Interactions between cover crops and weed management in Iowa's conventional cropping systems

by

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ABSTRACT

The effect of different levels of cereal rye (*Secale cereale* L.) residue on common waterhemp (*Amaranthus rudis* Sauer) and common lambsquarters (*Chenopodium album* L.) emergence was determined. Cereal rye seeding date had a greater effect on rye biomass accumulation and percent cover than seeding rate. Common waterhemp emergence was equal to or increased in the presence of cereal rye residue in both 2013 and 2014 compared to the control. Common lambsquarters emergence was increased in two treatments in 2014 but was otherwise unaffected by cereal rye. The presence of cereal rye residue increased the time to 10% and 50% emergence of common waterhemp in both years but had less effect on common lambsquarters. The lack of weed emergence suppression seen in these experiments is a concern for cover crop use in Iowa's conventional cropping systems, while the delay in weed emergence associated with cereal rye residue may be beneficial or detrimental to weed management. Greenhouse trials determined the soil activity of low rates of eleven corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] herbicides on five cover crops: cereal rye (*Secale cereale* L.), oat (*Avena sativa* L.), hairy vetch (*Vicia villosa* Roth), lentil (*Lens culinaris* Medik.), and radish (*Raphanus sativus* L.). Cereal rye was the most tolerant cover crop, whereas radish was the most sensitive species. Dry weight of radish was severely reduced by nearly all herbicides, whereas other cover crop species had smaller reductions due to herbicide injury. Root growth of oat was inhibited more by pendimethalin than the other species. Flumetsulam + clopyralid, atrazine, and herbicides containing isoxaflutole caused significant injury to most species studied.

Though it is difficult to make direct comparisons between these experiments and the potential for injury in the field, these studies provide guidelines for growers wanting to include cover crops within their current rotation.

CHAPTER I: GENERAL INTRODUCTION

Introduction

Many growers in the Midwest have mastered the corn monoculture or corn-soybean crop rotation and consistently achieve high yields. The addition of an extra crop or mix of crops to these systems complicates the management of all crops. The use of cover crops has become more common recently due to the availability of funds to assist with establishment and termination of crops, and due to concern regarding soil erosion and nutrient movement to water systems. Suppression of spring weed growth ranks just behind reducing soil erosion, reducing soil compaction, and nitrogen scavenging as a benefit of cover crops. The first chapter of this thesis describes experiments that determine whether cereal rye, when established prior to or after crop harvest in the fall and terminated prior to crop planting in the spring, will suppress weed emergence.

Cover crops have a very short time period for fall establishment, and the earlier a grower establishes the crop, the more likely the environmental benefits of cover crops will be achieved. Herbicides used in the corn or soybean crop that persist the entire season complicate cover crop establishment, with the possibility of cover crop failure due to herbicide injury. The second chapter of this thesis will describe experiments that determine the effect of low rates of common corn and soybean herbicides on cover crop establishment. The goal of this research is to provide guidelines for growers regarding herbicides that may reduce establishment of cover crop species.

Thesis Organization

This thesis is organized as two chapters each containing a paper suitable for submission to a scientific journal. The first paper is entitled “Effect of cereal rye biomass on emergence of common waterhemp and common lambsquarters” and is suitable for submission to Weed Technology. The second paper is entitled “Herbicide effects on establishment of five cover crops” and is suitable for submission to Crop Protection. Each paper includes an abstract, introduction, materials and methods, results and discussion, conclusions, references, tables, and figures. Preceding these papers is a general introduction and following them is a general conclusion.

CHAPTER II: EFFECT OF CEREAL RYE BIOMASS ON EMERGENCE OF COMMON WATERHEMP AND COMMON LAMBSQUARTERS

Abstract

Experiments were conducted to determine whether cereal rye (*Secale cereale* L.) suppresses emergence of two important weeds when seeded in late fall and chemically terminated prior to crop planting. Treatments designed to provide different levels of residue were seeded with either common waterhemp (*Amaranthus rudis* Sauer) or common lambsquarters (*Chenopodium album* L.). Cereal rye was terminated in early May and weed emergence was determined approximately every seven days following initial emergence of the species. September-seeded treatments produced greater biomass than October-seeded treatments, and seeding rate had less effect on biomass accumulation than seeding date. Common waterhemp emergence was equal to or increased in the presence of cereal rye residue in both 2013 and 2014 compared to the control. Common lambsquarters was increased in two treatments in 2014 but was otherwise unaffected by the presence of rye biomass. Cereal rye residue from the September rye seeding date increased the time to 10% (TE_{10}) and 50% (TE_{50}) emergence of common waterhemp in 2013 by at least nine days. In 2014, the TE_{10} was increased by at least 20 days and TE_{50} was increased by more than 10 days compared to the October cereal rye seeding date and the control. Common lambsquarters TE_{10} and TE_{50} were unaffected in 2013. In 2014, the TE_{10} was increased by less than three days and the TE_{50} was increased by between 13 and 40 days. The lack of weed emergence suppression seen in these experiments is a concern for cover crop use in

Iowa's conventional cropping systems, while the delay in weed emergence associated with cereal rye residue may be beneficial or detrimental to weed management.

Introduction

Common waterhemp (*Amaranthus rudis* Sauer) is a summer annual plant native to the North Central United States (Hager et al. 2000, Hartzler et al. 2004) It is a member of the Amaranthaceae family. Common waterhemp is dioecious and thus an obligate outcrosser. It can be differentiated from most other amaranths by its glabrous leaves and stem. Common waterhemp can also be differentiated from smooth and redroot pigweed, two other amaranths common to the upper Midwest, by its more lanceolate leaves.

Concern over this weed has increased in recent years due to increasing prevalence of herbicide resistance. Heap (2014) reports that common waterhemp has evolved resistance to five herbicide modes of action in Iowa including inhibitors of ALS, HPPD, EPSPS, photosystem II, and PPO. The prevalence of these resistant waterhemp biotypes has increased interest in alternative control tactics, including cover crops. Approximately 40% of growers surveyed by the Sustainable Agriculture, Research, & Education (SARE) group reported that weed control was a desired cover crop benefit (Myers et al. 2013).

Common waterhemp begins emerging later than many other agronomic weeds in Iowa and has a prolonged emergence pattern (Hartzler et al. 1999). Steckel et al. (2004) found that under dark conditions, common waterhemp germination increased when exposed to temperatures above 20 C. Higher rates of germination were observed under alternating temperature conditions of +/- 40% compared to constant temperature conditions (Steckel et al. 2004).

Common waterhemp has greater germination and plant survival under no-tillage treatments compared to tilled treatments in multiple studies, suggesting that seed proximity to the soil surface may be critical to germination and establishment. Steckel et al. (2007) found that emergence of common waterhemp was greater under no-till than in tilled treatments; other researchers had previously found similar results regarding common waterhemp response to tillage (Mohler and Calloway 1992, Refsell and Hartzler 2009). Leon and Owen (2006) found that waterhemp emergence was at least four times greater under no-tillage conditions than chisel plow or moldboard plow.

Waterhemp germination increased when exposed to red light, suggesting seed germination is phytochrome controlled to some extent (Leon and Owen 2003). However, they also discovered the light dependency could be overcome when exposed to high temperatures after a chilling period. Waterhemp seed is more persistent in the seed bank than some other weeds. In a study conducted by Buhler and Hartzler (2001), 12% of common waterhemp seed was recovered after four years of burial compared to 5% for velvetleaf (*Abutilon theophrasti* Medik.) and 0% for giant foxtail (*Setaria faberi* Herrm.).

Common lambsquarters (*Chenopodium album* L.) is a broadleaf summer annual in the Amaranthaceae family. Seedlings have linear cotyledons and a white, waxy substance on leaf surfaces. As plants grow, they develop grooved stems and “broadly triangle-shaped leaves with irregular, shallow-toothed margins” (Curran et al. 2007). This weed is noted as being a difficult weed for growers to manage, and thus is commonly found in corn and soybean fields in the Midwest, especially those with glyphosate-resistant crops (Owen and Zelaya 2005).

Common lambsquarters typically germinates and emerges earlier than common waterhemp. Chu et al. (1978) found that common lambsquarters germinated at lower temperatures than another member of the Amaranthaceae family, redroot pigweed (*Amaranthus retroflexus* L.), and Wiese and Binning (1987) reported that common lambsquarters germinated at temperatures above 8 C and had a linear relationship between increasing temperature and germination. Martinez-Ghersa et al. (1997) found that common lambsquarters, unlike redroot pigweed, germinated quickly when exposed to low soil water conditions following a period of dormancy, potentially making it more vulnerable to stress conditions if the soil were to dry again.

Seed harvested from common lambsquarters plants exposed to ammonium nitrate were found to have significantly lower dormancy than those from non-exposed plants, and seeds exposed to ammonium nitrate in the laboratory also had lower dormancy (Fawcett and Slife 1978). Bouwmeester and Karssen (1993) also found germination to increase when seed was exposed to ammonium nitrate under field conditions. Common lambsquarters seed germination requires or is enhanced by light (Bouwmeester and Karssen 1993, Cumming 1963). Other studies report variable response in germination due to light exposure during tillage. Gallagher and Cardina (1998) found common lambsquarters emergence to be unaffected by light environment during tillage, but Buhler (1997) found as much as a 70% reduction of common lambsquarters emergence when tillage was performed in darkness in mid-May compared to when tillage was conducted during the day. Buhler and Oplinger (1990) reported common lambsquarters density was unaffected by treatments of conventional tillage, chisel plow, and no tillage.

Research has shown that the residue from cereal rye grown as a cover crop can reduce establishment and growth of early-season or winter annual weeds. The cover crops are likely either growing or their residues have not degraded at the time of weed seed germination, providing maximum weed suppression by the cover crop (Didon et al. 2014).

Common waterhemp emergence was reduced by cereal rye residue when compared to a no cover control in two of three years (Davis 2010). The effect of cover crops has been more comprehensively studied on other amaranths, such as redroot pigweed, than on common waterhemp (Masiunas et al. 1995, Mohler and Calloway 1992, Mohler and Teasdale 1993, Moore et al. 1994, Shilling et al. 1985, Teasdale and Mohler 2000). Suppression of redroot pigweed by residues of cereal rye has been variable. Moore et al. (1994) found a reduction in redroot pigweed emergence early in the growing season with a rye cover crop compared with a no cover control but found no season-long difference in total emergence. Shilling et al. (1985) reported a decrease in redroot pigweed density with a cereal rye residue. Teasdale and Mohler (2000) reported suppression of redroot pigweed emergence when mulch mass was increased, but found increased redroot pigweed emergence with low mulch rates in one year of their two year study. Mohler and Teasdale (1993) distributed mowed cereal rye residue onto field plots at rates of 0, 1070, 2140, 4280, 8560, and 17120 kg ha^{-1} and reported a decreased emergence in both redroot pigweed and common lambsquarters with increasing residue rates. It is important to note that redroot pigweed and common waterhemp, though in the same genus, may respond differently to soil surface environment changes, especially temperature, associated with cereal rye residue (Steckel et al. 2004).

Mohler and Calloway (1992) reported little reduction in emergence of natural populations of both redroot pigweed and common lambsquarters by cereal rye. Rye residue in transplanted tomato provided similar redroot pigweed weed control to plots with conventional tillage combined with a herbicide (Masiunas et al. 1995). Both redroot pigweed and common lambsquarters appear to have highly variable responses to cereal rye residue under different conditions.

An earlier experiment by Teasdale found that common lambsquarters emergence increased following incorporation of rye residue compared to conventionally tilled controls with no cover crop residue (Teasdale et al. 1991). Moore et al. (1994), however, found no difference in emergence of common lambsquarters between no cover and cereal rye treatments in 1989 but found an approximately 78% reduction in common lambsquarters emergence due to rye residue compared with a no-cover treatment in 1990. Researchers have also reported that crimped cereal rye reduces weed biomass but does not reduce weed density when compared with cereal rye terminated with either tillage or chemical termination (Bernstein et al. 2014, Davis 2010). It appears cereal rye cover crops can be managed in a manner to reduce weed emergence, weed biomass, or both.

Common waterhemp is known for having a prolonged emergence pattern (Hartzler et al. 1999). The presence of cereal rye biomass on the soil surface has potential to retain moisture and allow seeds to germinate for extended periods following rainfall events, even late in the growing season. A recent study found that weed emergence peaked later in the season in crimped or mowed rye treatments compared to tilled rye treatments and the crimped or mowed treatments provided for greater weed suppression (Bernstein et al. 2014). This study supports the concern that waterhemp emergence could be extended during the season.

A rye cover crop reduced common lambsquarters biomass by 98% compared to the no cover crop control (Barnes and Putnam 1983). Mulched rye residue provided as much as 84% control of common lambsquarters, reducing both plant biomass and plant density (Shilling et al. 1985). The presence of living cover crops or recently terminated cover crops provided early-season weed control, but weed suppression decreased as the cover deteriorated (Smeda and Weller 1996).

Residues of many cover crop species can provide effective weed control, but they must be managed carefully to not reduce crop yield (Ateh and Doll 1996, Barnes and Putnam 1983, Brainard and Bellinder 2004, Crutchfield et al. 1985, Johnson et al. 1993). While many cover crop species have potential in current management schemes, cereal rye has been more widely used in agricultural fields and research than other cover crops (Barnes and Putnam 1983, Creamer et al. 1996, Johnson et al. 1993, Liebl et al. 1992).

Cereal rye can be planted and terminated in a number of ways for the benefit of the primary crop, soil conservation, or weed control. Researchers use various methods of managing rye depending on their particular interest. Ashford and Reeves (2003) described management methods of a rye cover crop, including herbicide termination, mechanical termination, and use of a roller crimper.

Some researchers have evaluated the allelopathic effects of rye on weeds (Barnes and Putnam 1983, 1986; Shilling et al. 1985). The role of allelopathic compounds from rye in suppressing weeds is still debated. Researchers have used non-toxic controls in order to separate effects of allelopathy from the physical barrier of mulch, often planting cereal rye and spreading another mulch, such as poplar excelsior, on the soil surface (Barnes and Putnam 1983). Samson et al. (1992) states that studies comparing a surface mulch to planted cereal rye ignore important soil fertility changes that might occur due to the prior growth of cereal rye in the soil. When comparing a surface mulch of rye to a surface mulch of poplar, there was no difference in weed suppression between the two mulches, suggesting stems and leaves of cereal rye did not contain allelochemicals (Samson et al. 1992).

Creamer et al. (1996) researched weed suppression with both leached and unleached rye residues to separate the effects of residue cover from allelopathic chemicals. They found no difference in weed suppression between plots with a leached or unleached rye residue, suggesting the physical presence of rye straw was the primary factor affecting weed suppression.

Other researchers have also found no evidence of allelopathic effects when using cereal rye as a cover crop. Teasdale et al. (1991) found that increasing rye or clover residue cover percent or weight resulted in a linear decrease in weed densities, though they found residue coverage needed to be at least 42% to provide any weed suppression. Teasdale and Mohler (2000) studied the effect of increasing mulch mass on weed suppression and found that emergence decreased with increasing mulch mass, suggesting effects of a combination of physical barrier and lack of light. Teasdale and Mohler (1993) also found that increasing cereal rye biomass decreased light transmittance to soil surface but suggested that the reduction in light transmittance was not enough to prevent seed germination. Instead, they reported that the physical barrier was the primary reason for suppression of weed emergence.

Finally, Kruidhof et al. (2011) found that incorporated cereal rye did not significantly inhibit establishment of 14 species, and Kruidhof et al. (2008) found that neither cereal rye nor radish reduced seedling establishment. The authors noted several management factors influence the level of weed suppression provided by a cover crop, including cover crop cultivar, the growth stage of the cover crop at time of residue incorporation or termination, biotic and abiotic conditions during cover crop growth and following residue incorporation or termination, weed seed mass, and time of weed emergence relative to termination timing (Kruidhof et al. 2011).

The objective of this research is to assess suppression of common waterhemp and common lambsquarters emergence under varying rye residue levels and determine whether rye would be an effective weed management tool in current management schemes in the north-central United States. We hypothesize that cereal rye residue will suppress the emergence of common lambsquarters more than common waterhemp, due to the later emergence of common waterhemp.

Materials and Methods

Common waterhemp and common lambsquarters seed used in the 2013 and 2014 field experiments were collected from the Iowa State University Curtiss Farm near Ames, Iowa. Seed was collected in September of 2012 and 2013 and spread to dry indoors. It was then cleaned using sieves and an air column separator to obtain pure, germinable seed. Three 500 seed samples of each seed species were counted and weighed. All samples varied less than five percent in weight. Seed lots of 5,500 seed were prepared based on the average weight collected from each species both years. Cereal rye[1] (*Secale cereale* L. var. 'Elbon') was cleaned to remove broken and other seed prior to measuring for plots. Three samples of cereal rye seed at each seeding rate were weighed and averaged to determine an average weight of each seeding rate. The average weight for each seeding rate was used to efficiently measure seed for each plot.

Field experiments were established at the Iowa State University Boyd farm near Boone, Iowa. The experimental area consisted of Clarion loam and Nicollet clay loam soil series (Andrews and Diderikson 1981). Clarion loam is a well-drained upland soil, and Nicollet clay loam is a somewhat poorly drained upland soil. Both are formed in glacial till. Cereal rye plots measuring 1.2- by 1.8-m (2.2-m^2) were established in a randomized block design with five replicates in September of 2012 and 2013 following soybean removal on August 28, 2012 and August 26, 2013, respectively. Soybeans were chopped prior to crop maturity each year. The plot area was disked to remove soybean residue from the soil surface following soybean removal on August 29, 2012 and August 29, 2013, and then field cultivated to prepare a level seedbed prior to plot establishment September 6, 2012 and September 9, 2013.

Each plot had a main plot factor of cereal rye seeding rate and seeding date and a subplot factor of weed species with a 0.3-m border between plots to prevent

[1] Justin Seed Company, Justin, Texas

interference between seeding rates (Figure 1). Each plot was repeated twice in every replicate to observe effects on the common lambsquarters and common waterhemp weeds in separate plots. The seeding rate and date treatments were intended to provide different levels of rye biomass at termination the following spring. The September seeding date represents the 'ideal' seeding date for a cereal rye cover crop in Iowa in terms of assuring consistent establishment in the fall. The October seeding date represents a more practical seeding date following crop harvest. Seeding rates were chosen based on current recommendations (Casey 2012). The addition of the highest seeding rate in the 2014 experiments was to determine whether increasing the seeding rate far above recommended rates would result in increased biomass accumulation and suppression of the two weed species. Seeding dates and rates are summarized in Table 1.

For cereal rye seeding, the 'Elbon' rye seed was evenly spread onto the soil surface by mixing with perlite in shaker bottles. Each plot was split into four areas of equal size to ensure even distribution. Seed was incorporated into the upper 2 cm of soil by hand mixing and raking.

After establishment of the late rye planting date, an area of 0.25-m^2 was seeded with 5,500 common lambsquarters or common waterhemp seed on October 21, 2012 and October 26, 2013. The seeding area was positioned 0.3-m from the outer edge of the plot. Seed was mixed thoroughly in sand and then spread with shaker bottles to ensure even distribution of seed. The area was left undisturbed with weed seed on soil surface.

On November 21, 2012, all plots were sprayed with 0.56 kg ha^{-1} bromoxynil ester to remove winter annual weeds. This operation was not performed in 2013 as winter annual weeds were not present.

Temperature data loggers[2] were buried approximately 3 cm under the soil surface on April 5, 2013 and April 10, 2014 in plots with three rye residue levels: control, treatment 2, and treatment 6. Burial occurred after the ground thawed and cereal rye resumed growth. Data loggers were buried in each of the five blocks, resulting in 15 total data loggers each season. Temperatures were recorded at 30 minute intervals until retrieval of data loggers at the completion of the experiment each year on July 8, 2013 and July 30, 2014.

Rye was terminated on May 6, 2013 and May 5, 2014 using a CO_2 backpack sprayer with a 3-m spray swath, applying 1.1 kg a.e. ha^{-1} glyphosate and 17 kg ha^{-1} ammonium sulfate when the most mature cereal rye was at Feeke's stage 8-9. At Feeke's stage 8, the flag leaf is visible and at Feeke's stage 9, the ligule of the flag leaf is visible. The inflorescence of the cereal rye was just beginning to swell within the stem of the plant and the most mature rye was approximately 0.45-m tall.

During the spring of 2013 and 2014, plots were observed to determine first emergence of common lambsquarters and common waterhemp. Once emergence was observed, counts were taken within a 0.1-m^2 quadrat placed in the center of the 0.25-m^2 quadrat approximately once every seven days until weed emergence ceased. During each season, rainfall and persistent wet conditions prevented access to the research area for longer than the seven days on at least one occasion. The first count was

[2] HOBO Pendant® Temperature/Alarm Data Loggers (#UA-001-08)

recorded on May 6, 2013 and April 22, 2014 and final count was recorded on July 8, 2013 and July 30, 2014. Seedlings were carefully removed after census with tweezers to minimize soil disturbance. Other weeds were controlled as necessary throughout the season using the same treatment and equipment as used for terminating the cereal rye. The weed subplots were covered with heavy plastic to avoid contacting seedlings with herbicide.

As the natural population of common waterhemp and common lambsquarters within the research area was unknown, seedlings of both species were counted in every plot. Seedling counts of the other species were recorded to be used as a covariate in data analysis.

Rye shoots were harvested at the soil line from the 0.25-m^2 rye sampling area at the time of rye termination in order to obtain an estimate of the rye cover present in the seeded weed subplot. The sample was dried for 72 hours at 60° C and weighed to determine dry weight per plot. The biomass from each plot was used to estimate the amount of biomass in kg ha^{-1} and was related to the percent cover estimates described below.

Rye biomass over both the area containing weed seed and the rye sampling area of each plot was photographed after the rye resumed growth in early spring, on the date of the first emergence count, and on the date of rye termination. A 0.25-m^2 frame was placed over the weed subplot and the rye residue sampling area to outline subplot borders. A grid containing 100 points was placed over each image to fit the subplot area and each point was counted as covering either cereal rye or bare soil to estimate percent cover. The average of two grid counts was used to estimate the average percent cereal rye cover for each subplot.

Rainfall data were collected from The Weather Channel, LLC historic rainfall data collected from the Ames, Iowa MesoNet station (Weather Underground 2014).

All data was transformed when necessary and transformed means separation is presented with non-transformed data. Emergence data were used to determine percent cumulative emergence and create the variables TE_{10} and TE_{50} by calculating the number of days until ten and fifty percent of the total emergence occurred for each individual plot. Rye seeding rates and dates were analyzed as individual treatments and years were analyzed separately. For each year of data, treatment differences were analyzed using a Fisher's LSD at $P \leq 0.05$. Rye biomass required a log (X + 1) transformation to normalize data. Ground cover was transformed using an arcsine transformation to normalize data. Total emergence (as a percent of total seed in each plot), TE_{10}, and TE_{50} data were analyzed using the generalized linear model in SAS assuming fixed treatment effects (SAS Institute 2014). Total emergence was transformed using an arcsine transformation for analysis. TE_{10} and TE_{50} data did not require transformation for either weed species and differences between treatments were analyzed using Fisher's LSD. Other weed species counted within plots were analyzed as a covariate in the model, but data were not linearly related or significant in either year. Dates of emergence counts were pooled into bimonthly time periods from Late April to Late July. Column graphs of weed emergence by year and time period were created using SigmaPlot 12.5 (SigmaPlot 2014). For these graphs, emergence data were pooled in three groups for each year based on biomass accumulation to show the effect on time of emergence. The percent ground cover provided by rye biomass at the time of rye termination was graphed in SigmaPlot 12.5 with the biomass of rye residue collected from the same area for each treatment (SigmaPlot 2014). A regression curve was added to these graphs using the same program.

Results and Discussion

The primary objective of this research was to determine if cereal rye residue could suppress common waterhemp and common lambsquarters emergence, therefore providing an additional management tactic to supplement herbicide use by conventional corn and soybean growers. Our hypothesis was that common lambsquarters emergence would be suppressed more than common waterhemp emergence due to its earlier germination when a greater amount of rye residue would remain on the soil surface.

Average daily soil temperatures during 2013 did not differ between the control and treatments with low and high residue levels, despite the expectation that the treatment with highest rye biomass, S3, would have the lowest average soil temperature (Table 2). Average daily soil temperatures in 2014 were lower in the presence of cereal rye compared to the control for most dates. The final three weed count dates had no decrease in soil temperature associated with increased rye biomass treatments in 2014.

Date of fall establishment of cereal rye was more important than seeding rate in accumulation of aboveground biomass in both years. Other researchers have reported that an increase in seeding rate did not increase cereal rye biomass at plant maturity (Boyd et al. 2009, Ryan et al. 2011a). All seeding rates in the September seeding date accumulated more than 2000 kg ha^{-1} biomass in 2013 (Treatments S1-S3) and over 3000 kg ha^{-1} in 2014 (S1-S4), while all October seeding date treatments (O1-O3) in both years accumulated less than 1000 kg ha^{-1} (Table 3). Tillering of individual cereal rye plants in the spring appeared to compensate for differences in plant stand both years, exemplified by the similar percent cover and biomass accumulation among different seeding rates in September 2012 and 2013 (Table 3). The October 2012 seedings accumulated more biomass than the 2013 October seedings, despite the fact that the 2013 October seedings included higher seeding rates and droughty conditions persisted late into fall 2012. October seeded plots accumulated 538 and 430 kg ha^{-1} biomass in 2012 and only 383 and 165 kg ha^{-1} biomass in 2013 (Table 3). Much greater variability was observed in the biomass accumulated within treatments in 2013 than in 2014, likely due to dry fall weather during rye establishment in September and October 2012 (data not shown).

Percent cover measurements were recorded during early spring to observe the change in ground coverage as cereal rye resumed growth. Higher seeding rates produced greater ground cover earlier in the spring (data not shown). For example, in 2014, the lowest September seeding rate provided approximately 70% cover on April 10, whereas the highest September seeding rate on this date provided over 90% cover. At the rye termination date, greater than 70 percent ground cover was recorded for plots seeded in September 2012 and greater than 90 percent ground cover was recorded for plots seeded in September 2013 (Table 3). Ground cover in the October seeding rates ranged from 35 to 52% in both years of the study. Percent cover was much more variable in 2013 than in 2014 (data not shown). The relationship between ground cover and rye biomass harvested is presented in Figures 2 and 3. Figure 2 shows the variability of biomass accumulation within rye treatments in 2013. Even with the variability in biomass within individual treatments, there is a consistent relationship between percent cover and biomass in late spring. Figure 3 presents the relationship between biomass accumulation and percent cover of each rye treatment in 2014. Treatments in 2014 were less variable around the regression curve. The data fit a logarithmic regression curve with an R^2 of 0.95 in 2013 and an R^2 of 0.99 in 2014.

In 2013 and 2014, total recruitment of common waterhemp in all cereal rye treatments was greater than or equal to that of the control, which had 4.4% emergence in both years (Table 3). In 2013, treatment S2 (September planting, 77.8 kg ha^{-1} rate), was the only treatment with higher emergence than the control (6.7% vs 4.4%). In 2014, September-seeded treatments ranged from 10.9 to 16.8% emergence, whereas emergence in the control was only 4.4%. The October rye seeding dates did not differ from the control.

In 2013, common lambsquarters recruitment in all treatments was equal to the control, which had 9.0% emergence. Seedling emergence ranged from 4.7% in treatment four to 11.4% in treatment one (Table 3). In 2014, common lambsquarters emergence ranged from 4.5 to 9.5%. One October-seeded treatment (O3) and one September-seeded treatment (S1) had significantly greater emergence than the control, with 9.5 and 8.6% emergence, respectively. All other treatments resulted in similar emergence to the control. Low levels of rye residue associated with the late rye seeding date may have provided a more favorable environment for germination and establishment than bare ground or high residue levels in treatment O3.

Residue of cereal rye also influenced emergence patterns of the two species. The high levels of biomass associated with September cereal rye seeding dates affected emergence timing of common waterhemp whereas October-seeded plots did not, and rye seeding rates had little affect (Table 3). Rye associated with the September planting dates increased the time to 10% emergence (TE_{10}) by 9 to 24 days. The time to 50% emergence (TE_{50}) increased in the September planting dates by at least ten days.

The TE_{10} and TE_{50} for common lambsquarters were unaffected by cereal rye biomass in 2013 but were both affected by cereal rye biomass in 2014 (Table 3). In 2013, over 80% of cumulative emergence occurred by the first census date in all treatments. Seeding date had a greater effect on emergence patterns than seeding rate in 2014. The TE_{10} increased by 2.4 days in 2014 compared to the control in treatment S4. September-seeded treatments increased the TE_{50} between 13 and 40 days compared to the control. The TE_{10} and TE_{50} of the two October-seeded treatments, O2 and O3, were not significantly different from those of the control.

Emergence of the September-seeded treatments and the October-seeded treatments were pooled due to the similarities in biomass and percent cover for each seeding date and each year in order to evaluate emergence patterns of the weed species. In addition, emergence count dates were pooled into bi-monthly periods. In the absence of rye residue or with low quantities of rye residue, the peak period of common waterhemp emergence occurred prior to June in both years (Figure 4a, b, c, and d). However, with high levels of rye associated with September planting approximately 70% and 90% of waterhemp emerged after June 1 in 2013 and 2014, respectively (Figure 4e and f). The increased late-season emergence resulted in higher total emergence over the entire growing season in treatment five in 2013 and all September seeding rates in 2014. Teasdale and Mohler (2000) also reported an increase in weed establishment with low levels of rye in certain situations. Degradation of the rye residue earlier in the season may have resulted in levels of rye that created a more favorable environment for waterhemp establishment during a time with optimum soil temperatures for waterhemp germination.

In 2013, more than 85% of cumulative common lambsquarters emergence occurred in early May (Figure 5). Plots were monitored on April 30, 2013 for weed emergence but none were observed at that time. In 2014, common lambsquarters emergence began approximately two weeks earlier than in 2013. This corresponded with earlier warming of soils in 2014 compared to 2013 (Table 2). The initial census in April accounted for more than 45% of total emergence in the control and October rye seeding date treatments but only 18% of total emergence in the September rye seedings in 2014 (Figure 5). Approximately 50% of common lambsquarters germinated after May 25 in the September rye seeding treatments in 2014. A possible explanation for the high numbers of late emerging common lambsquarters is that the rye residue that remained in the September rye seeding treatments protected seedlings from heavy rains that occurred in late June.

Summary and Conclusions

We hypothesized that the early emergence of common lambsquarters compared to common waterhemp would make common lambsquarters more susceptible to suppression by cereal rye residues. We must reject our hypothesis as neither common lambsquarters nor common waterhemp emergence was suppressed by cereal rye residues. Additionally, all rye treatments resulted in equivalent or increased common waterhemp emergence compared to the control. Researchers who have reported weed suppression with rye cover crops have typically allowed the rye to accumulate much greater biomass than the 200 to 4000 kg ha^{-1} of biomass present in this research. Bernstein et al. (2014) found greater weed suppression with 10,800 kg ha^{-1} compared to a tilled system with no cover crop. Smith et al. (2011) reported that 9,000 kg ha^{-1} cereal rye biomass was necessary to provide weed control that prevented soybean yield loss. Weed biomass was suppressed in tomato with 11,000 to 23,000 kg ha^{-1} rye biomass, but variable weed response was observed in treatments with less than 7,000 kg ha^{-1} rye biomass (Smeda and Weller 1996). De Bruin et al. (2005) found that rye mulch levels between 1,000 and 4,000 kg ha^{-1} did not inhibit weed growth. Moore et al. (1994) found that common lambsquarters emergence responded inconsistently to 500 to 4,000 kg ha^{-1} of rye residue. Importantly, multiple researchers have concluded that management tactics to supplement rye ground cover are necessary for full-season weed control (Davis 2010, Gallandt 2006, Nord et al. 2011, Ryan et al. 2011b).

In both 2013 and 2014, total emergence of common waterhemp in all rye treatments was greater than or equal to the control treatment. The degradation of cereal rye biomass as the season progressed likely created less of a physical barrier to emerging seedlings and increased light transmittance to the soil surface. Teasdale and Mohler (1993) found that light transmittance through rye residue declined exponentially with increasing ground cover and the presence of cereal rye residue prevented weed emergence by acting as a physical barrier, but also found that cereal rye residue prevented a decline in soil water content during droughty periods that could increase weed emergence. Neither 2013 nor 2014 had extended dry periods early in the growing season, so conservation of soil moisture is probably not the primary factor leading to increased emergence later in the season commonly seen with rye residue. It is possible that the increased emergence later in the season with rye residue was because the rye provided a more favorable environment for seed germination than bare soil. Duncan et al. (2009) and Harper et al. (1961) reported that safe sites are areas suitable for seeds to germinate and seedlings to establish, and the presence of low levels of rye residue may provide more safe sites allowing for increased seedling establishment and establishment later into the season than is seen without residue present in both common lambsquarters and common waterhemp. Safe sites may be areas with appropriate cues for seed germination or areas that protect seedlings from hazards that could otherwise result in plant death.

The response of common lambsquarters to rye residue was similar to that of common waterhemp. In 2013, all treatments resulted in emergence not significantly different from the control. In 2014, however, two treatments had significantly higher emergence compared to the control. A September-seeded treatment (S1) resulted in significantly higher emergence compared to the control despite its similar biomass to other September-seeded treatments that did not increase emergence. One October-seeded treatment (O3) also increased emergence significantly compared to the control. Differences in the quality of the rye residue attributed to the different seeding rates or the consistency of soil coverage by plants might account for the differences in common lambsquarters emergence when there was little difference in total biomass or ground cover (Table 3).

The later emergence of common waterhemp compared to common lambsquarters allowed for greater cereal rye residue degradation prior to peak periods of waterhemp emergence. The TE_{10} and TE_{50} of common waterhemp were increased in September-seeded treatments in both 2013 and 2014 due to suppression of emergence early in the season coinciding with increased emergence later in the season. The higher TE_{10} and TE_{50} values for common lambsquarters in 2014 indicate that some suppression of emergence did occur early in the season compared to the control, but greater than 50% of emergence had occurred on the date of initial census in 2013. The common lambsquarters TE_{50} increased greatly in September rye seeding treatments in 2014, possibly due to cereal rye protecting seedlings from heavy rains and providing safe sites for establishment.

In Iowa, it is unlikely that most conventional corn and soybean growers would alter their practices to allow for more rye biomass accumulation in the spring to suppress weed emergence due to the likelihood of corn yield loss associated with rye cover crops and delayed planting dates. Many researchers have reported yield decreases in corn following use of cereal rye as a cover crop (Clark et al. 1994, GA Johnson et al. 1993, TJ Johnson et al. 1998, Sawyer et al. 2011). To avoid yield loss due to cereal rye biomass interference with corn, growers are advised to terminate cereal rye early in the spring, preferably at least two weeks prior to corn planting (Singer et al. 2005). Additionally, soybean yield loss from delayed planting dates makes it unlikely that growers would alter practices to allow for a longer period of cereal rye growth in the spring prior to soybean planting (De Bruin and Pedersen 2008).

The increase in recruitment of common waterhemp and, in some instances, common lambsquarters with cereal rye cover crops observed in this research is a concern. Common waterhemp is already a difficult to control weed with multiple herbicide resistances and a prolonged emergence pattern. The combination of an increase in weed recruitment and delays in weed emergence make it difficult to predict the effect rye cover crops would have on weed management. Delays in weed emergence reduce the competitiveness of the weed with the crop and reduce weed seed production. However, late-emerging weeds prolong the time that growers must manage the weeds by using tactics that persist longer into the growing season (e.g. higher residual herbicide rates or later postemergence herbicide applications). Increasing crop competitiveness through use of narrow row width or increased seeding rates is one way to reduce interference of late-emerging weeds.

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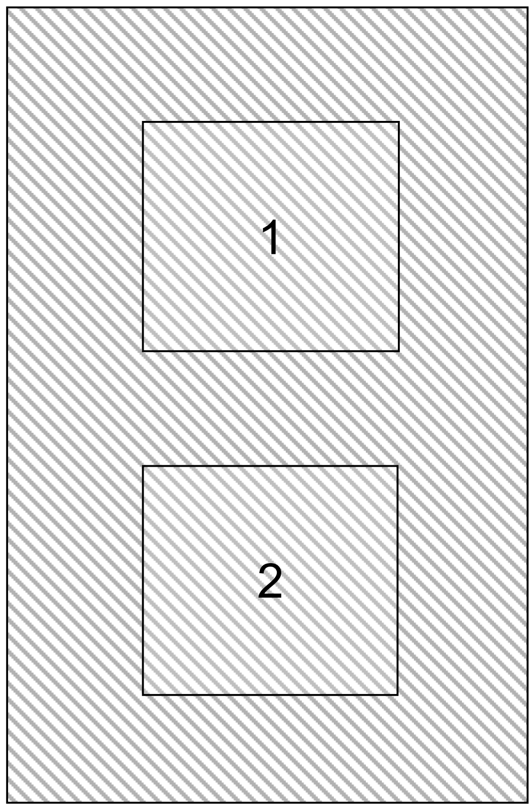


Figure 1. Plot layout (1.2-m by 1.8-m) with diagonal shading of seeded rye area where (1) represents the 0.25-m^2 subplot for rye biomass collection at time of termination and (2) represents the 0.25-m^2 subplot area of weed species seeding for emergence data collection. The two subplots were separated by a distance of 0.30-m.

Table 1. Planting date and rye seeding rates used to establish different levels of rye biomass.

	2012-2013		2013-2014	
Treatment	Planting date[1]	Seeding rate	Planting date[2]	Seeding rate
		kg ha^{-1}		kg ha^{-1}
Control	-	-	-	-
O1	LP	31.2	-	-
O2	LP	77.8	LP	77.8
O3	LP	-	LP	155.5
S1	EP	31.2	EP	31.2
S2	EP	77.8	EP	77.8
S3	EP	155.5	EP	155.5
S4	EP	-	EP	311.5

[1]2012: EP = September 14; LP = October 11
[2]2013: EP = September 12; LP = October 14

Table 2. Average soil temperature of three cereal rye treatments on 2013 and 2014 weed emergence count dates[1].

Treatment[2]	Date											
2013	5/6	5/21	6/3	6/11	6/17	6/25	7/1	7/8				
	°C											
Control	14.5a	17.1b	16.9b	23.3b	25.4a	24.5b	26.4a	30.9a				
O2	14.3b	17.5a	17.1a	23.5a	25.2b	24.7a	26.5a	30.9a				
S3	14.0c	17.4a	16.9b	23.2c	25.2b	24.5b	26.4a	30.9a				
2014	4/22	5/5	5/14	5/21	5/28	6/3	6/10	7/1	7/9	7/16	7/23	7/30
Control	14.8a	17.8a	14.4a	20.6a	22.9a	22.0a	23.5a	20.4a	26.0a	25.0a	30.0a	21.0b
O2	13.6b	13.1c	13.1c	19.9b	22.1b	20.3b	21.4b	20.2b	25.6b	24.8a	30.0a	21.1ab
S3	13.2c	13.3b	13.4b	19.9b	22.2b	20.3b	21.0c	20.2b	26.1a	24.9a	30.0a	21.2a

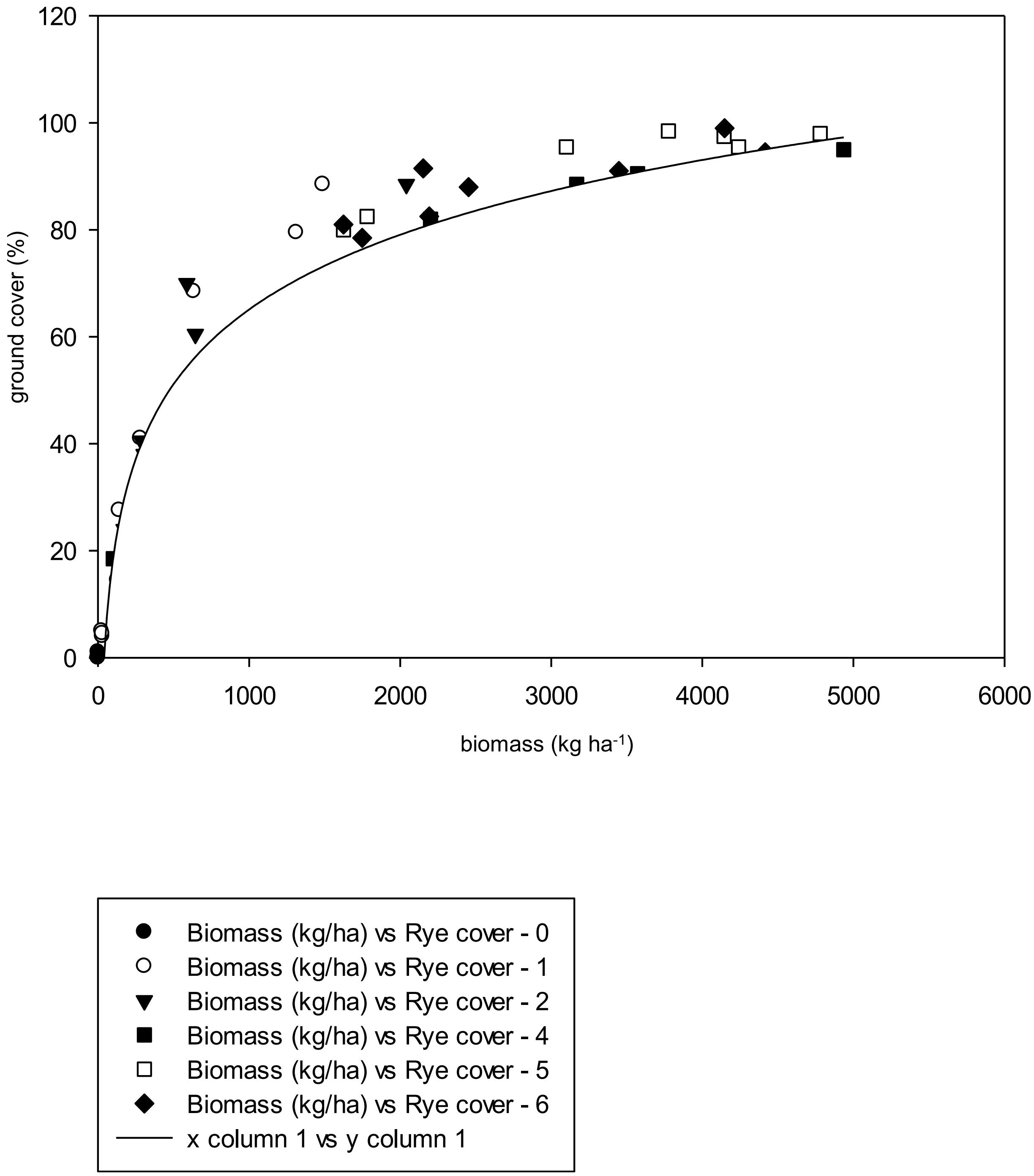
[1]Temperatures within a column and year followed by the same letter are not different at *P≤0.05* according to Fisher's LSD

[2]Control = no rye; Treatment O2 = October rye planting date, 77.8 kg seed ha^{-1}; Treatment S3 = September rye planting date, 155.5 kg seed ha^{-1}

Table 3. Effect of rye planting date and seeding rate on biomass accumulation and emergence characteristics of common waterhemp and common lambsquarters[1].

				common waterhemp			common lambsquarters		
Treatment[a]	Seeding rate	Biomass	Ground cover	Emergence[b]	TE$_{10}$[c]	TE$_{50}$[d]	Emergence	TE$_{10}$	TE$_{50}$
2013	kg ha^{-1}		%	%	days		%	days	
Control	-	0d	0c	4.4b	2.2c	22.6c	9.0abc	0a	0a
O1	31.2	430c	35b	6.4ab	5.2bc	27.8bc	11.4a	0a	0a
O2	77.8	538b	46b	5.3ab	3.0c	26.0c	11.1a	0a	0a
S1	31.2	2287a	72a	6.2ab	15.4a	36.0a	4.7c	0a	0a
S2	77.8	2837a	83a	6.7a	17.2a	36.2a	5.6bc	0a	0a
S3	155.5	2733a	84a	5.0ab	11.4ab	32.8ab	9.5ab	0a	0a
2014									
Control	-	0d	0d	4.4c	12.4c	34.0c	5.5bc	0b	2.0c
O2	77.8	165c	35c	5.3c	14.6c	35.0c	6.7b	0b	4.6bc
O3	155.5	383b	52b	6.3c	14.2c	37.4c	9.5a	0b	4.0bc
S1	31.2	3493a	95a	16.8a	32.0b	46.2b	8.6a	0b	15.2b
S2	77.8	3759a	96a	14.7ab	35.0ab	51.8a	5.9bc	0b	35.4a
S3	155.5	3649a	96a	15.4a	35.6ab	51.2a	5.5bc	0.4b	32.4a
S4	311.5	3501a	95a	10.9b	36.8a	54.8a	4.5c	2.4a	42.8a

[1]Means within columns and years followed by the same letter do not differ at *P≤0.05* according to Fisher's LSD
[a]Treatments designated by date of seeding and seeding rate where: O = October; S = September; 1-4 are seeding rates
[b]Emergence is calculated as percent of the total seed added to each plot
[c]Time to 10% emergence in days after May 6, 2013 and April 22, 2014
[d]Time to 50% emergence


120
100
80
60
40
20
0
ground cover (%)
0
1000
2000
3000
4000
5000
6000
biomass (kg ha-1)
Biomass (kg/ha) vs Rye cover - 0
Biomass (kg/ha) vs Rye cover - 1
Biomass (kg/ha) vs Rye cover - 2
Biomass (kg/ha) vs Rye cover - 4
Biomass (kg/ha) vs Rye cover - 5
Biomass (kg/ha) vs Rye cover - 6
x column 1 vs y column 1

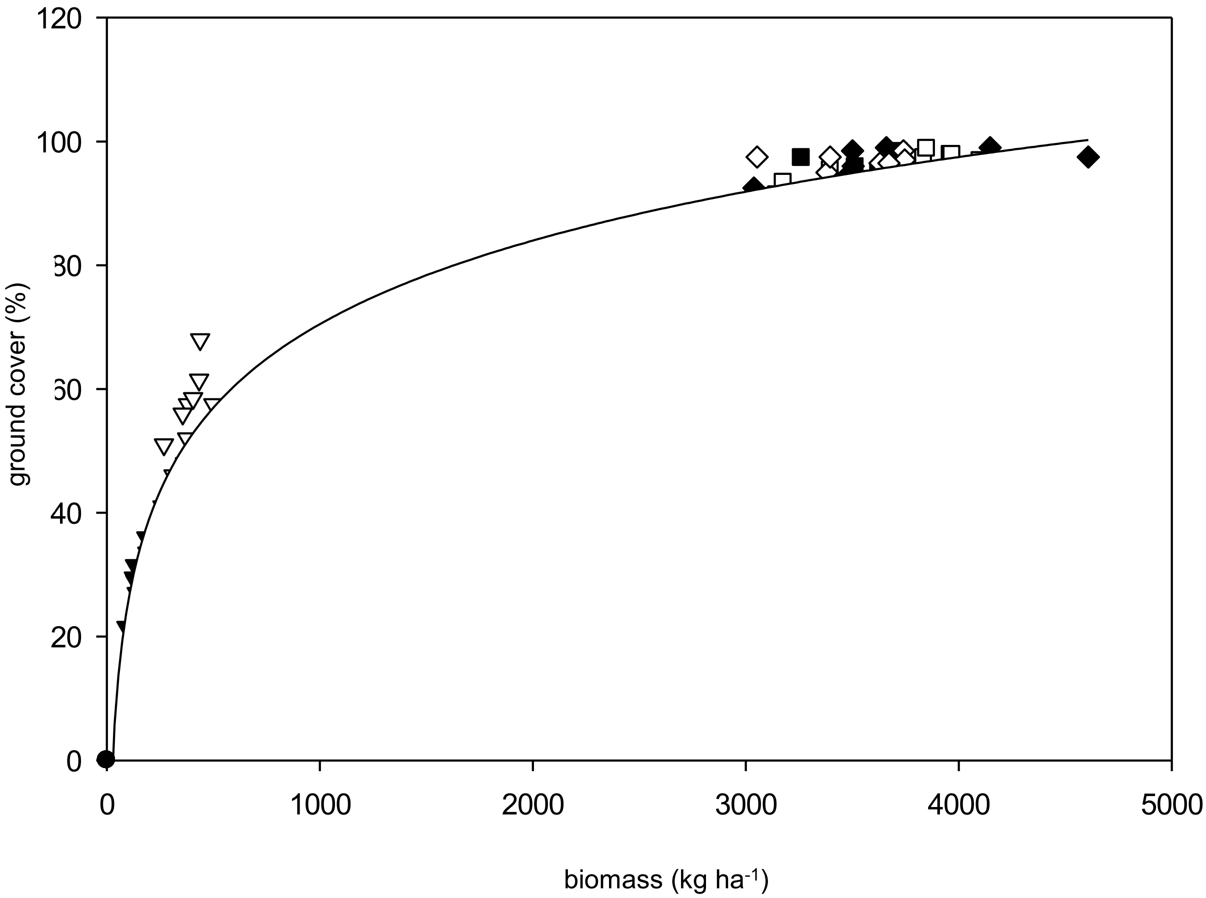


Figure 3. Relationship between percent cover at time of rye termination (May 5, 2014) and biomass (kg ha^{-1}) removed from each plot by rye treatment. Control (●), treatment O2 (▼), treatment O3 (▽), treatment S1 (■), treatment S2 (□), treatment S3 (◆), and treatment S4 (◇) biomass were fit to a logarithmic regression line with equation $y = 19.5\ln(\text{abs}(x)) - 64$ and $R^2 = 0.99$. Treatments are designed by date of seeding and seeding rate where: O = October; S = September; 1-4 are seeding rates.

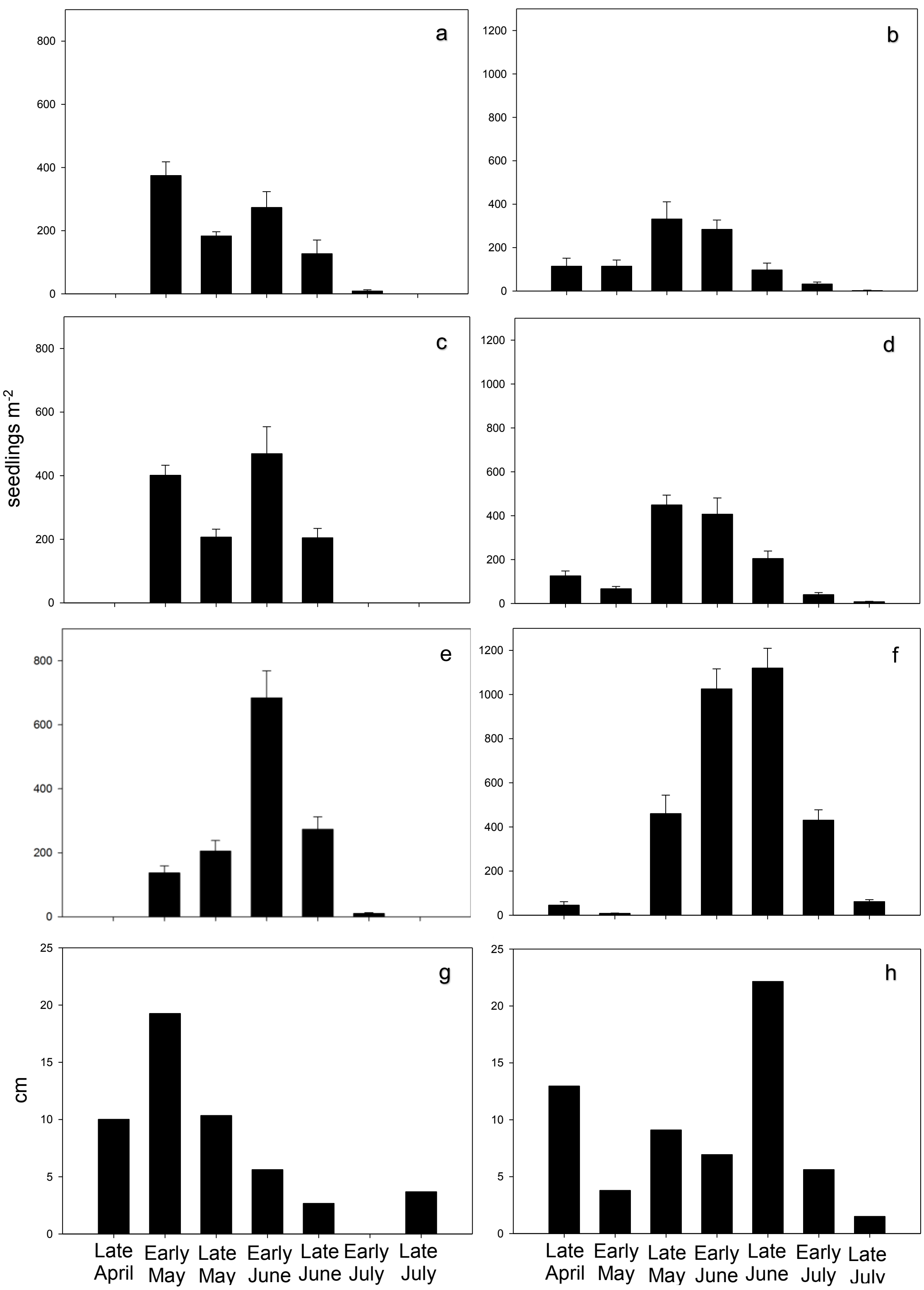


Figure 4. Common waterhemp emergence patterns as affected by cereal rye planted on two dates. a = 2013 control; b = 2014 control; c = 2013 October seeding date; d = 2014 October seeding date; e = 2013 September seeding date; f = 2014 September seeding date. Bars represent standard error of means. Precipitation for 2013 (g) and 2014 (h) are provided.

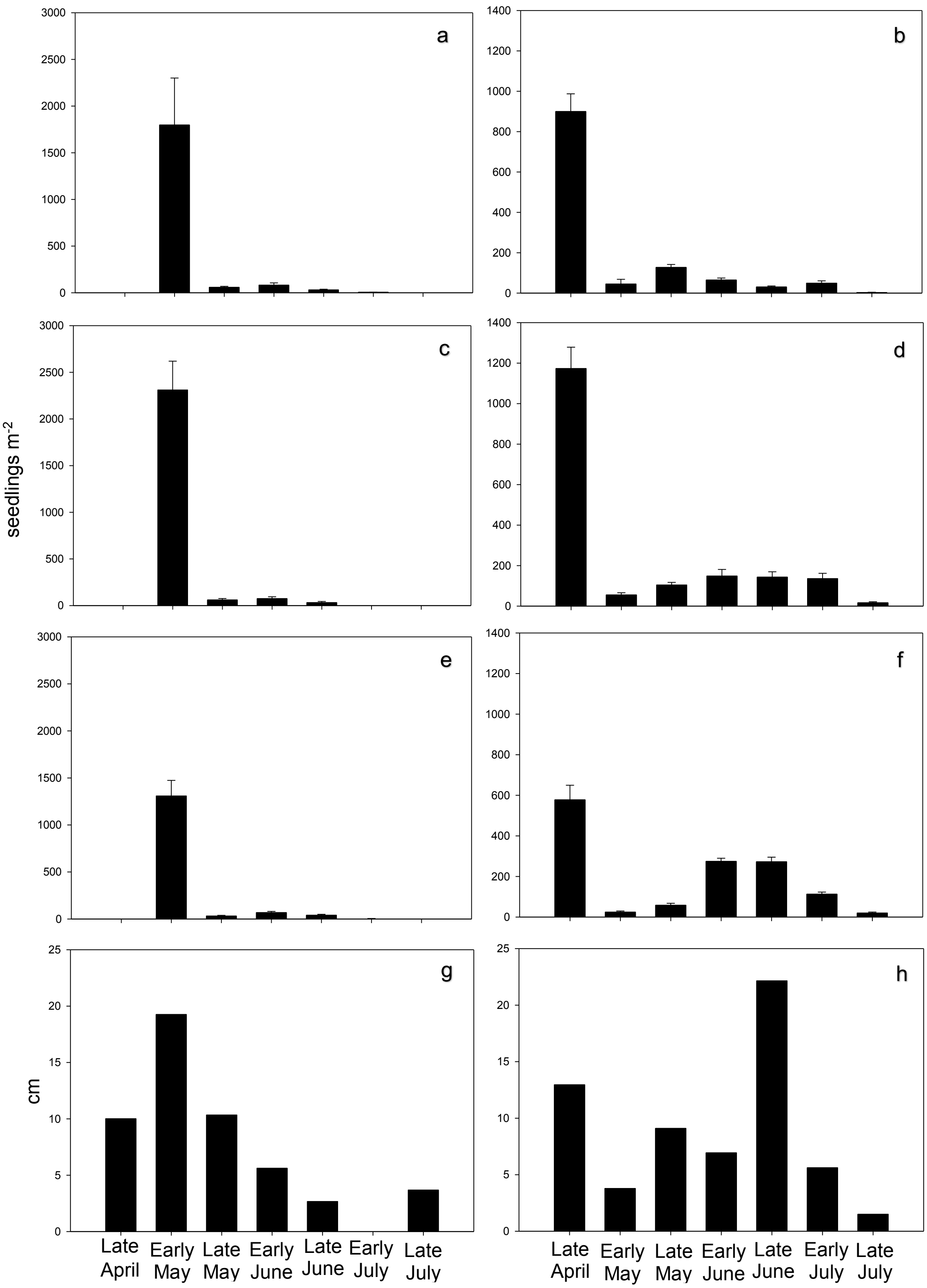


Figure 5. Common lambsquarters emergence patterns as affected by cereal rye planted on two dates. a = 2013 control; b = 2014 control; c = 2013 October seeding date; d = 2014 October seeding date; e = 2013 September seeding date; f = 2014 September seeding date. Bars represent standard error of means. Precipitation for 2013 (g) and 2014 (h) are provided.

CHAPTER III: HERBICIDE EFFECTS ON ESTABLISHMENT OF FIVE COVER CROPS

Abstract

The effects of low rates of eleven corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] herbicides were evaluated on five cover crops: cereal rye (*Secale cereale* L.), oat (*Avena sativa* L.), hairy vetch (*Vicia villosa* Roth), lentil (*Lens culinaris* Medik.), and radish (*Raphanus sativus* L.). Cereal rye was the most tolerant of all species evaluated. Radish was the most sensitive of the cover crops to the herbicides. Dry weight of radish was severely reduced by nearly all herbicides, whereas other cover crop species had smaller reductions in dry weight. Root growth of oat was inhibited more by pendimethalin than the other species. Flumetsulam + clopyralid, atrazine, and herbicides containing isoxaflutole caused significant injury to most species studied. Though it is difficult to make direct comparisons between these experiments and the potential for injury in the field, these studies provide guidelines for growers wanting to include cover crops within their current cropping system.

Introduction

Small grain, legume, and Brassica cover crops are rarely used in the corn (*Zea mays* L.) monocultures or corn-soybean [*Glycine max* (L.) Merr.] rotations of the Midwest; however, interest in these cover crops in recent years has increased. The United States Department of Agriculture (USDA) and the Iowa Department of Agriculture and Land Stewardship (IDALS) have offered economic incentives to plant a cover crop, thus amplifying interest in cover crops, primarily cereal rye (*Secale cereale*

L.). The Environmental Quality Incentives Program (EQIP) is one available program that provides growers payments for the establishment and termination of cover crops for up to three years (Goldsmith 2014). This program assists growers in the initial years of growing a cover crop with the hope they will recognize the benefits of the cover crops and continue establishing them after the program ends.

Growers also have increased interest in using cover crops for the environmental benefits they provide. Proposed benefits of cover crops include that legumes contribute nitrogen via biological fixation, radishes break up soil compaction, and cereal rye and other grasses produce large root systems that reduce soil erosion and nutrient losses. The Iowa Nutrient Reduction Strategy lists such benefits as wildlife habitat, soil erosion protection, reduction in losses of nitrogen and phosphorus, and other benefits to soil health with cereal rye cover crops (Anonymous 2013). Farmer responses to a Sustainable Agriculture, Research, & Education (SARE) survey most commonly cited the term “soil health” when describing the purpose of using a cover crop (Myers et al. 2013). Reductions in soil compaction (58%) and soil erosion (56%), and nitrogen scavenging (41%) were the top three cover crop benefits from cover crops cited. Researchers have looked at the effects of many popular cover crops on soil quality. Snapp et al. (2005) summarized benefits of cover crops, including soil erosion protection, nitrate leaching reduction, and improving the soil environment. Kaspar and Singer (2011) also described the benefits of cover crops to soil health and nutrient management. Specific benefits of the cover crops vary among species, production system, and environment.

Herbicides are commonly used in crop fields. Fernandez-Cornejo et al. (2014) reported that over 97% of acres planted to corn and 98% of acres planted to soybeans were treated with herbicides in the United States in 2006. The presence of herbicide resistant weeds has led to an increase in the use of and diversity of these crop protection tools. A primary concern of farmers considering adopting cover crops is the impact of herbicides on the establishment of cover crops.

Many herbicides used during corn and soybean production pose a risk to crops planted the following spring. Examples include atrazine (Buchanan and Hiltbold 1973, Burnside and Wicks 1980, Rauch et al. 2007), trifluralin (Burnside 1974, Gaynor 1985, Hartzler et al. 1989, Rogers et al. 1986, Wilson et al. 1995), imazethapyr (Greenland 2003, Loux and Reese 1993, Loux et al. 1989, Moyer et al. 2010, Walsh et al. 1993), and fomesafen (Cobucci et al. 1997, 1998, Johnson and Talbert 1993, Rauch et al. 2007).

Growers need to consider the potential for herbicides used in corn and soybean to injure fall-seeded cover crops. Herbicide labels include information regarding crop rotation intervals; however, crops listed on the label are generally limited to those most commonly planted after corn or soybean [e.g. alfalfa (*Medicago sativa* L.), small grains, corn, soybean]. If the crop is not explicitly labeled on the rotation restrictions portion of the herbicide label, the grower accepts liability for failed establishment when planting a cover crop following the herbicide application. Furthermore, label restrictions may pertain to herbicide residues accumulating in cover crops intended for grazing or forage, rather than the risk the herbicides pose to cover crop establishment. Thus, growers have little information to evaluate the risks associated with establishing cover crops following herbicide applications in corn or soybean.

Another consideration is planting of cover crops on fields intended for corn or soybean that were unable to be planted due to weather conditions. The shorter time period between herbicide application and cover crop planting increases the likelihood of crop injury. These situations require managers to consider their herbicide program carefully when planning for a cover crop following the herbicide application.

The risk posed to cover crops is determined by herbicide concentration and availability, and sensitivity of the species to the herbicide. After application to soil, herbicides begin to degrade. Herbicide chemical properties, environmental conditions, and soil characteristics, including biological activity, soil texture, soil pH, and organic matter content, all affect the degradation rate of a particular herbicide (Gillespie et al. 2011). These factors are important in determining the herbicide half-life, the amount of time the herbicide requires to degrade to half its original concentration in the soil. Herbicides with longer half-lives provide extended weed control during the crop season. It is when these herbicides persist at phytotoxic concentrations late into the growing season that herbicide injury to cover crops becomes a concern.

Herbicide degradation is influenced by many factors, and the relative importance of these processes varies among herbicides. For example, the persistence of atrazine and chlormimuron is strongly affected by soil pH. In the case of chlorimuron, persistence increases at high pH due to the lack of chemical hydrolysis. Chlorimuron is broken down by both hydrolysis and biological processes in neutral and acid soils, resulting in much shorter half-lives in these soils (Beyer et al 1988, Goetz et al. 1989, Newsom and Shaw 1992, Schroeder 2014, Wiese et al. 1988). Soil adsorption of atrazine increases under low pH conditions, resulting in more rapid degradation (McGlamery and Slife 1966). In contrast, mesotrione degrades more rapidly under alkaline conditions (Dyson et al. 2002, Riddle et al. 2013). Loux et al. (1993) reported that the risk of carryover of imidazolinone herbicides was influenced by soil type.

Many herbicides are degraded primarily by microbial degradation, thus their persistence increases greatly during dry conditions that limit soil biological activity. Most herbicides are labeled at a range of rates, the risk of toxic residues remaining in the soil is directly related to the rate applied. Since the factors that influence degradation vary widely among herbicides, each compound must be evaluated based on its characteristics and the rate applied.

The other factor that determines the potential for injury is the sensitivity of the species planted. Cover crops are at a higher risk for injury than spring planted rotational crops due to the shorter interval between herbicide application and planting. Furthermore, a plant's ability to tolerate stress during establishment is directly related to its seed size (Muller-Landau 2010). Many species used as cover crops have relatively small seed, making them more susceptible to herbicide residues and other stressors than larger seeded plants.

Much of the previous research involving herbicides and cover crops examined the effect of a cover crop on herbicide degradation and performance. Banks and Robinson (1982) found that the presence of wheat straw decreased the amount of herbicide that reached the soil surface and thus could result in reduced weed control. Teasdale et al. (2003) found that hairy vetch residue reduced the concentration of metolachlor in the soil but had no effect on atrazine concentration. Chlorimuron-ethyl was retained by cereal rye and hairy vetch residues, preventing the herbicide from immediately reaching the soil surface (Reddy et al. 1995). This research illustrates some of the interactions that may occur when cover crops are introduced to systems relying on herbicides for weed management.

Only recently have researchers investigated possible residual effects of herbicides on fall seeded cover crops, and to the author's knowledge no research has been published in a peer-reviewed journal. However, information from the University of Missouri and Pennsylvania State University Extension is readily available on the internet (Bradley 2013, Curran 2013). Bradley (2013) studied herbicide effects on establishment of eight cover crops. He found that radish was the most sensitive species whereas cereal rye was the least affected species by both corn and soybean herbicide programs. Curran (2013) reported no problems with the establishment of oat, wheat, or rye in the fall following spring herbicide application. Curran (2013) also evaluated reduced rates of herbicides to mimic herbicide carryover and found that radish was highly sensitive to most herbicides tested, even at rates as low as 1/8 of the labeled rate. Under these conditions atrazine reduced growth of most cover crops tested, and *S*-metolachlor reduced cereal rye growth more than oat (Curran 2013). Curran and Lingenfelter (2012) produced a table of herbicide half-lives, and described specific combinations of concern for many common residual herbicides and cover crop species. Their information was compiled from other scientific literature and the Weed Science Society of America Handbook (Weed Science Society of America 2007).

It is important to study the effects of persistent herbicides used in the Midwest to generate information for growers hoping to use fall cover crops after using herbicides during corn or soybean production. The purpose of this study was to evaluate sensitivities of five cover crops to low rates (1/8X to 1/2X) of common corn and soybean herbicides. Plant injury rating and plant weight data collected provide information regarding relative sensitivity of crops to herbicides and herbicides of concern for use prior to these cover crop species. This information can help growers develop strategies that reduce risks associated with integrating cover crops into current production systems.

Materials and Methods

Cover crop seed[3] was obtained by Practical Farmers of Iowa in July 2013 and were kept in cold storage at approximately 4°C until time of seeding. Seed cleaning was necessary to remove immature, damaged, and other seed. A warm germination test was performed on all seed in August 2013 prior to the initiation of experiments. Cereal rye (*Secale cereale* L.), oat (*Avena sativa* L. var. Rockford), lentil (*Lens culinaris* Medik. var. Richlea green), and radish (*Raphanus sativus* L. var. Nitro™) had germination percentages greater than 90%, while hairy vetch (*Vicia villosa* Roth var. Vallana) had a germination rate of approximately 65%.

Greenhouse flats measuring 22.5 cm by 36.9 cm by 5.8 cm depth were prepared for experiments by lining the bottom with a brown paper towel. Flats were filled with a loam field soil obtained from an Iowa State University farm in Ames, Iowa and were

[3] Green Cover Seed, Bladen, Nebraska

sprayed with 0, 1/8, 1/4, 3/8, and 1/2 times the recommended label rate of herbicides. Herbicide was sprayed on the soil surface using a laboratory track sprayer, soil was then removed from the flat, the herbicide was mixed thoroughly in the soil, and then the soil was returned to the flat the same day. Recommended label rates of each herbicide used for the calculation of reduced rates are listed in Table 4. Corn herbicides studied were commercial formulations of atrazine (Aatrex® 90DF), isoxaflutole (Balance® Flexx), mesotrione (Callisto®), tembotrione (Laudis®), *S*-metolachlor (Dual II Magnum®), thiencarbazone-methyl + isoxaflutole (Corvus®), and flumetsalem + clopyralid (Hornet® WDG). The soybean herbicides evaulated were commercial formulations of pendimethalin (Prowl® H_2O), chlorimuron-ethyl (Classic®), imazethapyr (Pursuit®), and fomesafen (Reflex®). Individual experiments with four replications were conducted for each of the 11 herbicides, and each experiment was repeated twice. A control, the zero rate, was used for each herbicide experiment.

Ten seed of each cover crop were planted in rows with a 7 cm spacing and each seed within a row approximately 1.5 cm apart. Seeds were covered with approximately 0.6 cm of the soil. Flats were arranged in greenhouse in a randomized complete block design under 16/8 hours of light/dark and were watered from above as needed for the duration of the experiment.

Visual injury ratings were recorded at 7, 14, 21, and 28 days after planting, while stand counts were recorded until a maximum emergence for each species was reached, approximately 14 days after trial initiation. Injury ratings were on a 1 to 5 scale where 1 = normal plant growth; 2 = abnormal plant growth not definitively related to herbicide injury (plant yellowing, stunted growth); 3 = minor herbicide-related injury; 4 = severe herbicide-related injury; and 5 = significant herbicide-related injury and greater than 50 percent plant death. Plants were harvested at ground level after 28 days and oven dried for 72 hours at approximately 60°C. Biomass was then weighed and converted to a weight per plant based on the number of seedlings for each species in an experimental unit (greenhouse flat).

Trials with pendimethalin were terminated 7 days after planting with the harvest of plants. Root length of each germinated seedling was measured due to the effect of pendimethalin on root cell division and elongation (Parka and Soper 1977) and was used to determine whether root growth was inhibited by the herbicide.

Data were analyzed as a split-plot in time design using the MIXED procedure of SAS for all herbicides except pendimethalin (SAS Institute 2014). After performing this analysis, only results from the day 28 injury evaluation were analyzed using the MIXED procedure for presentation in this thesis. Experiment and repetition were analyzed as random variables, with cover crop and rate analyzed as fixed variables. A square root transformation was performed but did not result in different results, so non-transformed data were analyzed. Plant weight data required a natural log transformation to reduce skew and normalize data. Plant weight was also analyzed using the MIXED procedure to determine whether increasing herbicide rates significantly reduced plant biomass. Non-transformed data are presented in tables with means comparison of transformed data at a significance of $P \leq 0.05$. Pendimethalin data were summarized by collecting the average root length for each herbicide rate by crop replication and analyzed using the generalized linear model in SAS with means separation at a significance of $P \leq 0.05$ (SAS Institute 2014).

Results and Discussion

The objective of this research was to determine the sensitivity of five cover crop species to herbicides commonly used in Iowa corn and soybean production. Our hypothesis was that higher rates of herbicides will result in greater inhibition of susceptible cover crops, and the goal was to identify herbicides that posed a high risk to specific cover crops.

Atrazine caused visible injury and reduced weight on all species (Table 5). Oat, radish and lentil scored injury ratings of 3 or higher at the 1/8X atrazine rate and ratings of 4 or more at rates higher than 1/4X. Greater than 50% plant death was observed in lentil at the 1/2X rate and in radish and oat at rates greater than or equal to 1/4X. Cereal rye had the lowest injury ratings of the five cover crops. Rye has a higher tolerance to atrazine than other small grains (R. G. Hartzler, personal communication)

Flumetsulam + clopyralid caused visible injury and reduced dry weight to hairy vetch, lentil, and radish (Table 6). Herbicide injury ratings were greater than 4 on lentil at rates higher than 1/8X. Hairy vetch and radish had injury ratings greater than 3 at all flumetsulam + clopyralid rates higher than 1/8X, and hairy vetch had greater than 50% plant death (injury rating 5) at the 1/2X rate. Greater than 50% plant death did not occur in radish, but biomass was reduced by at least 85% at all rates. Grasses did not show visible injury symptoms and dry weights were not reduced compared to the control, suggesting they have higher tolerance to flumetsulam + clopyralid than broadleaves. Oat exposed to the 1/8X rate had an increase in dry weight compared to the control.

Isoxaflutole caused visible injury to all species with the exception of cereal rye, but only reduced dry weight of hairy vetch, lentil, and radish (Table 7). Injury ratings of

3 or higher were observed with the 1/8X rate of isoxaflutole in hairy vetch, lentil, and radish. At 3/8X rate or higher of isoxaflutole, injury ratings of 4 or greater were observed in those crops. Dry weight of hairy vetch, lentil, and radish decreased with increasing isoxaflutole rates. Oat demonstrated low levels of injury from isoxaflutole, with ratings ranging from 1.6 to 2.1. Hairy vetch, lentil, and radish were highly sensitive to isoxaflutole, while cereal rye and oat were more tolerant.

Mesotrione caused visible injury to hairy vetch, lentil, and radish, but only reduced plant dry weight in radish and hairy vetch (Table 8). Injury ratings of 3 or higher in those three crops were observed at all mesotrione rates above 1/8X and those ratings increased to 4 at 1/2X. Radish dry weight decreased by approximately 50% with all mesotrione rates. Hairy vetch dry weight was reduced with exposure to the 1/8X and 1/2X rate. Cereal rye and oat both had no visible injury or reduction in dry weight.

Cereal rye was the only species affected by *S*-metolachlor (Table 9). Injury ratings of 3 or higher were observed in all herbicide rates 1/8X or higher, but dry weight was only reduced at rates greater than or equal to 1/4X. Cereal rye injury caused by *S*-metolachlor was typical for the herbicide, including improper leaf unfurling. This result is especially interesting, as it caused little to no damage to oat, a crop that is typically more sensitive to herbicides than cereal rye.

Tembotrione caused visible injury to hairy vetch, lentil, and radish, but only reduced dry weight in lentil and radish (Table 10). Injury ratings of 3 or greater were only observed in hairy vetch with greater than or equal to a 3/8X rate of tembotrione, but were observed in radish at rates as low as 1/4X and in lentil at rates as low as 1/8X. Lentil dry weight was reduced at the 1/2X rate. Of the three crops affected, hairy vetch had lower injury ratings than lentil and radish. Cereal rye and oat were not affected by tembotrione.

Thiencarbazone-methyl + isoxaflutole caused visible injury and reduced plant weight to all crop species (Table 11). This herbicide caused serious plant injury with symptoms of reduced plant growth and bleaching of leaves. Injury ratings were lowest in cereal rye, with only the 1/2X rate of thiencarbazone-methyl + isoxaflutole causing significant injury. Oat had injury ratings of greater than 3 at all herbicide rates and significant reductions in dry weight at herbicide rates greater than or equal to 1/8X. Hairy vetch had injury ratings greater than 3 at the 1/4X herbicide rate and injury ratings were greater than 4 at the 1/2X herbicide rate. Hairy vetch dry weight was reduced at rates of 1/4X or higher. Lentil and radish were the most sensitive crops evaluated to thiencarbazone-methyl + isoxaflutole. Both crops had injury ratings of 4 or greater at or above the 1/4X herbicide rate. Lentil dry weight and radish dry weight were affected at all herbicide rates. Radish dry weight was reduced by more than 90% at rates greater than 1/8X. Injury ratings for the dicot species were similar between isoxaflutole by itself (Table 7) and the combination of thiencarbazone-methyl + isoxaflutole (Table 11). The two grass species were injured more by the combination product than isoxaflutole alone, and oat was more sensitive than rye.

Chlorimuron-ethyl caused visible injury in four species and reduced dry weight in only two of those (Table 12). Oat was unaffected by exposure to chlorimuron-ethyl. Cereal rye demonstrated low levels of injury at only the 1/2X rate. Hairy vetch also demonstrated low levels of injury at only the 3/8X rate. Lentil had visible injury ratings of 3 or higher at herbicide rates greater than or equal to 3/8X, and dry weight was reduced by exposure to the herbicide. Radish had injury ratings of greater than 3 at all rates and injury ratings of 4.0 were observed at both the 3/8X and 1/2X herbicide rate. Radish dry weight was reduced by 90% or more with exposure to any rate of chlorimuron-ethyl.

Fomesafen caused significant injury to lentil and radish and reduced dry weight of radish (Table 13). Visible injury was observed on lentil at rates of 1/4X or greater, but injury ratings were 2.0 or less. Lentil dry weight was unaffected by fomesafen. Visible injury ratings of 4 were observed on radish at the 1/4X herbicide rate, and greater than 50% plant death (injury rating 5) occurred with exposure to the 3/8X and 1/2X herbicide rates. Radish dry weight was reduced by more than 90% in the 3/8X and 1/2X fomesafen rates.

Imazethapyr caused visible injury to four species and reduced dry weight in only oat and radish (Table 14). Cereal rye was unaffected by any rate of imazethapyr. Injury rating was increased to two or less in oat at the 3/8X and 1/2X rate and in hairy vetch and lentil at the 1/2X rate. Oat dry weight was reduced at only the 3/8X rate. Injury ratings greater than 3 were recorded for the 3/8X and 1/2X rate in radish, but dry weight was reduced by between 75% (1/8X) and 85% (1/2X) with any exposure by imazethapyr.

Pendimethalin injury was determined by measuring root length since it inhibits cell division in roots of sensitive species (Parka and Soper 1977). Any effect on shoots is due to inhibited root growth. Pendimethalin caused a reduction in root length in both cereal rye and oat, whereas the dicot species were unaffected (Table 15). Cereal rye root length was reduced at only the 1/2X rate of pendimethalin. Oat root length was reduced with exposure to any rate of pendimethalin, and at the 1/2X rate, it was less than 50% of the control root length.

Cereal rye was the most tolerant of the five cover crops to the herbicides evaluated, with injury occurring with only four of the herbicides. Radish was the most sensitive, with nine of the 11 eleven herbicides causing both visible injury and reductions in dry weight. Atrazine was the only herbicide to affect growth of all species, whereas significant responses were only observed on one species with *S*-metolachlor and imazethapyr.

With the exception of radish, dry weight was less responsive than injury ratings to the herbicides evaluated. Two possible explanations exist for the lack of significance in dry weight data compared to visible injury ratings. Crops were only grown for 28 days for each experiment, so while injury symptoms were observed on many plants at higher herbicide rates, they may not have grown for a long enough time for control plants to accumulate greater biomass than plants exposed to herbicide. The second explanation is that the cover crops were grown in plastic flats in the greenhouse, which likely restricted crop root growth and resulted in competition among plants with the 28 days. If grown in a larger experimental unit, differences in plant weight may show more significance in crops other than radish at the completion of the experiment.

Summary and Conclusions

These experiments provide information on the relative sensitivity of five cover crops to eleven commonly used herbicides in Iowa corn and soybean production. Since degradation and availability of herbicides varies greatly following field applications, it is difficult to make strong inferences to risks associated with establishing cover crops following use of the herbicides studied based on this research. An example of this is the damage observed on rye caused by *S*-metolachlor (Table 9). Under field conditions in central Iowa, rye has successfully been established following *S*-metolachlor with no evidence of field injury (K. Kohler, personal communication). These ratings, combined with other available information (Curran and Lingenfelter 2012), can be used to establish guidelines for growers with intentions of using these cover crops following use of these herbicides.

Cereal rye is the most tolerant crop to the herbicides evaluated, but the greatest potential for injury with rye exists following atrazine, pendimethalin, and *S*-metolachlor applications. Oat is more sensitive to most herbicides than cereal rye. Atrazine, thiencarbazone-methyl + isoxaflutole, and pendimethalin are most likely to reduce growth of oat, but isoxaflutole could also cause injury. Concern exists for establishing hairy vetch following use of atrazine, isoxaflutole, mesotrione, tembotrione, and thiencarbazone-methyl + isoxaflutole. Due to significant injury and potential for persistence late into the season, establishment of hairy vetch following applications of flumetsulam + clopyralid is not recommended. Lentil growth is likely to be reduced by all herbicides of concern for hairy vetch, plus chlorimuron-ethyl, and establishment following use of flumetsulam + clopyralid is again not suggested. All herbicides tested, with the exception of S-metolachlor and pendimethalin, caused significant injury to radish in these experiments. Growers should carefully consider application timing, herbicide rate, soil type, and environmental conditions prior to seeding radish following any of these herbicide applications. Establishment of radish following flumetsulam + clopyralid, isoxaflutole, and thiencarbazone-methyl + isoxaflutole is not advised.

Much more opportunity exists for future study of herbicide effects on cover crops. Establishing experiments on different soil types with spring-applied herbicides and fall-seeded cover crops would be of interest for growers, as this research only uses a single loam soil from central Iowa. Environmental conditions also vary from one season to the next, making long-term experiments more useful, because soil type is only one important factor in determining soil persistence of herbicides.

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Table 4. Corn and soybean herbicides and rates used for greenhouse experiment.

Herbicide	Commercial formulation	Label rate[1]	Active ingredient
Corn products			g ha^{-1}
atrazine	Aatrex® 90DF	1.1 lb	1120
isoxaflutole	Balance® Flexx	5 fl oz	88
mesotrione	Callisto®	3 fl oz	105
thiencarbazone-methyl + isoxaflutole	Corvus®	5.6 fl oz	92 + 37
s-metolachlor	Dual II Magnum®	1.5 pt	1610
flumetsalem + clopyralid	Hornet®	5 oz	17 + 175
tembotrione	Laudis®	3 fl oz	92
Soybean products			
chlorimuron-ethyl	Classic®	1 oz	17
pendimethalin	Prowl® H_2O	3 pt	1600
imazethapyr	Pursuit®	4 fl oz	70
fomesafen	Reflex®	1.25 pt	350

[1]Rate provided on a product $acre^{-1}$ basis

Table 5. Response of five cover crops to preemergence applications of atrazine (1X rate: 1.1 kg ha^{-1})[1].

Rate	Cereal rye	Oat	Hairy vetch	Lentil	Radish
	dry weight (g $plant^{-1}$)				
Control	0.08a[2]	0.11a	0.06a	0.05a	0.39a
1/8 X	0.04ab	0.02b	0.08a	0.04ab	0.01b
1/4 X	0.03b	0.01c	0.06ab	0.02bc	0.01c
3/8 X	0.04ab	0.01c	0.03b	0.02c	0.00d
1/2 X	0.03b	0.01c	0.03b	0.01c	0.00d
	Injury rating (1-5)[3]				
Control	1.0a	1.0a	1.0a	1.1a	1.4a
1/8 X	1.8ab	3.1b	1.5ab	3.5b	4.8b
1/4 X	2.6bc	4.9c	2.3b	4.5c	5.0b
3/8 X	2.3b	4.8c	3.3c	4.3bc	5.0b
1/2 X	2.8c	5.0c	3.4c	4.9c	5.0b

[1]experiments were conducted in greenhouse and data collected 28 days after planting
[2]means in the same column and section followed by the same letter are not significantly different at *P≤0.05*
[3]1 = normal plant growth; 2 = abnormal plant growth not definitively related to herbicide injury (plant yellowing, stunted growth); 3 = minor herbicide-related injury; 4 = severe herbicide-related injury; and 5 = significant herbicide-related injury and greater than 50 percent plant death

Table 6. Response of five cover crops to preemergence applications of flumetsulam + clopyralid (1X rate: 17 + 175 g ha^{-1})[1].

Rate	Cereal rye	Oat	Hairy vetch	Lentil	Radish
	dry weight (g $plant^{-1}$)				
Control	0.16a[2]	0.21a	0.05a	0.06a	0.68a
1/8 X	0.18a	0.30a	0.03b	0.02b	0.10b
1/4 X	0.14a	0.29a	0.01c	0.00c	0.06b
3/8 X	0.15a	0.24a	0.00d	0.00cd	0.05b
1/2 X	0.14a	0.25a	0.00e	0.00d	0.05b
	Injury rating (1-5)[3]				
Control	1.0a	1.0a	1.8a	1.8a	1.3a
1/8 X	1.0a	1.0a	3.0b	4.0b	3.3b
1/4 X	1.0a	1.0a	3.9c	4.9c	3.6bc
3/8 X	1.3a	1.1a	3.3c	5.0c	3.6bc
1/2 X	1.1a	1.3a	5.0c	4.3c	3.9c

[1]experiments were conducted in greenhouse and data collected 28 days after planting
[2]means in the same column and section followed by the same letter are not significantly different at $P \leq 0.05$
[3]1 = normal plant growth; 2 = abnormal plant growth not definitively related to herbicide injury (plant yellowing, stunted growth); 3 = minor herbicide-related injury; 4 = severe herbicide-related injury; and 5 = significant herbicide-related injury and greater than 50 percent plant death

Table 7. Response of five cover crops to preemergence applications of isoxaflutole (1X rate: 88 g ha^{-1})[1].

Rate	Cereal rye	Oat	Hairy vetch	Lentil	Radish
	dry weight (g $plant^{-1}$)				
Control	0.11a[2]	0.14a	0.06a	0.07a	0.48a
1/8 X	0.11a	0.12a	0.02b	0.03ab	0.21b
1/4 X	0.09a	0.11a	0.02b	0.02b	0.13bc
3/8 X	0.10a	0.11a	0.01b	0.02b	0.09cd
1/2 X	0.09a	0.11a	0.01b	0.02b	0.08d
	Injury rating (1-5)[3]				
Control	1.0a	1.0a	1.0a	1.4a	1.5a
1/8 X	1.0a	1.6b	3.4b	3.8b	3.9b
1/4 X	1.1a	1.8b	3.5b	4.1b	4.4bc
3/8 X	1.0a	2.1b	4.1c	4.3b	4.5c
1/2 X	1.3a	2.1b	4.3c	4.3b	4.3bc

[1]experiments were conducted in greenhouse and data collected 28 days after planting
[2]means in the same column and section followed by the same letter are not significantly different at $P \leq 0.05$
[3]1 = normal plant growth; 2 = abnormal plant growth not definitively related to herbicide injury (plant yellowing, stunted growth); 3 = minor herbicide-related injury; 4 = severe herbicide-related injury; and 5 = significant herbicide-related injury and greater than 50 percent plant death

Table 8. Response of five cover crops to preemergence applications of mesotrione (1X rate: 105 g ha^{-1})[1].

Rate	Cereal rye	Oat	Hairy vetch	Lentil	Radish
	dry weight (g $plant^{-1}$)				
Control	0.11a[2]	0.11a	0.03a	0.05a	0.64a
1/8 X	0.11a	0.11a	0.01b	0.03a	0.31b
1/4 X	0.11a	0.14a	0.02ab	0.02a	0.31b
3/8 X	0.11a	0.13a	0.02ab	0.02a	0.29b
1/2 X	0.11a	0.13a	0.02b	0.03a	0.32b
	Injury rating (1-5)[3]				
Control	1.0a	1.0a	1.1a	1.0a	1.0a
1/8 X	1.1a	1.1a	3.6b	3.0b	3.1b
1/4 X	1.1a	1.1a	3.8b	3.9c	3.6bc
3/8 X	1.0a	1.0a	3.8b	3.6bc	3.6bc
1/2 X	1.3a	1.1a	4.0b	3.9c	3.9c

[1]experiments were conducted in greenhouse and data collected 28 days after planting
[2]means in the same column and section followed by the same letter are not significantly different at $P \leq 0.05$
[3]1 = normal plant growth; 2 = abnormal plant growth not definitively related to herbicide injury (plant yellowing, stunted growth); 3 = minor herbicide-related injury; 4 = severe herbicide-related injury; and 5 = significant herbicide-related injury and greater than 50 percent plant death

Table 9. Response of five cover crops to preemergence applications of *S*-metolachlor (1X rate: 1.6 kg ha^{-1})[1].

Rate	Cereal rye	Oat	Hairy vetch	Lentil	Radish
	dry weight (g $plant^{-1}$)				
Control	0.16a[2]	0.12a	0.05a	0.06a	0.55b
1/8 X	0.08b	0.12a	0.04a	0.06a	0.61ab
1/4 X	0.06bc	0.09a	0.05a	0.06a	0.66a
3/8 X	0.04cd	0.09a	0.05a	0.07a	0.65a
1/2 X	0.03d	0.09a	0.05a	0.06a	0.62ab
	Injury rating (1-5)[3]				
Control	1.0a	1.0a	1.0a	1.5a	1.0a
1/8 X	3.0b	1.0a	1.0a	1.1a	1.0a
1/4 X	3.4bc	1.0a	1.3a	1.4a	1.4a
3/8 X	3.5bc	1.3a	1.0a	1.0a	1.0a
1/2 X	3.9c	1.3a	1.0a	1.0a	1.0a

[1]experiments were conducted in greenhouse and data collected 28 days after planting
[2]means in the same column and section followed by the same letter are not significantly different at *$P \leq 0.05$*
[3]1 = normal plant growth; 2 = abnormal plant growth not definitively related to herbicide injury (plant yellowing, stunted growth); 3 = minor herbicide-related injury; 4 = severe herbicide-related injury; and 5 = significant herbicide-related injury and greater than 50 percent plant death

Table 10. Response of five cover crops to preemergence applications of tembotrione (1X rate: 92 g ha^{-1})[1].

Rate	Cereal rye	Oat	Hairy vetch	Lentil	Radish
	dry weight (g $plant^{-1}$)				
Control	0.11a[2]	0.13a	0.04a	0.07a	0.78a
1/8 X	0.12a	0.16a	0.05a	0.06ab	0.49b
1/4 X	0.14a	0.18a	0.03a	0.05ab	0.36b
3/8 X	0.14a	0.20a	0.03a	0.05ab	0.43b
1/2 X	0.13a	0.18a	0.03a	0.03b	0.22c
	Injury rating (1-5)[3]				
Control	1.0a	1.0a	1.5a	1.4a	1.4a
1/8 X	1.0a	1.0a	2.0ab	3.1b	2.9b
1/4 X	1.0a	1.0a	2.8bc	3.1b	3.6bc
3/8 X	1.0a	1.0a	3.3c	3.8b	3.6bc
1/2 X	1.0a	1.0a	3.3c	3.9b	4.1c

[1]experiments were conducted in greenhouse and data collected 28 days after planting
[2]means in the same column and section followed by the same letter are not significantly different at *P≤0.05*
[3]1 = normal plant growth; 2 = abnormal plant growth not definitively related to herbicide injury (plant yellowing, stunted growth); 3 = minor herbicide-related injury; 4 = severe herbicide-related injury; and 5 = significant herbicide-related injury and greater than 50 percent plant death

Table 11. Response of five cover crops to preemergence applications of thiencarbazone-methyl + isoxaflutole (1X rate: 37 + 92 g ha^{-1})[1].

Rate	Cereal rye	Oat	Hairy vetch	Lentil	Radish
	dry weight (g $plant^{-1}$)				
Control	0.08a[2]	0.11a	0.04a	0.06a	0.34a
1/8 X	0.07a	0.04b	0.02b	0.02b	0.18b
1/4 X	0.07a	0.03bc	0.02b	0.01c	0.04c
3/8 X	0.06ab	0.02c	0.01b	0.01c	0.01d
1/2 X	0.04b	0.02c	0.02b	0.01c	0.03c
	Injury rating (1-5)[3]				
Control	1.0a	1.0a	1.0a	1.0a	1.1a
1/8 X	1.0a	3.1b	2.5b	3.4b	2.9b
1/4 X	1.0a	3.5bc	3.4c	4.0c	4.4c
3/8 X	1.5a	4.0c	3.6cd	4.0c	5.0d
1/2 X	2.4b	4.0c	4.1d	4.1c	4.5c

[1]experiments were conducted in greenhouse and data collected 28 days after planting
[2]means in the same column and section followed by the same letter are not significantly different at *$P \leq 0.05$*
[3]1 = normal plant growth; 2 = abnormal plant growth not definitively related to herbicide injury (plant yellowing, stunted growth); 3 = minor herbicide-related injury; 4 = severe herbicide-related injury; and 5 = significant herbicide-related injury and greater than 50 percent plant death

Table 12. Response of five cover crops to preemergence applications of chlorimuron-ethyl (1X rate: 70 g ha^{-1})[1].

Rate	Cereal rye	Oat	Hairy vetch	Lentil	Radish
			dry weight (g $plant^{-1}$)		
Control	0.06a[2]	0.08a	0.04a	0.05a	0.44a
1/8 X	0.07a	0.10a	0.04a	0.03b	0.04b
1/4 X	0.07a	0.09a	0.04a	0.03b	0.03b
3/8 X	0.06a	0.09a	0.04a	0.02bc	0.02b
1/2 X	0.05a	0.08a	0.03a	0.01c	0.03b
			Injury rating (1-5)[3]		
Control	1.3a	1.3a	1.1a	1.1a	1.1a
1/8 X	1.8ab	1.3a	1.0a	2.5b	3.5b
1/4 X	1.6ab	1.4a	1.1a	2.6b	3.5b
3/8 X	1.8ab	1.6a	1.8b	3.3c	4.0b
1/2 X	2.0b	1.5a	1.5ab	3.5c	4.0b

[1]experiments were conducted in greenhouse and data collected 28 days after planting
[2]means in the same column and section followed by the same letter are not significantly different at *P≤0.05*
[3]1 = normal plant growth; 2 = abnormal plant growth not definitively related to herbicide injury (plant yellowing, stunted growth); 3 = minor herbicide-related injury; 4 = severe herbicide-related injury; and 5 = significant herbicide-related injury and greater than 50 percent plant death

Table 13. Response of five cover crops to preemergence applications of fomesafen (1X rate: 350 g ha^{-1})[1].

Rate	Cereal rye	Oat	Hairy vetch	Lentil	Radish
	dry weight (g $plant^{-1}$)				
Control	0.12a[2]	0.15a	0.05a	0.07a	0.44a
1/8 X	0.13a	0.14a	0.04a	0.06a	0.33a
1/4 X	0.13a	0.16a	0.05a	0.09a	0.22b
3/8 X	0.12a	0.21a	0.07a	0.06a	0.02c
1/2 X	0.11a	0.15a	0.05a	0.07a	0.01d
	Injury rating (1-5)[3]				
Control	1.1a	1.0a	1.0a	1.0a	1.0a
1/8 X	1.1a	1.0a	1.0a	1.4ab	1.6b
1/4 X	1.0a	1.0a	1.1a	1.9bc	4.1c
3/8 X	1.0a	1.1a	1.0a	2.0c	5.0d
1/2 X	1.0a	1.0a	1.3a	2.0c	5.0d

[1]experiments were conducted in greenhouse and data collected 28 days after planting
[2]means in the same column and section followed by the same letter are not significantly different at *P≤0.05*
[3]1 = normal plant growth; 2 = abnormal plant growth not definitively related to herbicide injury (plant yellowing, stunted growth); 3 = minor herbicide-related injury; 4 = severe herbicide-related injury; and 5 = significant herbicide-related injury and greater than 50 percent plant death

Table 14. Response of five cover crops to preemergence applications of imazethapyr (1X rate: 70 g ha^{-1})[1].

Rate	Cereal rye	Oat	Hairy vetch	Lentil	Radish
	dry weight (g $plant^{-1}$)				
Control	0.09a[2]	0.14a	0.05b	0.06b	0.41a
1/8 X	0.09a	0.13a	0.09ab	0.09a	0.10b
1/4 X	0.10a	0.15a	0.09ab	0.09ab	0.05c
3/8 X	0.09a	0.08b	0.09ab	0.11a	0.07bc
1/2 X	0.09a	0.11ab	0.11a	0.09ab	0.05c
	Injury rating (1-5)[3]				
Control	1.1ab	1.0a	1.0a	1.0a	1.0a
1/8 X	1.0a	1.1a	1.0a	1.0a	2.6b
1/4 X	1.1ab	1.1a	1.1ab	1.1a	2.9b
3/8 X	1.3ab	1.9b	1.3ab	1.0a	3.8c
1/2 X	1.4b	2.0b	1.4b	1.8b	3.9c

[1]experiments were conducted in greenhouse and data collected 28 days after planting
[2]means in the same column and section followed by the same letter are not significantly different at *P≤0.05*
[3]1 = normal plant growth; 2 = abnormal plant growth not definitively related to herbicide injury (plant yellowing, stunted growth); 3 = minor herbicide-related injury; 4 = severe herbicide-related injury; and 5 = significant herbicide-related injury and greater than 50 percent plant death

Table 15. Pendimethalin (1X rate: 1600 g ha-1) effect on cover crop root length.[1]

Rate	Cereal rye	Oat	Hairy vetch	Lentil	Radish
	root length (cm)				
Control	6.25a	5.77a	5.13a	7.15a	5.67a
1/8 X	6.27a	4.87b	6.05a	6.98a	5.42a
1/4 X	4.72ab	3.48c	4.84a	6.26a	4.95a
3/8 X	5.34a	3.59c	5.72a	7.47a	5.01a
1/2 X	3.30b	2.60d	5.55a	7.12a	5.19a

[1]means in the same column and section followed by the same letter are not significantly different at *P≤0.05*

CHAPTER IV: GENERAL CONCLUSIONS

The objective of the cereal rye research was to determine whether cereal rye residue managed in a manner to maximize corn and soybean yields would suppress common lambsquarters and common waterhemp. We hypothesized that common lambsquarters would be inhibited more than common waterhemp due to its earlier emergence when greater rye residue would be present on the soil surface. Neither common waterhemp nor common lambsquarters densities were reduced by cereal rye biomass. Common waterhemp recruitment was equal to or increased compared to the control in the presence of any rye biomass and the time to 10 (TE_{10}) and 50% (TE_{50}) emergence was increased due to the cereal rye. The delay in emergence in treatments with rye cover may have been due to rye biomass only providing a physical barrier and reducing light transmittance for a short period of time. The increased emergence of common waterhemp with a rye cover crop is a concern as many growers already have difficulty controlling this weed. Common lambsquarters emergence was often the same as the control, but in some treatments, common lambsquarters emergence also increased in the presence of rye biomass compared to a no cover treatment. Late season emergence in 2014 resulted in a much longer TE_{50} in treatments with higher rye biomass compared to the no cover treatment.

The increase in weed densities with the presence of rye was unexpected, and our null hypothesis that common lambsquarters would be affected more by the presence of rye biomass than common waterhemp must be rejected. The impact of the increasing weed densities with rye cover crops on weed management is difficult to assess since it was accompanied by a delay in emergence timing. Weeds that emerge much later than the crop are less competitive with the crop, but the later emergence prolongs the time where weeds must be managed (e.g. more persistent residual herbicides or later postemergence applications). The impact of late-emerging weeds can be minimized using tactics that enhance early season crop canopy development, such as narrow row spacings or increased seeding rates.

The objective of the herbicide research was to determine the effect of several common corn and soybean herbicides on the establishment of five cover crop species. The primary goal was to identify the relative sensitivity of these cover crops to corn and soybean herbicides that may persist from application to the time of cover crop planting. Cereal rye was most tolerant to all herbicides tested, but concern may exist for establishing this crop following applications of atrazine or pendimethalin. Oat, hairy vetch, and lentil all were moderate in their susceptibility to the herbicides tested and the order of herbicide tolerance was oat>hairy vetch>lentil. Radish was much more susceptible to the herbicides in this experiment than the other species. Growers should carefully evaluate their herbicide program and factors like soil type, environmental conditions, herbicide application timing, and rate used when determining a cover crop species to seed.

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