86 and 78% BR, respectively (data not shown). In addition, overall the early application timing resulted in statistically greater control and BR than the late application timing.

In general, glyphosate-based herbicide programs provided the most consistent control of winter wheat, cereal rye, and Italian ryegrass (Table 3.5). With the exception of glyphosate, glyphosate + chlorimuron + metribuzin, and paraquat + atrazine, all herbicide programs provided statistically greater control at the early compared to the late application timing. BR was also greater at the early timing following treatment with glyphosate, glyphosate + 2,4-D, glyphosate + saflufenacil, and glyphosate + atrazine.

At the early timing, control of winter wheat was 85% or greater following applications of glyphosate, glyphosate + 2,4-D, glyphosate + dicamba, glyphosate + saflufenacil, glyphosate + atrazine, paraquat + atrazine, and glyphosate + chlorimuron + metribuzin. Glyphosate alone or in combination with 2,4-D, dicamba, or saflufenacil provided 94 to 95% control of winter wheat at the early timing, and this was greater than that provided by all other treatments evaluated. Glyphosate + chlorimuron + metribuzin and paraquat + atrazine resulted in 85 and 89% control of winter wheat, respectively, while paraquat and paraquat + 2,4-D provided lower levels of winter wheat control than all other treatments evaluated. At the late timing, glyphosate and glyphosate + saflufenacil provided the highest levels of winter wheat control. Both of these herbicide programs provided greater winter wheat control than all paraquat-containing herbicide treatments across both timings. These results are similar to research presented by Rainbolt et al. (2004) that showed 95% control of winter wheat with glyphosate at 0.43 kg ae ha^{-1} and 63% control with paraquat at 0.56 kg ai ha^{-1}. Although glyphosate alone provided a high level of control at the late timing, tank mixing 2,4-D and dicamba with glyphosate reduced winter wheat control to 76 and 82%, respectively. O'Sullivan and O'Donovan (1980) reported that 0.07 kg glyphosate ha^{-1} provided 76% BR of winter wheat but that a tank mix of glyphosate + 2,4-D (0.105 kg ha^{-1}) or dicamba (0.035 kg ha^{-1}) resulted in only 29 and 26% BR of winter wheat, respectively. In general, less variation was observed for BR relative to visual control ratings of winter wheat (Table 3.6). At the early timing, glyphosate + atrazine provided 86% BR of winter wheat, but this was similar to all other herbicide programs excluding paraquat and paraquat + 2,4-D. In contrast, no differences between any treatments were observed for winter wheat BR at the late application timing.

At the early timing, cereal rye control was at least 98% while BR ranged from 81% to 88% following applications of glyphosate, glyphosate + 2,4-D, glyphosate + dicamba, and glyphosate + saflufenacil (Table 3.5 and 3.6). In addition, all of these herbicide programs resulted in greater control at the early compared to late timing. In contrast, glyphosate + chlorimuron + metribuzin, paraquat, paraquat + 2,4-D, and paraquat + atrazine provided greater control at the late compared to early timing. At the late timing, all glyphosate-based herbicide programs except glyphosate + saflufenacil provided similar levels of cereal rye control ranging from 87 to 91%. All glyphosate based herbicide programs and paraquat + atrazine provided similar BR at the early timing and all herbicide programs provided similar BR at the late timing. The early timing resulted in greater BR for all glyphosate based herbicide programs and paraquat + atrazine. Teasdale and Moehler (1993) reported that a cover crops ability to suppress summer annual weed emergence increases as above ground biomass increases. Therefore, herbicide programs that provided high levels of control at the late timing should be considered by growers that seek to suppress summer annual weed emergence. With the exception of glyphosate + saflufenacil, all glyphosate-containing treatments provided greater control compared to paraquat-containing treatments at either timing. For both timings, cereal rye control ranged from 57 to 78% following paraquat, paraquat + 2,4-D, and paraquat + atrazine. The observed consistency of glyphosate based herbicide programs for the control of cereal rye is similar to the findings of Young et al.

(2016) who showed 98% control of cereal rye following glyphosate at 0.86 kg ae ha^{-1}. Several herbicide programs applied at the early timing provided a high level of control, but there were also herbicide programs that provided a high level of control at the late timing while maintaining higher levels of residue.

With the exception of the glyphosate + saflufenacil and paraquat + 2,4-D treatments, Italian ryegrass control was greater at the early compared to the late application timing (Table 3.5). In addition, glyphosate-based programs provided greater control of Italian ryegrass at the early and late timing. These results are similar to Griffin et al. (2004) who reported inconsistent control (32 to 80%) of Italian ryegrass following an application of paraquat at 0.53 kg ai ha^{-1}. At the early timing, glyphosate + 2,4-D and glyphosate + saflufenacil provided 98 and 96% Italian ryegrass control, respectively. However, at the late timing, glyphosate, glyphosate + 2,4-D, glyphosate + dicamba, and glyphosate + chlorimuron + metribuzin provided similar levels of control. Glyphosate + saflufenacil was the only herbicide program to provide greater than 90% control regardless of application timing. BR was also similar between the early and late application timing with all herbicide treatments. At the early timing, Italian ryegrass BR ranged from 85 to 91% with all glyphosate-containing treatments and paraquat + atrazine. At the late timing, all herbicide treatments except paraquat + 2,4-D,provided similar Italian ryegrass BR which ranged from 79 to 88%.

Crimson clover control varied based on herbicide treatments and application timings. The late timing of glyphosate, paraquat, and paraquat + 2,4-D provided 23, 31, and 16% greater control than the early timing of these same herbicide treatments. In contrast, glyphosate + 2,4-D, glyphosate + dicamba, glyphosate + atrazine, and glyphosate + chlorimuron + metribuzin all provided higher levels of crimson clover control when applied at the early timing. At the early timing, glyphosate + 2,4-D, glyphosate + dicamba, glyphosate + saflufenacil, and paraquat + atrazine provided 90 to 92% control of crimson clover. McCurdy et al. (2013) also observed 91% control of crimson clover following applications of 1.58 kg ae ha^{-1} 2,4-D. At the late timing, glyphosate, glyphosate + saflufenacil, paraquat, paraquat + 2,4-D, and paraquat + atrazine all provided greater than 90% control of crimson clover, and these treatments also provided the highest levels of BR (Table 3.6). Glyphosate + saflufenacil provided at least 92% control of crimson clover regardless of timing but BR was 16% lower at the late compared to the early timing (Table 3.6). Paraquat-containing treatments and glyphosate provided a similar level of BR regardless of application timing, but all other herbicide treatments provided greater BR at the early compared to late timing.

Of the cover crops evaluated in these experiments, hairy vetch exhibited the greatest response to herbicide treatments that contained 2,4-D or dicamba (Table 3.5). At the early timing, the addition of 2,4-D or dicamba to the glyphosate treatment increased control by 27 or 26%, respectively. Similarly, the addition of 2,4-D to paraquat increased hairy vetch control by 35% compared to paraquat alone. Herbicide treatments that contained 2,4-D or dicamba also provided the highest levels of hairy vetch control at the late timing. BR was also similar across application timings with all treatments that contained 2,4-D and dicamba (Table 3.6). These results are consistent with other reports in the literature. For example, Curran et al. (2015) found that 2,4-D and dicamba at 0.14 kg ae ha^{-1} provided at least 90% control of hairy vetch when applied in the spring or fall.

Several herbicide treatments provided effective control of Austrian winter pea at both application timings (Table 3.5). At the early timing, Austrian winter pea control was similar and ranged from 93 to 98% following applications of glyphosate, glyphosate + 2,4-D, glyphosate + dicamba, and glyphosate + atrazine. At the late timing, glyphosate + dicamba, glyphosate + chlorimuron + metribuzin, paraquat, paraquat + 2,4-D, and paraquat + atrazine provided 91 to 96% control of Austrian winter pea. Glyphosate + dicamba, glyphosate + saflufenacil, paraquat + 2,4-D, and paraquat + atrazine provided similar control regardless of application timing. BR was similar across timings for all treatments except glyphosate + 2,4-D, which provided 18% less BR at the late compared to the early application timing. As with hairy vetch, the most effective treatments for Austrian winter pea were those that contained 2,4-D or dicamba.

Italian Ryegrass Experiment. Italian ryegrass control varied greatly by herbicide treatment and application timing and a herbicide x application timing interaction was present for visual control ($P = <0.0001$) and BR ($P = <0.0001$). When averaged across all herbicide treatments, control of Italian ryegrass with the early, middle and late spring timing was 77, 68, and 79%, respectively (data not shown). However, BR in response to the early, middle, and late spring timings was 83, 77, and 58%, respectively (data not shown). Therefore, timing can have a major impact on the amount of biomass remaining on the soil surface, but it is still possible to achieve effective visual control of Italian ryegrass with certain treatments at late spring application timings.

Glyphosate at 1.4 and 2.8 kg ae ha^{-1} provided greater than 80% Italian ryegrass control across all three timings, but the 2.8 kg ha^{-1} rate provided greater control than the 1.4 kg ha^{-1} rate at the mid and late timings (Table 3.7). The 1.4 kg ha^{-1} rate of glyphosate also provided better Italian ryegrass control than 0.84 kg ha^{-1} glyphosate at the mid and late application timings. Although 2.8 kg ha^{-1} glyphosate provided the most consistent control of Italian ryegrass (91 to 98%), a single application of glyphosate at this rate would exceed that allowed by the label (Anonymous 2007). These results indicate that1.4 kg ha^{-1} glyphosate is needed to achieve consistent control of Italian ryegrass across application timings. Lins et al. (2007) also reported that 1.6 kg ha^{-1} glyphosate is needed to achieve consistent control of Italian ryegrass.

The addition of 0.136 kg ha^{-1} clethodim to 1.4 kg ha^{-1} glyphosate increased Italian ryegrass control compared to the same rate of glyphosate alone when applied at the mid and late application timing (Table 3.7). Glyphosate + clethodim at 1.4 kg ha^{-1} + 0.136 kg ha^{-1} and glyphosate at 2.8 kg ha^{-1} were the only two herbicide treatments to provide >90% control across all three timings. These results are similar to Nandula et al. (2007) who showed at least 98% control of 8- to 20-cm Italian ryegrass following 0.14 kg ha^{-1} clethodim. At the early and mid-timing, 1.4 and 2.8 kg ha^{-1} glyphosate and 1.4 kg ha^{-1} glyphosate + clethodim at 0.085 and 0.136 kg ha^{-1} provided similar BR levels that ranged from 84 to 93% (Table 3.7). At the late timing, there were also no differences in BR between these herbicide treatments. At the early timing, none of the herbicides that were added to 1.4 kg ha^{-1} glyphosate increased Italian ryegrass control compared to 1.4 kg ha^{-1} glyphosate alone. However, at the mid timing both rates of clethodim increased control compared to 1.4 kg ha^{-1} alone, while only 0.136 kg ha^{-1} clethodim increased control compared to 1.4 kg ha^{-1} glyphosate alone at the late timing.

Paraquat based herbicide programs did not provide consistent control of Italian ryegrass (Table 3.7). At the early and mid-timing, Italian ryegrass control with paraquat-containing herbicide treatments was inconsistent and ranged from 52 to 72%. However, at the late timing, paraquat + metribuzin + 2,4-D and paraquat + metribuzin + dicamba provided 84 and 87% control, respectively. The variable response observed from paraquat-containing treatments is contrary to results presented by Nandula et al. (2007) who observed at least 98% control of 8- to 20-cm Italian ryegrass with 0.70 and 0.98 kg ha^{-1} paraquat. Glufosinate and glufosinate + atrazine also did not provide consistent Italian ryegrass control (Table 3.7). At all three timings, glufosinate and glufosinate + atrazine provided between 14 and 41% control of Italian ryegrass. In addition, BR did not exceed 52% at all three timings following either herbicide treatment.

The results from these experiments indicate that application timing and proper herbicide selection are essential for effective termination of various cover crop species. Although herbicide application timing was important for several herbicide treatments, there were also certain treatments that provided similar levels of control across timings. Specifically, broadleaf cover crops such as crimson clover, hairy vetch, and Austrian winter pea were more consistently controlled when glyphosate was tank mixed with 2,4-D, dicamba, or saflufenacil. Increasing the rate of glyphosate to 2.8 kg ha^{-1} and tank mixing glyphosate and clethodim also proved to be the most effective herbicide treatment for termination of Italian ryegrass, regardless of application timing. Cover crop users list multiple reasons for adopting these species in their rotations, but one common expectation is some level of weed control from the cover crop residue (SARE 2014). It is also widely accepted that increasing amounts of residue are directly correlated to higher levels of weed control. These results prove it is possible to achieve adequate levels of control at late spring application timings while still accumulating high levels of residue.

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Table 3.1. Monthly rainfall (mm) and average monthly temperatures (C) in comparison to the 30-yr average in 2012 through 2015 at the Bradford Research Center in Columbia, Missouri.

	Rainfall					Temperature				
Monthly	2012	2013	2014	2015	30 yr avg.	2012	2013	2014	2015	30 yr avg.
	mm					C				
January	26	61	23	24	56	1	1	-4	0	-1
February	55	98	35	36	63	3	1	-4	-4	2
March	113	84	31	39	81	14	4	5	8	8
April	171	188	210	84	114	14	12	13	14	14
May	25	249	78	144	138	21	18	19	19	18
June	39	52	129	192	132	24	23	23	24	24
July	18	62	37	213	115	29	24	23	25	26
August	49	48	75	80	114	25	24	25	23	25
September	46	62	156	29	109	20	22	19	20	21
October	68	72	259	25	85	13	14	14	14	14
November	25	37	34	--	105	8	6	4	--	8
December	42	43	56	--	64	4	-1	3	--	1

[a] 30-yr averages (1981-2010) obtained from National Climatic Data Center (2011).

Table 3.2. Sources and rates of chemicals used in the multi-species experiment.

Herbicide[a]	Trade Name	Rate	Formulation	Manufacturer	Address
		kg ai or ae ha^{-1}			
Atrazine	Aatrex	1.12	4 L	Syngenta	Greensboro, NC
Paraquat	Gramoxone Inteon	1.12	2 L	Syngenta	Greensboro, NC
Glyphosate	Roundup PowerMax	1.12	4.5 L	Monsanto	St. Louis, MO
Dicamba	Clarity	0.56	4 L	BASF	Research Triangle, NC
2,4-D Ester	Lo-Vol 4	0.56	4 L	Tankoz, Inc	Alpharetta, GA
Saflufenacil	Sharpen	0.025	2.85 L	BASF	Research Triangle, NC
Chlorimuron + Metribuzin	Canopy	0.14 + 0.023	75 WG	DuPont	Wilmington, DA
Ammonium Sulfate	N-Pak AMS	2.9	3.4 L	Winfield Solutions	St. Paul, MN
Crop Oil Concentrate	Relay	0.35 L ha^{-1}	100L	Van Diest Supply	Webster City, IA
Non-Ionic Surfactant	Astute	0.35 L ha^{-1}	100 L	MFA	Columbia, MO

[a] Abbreviations: L, liquid; WG, water-dispersible granule.

Table 3.3. Height of cover crops and dates of herbicide application at the early and late spring application timing in 2013, 2014, and 2015.

Cover crop	Year, Application Timing and Date					
	2013		2014		2015	
	Early (April 5)	Late (May 1)	Early (April 15)	Late (May 9)	Early (April 4)	Late (April 28)
	---cm---					
Winter wheat	15-25	48-58	12-22	40-51	18-26	42-50
Cereal rye	25-35	93-114	22-30	80-95	26-45	88-109
Italian ryegrass	10-15	27-50	8-16	21-40	12-18	20-41
Crimson clover	10-15	22-30	13-19	25-35	11-16	21-32
Hairy vetch	10-18	20-31	11-17	25-38	13-19	26-34
Austrian winter pea	8-13	15-30	6-15	20-26	8-15	22-33

Table 3.4. Sources of chemicals used in the Italian ryegrass experiment.

Herbicide[a]	Trade Name	Formulation	Manufacturer	Address
Metribuzin	Sencor	75 DF	Bayer CropScience	Research Triangle Park, NC
Atrazine	Aatrex	4 L	Syngenta	Greensboro, NC
Paraquat	Gramoxone Inteon	2 L	Syngenta	Greensboro, NC
Glufosinate	Liberty	280 SC	Bayer CropScience	Research Triangle Park, NC
Glyphosate	Roundup PowerMax	4.5 L	Monsanto	St. Louis, MO
Dicamba	Clarity	4 L	BASF	Research Triangle, NC
2,4-D Ester	Lo-Vol 4	4 L	Tankoz, Inc	Alpharetta, GA
Saflufenacil	Sharpen	2.85 L	BASF	Research Triangle, NC
Clethodim	Select Max	0.97 L	Valent	Walnut Creek, CA
Chlorimuron + Metribuzin	Canopy	75 WG	DuPont	Wilmington, DA
Rimsulfuron + thifensulfuron	Basis Blend	75 WG	DuPont	Wilmington, DA
Crop Oil Concentrate	Relay	100L	Van Diest Supply Co.	Webster City, IA
Ammonium Sulfate	N-Pak AMS	3.4 L	Winfield Solutions	St. Paul, MN
Non-Ionic Surfactant	Astute	100 L	MFA	Columbia, MO

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

Table 3.5. Height of Italian ryegrass and dates of herbicide application at the early, mid, and late spring herbicide timing in 2013, 2014, and 2015.

Year, Timing, and Date of Application								
2013			2014			2015		
Early (Apr. 4)	Mid (Apr. 22)	Late (May 16)	Early (Apr. 17)	Mid (May 9)	Late (May 22)	Early (Mar. 31)	Mid (Apr. 23)	Late (May 12)
----------cm----------								
15-20	35-50	76-91	12-19	31-49	73-88	17-23	29-46	70-89

Table 3.6. Influence of herbicide treatments on the visual control of various cover crop species 28 DAA in 2013, 2014 and 2015.

	Cover Crop Species											
	Winter Wheat		Cereal Rye		Italian Ryegrass		Crimson Clover		Hairy Vetch		Austrian Winter Pea	
Herbicide	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late
	% Control											
Glyphosate	94	94	98	87	92	84	77	90	73	57	93	74
Glyphosate + 2,4-D	95	76	98	88	98	80	92	84	100	84	96	84
Glyphosate + Dicamba	94	82	98	87	92	79	92	78	99	88	98	94
Glyphosate + Saflu	95	89	98	82	96	93	92	95	69	70	92	88
Glyphosate + Atrazine	91	65	85	89	89	77	81	74	71	57	94	80
Gly + Chlor + Metri	85	85	77	91	90	80	79	73	57	76	82	96
Paraquat	66	48	57	70	68	53	69	100	54	64	71	91
Paraquat + 2,4-D	65	58	58	72	58	56	76	92	89	86	91	91
Paraquat + Atrazine	89	74	70	78	80	61	90	92	81	79	90	95
LSD (0.05):	5											

[a] Abbreviations: DAA, days after application; Saflu, saflufenacil; Chlor, chlorimuron; Metri, metribuzin.

Table 3.7. Influence of herbicide treatments on the biomass reduction of various cover crop species 28 DAA in 2013, 2014 and 2015.

	Cover Crop Species											
	Winter Wheat		Cereal Rye		Italian Ryegrass		Crimson Clover		Hairy Vetch		Austrian Winter Pea	
Herbicide	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late
	% Biomass reduction											
Glyphosate	82	70	81	69	90	82	82	78	68	70	85	94
Glyphosate + 2,4-D	84	72	86	66	85	79	88	71	97	94	98	80
Glyphosate + Dicamba	85	77	84	71	87	81	94	68	99	89	100	94
Glyphosate + Saflu	83	67	86	75	86	88	99	83	86	79	85	87
Glyphosate + Atrazine	86	68	88	68	87	81	87	75	71	84	87	88
Gly + Chlor + Metri	81	72	83	65	91	85	92	67	74	84	88	93
Paraquat	75	71	77	73	72	80	86	90	68	86	87	92
Paraquat + 2,4-D	72	71	76	72	75	65	92	92	98	91	96	97
Paraquat + Atrazine	77	69	88	70	89	79	97	87	79	94	82	87
LSD (0.05):	10											

[a] Abbreviations: DAA, days after application; Saflu, saflufenacil; Chlor, chlorimuron; Metri, metribuzin.

Table 3.8. Influence of herbicide programs on Italian ryegrass biomass reduction and visual control 28 DAA in 2013, 2014 and 2015.

	Rate	Visual Control			Biomass Reduction		
Herbicide[a]	kg ai or ae ha^{-1}	Early	Mid	Late	Early	Mid	Late
		---------------	---------------	---%	---------------	---------------	---------------
Glyphosate	0.84	85	62	70	82	78	47
Glyphosate	1.4	92	81	87	89	86	63
Glyphosate	2.8	98	91	96	91	84	72
Glyphosate + Clethodim	1.4 + 0.085	99	91	88	90	93	69
Glyphosate + Clethodim	1.4 + 0.136	99	98	98	90	84	64
Glyphosate + 2,4-D	1.4 + 0.56	94	81	89	90	78	54
Glyphosate + Saflufenacil	1.4 + 0.025	95	79	91	90	83	61
Glyphosate + Atrazine	1.4 + 1.12	83	71	74	89	78	53
Glyphosate + Metribuzin + Chlorimuron	1.4 + 0.18 + 0.03	85	66	77	89	77	50
Glyphosate + Rimsulfuron + Thifensulfuron	1.4 + 0.018 + 0.0088	94	86	91	81	77	56
Glyphosate + Dicamba	1.4 + 0.56	91	64	87	88	71	53
Paraquat + Metribuzin + 2,4-D	1.12 + 0.21 + 0.56	69	65	84	89	82	64
Paraquat + Metribuzin + Dicamba	1.12 + 0.21 + 0.56	72	60	87	90	82	69
Paraquat	1.12	56	53	78	79	73	55
Paraquat + 2,4-D	1.12 + 0.56	63	52	78	86	77	57
Paraquat + Atrazine	1.12 + 1.12	68	64	74	88	79	67
Glufosinate	0.56	14	27	41	29	44	45
Glufosinate + Atrazine	0.56 + 1.12	21	29	34	56	52	50
LSD (0.05):		---------------7------------			-------------9--------------		

[a] Abbreviations: DAA, days after application.

Chapter IV

Influence of Various Cover Crop Species on Winter and Summer Annual Weed Emergence in Soybean

Cody D. Cornelius and Kevin W. Bradley

Abstract

Field experiments were conducted in 2013, 2014, and 2015 in Columbia and Moberly, Missouri to determine the effects of cereal rye, Italian ryegrass, winter wheat, winter oat, crimson clover, Austrian winter pea, hairy vetch, tillage radish and cereal rye plus hairy vetch on winter and summer annual weed emergence in soybean. For comparison purposes, each experiment included a Fall PRE, Spring PRE w/o residual, and Spring PRE residual herbicide programs. Cereal rye and cereal rye plus hairy vetch reduced winter annual weed emergence by 72 and 68%, but were not comparable to the Fall PRE which reduced winter annual weed emergence by 99%. Early season waterhemp emergence was similar among treatments of cereal rye, cereal rye plus hairy vetch, and the Spring PRE residual herbicide program. In contrast, cereal rye, cereal rye + hairy vetch, winter wheat, winter oat, crimson clover, Austrian winter pea, hairy vetch, and tillage radish reduced late season waterhemp emergence between 21 and 40%, but were not comparable to the Spring PRE residual herbicide program, which reduced late season waterhemp emergence by 97%. All other summer annual weeds excluding waterhemp showed a similar response among cover crop and herbicide treatments. Overall, results from this experiment indicate that certain cover crops are able to suppress

winter and summer annual weed emergence, but soil applied residual herbicides provide more consistent control.

Introduction

In recent years cover crops have become increasingly common in the Midwestern United States. Several species, such as Italian ryegrass [*Lolium perenne* L. *ssp. multiflorum (Lam.) Husnot*], barley (*Hordeum vulgare* L.), winter oat (*Avena sativa* L.), cereal rye (*Secale cereal* L.), winter wheat (*Triticum aestivum* L.), hairy vetch (*Vicia vilossa* L.), and various clovers (*Trifolium* spp.) have been identified for their utility as cover crops and are being widely recommended (Johnson et al. 1998; Kuo et al. 1997; Teasdale and Mohler 1993; Weston 1990). Cover crops offer several agronomic benefits such as reducing soil erosion, reducing water runoff, improving water infiltration, increasing soil moisture retention, increasing soil tilth, and increasing organic carbon and nitrogen (Mallory et al. 1998; Sainju and Singh 1997; Teasdale 1996; Varco et al. 1999; Yenish et al. 1996). However, according to a recent SARE survey (2014), farmers planting cover crops ranked weed control as the fourth highest reason for adopting them on their operation. Although numerous studies have proven certain agronomic reasons for planting a cover crop in a corn and soybean rotation, there is still the need to quantify what level of weed control to expect following various winter annual cover crops.

Cover crop residues have the ability to suppress weed growth by releasing allelopathic volatile chemicals into the weed rooting zone (Olofsdotter et al. 2002; Barnes and Putnam 1986; Burgos et al. 1999; White et al. 1989), by changing microclimatic conditions, and/or through the creation of a physical barrier created by cover crop mulches (Ateh and Doll 1996; Collins et al. 2007; Reddy 2001; Teasdale et al 1991;

Yenish et al. 1996; Teasdale and Moehler 2000). In addition, cover crops can reduce weed density by interacting as living plants, and when cover crops are able to be planted in this manner, they have a much higher weed suppressive potential than non-living cover crop residues (Teasdale et al. 2007). Throughout most of the United States, winter annual cover crops are planted in the fall and terminated the following spring prior to planting a cash crop of corn, cotton, or soybean. Under this scenario, the cover crops species will remain alive and will be in the most direct competition with winter annual weed species. For example, Hayden et al. (2012) reported that cereal rye and hairy vetch reduced winter annual weed biomass by 95 to 98% and 71 to 91%, respectively. Davis and Johnson (2008) found that horseweed (*Conyza canadensis*), which is typically classified as a winter annual, can emerge from October through early August; however, 90% of horseweed emergence occurred in the spring. Also, horseweed can be difficult to control in no-till production systems due to wide-spread glyphosate resistance and limited POST control options (Buhler and Owen 1997; Heap 2015). Previous research has shown that cereal rye and winter wheat can reduce horseweed emergence up to 90% and adding a residual herbicide such as flumioxazin can provide additional control (Christenson et al. 2014; Davis et al. 2007). Thus, it is widely accepted that certain winter annual cover crop species can have a substantial suppressive impact on winter annual weeds.

In a corn and soybean production system, summer annual weeds are responsible for the majority of the economic losses incurred because of their overlapping lifecycles. In the United States, crop production losses from weed competition are estimated to be as high as $33 billion annually (Pimentel et al. 2005). Therefore, the ability of cover crops to suppress summer annual weeds would be of great value in these systems. Webster et al. (2013) found that a cereal rye cover crop reduced palmer amaranth densities from 40 to 88% between cotton rows in a strip tillage system, but the aggressive growth of palmer amaranth (*Amaranthus pameri* S. Wats) within the cotton row still prevented the cotton from producing lint. Similarly, cereal rye reduced total weed biomass from 60 to 90% in a three year study where giant foxtail (*Setaria faberi* Herm.), common lambsquarters (*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* Medik), and Pennsylvania smartweed (*Polygonum pensylvanicum* L.) were the main weeds present (Ateh and Doll 1996). Teasdale and Moehler (1993) concluded that the suppressive potential of a cover crop declines as the amount of residue decreases. The level of summer annual weed control that can be achieved with cover crops is largely dependent on the species due to the fact that some cover crops produce more biomass than others. Also, those cover crops that have a faster rate of decomposition will result in lower levels of summer annual weed control later in the season as opposed to ones that decompose more slowly (Teasdale et al. 2007). Palmer amaranth control was less than 65% following cereal rye, winter wheat, crimson clover, hairy vetch, and cereal rye plus legume mixes; however, control increased to 87% or greater when acetochlor or fluometuron were applied in combination with these same species (Wiggins et al. 2016). Although a cover crops ability to control summer annual weeds decreases throughout the growing season, adding a residual herbicide can provide additional late season control.

Waterhemp (*Amaranthus tuburculatus)* is the most common and troublesome weed in Missouri, Illinois, Iowa and is a significant problem in many other areas in the Midwest (Webster 2013; Bradley et al. 2007; Hager et al. 2000; Legleiter and Bradley

2008; Rosenbaum and Bradley 2013; Waggoner and Bradley 2011). In addition, waterhemp can be extremely difficult to combat as a result of its extended period of emergence, rapid growth at high light intensities and temperatures, and prolific seed production (Hartzler et al. 1999; Jha et al. 2008; Massinga et al. 2003; Sauer 1957). Waterhemp in Missouri, Iowa, and Illinois has evolved resistance to 5-enolpryuvylshikimate-3-phosphate synthase (EPSPS)-, protoporphyrinogen oxidase (PPO)-, 4-hydroxyphenylpyruvate dioxygenase (HPPD)-, photosystem II-, and acetolactate synthase (ALS)-inhibiting herbicides, and one population in Missouri is also resistant to the synthetic auxins (Heap 2015; Schultz et al. 2015; Barlow et al. 2016). Kansas has documented waterhemp with resistance to EPSPS-, PPO-, photosystem II-, and ALS inhibitors, and Nebraska has documented waterhemp with resistance to synthetic auxins, EPSPS-, HPPD-, and photosystem II-inhibiting herbicides (Bernards et al. 2012; Heap 2014; Shoup et al. 2003). Due to waterhemp populations that exhibit resistance to multiple sites of action and its inherent ability to germinate multiple times throughout the season (Horak and Loughin 2000; Sellers et al. 2003), currently one of the primary methods of waterhemp control in soybean production is through the application of pre-emergence (PRE), residual herbicides that act at multiple sites of action (Norsworthy et al. 2012).

To date, most of the research to determine the effects of cover crops on weed control has been conducted with only a few species, such as cereal rye and hairy vetch, and has often been done in organic-based systems where the use of herbicides for cover crop termination is prohibited. Additionally, there is little published research that shows the effects of cover crops on waterhemp emergence throughout the season. The objective of this research is to determine the effects of eight winter annual cover crop species on winter and summer annual weed emergence in soybean.

Materials and Methods

Site Description. Field experiments were conducted in 2013 and repeated in 2014, and 2015 in Boone County at the University of Missouri Bradford Research Center near Columbia, Missouri (38˚53'53.22"N, 92˚22'14.42"W), and in Randolph County near Moberly, Missouri (39˚18'10.29"N, 92˚22'14.42"W). Site selection was based on the presence of a variety of common summer annual grass and broadleaf weed species at the Columbia site and the presence of dense infestations of common waterhemp (*Amaranthus rudis* Sauer) that exhibited resistance to glyphosate, ALS-, and PPO- inhibiting herbicides at the Moberly site. The soil type at the Columbia site was a Mexico silt loam (fine, smectic, mesic Aeric Vertic Epiaqualfs) with 2.3% organic matter and a pH of 6.5 in 2013, 2.1% organic matter and pH of 6.4 in 2014, and 2.2% organic matter and pH of 6.3 in 2015. At the Moberly site, the soil was a Putnam silt loam (fine, smetitic, mesic Vertic Albaqualfs) with 2.2% organic matter and pH of 6.3 in 2013, 1.9% organic matter and pH of 6.3 in 2014, and 1.6% organic matter and pH of 6.0 in 2015. Both sites were upland areas with a clay pan soil. Monthly rainfall totals and average monthly temperatures are presented in Table 4.1. The dates of major field operations are shown in Table 4.2.The experiment was conducted in a randomized complete block design with 4 replications of every treatment at the Columbia location and with 5 replications at the Moberly location. Individual plots measured 3 x 14 m in size.

Eight winter annual cover crops were planted at the following seeding rates on September 11, 12, and 10 in 2013, 2014, and 2015, respectively: winter wheat at 135 kg ha^{-1}, cereal rye at 123 kg ha^{-1}, Italian ryegrass at 28 kg ha^{-1}, winter oat at 78 kg ha^{-1}, crimson clover (*Trifolium incarnatum* L.) at 34 kg ha^{-1}, Austrian winter pea (*Pisum sativum* L.) at 56 kg ha^{-1}, hairy vetch at 34 kg ha^{-1}, and tillage radish (*Raphanus sativus* L.) at 9 kg ha^{-1}. A mix of cereal rye plus hairy vetch mixture was also planted at 78 + 34 kg ha^{-1}. All cover crops were planted with a 750 no-till drill (Deere & Company, 1 John Deere Place, Moline, IL 61265) into fields that had previously been in soybean production. In order to compare the levels of winter and summer annual weed control provided by cover crops with current standards, three herbicide programs were evaluated on plots that did not have a cover crop planted. These consisted of: 1) a fall treatment of glyphosate at 0.86 kg ha^{-1} plus 2,4-D ester at 0.56 kg ha^{-1} plus sulfentrazone at 0.122 kg ha^{-1} plus chlorimuron-ethyl at 0.0157 kg ha^{-1}, referred to as the Fall herbicide program, 2) a spring pre-emergence (PRE) application of glyphosate at 1.72 kg ha^{-}plus 2,4-D ester at 0.56 kg ha-^{1} plus sulfentrazone at 0.098 kg ha^{-1} plus cloransulam-methyl at 0.01 kg ha^{-1} followed by a V2/V3 post-emergence (POST) application of fomesafen at 1.22 kg ha^{-1} plus *S*-metolachlor at 0.27 kg ha^{-1}, referred to as the Spring PRE residual herbicide program, and 3) a spring PRE application of glyphosate at 1.72 kg ha^{-}plus 2,4-D ester at 0.56 kg ha^{-1}, referred to as the Spring PRE w/o Residual herbicide program. Prior to soybean planting, all cover crops were terminated with an herbicide application of glyphosate at 1.72 kg ha^{-}plus 2,4-D ester at 0.56 kg ha-^{1}. The specific herbicide formulations utilized are listed in Table 4.3. Prior to termination, above ground cover crop biomass was harvested from each cover crop species within 3, 0.33 m^2 quadrats (Table 4.4). At each location and in all years, soybean (*Glycine max* L. ‘MorSoy 3759N LL’) with a glufosinate resistance trait was seeded at 370,000 seeds ha^{-1} in rows spaced

76 cm apart into a no-tillage seedbed. All herbicide treatments were applied with a CO_2-pressurized backpack sprayer equipped with XR8002 flat fan nozzle tips (TeeJet®, Spraying Systems Co., P.O. Box 7900, Wheaton, IL. 60187) calibrated to deliver 140 L ha^{-1} at 117 kPa. Treatments were applied at a constant speed of 5 km hr^{-1}. A non-treated control that contained no herbicide application or cover crop was also included for comparison.

Treatment Evaluation and Data Collection. Winter annual weed densities were determined by counting individual plants within two, 0.5 m^2 quadrats in the same location in each plot just prior to the spring herbicide applications each year. Summer annual weed emergence throughout the season was determined by counting all weeds within two 0.5 m^2 quadrats in the same location in each plot starting two weeks after cover crop termination and continuing every two weeks throughout the soybean growing season. The final count was conducted when soybean reached the R2 growth stage. After each count, glufosinate was applied at 0.41 kg ha^{-1} over the entire trial to eliminate any emerged weeds that were present during the previous two week period. As waterhemp was the predominant weed in all locations, the summer annual weed emergence data were separated into waterhemp and all other summer annual weeds other than waterhemp. Emergence data was also separated into an early- and late-season total which was differentiated by the total weed counts made before and after the POST application of fomesafen + *S*-metolachlor in the Spring PRE residual herbicide program.

Statistical Analysis. All data were analyzed using the PROC GLIMMIX procedure in SAS (SAS 9.3, SAS® Institute Inc. Cary, NC). Environments and replications (nested within environments) were considered random effects, and herbicide treatments and cover crop species were considered fixed effects. Considering year as a random effect in the model allows inferences about treatments over a wide range of environments (Blouin et al. 2011; Carmer et al. 1989). Individual treatment differences were detected using Fisher's Protected LSD at $P \leq 0.05$.

Results and Discussion

Winter Annual Weed Emergence. Several cover crop species provided a significant reduction in winter annual weed emergence (Figure 4.1). The cover crop species evaluated in this research reduced winter annual weed emergence between 23 and 72% relative to the non-treated control. However, the fall herbicide program provided a 99% reduction in winter annual weed emergence which was greater than that provided by any cover crop. Cereal rye and cereal rye plus hairy vetch provided higher reductions (68-72%) in winter annual weed emergence than any other cover crop species evaluated. The ability of cereal rye or cereal rye plus legume mixes to reduce winter annual weed emergence has been reported elsewhere (Teasdale and Moehler 1993; Hayden et al. 2012; Teasdale 2007). Hayden et al. (2012) showed up to an 89% reduction in winter annual weed emergence with a cereal rye plus hairy vetch cover crop mix. Living cereal rye is known to exude phytotoxic allelopathic compounds that are broadly defined as benzoxazinones, but more specifically DIBOA and its breakdown product BOA (Barnes et al. 1987). Two other compounds, β-phenylactic acid (PLA) and β-hydroxybutyric acid (HBA) also have been identified from cereal rye extracts as having allelopathic properties (Shilling et al. 1985), but other studies have shown that DIBOA and BOA were more of a contributor to seedling growth suppression than PLA and HBA (Barnes and Putnam 1987). These compounds accumulate in the tissue at varying degrees depending on environment, growth stage, and cultivar which likely contributes to the level of winter annual weed suppression observed in this research (Tabaglio et al. 2013; Barnes and Putnam 1986). Relative to cereal rye and cereal rye plus hairy vetch, Italian ryegrass and winter wheat provided the next highest level of winter annual weed reduction at 53 and 50%, respectively. Austrian pea, hairy vetch, crimson clover, tillage radish, and winter oat all provided similar levels of winter annual weed reduction, which ranged from 23 to 36%. The lower suppressive potential observed from leguminous compared to cereal grain cover crops is consistent with results from Putnam and Duke (1978), who reported that leguminous cover crops produce allelopathic compounds in much smaller amounts than cereal grains. Winter oat and tillage radish were not able to overwinter in our experiments (Table 4.3), which explains why winter annual weed density was higher in these treatments compared to the other species evaluated. However, both species reduced winter annual weed emergence compared to the non-treated control; more than likely due to direct competition with fall-emerging winter annual weed species. In addition, *Brassica* species, like tillage radish are known to produce glucosinolates that are released once plant tissue begins to decompose (Brown and Morra 1996). Therefore, in climates where tillage radish is not able to overwinter, its greatest potential for weed suppression may not be fully realized because decomposition occurs at a time when there is little or no weed emergence. In this research, we attribute the higher level of winter annual weed suppression with cereal rye, winter wheat, and Italian ryegrass compared to Austrian pea, hairy vetch, crimson clover, tillage radish, and winter oat to: faster emergence and growth, better winter hardiness, greater percent ground cover, and most likely higher levels of allelopathic compounds like benzoxazinones.

Waterhemp Emergence. Cereal rye reduced early-season waterhemp emergence by 35% relative to the non-treated control and was similar to the level of reduction provided by the Spring PRE residual and Fall herbicide programs which both reduced early-season waterhemp emergence by 26% (Figure 4.2). All other cover crop species did not significantly reduce early season waterhemp emergence relative to the non-treated control. In contrast, Austrian pea, hairy vetch, crimson clover, tillage radish and winter oat increased early season waterhemp emergence by 36, 31, 28, 28 and 22%, respectively. Legume cover crops such as Austrian winter pea, hairy vetch and crimson clover biologically fix atmospheric nitrogen that subsequently becomes available during residue decomposition (Sainju and Singh 1997; Varco et al. 1999). Thus, the increased waterhemp emergence in these cover crop treatments is likely because of greater soil nitrogen availability. As previously reported, tillage radish and winter oat were not able to overwinter, which resulted in less residue on the soil surface to impede waterhemp germination (Table 4.3). In addition, the non-treated control had more ground cover as a result of dense winter annual weed cover (236 m^{-2}) in comparison to tillage radish and winter oat (Table 4.3). Italian ryegrass, winter wheat, cereal rye plus hairy vetch, and the Spring PRE w/o residual herbicide program each resulted in early-season waterhemp emergence similar to the non-treated control. In the case of late-season waterhemp emergence, cereal rye provided a 40% reduction, but neither cereal rye nor any other winter cover crop was comparable to the Spring PRE residual herbicide program, which provided a 97% reduction in late-season waterhemp emergence (Figure 4.3). Although cereal rye provided some reduction in late-season waterhemp emergence, it was statistically similar to that provided by all other cover crops except Italian ryegrass.

Compared to the residual herbicide treatments, cereal rye exhibited a similar level of waterhemp suppression early in the soybean growing season, but the suppressive potential decreased as the season progressed. These results are similar to those from Webster et al. (2013), who showed that Palmer amaranth densities increased by 43% from early June to late July within plots that contained a cereal rye cover crop.

Summer Annual Weed Emergence Excluding Waterhemp. There were few cover crop species that reduced early- or late-season summer annual weed emergence to the same degree as the residual herbicide treatments, and overall the trends were similar to that observed with waterhemp (Figures 4.4 and 4.5). Cereal rye and cereal rye plus hairy vetch reduced early-season summer annual weed emergence by 41 and 24%, respectively, which was similar to that provide by the Spring PRE residual and Fall herbicide programs. In contrast to waterhemp, the only cover crop that increased summer annual weed emergence compared to the non-treated control was Austrian winter pea, which increased early-season summer annual weed emergence by 22%, which may be due to a nitrogen contribution as explained previously. Italian ryegrass, winter oat, tillage radish, crimson clover, and hairy vetch all resulted in early-season summer annual weed emergence similar to the non-treated control. Much like what was observed with waterhemp, late-season summer annual weed emergence was reduced by 42% in response to cereal rye, but did not compare to the Spring PRE residual herbicide program, which reduced late-season summer annual weed emergence by 93%. Winter wheat, cereal rye plus hairy vetch, Italian ryegrass, winter oat, tillage radish, crimson clover, and hairy vetch each resulted in late-season summer annual weed emergence that was similar to the non-treated control.

These results indicate that cereal rye, Italian ryegrass, winter wheat, winter oat, crimson clover, Austrian winter pea, hairy vetch, tillage radish and cereal rye plus hairy vetch are each able to provide some degree of winter annual weed suppression, but that only certain cover crop species such as cereal rye or cereal rye plus legume mixes are able to provide reductions in early-season summer annual weed emergence similar to a residual herbicide programs. In addition, no cover crops were able to reduce late season weed emergence to the same degree as a residual herbicide program. Teasdale and Moehler (1993) found that residue from cereal rye decomposes slower than leguminous cover crops such as hairy vetch. Therefore, the higher level of weed suppression observed with cereal rye may be at least partially due to a higher persistence of residue into the soybean growing season compared to other cover crop species. Cereal rye also provided some degree of late-season waterhemp and other summer annual weed suppression, but there is a need for the integration of additional management strategies to combat late season weed flushes. Therefore, additional research is needed to determine if integrating high residue cover crops, with residual herbicides will provide greater weed control than each system does individually.

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Table 4.1. Monthly rainfall (mm) and average monthly temperatures (C) in comparison to the 30-yr average in 2012 through 2015 at the Bradford Research Center in Columbia and Moberly, Missouri.

	Rainfall					Temperature				
Month and Location	2012	2013	2014	2015	30 yr. avg.	2012	2013	2014	2015	30 yr. avg.
	--------------------mm------------------					---------------------C------------------				
Columbia										
January	26	61	23	24	56	1	1	-4	0	-1
February	55	98	35	36	63	3	1	-4	-4	2
March	113	84	31	39	81	14	4	5	8	8
April	171	188	210	84	114	14	12	13	14	14
May	25	249	78	144	138	21	18	19	19	18
June	39	52	129	192	132	24	23	23	24	24
July	18	62	37	213	115	29	24	23	25	26
August	49	48	75	80	114	25	24	25	23	25
September	46	62	156	29	109	20	22	19	20	21
October	68	72	259	--	85	13	14	14	--	14
November	25	37	34	--	105	8	6	4	--	8
December	42	43	56	--	64	4	-1	3	--	1
Moberly										
January	13	73	12	21	49	0.4	-1	-6	-2	-2
February	40	94	34	44	53	3	-1	-6	-5	0
March	126	81	17	59	75	13	1	3	6	6
April	126	231	156	65	104	13	10	12	14	13
May	77	167	64	119	131	20	17	18	19	18
June	57	82	141	299	130	23	22	23	22	22
July	36	36	92	223	122	28	23	22	25	25
August	9	32	120	73	106	24	23	24	23	24
September	141	57	64	20	110	18	21	19	22	19
October	113	100	203	--	84	12	13	13	--	13
November	57	58	38	--	74	7	4	3	--	6
December	37	34	45	--	60	3	-3	2	--	-0.4

[a] 30-yr averages (1981-2010) obtained from National Climatic Data Center (2011).

Table 4.2. Dates of major field operations.

	Year and Date of Operation			
Field operation	2012	2013	2014	2015
Cover crop seeding date	9/11	9/12	9/11	---
Soybean seeding date		6/12	5/21	5/4
Dates of herbicide application				
Fall PRE herbicide program	11/14	11/19	11/20	---
Spring PRE residual herbicide program	---	4/15 fb[a] 7/12	4/9 fb 6/18	4/8 fb 5/28
Spring PRE without residual herbicide program		4/25	5/2	4/23
Dates of cover crop termination		4/25	5/2	4/23

[a] Abbreviations: fb, followed by.

Table 4.3. Sources of materials used in the experiment

Herbicide[a]	Trade Name	Formulation	Manufacturer	Address
Sulfentrazone + cloransulam	Authority First	0.7 WG	FMC Corporation	Philadelphia, PA
Sulfentrazone + chlorimuron	Authority XL	0.7 WG	FMC Corporation	Philadelphia, PA
Fomesafen + *S*-metolachlor	Prefix	5.92 L	Syngenta	Greensboro, NC
Glufosinate	Liberty	2.3 L	Bayer CropScience	Research Triangle Park, NC
Glyphosate	Roundup Powermax	4.5 L	Monsanto	St. Louis, MO
2,4-D ester	LO-VOL 4	4 L	Tankoz, Inc	Alpharetta, GA
Ammonium sulfate	N-Pak AMS	3.4 L	Winfield Solutions	St. Paul, MN

[a] Abbreviations: WG, water-dispersible granule; L, liquid.

Table 4.4. Above ground biomass (kg ha^{-1}) and height (cm) of cover crop species at the time of termination in Columbia and Moberly Missouri.

	Columbia								Moberly			
	Dry weight				Height				Dry weight		Height	
Species	2013	2014[a]	2014b[a]	2015	2013	2014a[a]	2014b[a]	2015	2014	2015	2014	2015
	-------------kg ha^{-1}---------------				-------------------cm-------------------				----kg ha^{-1}---		--------cm--------	
Wheat	1431	1845	1152	804	20-28	25-32	18-24	25-30	1056	2253	20-30	20-30
Cereal rye	2892	2445	1941	1149	55-60	48-54	50-55	35-50	1386	3930	65-75	40-55
Italian ryegrass	1179	873	384	768	15-20	8-12	5-8	18-24	282	2232	15-25	25-34
Winter oat	612	102	96	0	10-15	5-10	4-6	0	0	0	0	0
Crimson clover	318	339	348	1074	12-18	8-12	10-15	28-34	0	534	0	20-25
Hairy vetch	1356	1527	270	165	12-16	25-35	5-9	15-25	6	1566	5-8	20-30
Cereal rye/ Hairy vetch	2481	2712	1554	3015	50-60/ 20-30	65-75/ 22-32	40-50/ 15-20	45-60/ 20-26	1839	5040	75-85/ 8-15	45-55/ 14-21
Austrian winter pea	915	273	81	0	15-22	10-15	5-8	0	0	66	0	12-17
Tillage radish	0	0	0	0	25-32	0	0	0	0	0	0	0

[a] Two separate trials were conducted in Columbia in 2014.

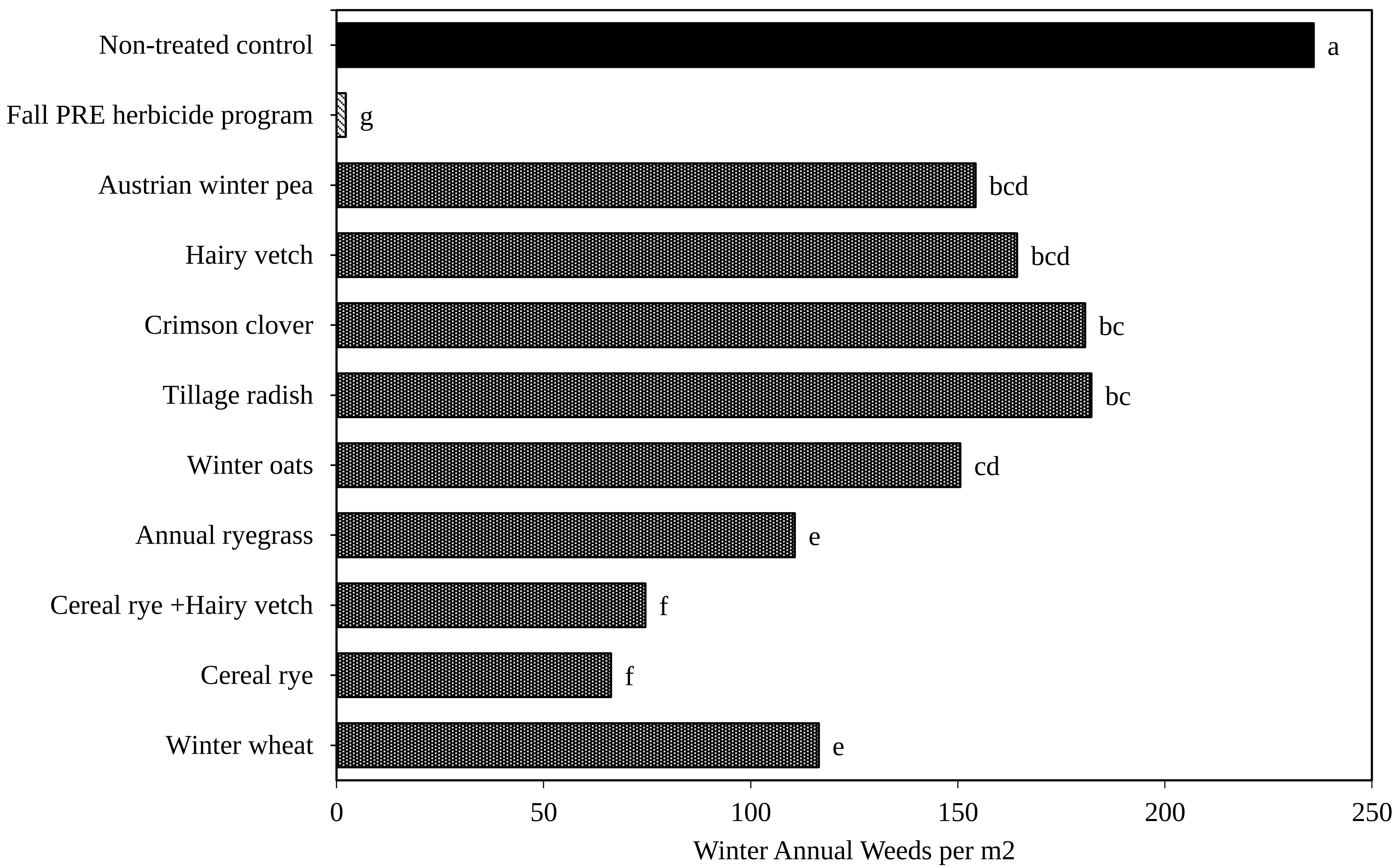

Figure 4.1. Influence of cover crops and herbicide treatments on total winter annual weed density across eight site years in Missouri.

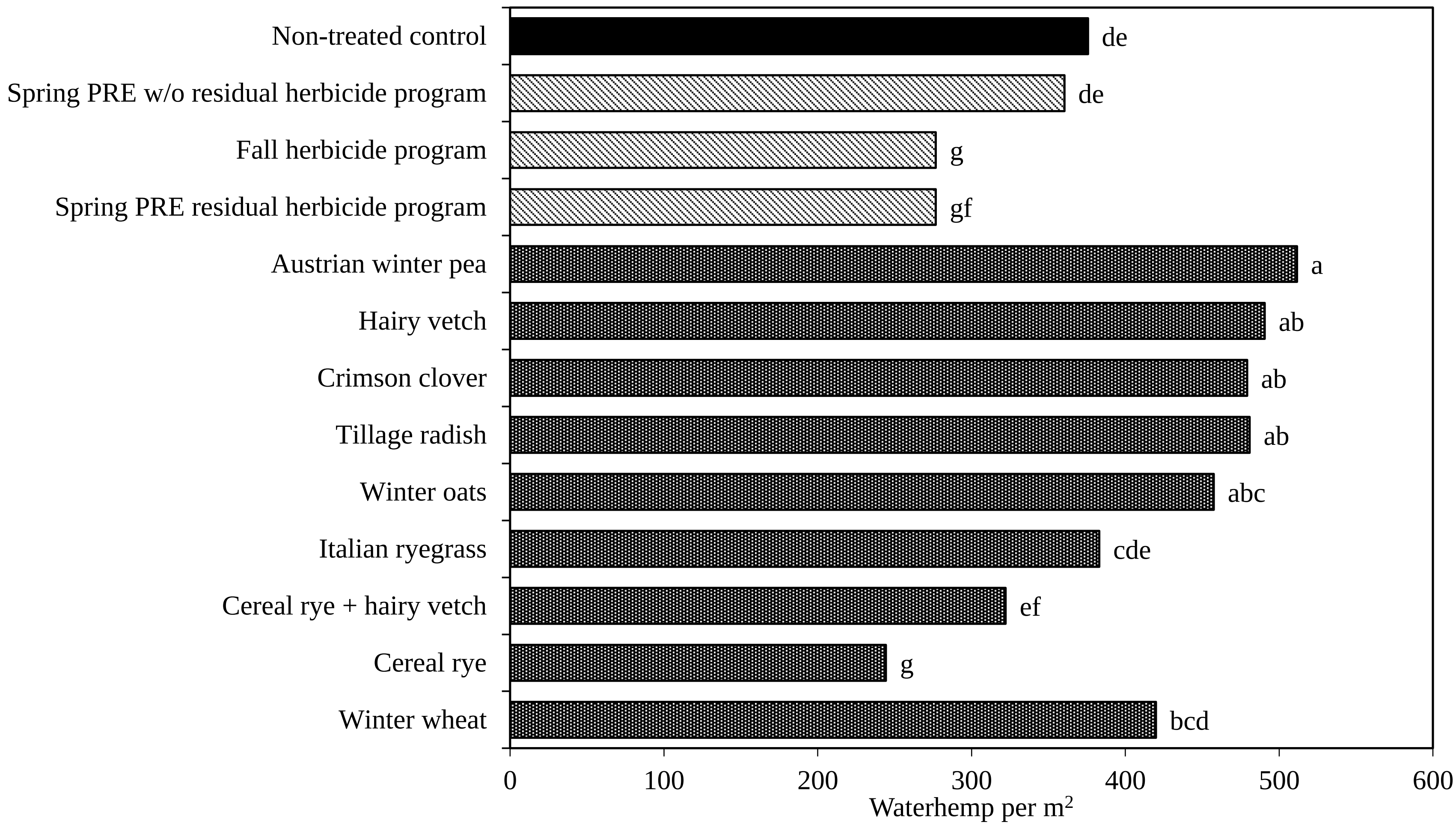

Figure 4.2. Influence of cover crops and herbicide treatments on early season waterhemp emergence across eight site years in Missouri.

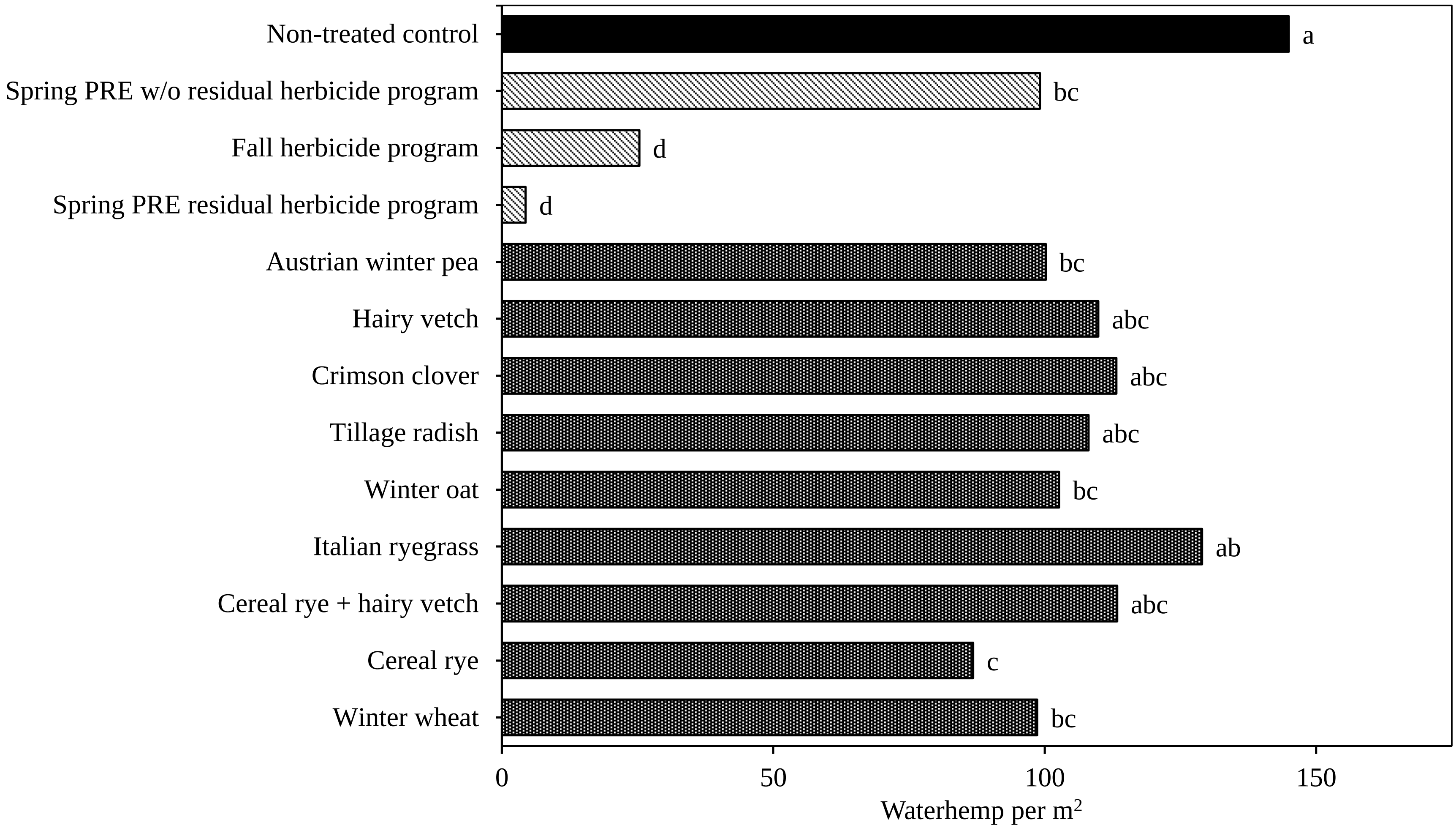

Figure 4.3. Influence of cover crops and herbicide treatments on late season waterhemp emergence across eight site years in Missouri.

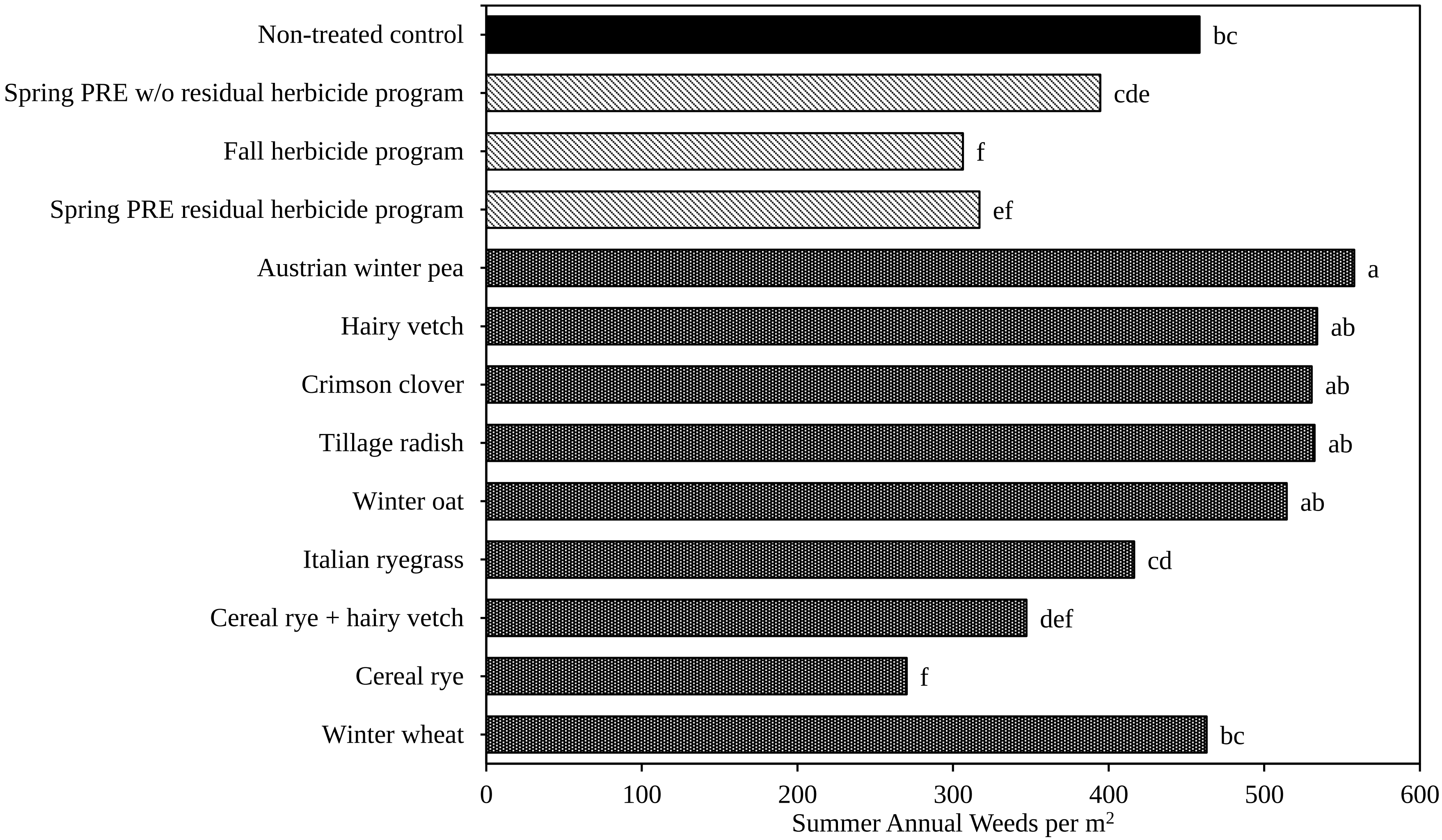

Figure 4.4. Influence of cover crops and herbicide treatments on early season summer annual weed emergence, excluding waterhemp, across eight site years in Missouri.

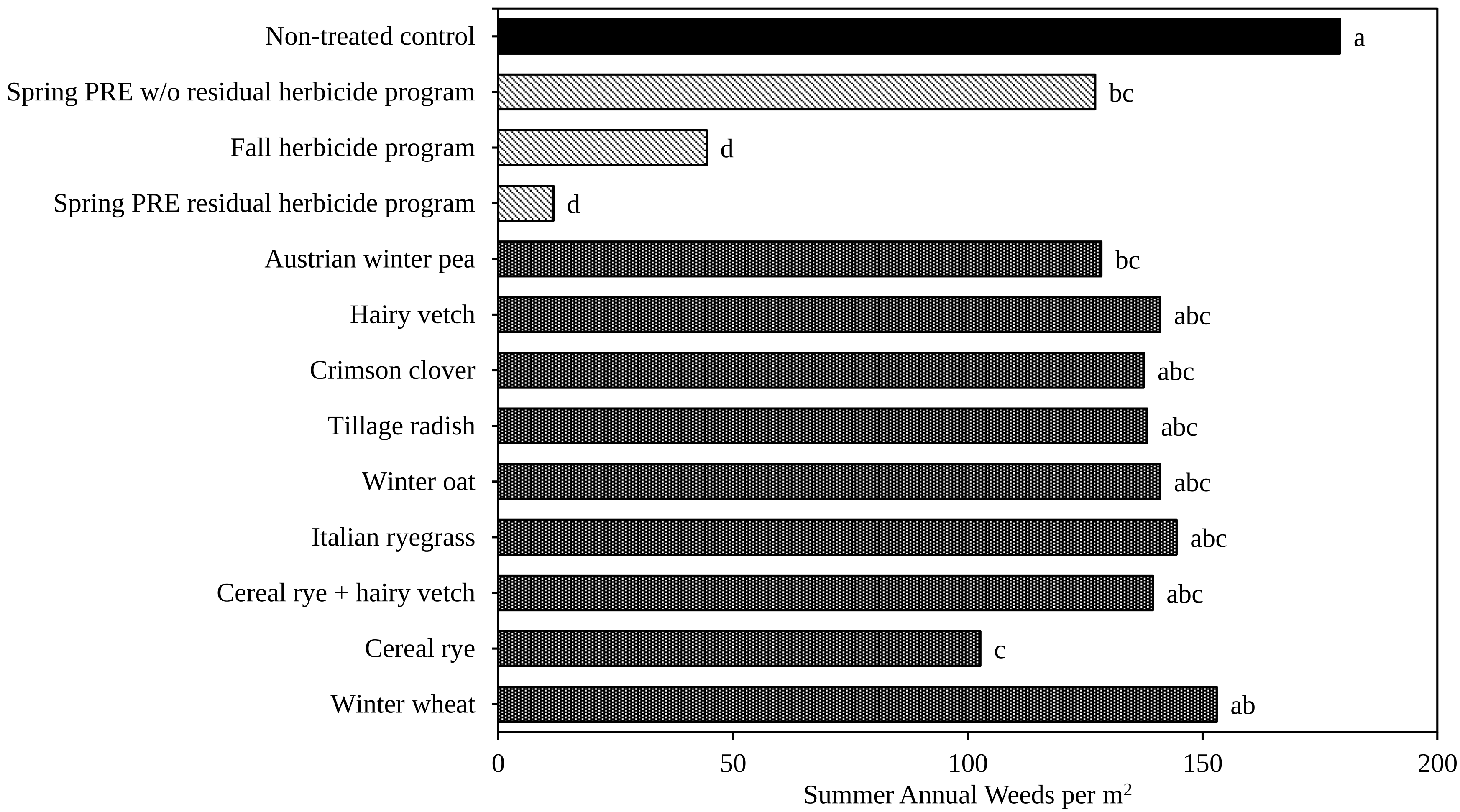

Figure 4.5. Influence of cover crops and herbicide treatments on late season summer annual weed emergence, excluding waterhemp, across eight site years in Missouri.