The Pennsylvania State University

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INCORPORATING COVER CROPS AND DIVERSIFIED WEED MANAGEMENT TO IMPROVE CROPPING SYSTEM PRODUCTIVTY

A Thesis in

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by

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ABSTRACT

To address the need for diversified weed management and innovative methods of cover crop incorporation, two distinct experiments were performed. The first, was based in a diverse, no-till dairy cropping systems study was established in 2010 seeking to produce enough feed, forage, and fuel to supply a 65-cow, 97 hectare dairy farm in Pennsylvania while minimizing off farm inputs. A 6-year diverse crop rotation, the Pest Management rotation, evaluated strategies that attempted to reduce herbicide inputs and the risk of herbicide resistant weeds. The rotation was composed of a sequence of annual crops, cover crops, and a perennial hay crop. A Reduced Herbicide (RH) treatment was compared to a Standard Herbicide (SH) treatment that was more reliant on chemical weed control. Both treatments utilized Integrated Weed Management where the RH treatment incorporated more cultural and mechanical methods of control. Management was altered in 2013 to address challenges faced in the first three years and results of 2013-2015 are analyzed here. Weed management was evaluated for the corn silage and soybean portion of the rotation as this is where the most intensive weed management occurs. The RH and SH treatments were compared based on crop yield, weed biomass, and net return to the farm enterprise. Both the RH and SH treatments generally maintained adequate weed control during 2013-2015 but biomass was generally greater in RH. Soybean yield varied between the treatment in one year, but these differences were not attributed to weed biomass. A greater net return to the farm was seen under SH management in soybean and RH in corn silage.

The second study sought to address cover crop adoption in the Northeast, that has been slow and limited due to a number of factors. Farmers are faced with a constricted time window for cover crop planting following harvest and before weather conditions prevent fall growth. Multiple methods have been evaluated to expand this restricted planting window including aerial seeding, underseeding and relay intercropping. All of these methods face additional challenges in no-till production systems. Researchers at Penn State developed an innovative cover crop interseeder to address establishment restrictions in no-till grain production. After design of the machine was completed, a number of successful intseeder cover crops needed to be selected. A successful interseeded cover crop may require traits that are not normally associated with post-harvest established cover crops. These species need to tolerate low light and moisture conditions while being able to establish. Annual ryegrass (*Lolium multiflorum*) has been shown to be a strong candidate for interseeding in earlier studies and a trial was conducted to test different varieties for interseeding ability. A Species Trial was conducted to evaluate different grass and legume species in either corn or soybean. These trials were conducted in Pennsylvania (PA), New York (NY), and Maryland (MD). Several species were shown to be better candidates for interseeding based on fall and spring biomass. These species were: Medium Red Clover (*Trifolium pretense*), Annual ryegrass, and Orchardgrass (*Dactylis glomerata* L.). The annual ryegrass trial showed similar performance across varieties with few performing better than others. A better understanding of appropriate cover crop selection can be used in conjunction with ongoing work with herbicide selection to create recommendations for farmers.

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Prologue

No-till agronomic production is a widely-adopted practice across Pennsylvania with 66% of the major crop acreage under its management (NASS USDA 2015). No-till management is defined by the Natural Resource Conservation Service to be a method of production where the amount, orientation, and distribution of crops and plant residue is maintained on the soil surface year-round while limiting soil disturbance. Passionate groups, such as the PA No-Till Alliance, support and encourage the adoption of this form of conservation management. Producers often adopt no-till practices for the many soil health benefits, reduction in fuel costs, and economic advantage.

Implementation of no-till management strengthens the ecosystem services that are necessary for agricultural systems to meet the demands of production while reducing soil erosion and environmental impact (Lal et a. 2013). In water-limited areas of the country, no-till is frequently adopted as a water conserving practice (Munawar et al. 1990). In the east, where topography can be more challenging, no-till reduces soil erosion by removing tillage operations conserving below and above-ground plant residues. Soil sequestration of carbon and nitrogen increases under no-till when compared to conventional tillage (Dell et al. 2008). The preservation of soil organic carbon and soil moisture increases the efficiency of fertilizer use and ultimately benefits crop yield (Brady et al. 2015). Retention of residues on the soil surface creates a more diverse habitat for ground dwelling, beneficial insects (Estrade et al. 2010). Lastly, no-till reduces the fuel requirements for crop production by 60% compared to conventional management (Helsel et al. 2012), creating a financial incentive.

Adoption of no-till in the mid-Atlantic region increased starting in the late 1990's as the cost of energy increased along with the introduction of herbicide resistant crops to the market. Glyphosate resistant soybean (Roundup Ready) was first introduced in 1996 and by 2006, 86% of the planted soybean in the US was herbicide-resistant. Prior to the more simplified weed management offered with herbicides (glyphosate) associated with herbicide-resistant crops, weed control often included multiple herbicide mixtures or applications and/or mechanical control operations each season. While land under no-till management has increased, benefitting soil conservation, so has land planted with herbicide-resistant crops and the over reliance on a select number of herbicide active ingredients has created the new and growing challenge of herbicide resistant weeds (Duke et al. 2008). A growing number of calls have gone out to address the problem of herbicide resistant weeds by using diversified methods that reduce the dependency on herbicides as a single form of weed control (Norsworthy et al. 2012, Mortensen et al. 2012).

Numerous studies have reported on the benefits of the addition of cover crops to an agroecosystem (Schipanski et al. 2014, Snapp et al. 2012). Cover crop use, while not as widely adopted as no-till, is steadily increasing across the country, especially in the northeast region (Hamilton 2016). The USDA broadly describes cover crops as “grasses, legumes, and other forbs that are planted for erosion control, improving soil structure, moisture, and nutrient content, increasing beneficial soil biota, suppressing weeds, providing habitat for beneficial predatory insects, facilitating crop pollinators, providing wildlife habitat, and as forage for farm animals”. Typically planted between cash crops, the selected cover crops are generally based on producer goals, cost of seed, and seed availability. While many cover crops offer benefits including soil erosion protection, certain species may offer unique benefits desired by the producer. Some species, such as cereal rye, aid in reducing weed competition (Mirsky et al. 2011) and the addition of legumes can contribute nitrogen to the soil. Mixes of different species can work in conjunction to offer a host of benefits rather than isolating a few unique ones (Finney et al. 2016).

No-till producers often plant cover crops in the fall following the harvest of corn or soybean grain. When winter hardy species are utilized in a no-till system, the cover crops will survive the winter and produce biomass in the spring before being terminated with an herbicide. Grain producers in the mid-Atlantic region face a number of barriers that limit adoption. One of those barriers is the small window of time following grain harvest that allows cover crop establishment and growth before temperatures become cold and plant growth slows. This period of only a few weeks after harvest makes it challenging for farmers to establish cover crops, realize potential benefits, and feel positive about the time and effort they spent. One tactic that can help improve cover crop establishment and that can expand the fall growing window is interseeding. Interseeding is a method of relay cropping where the cover crop is seeded directly into the growing cash crop rather than waiting until the cash crop is harvested. Interseeding can facilitate cover crop establishment prior to cash crop harvest and thereby broaden the window of opportunity for cover crop establishment.

This thesis has two distinct and related chapters. Although the two chapters report on two separate studies, they both center on assessing a more diversified approach to making no-tillage and cover cropping work in the region. The first chapter focuses on an integrated weed management approach that integrates cover crops into a herbicide-based strategy in no-till corn and soybean. The NE SARE Dairy Cropping Systems Study was established in 2010 with the goal of producing enough feed, forage and fuel for a typical PA dairy farm while reducing off-farm inputs. A unique, six-year diverse crop rotation that incorporates all aspects of IWM to reduce herbicide inputs was compared to the same diverse rotation where weed management was a regionally representative herbicide based program. The goal of this study was to evaluate the effectiveness at the diverse rotation at reducing herbicide inputs without losing the integrity of the crop yield or economic viability of production when compared to the herbicide based system. Knowledge gained from this study can help demonstrate the effectiveness of applying IWM on a production scale and encourage producers to diversify their approach to weed management.

To address the short fall growing window for cover crops in the mid-Atlantic region, the second chapter focused on evaluating the use of the Penn State cover crop interseeder for establishment of cover crops in no-till corn and soybean. This piece of equipment is designed as a no-till drill, with three planting units per row that are capable of planting covers into standing corn or soybean. Previous studies have evaluated a select number of cover crop species but not fully explored a diversity of potential candidate species. The evaluation of interseeding cover crops was conducted in Maryland, Pennsylvania, and New York to determine the viability across the region. The specifics of this project are presented in Chapter 2.

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Chapter 1

Weed and Crop Response to Integrated Weed Management in a Diverse Dairy Cropping System

NE Region SARE Dairy Cropping Systems Project

Abstract

A diverse, no-till dairy cropping systems study was established in 2010 seeking to produce enough feed, forage, and fuel to supply a 65-cow, 97 hectare dairy farm in Pennsylvania to minimize off farm inputs. A 6-year diverse crop rotation, the Pest Management rotation, evaluated strategies that attempted to reduce herbicide inputs and the risk of herbicide resistant weeds. The rotation was composed of a sequence of annual crops, cover crops, and a perennial hay crop. A Reduced Herbicide (RH) treatment was compared to a Standard Herbicide (SH) treatment that was more reliant on chemical weed control. Both treatments utilized Integrated Weed Management where the RH treatment incorporated more cultural and mechanical methods of control. Management was altered in 2013 to address challenges faced in the first three years and results of 2013-2015 are analyzed here. Weed management was evaluated for the corn silage and soybean portion of the rotation as this is where the most intensive weed management occurs. The RH and SH treatments were compared based on crop yield, weed biomass, and net return to the farm enterprise. Both the RH and SH treatments generally maintained adequate weed control during 2013-2015 but biomass was generally greater in RH. Soybean yield varied between the treatment in one year, but these differences were not attributed to weed biomass. A greater net return to the farm was seen under SH management in soybean and RH in corn silage.

Introduction

Adoption of no-till has grown at a rate of 1.5 percent annually for corn, cotton, soybean and rice from 2000-2007 (Horowitz et al. 2010). As of the 2012 USDA Census of Agriculture, roughly 287,000 farms were under no-till management, covering 39 million hectacres across the United States. Within Pennsylvania in 2014, 66% or 0.6 million hectares of the major commodity crop acres were under no-till management (NASS USDA 2015). In general, no-till production can help to bolster the ecosystem services that are required to meet the demands of a growing population while reducing soil degradation and environmental impact (Lal 2013).

With the introduction of synthetic herbicides following World War II, it became possible to manage weeds without primary and secondary tillage. Research into modern no-till techniques began in the 1960's and has grown to address concerns of soil degradation over the world's arable land (Huggins and Reganold, 2008). The Natural Resource Conservation Service defines no-till production as "managing the amount, orientation, and distribution of crop and other plant residue on the soil surface year-round while limiting soil disturbing activities to only those necessary to place nutrients, condition residue, and plant crops".

Land managers may use no-till tactics for a host of reasons from nutrient conservation to maintaining soil quality. Soil moisture conservation is generally greater in no-till settings and is a principle reason for adoption in moisture limited areas of the country (Munawar et al. 1990). Conserving soil moisture can be a valuable asset during dry periods and is increasingly important in drought years.

The use of no-till management has also been shown to increase the sequestration of carbon and nitrogen when compared to conventional tillage (Dell et al. 2008). Loss of soil organic carbon impacts soil moisture retention and fertilizer use efficiency, ultimately impacting yield (Brady et al. 2015). The retention of plant residues on the soil surface creates a more diverse habitat and can increase the diversity of beneficial organisms, including generalist predators such as ground beetles (Estrade et al. 2010).

No-till methods can reduce fuel costs by upwards of 60% in corn when compared with a conventionally tilled approach (Helsel et al. 2012). In addition to reduced fuel savings, the method has been shown to increase field working days and reduce the time in the field otherwise spent conducting primary and secondary tillage operations, all of these factors taken together create a compelling financial incentive to adopt the practice. Incorporating cover crops into no-till systems further aids with beneficial ecosystem services (Duiker and Myers 2006), as winter cover crops can scavenge previously applied nutrients, particularly nitrogen, reduce soil erosion while at the same time moderating soil temperatures over the growing season (Dabney et al. 2001).

By 2006, 86% of herbicide-resistant soybean were planted under conservation tillage (Fernandez-Cornejo et al. 2014). While no-till offers a host of environmental and producer benefits, it has also reduced the diversity of weed control options. Those options were further reduced when glyphosate resistant crops were sold as the panacea to weed management and non-transformed germplasm grew increasingly harder to find. Market-based incentives where offered to producers in order to "lock-in" benefits of the herbicide-tolerant seed and the matching glyphosate focused program (Mortensen et al, 2012). The combination of factors resulted in rapid adoption of the seed and herbicide package which dramatically drove the evolution of glyphosate resistant weeds. This increased reliance on a single herbicide active ingredient contributed to the evolution of herbicide-resistant weeds (Duke et al. 2008). Glyphosate resistant soybean was introduced onto the market in 1996, and glyphosate-resistant horseweed (*Conzya*

Canadensis L.*)* was first observed in 2001 (VanGessel 2001). Herbicide resistance is not isolated to glyphosate, though it remains one of the most prominent concerns. Currently there are 471 unique cases and 250 weed species reported to be herbicide resistant (Heap 2016).

In an effort to understand the decision-making process behind the use of herbicide resistant crops, a recent survey reported that 95% of farmers find protection from yield loss and consistent weed control to be very important when making herbicide and herbicide resistant crop choices (Hurley et al. 2010). Unfortunately, while farmers may select herbicide resistant crops to prevent yield loss from weed competition, doing so may only encourage the problem of herbicide resistant weeds. According to the Weed Science Society of America, herbicide resistance has been rising since the first reported cases in the 1950s. Pennsylvania farmers have already been exposed to the challenges of triazine, glyphosate, and ALS resistance. In 2005, glyphosate-resistant Palmer amaranth (*Amaranthus palmeri L.*) was first identified in Georgia (Culpepper et al. 2006). The glyphosate-resistant biotype has progressively spread through the southern states and has been identified in PA fields (Curran and Lingenfelter n.d.). The highly competitive weed germinates best at shallow planting depths, has a rapid growth rate, can produce 200,000-600,000 seeds per plant, and can germinate over an extended period during the crop growing season (Ward et al. 2013). Palmer amaranth poses a unique threat as it is perfectly poised to take advantage of conservation tillage systems and glyphosate focused herbicide programs (Price et al. 2011). The spread of invasive *Amaranthaceae* plants places an urgency on the greater adoption of diverse weed management tactics. There is a growing need for the employment of a variety of weed control practices in conservation tillage to address the evolution and spread of highly competitive, herbicide resistant weeds.

Integrated Weed Management (IWM) is necessary to provide adequate weed control at an economic cost, while at the same time reducing the potential for evolution of herbicide resistant weeds and other potential negative environmental impacts. IWM is the application of multiple weed control tactics that can include cultural, genetic, mechanical, biological, and chemical approaches (Swanton and Weise 1991). The management approach taken within the cropping-system will impact the abundance, diversity, and consistency of a weed community ultimately determining IWM options (Menalled et al. 2001). Integrated Weed Management does not call for the elimination of herbicides, but rather the reduction of single tactic management strategies; no one tactic should be solely relied upon for total weed management, whether it be herbicides, tillage, or other practices. The continued reliance of herbicides to address herbicide resistant weeds will result in the further evolution of weed biotypes with multiple resistance (Mortensen et al. 2012). While the next generation of herbicide resistance crops is on the horizon promising additional herbicide options, nonchemical management tactics are sorely needed to diversify management inputs.

The NE SARE Dairy Cropping Systems study was established in 2010 with the goal of producing enough feed, forage, and fuel to supply the needs of a 97-hectare, 65 milking head, dairy farm typical of PA while reducing off-farm inputs. Two diverse, six-year crop rotations were established to evaluate innovative methods in either manure management or pest management. The Pest Management rotation was designed to incorporate the principles of IWM, while maintaining the integrity of the no-till crop production system. Within the Pest Management rotation, Standard Herbicide (SH) management was compared to Reduced Herbicide management (RH). The SH management relied upon a chemical based weed control plan, while the RH management reduced herbicide use and incorporated additional IWM practices. The goal of the Pest Management rotation was to evaluate an IWM plan that reduced herbicide inputs while at the same time maintained weed control efficacy and crop yield relative to SH management.

The first three years of the study (2010-2012) demonstrated that RH management was an effective weed control approach. While RH did generally have greater weed biomass than SH, biomass never reached levels where yield suppression would occur. Although yield sometimes differed between the two systems, disparities were due to differences with agronomic management challenges and not due to differences in weed control (Synder et al. 2016). Yield differences were primarily isolated to soybean where lower plant populations between treatments led to reduced yields. The lowered plant populations were attributed to a number of factors including: planting difficulties into heavy residue, equipment challenges, and slug herbivory (Synder et al. 2016). During this first three-year period, herbicide use was reduced by 26% in soybean and 48% in corn under RH management when compared to SH.

Although, weed control was effective and consistent across both management regimes, direct comparisons were difficult to make as herbicide mixtures differed somewhat between the two systems. Starting in 2013, several changes were made to the Pest Management rotation to improve cash crop performance and more directly compare herbicide inputs and weed control. The objective of this research was to evaluate the effectiveness of an integrated weed management approach that reduced herbicide inputs by integrating cultural and mechanical tactics in comparison to an herbicide-based approach. It was hypothesized that the RH management might result in greater weed biomass, but crop yields would not be impacted by the different weed control tactics, and crop yields under the RH management would be similar to the SH management.

Methods

The Sustainable Dairy Cropping Systems project was established at the Russell E. Larson Agricultural Research Station in Pennsylvania Furnace, PA (40.72°N 77.92°W). The soil types across the site were Murrill channery silt loam (fine-loamy, mixed, mesic Typic Hapludalts) with areas of Buchanan channery silt loam (fine-loamy, mixed, semiactive, mesic Aquic Fraguidults). The average growing season (April-November) precipitation across 2013 to 2015 was 70 cm. Over the six-year study (2010-2015) the growing season average precipitation was 66 cm.

The Pest Management cropping sequence and management practices were designed around the four primary types of IWM. The rotation incorporates cover crops, cash grain, oil seed, and a silage crop in a sequence followed by a three-year perennial forage stand (Figure 1-1). The full rotation is a winter canola-cereal rye cover crop-soybean-cereal rye cover crop-corn silage-oat cover crop-3-year alfalfa (±orchardgrass) forage sequence. Two weed management regimes were compared across the six-year rotation. For the purposes of this paper the area of focus will be the rye-soy-rye-corn silage portion, where the greatest comparison between weed management tactics occurs.

Standard herbicide or SH management was a regionally representative program that included sequential soil and foliar-applied herbicides. The reduced herbicide or RH management decreased herbicide inputs and incorporated additional cultural and mechanical weed control methods. Both treatments were managed under no-till practices. The SH and RH treatments are referred to as ‘main management’. The RH regime was further split into ‘sub-management’ tactics that compared inter-row cultivation to postemergence herbicide use. Within the soybean crop, SH was also split into sub-managements to compare row spacing.

The study design was a randomized complete block with full-entry, nested-split plots with four replications. Each crop entry of the six-year rotation was planted every year in the main plots that measured 120 m x 90 m. The SH and RH treatments were compared in split plots (60 m x 90 m), and sub-management practices were evaluated in split-split plots (30 m x 90 m). Field scale equipment was used for most field operations, as permitted by the plot size. Harvest was performed using small plot equipment and the yield strip width varied with crop entry and is described by crop.

Soybean. A cereal rye (*Secale* cerale L.) variety 'Aroostook' cover crop was planted following winter canola. Rye was drilled into either mowed down canola regrowth (RH) or volunteer canola managed with a burndown herbicide (SH). The cover crop was drill seeded at a rate of 134 kg ha^{-1} in both main management treatments on September 24, 2012, October 4, 2013 and October 9, 2014. Rye was terminated on May 3, 18, and 14 in each consecutive year using a mixture of glyphosate plus 2,4-D low volatile ester [(2,4-dichlorophenoxy) acetic acid] at 0.84 kg + 0.56 kg ha^{-1}, respectively. Roller crimping of the cereal rye was performed only in 2013 and 2014 following herbicide termination when cover crop residue impeded planting and occurred directly prior to soybean planting. The rye cover crop was replanted on October 27, 2014 due to poor germination of low quality seed.

Soybean planting occurred a minimum of 7-days following cereal rye burndown to avoid concerns of 2,4-D injury. Soybean was planted using a Monosem vacuum planter (Edwardsville, KS), equipped with no-till coulters and Shark Tooth residue managers (Yetter Manufacturing, Colchester, IL) on May 20, 2013, June 6, 2014, and May 22, 2015. Growmark HS28A12 was planted in the first two years and TS2849-RS2 was planted in the third year. Both varieties are glyphosate resistant. Soybean were planted at a rate of 494,000 plants ha^{-1} in all plots. Based on annual soil tests, fertilizer was only applied as a post application on June 16, 2014 at a rate of 67 kg ha^{-1} of K_2O to only the RH management. Lime was broadcast applied at a rate of 3,360 kg ha^{-1} in 2014. Soybean harvest occurred in October when approximately 16% moisture was reached (Table 1-1).

Herbicides were soil applied at planting with a mixture that targeted both grass and broadleaf weeds (Table 1-2). In the SH managements, the soil applied herbicides were broadcast immediately following planting using a tractor-mounted boom sprayer at 187 L ha^{-1} and 275 kPa using TeeJet AI11002 tips. In both RH, sub-managements, the same herbicide mix was applied using a banding application method at planting (Table 1-2). Banded herbicides were applied in a 25-cm band over the crop row at 142 L ha^{-1} 275 kPA using TeeJet (Wheaton, IL) TP4002E nozzles positioned approximately 35 cm above the soil surface. This effectively reduced the amount of soil applied active ingredient by two-thirds compared to the broadcast application. A second foliar-applied herbicide mixture (Table 1-2) was applied to both SH sub-management treatments and the RH-postemergence (POST) management using the same equipment described above within 4 to 7 weeks after planting (WAP). In the RH-Cult treatment, high residue cultivation was performed twice, within 4 to 7 WAP, using a John Deere 886 high-residue inter-row cultivator (Moline, IL) equipped with 51 cm wide sweeps. Post-emergence herbicide application and the first cultivation event were performed on the same day. Cultivation events were performed within a maximum of five days apart.

Corn. The cereal rye cover crop preceding corn silage was planted after soybean harvest in the fall on October 26, 28, and 29, in 2012, 2013, 2014 respectively, and manure was applied using shallow disk injection to corn silage on May 6, 2013, and prior to planting rye cover crop on October 22, 2013 and October 28, 2014 (Table 1-3). The rate of manure applied was determined by the manure analysis, following the recommendations of The Pennsylvania State University Soil Analytical Lab (University Park, PA). Cereal rye was planted at 134 kg ha^{-1} in both management systems and was terminated at least two weeks before corn planting using the same herbicide mix as in rye before soybean.

Corn silage was planted May 8 (SH) and 14 (RH), 2013 May 31, 2014 and May 15, 2015. Different corn hybrids were planted each year (Table 1-1), all had a relative maturity of 89 days and were planted at a population of 79,000 plants ha^{-1} in all management systems. Untreated seed was used in both management systems. Corn silage was planted on 76- cm rows in all treatments using the same Monosem planter as described in soybean. Starter fertilizer of NPK was applied at planting at rate of 94 kg ha^{-1}, additional K was applied based on soil fertility test recommendations, and side-dress N was applied based on pre-sidedress soil nitrate tests (PSNTs) analyzed by the Penn State Analytical Services Lab (University Park, PA, 16802) (Table 1-3). Corn was harvested as silage in September of each year (Table 1-1) using a Kempler Champion C1200 (Champion Denmark A/S, Christiansfeld 6070, Denmark) small plot silage harvester when it reached a moisture level of approximately 60%.

The same equipment and sequence of herbicide application timing as soybean was utilized in the corn silage. A soil applied application of the same herbicide mixture was either broadcast (SH) or band-applied (RH) at crop planting (Table 1-4). The mix of POST herbicides varied by year with the herbicide-tolerance traits of the corn seed varieties (Table 1-4). Glufosinate-resistant corn allowed glufosinate use in 2013, glyphosate-resistant corn allowed use of glyphosate in 2014, and the corn was not herbicide resistant in 2015 to allow for purchase of seed available without Bt traits and seed-treated insecticide and fungicide. It was the general goal of the study to strive to use seeds without Bt traits or seed treatments, but seed selection was often made based on availability. Mesotrione was substituted for pendimethalin in the second and third year to improve broadleaf weed control and reduce the potential for herbicide injury. In the RH-Cult sub-management, high residue cultivation was performed twice, within 4 to 6 WAP. In the SH and RH-POST sub-management treatments, postemergence herbicide applications were broadcast applied the same day as the first cultivation event.

Soybean and Corn Weed Data Collection. Cover crop and weed biomass were sampled by removing to ground level eight random 0.5 m^2 quadrats per plot prior to cover crop termination. Harvested biomass was sorted into cover crop and weeds and oven dried at 50˚C for at least 48 h prior to weighing. Weeds were identified at the species level in each plot. On August, 12, 11, and 13 of 2013, 2014, and 2015 respectively, weed biomass was collected from two random 0.67 m^2 quadrats within each split-split plot in all years between 10 and 12 WAP. Weeds were sorted and identified to species and life cycle before being dried at 50˚C for at least 48 hours and weighed.

Partial Budget Analysis. A partial budget analysis was performed to compare the relative differences in input costs and net return based on the sub-managements for both corn and soybean. The same methodology was used as in Synder et al. 2016, in order to make direct comparison between the 2010-2012 and the 2013-2015 portions of the study. Costs were updated where available based on experimental changes and the PSU Agronomy Guide. Other costs were sourced from the Mississippi State Budget Generator Version 6.0 (Department of Agricultural Economics, Mississippi State University, MS). Annual yields, input costs, and crop prices were used to generate the budgets for each management and averaged over the three years.

Analysis. All data (rye cover crop biomass, weed biomass, cash crop plant population, and cash crop yield) were analyzed using PROC Mixed in SAS statistical software (SAS for Windows v. 9.4 SAS Institute, Inc.) with the Satterwithe adjustment. Herbicide main managements and sub-management treatments were treated as fixed effects and block and block*herbicide management and sub-management interaction were random in all models. A two-sided F-test was performed (alpha = 0.01) with residual values to compare variance among years. Where variance was determined not to be significant, data was pooled over multiple years. Weed biomass was natural log transformed in order to meet the normality assumptions of ANOVA. Significance reported is based on the results of natural log transformations. Significance between main effects were determined using a Tukey's test of mean comparison. Sub-managements and years were compared, model on to test a priori hypotheses using either the 'Slice' function. The Slice function performs a partitioned analysis of least-square means for a designated interaction. This method can also be referred to as an analysis of simple effects (SAS/STAT(R) 9.3 User Guide). Where sub-management and year differed based on the Slice test, Tukey's test was used to compare means and considered significantly different when $p<0.05$.

An additional linear regression model was performed to determine significant predictors of soybean yield. Linear regression was performed using the Proc Reg in SAS where factors were considered significant when $p<0.05$. Models were selected based using the stepwise method of elimination. Factors tested included the biomass of the previous cover crop, soybean plant population, and weed biomass before harvest.

Results

Weather. Precipitation in 2013 and 2014 varied in the spring but was consistent during the growing season across the two years. Comparatively, rainfall in May 2015 was much lower, followed by greater precipitation in June and July (Table 1-5). The increased precipitation in

June and July would create challenges in maintaining the effectiveness of different weed control tactics.

Soybean. Cereal rye biomass variance significantly differed from 2013 compared to 2014/2015 and could not be pooled over the three years. Biomass averaged 5,289 kg ha^{-1} in 2013, 2,607 kg ha^{-1} in 2014, and 1,613 kg ha^{-1} in 2015. There was no difference in rye biomass between weed management treatments in any year (Table 1-6). The higher rye biomass in 2013 and 2014 was due in part to weather conditions that delayed earlier termination rather than a management strategy. Reduced biomass in 2015 was caused by a combination of poor seed quality that required late reseeding, as well as dry spring weather. Weed biomass consisting of mainly winter annuals such as horseweed [*Conzya candensis* (L.) Cronq.] were sampled in the rye but were determined to be minimal and would be controlled during the burndown herbicide application (data not provided).

Weed biomass was pooled over the three years as variance did not differ between years. Both main herbicide tactics (RH vs. SH) and the sub-management (38-cm row vs. 76-cm rows and cultivation vs. POST herbicide) had significant effects on weed biomass. In general, the RH management had greater weed biomass than SH over the three years (Table 1-6) with approximately 77 kg ha^{-1} more weed biomass on average in the RH management than the SH. The species collected were majority summer annuals common to cash crops in the area. Grass species were mostly foxtails (*Setaria spp.),* large crabgrass [*Digitaria sanguinali* (L.) Scop.] and fall panicum *(Panicum dichotomiflorum)*. Common broadleaf species included annuals such as pigweeds *(Amaranthus spp.),* common lambsquarter *(Chenopodium album),* and the perennial dandelion *(Taraxacum officinale)*. A Slice test of the year by sub-management interaction revealed that mean weed biomass between the four sub-management treatments differed only in one year. In 2015, weed biomass in RH-Cult was over 300 kg ha^{-1} greater than in SH-38cm, SH-76-cm or RH-POST (Table 1-7). While year was not significant for weed biomass, there was a trend for increasing amounts of weed biomass in RH-Cult from 2014 to 2015 (109 to 332 kg ha^{-1}). This trend could be attributed to wet weather patterns that reduced the effectiveness of the cultivation events in 2015 (Table 1-5), as well as the decreased weed suppression from a low biomass cover crop. Weed control treatments were effective in the RH-POST and the two SH sub-management treatments over the three years. There was little variation between years in terms of weed biomass with end of season dry matter ranging from 0 to 8 kg ha^{-1}.

Soybean population was pooled over the three years. Year and the interaction of year and herbicide main management had significant effects on soybean population. In 2013, population did not differ between main management treatments, but both were below the targeted population by 71,000 plants (RH) to 114,000 (SH) plants (Table 1-6). Plant populations in 2014 and 2015 were closer to the targeted soybean population and in 2015, soybean populations in SH were approximately 21% greater than RH. Based on the Slice test of year and sub-management in only one of three years was there a difference in population between sub-management treatments. In 2015 the SH-38 cm had a 13% greater plant population than SH-76 cm (Table 1-7). Numerically, SH-38 cm also had more plants than RH-POST and RH-Cult but did not differ statistically ($p>0.06$, Table 1-7). The lack of significance, despite large numerical differences, was likely due to the variability of the nested sub-management treatments.

Similar variances between years allowed soybean yield to be pooled over the three years. Main herbicide management had a significant effect and yield under SH management was 7% greater than RH over three years (Table 1-7). The Slice test that allowed sub-management treatment comparisons within years indicated that yield only differed in 2015. In 2015, yield in the SH-38 cm was greater than RH-Cult (Table 1-7). The 16% difference in yield was likely caused by the 28% higher ($p<0.06$) plant population of the narrow row SH soybean than the RH-Cult. Numerically, the SH-38 cm soybean yield was highest, but not statistically different than SH-76 cm and RH-POST.

Data was again pooled across the three years to perform a linear regression analysis for soybean yield. The factors included in the model included the biomass of the previous rye cover crop, soybean plant population, and weed biomass before harvest. The stepwise method was used for factor elimination and the significance level for entry was 0.15. Soybean population was the only factor determined to be significant and included in the final model:

$$Yield = 48 + Population*0.00007$$

While soybean population was a significant factor ($p=0.03$), the final model had a low R^2 value of 0.1.

Corn. Cereal rye biomass variance differed between 2014 and 2013/2015, so 2014 was analyzed individually. Rye biomass before corn did not differ between SH and RH main management in any year, and averaged 227 kg ha^{-1} in 2013, 1,137 kg ha^{-1} in 2014 and 370 kg ha $^{-1}$ in 2015 (Table 1-8). The greater amount of rye biomass in 2014 was likely due to the lack of fall 2012 manure application to rye versus manure application prior to rye 2013, as well as weather conditions that delayed termination approximately 25 days later in 2014 than in 2013. Rye was terminated 10 days earlier in 2015 than 2014, but had reduced biomass in 2015 due to the same poor emergence that required reseeding as observed in cereal rye before soybean. Cereal rye was planted later in the fall and terminated earlier than the rye before soybean in two out of three years.

There was a significant interaction between year and SH and RH main management for weed biomass; the main effects of SH and RH management and the sub-management treatments were also significant. In 2013 and 2015, RH had greater weed biomass than SH by about 120 and 168 kg ha^{-1}, respectively (Table 1-8). Weed biomass did not differ between main management treatments in 2014. Comparisons between sub-management treatments revealed significant differences within each year (Table 1-9). A general trend occurred across years where RH-Cult had the numerically greatest amount of weed biomass (two out of three years). In 2013, RH-Cult had greater weed biomass than SH, while RH-POST was similar to both. In 2014, RH-Cult had greater weed biomass than the other treatments; and in 2015, all sub-management treatments differed from one another with RH-Cult having the greatest amount and SH management the least. Weed control was most effective in 2014, when RH-POST and SH effectively had complete weed control and RH-Cult produced only 16 kg ha^{-1}. Some control was likely lost in 2015 when rain events reduced the effectiveness of the cultivation. Weed species present in corn were very similar to those noted in soybean and overall abundance of weeds was greatest in the RH-Cult management.

The variances for corn population and silage yield did not differ over years allowing it to be pooled. Year was the only significant effect on both plant population and yield (Table 1-8). Population in 2013 averaged 65,391 plants ha^{-1}, about 14,000 less than what was targeted and the only year when corn population did not meet the intended goal. The average plant population was 82,000 plants ha^{-1} in 2014 and 81,000 in 2015, and populations did not vary between sub-management treatments within year (data not shown). Average yield across managements in 2013 was 13,008 kg ha^{-1}, while yields averaged 16,000 and 17,000 kg ha^{-1} in 2014 and 2015. The depressed yields in 2013 were likely a result of the lower plant population rather than some other management factor. Differences in weed control likely did not influence yield in any year. Weed biomass was greatest in 2015 in the RH treatments, but yield and plant population were similar across treatments (Table 1-8).

Herbicide Reduction. In incorporation of IWM practices and the use of banded application generated a reduction in herbicide inputs in both the soybean and corn crops. The total amount of herbicide active ingredients (ai) applied in RH-POST (excluding the burndown) in soybean was 89% (11% reduction) of that applied in SH management (Table 1-2). Because the PRE herbicides are applied at low rates relative to the POST, reducing the PRE herbicide by two-thirds, did not greatly reduce overall herbicide application. However, combining the banding application and substituting inter-row cultivation for the POST application reduced herbicide inputs by 95% compared to SH herbicide management (Table 1-2). This eliminated the POST glyphosate application which accounted for the majority of the herbicide inputs.

For corn, herbicide programs varied among years based on the herbicide-resistance of the corn seed (see methods). On average, RH-POST used 48% of the ai used in SH (52% reduction) and RH-Cult reduced use by 74% (26% of SH) (Table 1-3). The greatest reduction occurred in 2014, when RH-Cult used only 22% ai or a 78% reduction compared to what was used in SH. Total applied ai in RH-Cult was the same in 2014 and 2015, but reductions were greater in 2014 due to the higher rate of POST herbicides used in SH. The difference in amount of herbicide used was largely a difference in the amount of glufosinate (Liberty Link), glyphosate (Roundup Ready), or a mix of nicosulfuron plus rimsulfuron (Conventional seed) applied, all of which provide postemergerence control of grass and broadleaf species. Conventional corn was planted in 2015 precluding the use glufosinate and glyphosate; glufosinate and glyphosate require higher herbicide inputs based on active ingredient compared to nicosulfuron plus rimsulfuron which are used at relatively low rates. The different postemergent herbicides appear to have been equally effective. Weed biomass was greatest in SH in 2013, but weed biomass greater across all of the sub-management. The greatest difference in weed biomass between RH-Cult and RH-POST, where the evidence of more effect postemergent broadcast would be most evident, was in 2015. It is difficult to determine if this large difference is due to the success of the herbicide or the failing of cultivation.

Partial Budget Analysis. The partial budget showed that in soybean, the SH-38 cm management garnered the highest net return (Table 1-10). Returns from SH-38 cm were \$131 kg^{-1} higher than from RH-Cult, \$114 kg^{-1} higher than RH-POST, and \$30 kg^{-1} higher than SH-76 cm. RH-Cult had the greatest total cost of production due to the additional cost of the herbicide banding equipment and high residue cultivator that are not used in SH (data not shown). While difference in production cost between RH-Cult and SH-38 cm are only \$25 ha^{-1}, the larger average yield of SH-38 cm causes the net return to the farm to be higher. In 2010-2013, SH soybean also generated greater returns than RH (\$44 ha^{-1}), but had greater production costs. The overall cost of soybean production was greater in 2010-2013 (Synder et al 2016). Production costs were lowered in the second three-years due to alterative herbicide use, the removal of the roller-crimper, and elimination of needing to replant soybean.

Corn silage generated higher net returns under RH-Cult management than RH-POST (\$114 ha^{-1} less than RH-Cult) or SH (\$182 ha^{-1} less than RH-Cult) (Table 1-9). Despite the additional cost of equipment and labor needed in RH-Cult, it was not greater than the cost of the total herbicide program used in SH (data not shown). A similar advantage was observed in 2010-2013, when RH offered \$34 ha^{-1} greater return than SH and corn was harvested for grain (Synder et al. 2016). Overall cost of production in corn was greater in 2013-2015 than the first three years, due in part to changing seed prices and cost of silage harvesting compared to grain harvest.

Discussion

In the second three years of the dairy cropping systems experiment, weed biomass was comparable to the first three years of the study. From 2010 to 2012, weed biomass under SH management ranged from 0 to 9 kg ha^{-1} and from 9 to 213 kg ha^{-1} under RH management across both soybean and corn, respectively (Synder et al. 2016). Adjustments made to the weed and agronomic management did serve to correct some challenges, such as planting difficulties and direct herbicide comparisons, but differences in weed biomass and yield still continued to be similar to the first three years under RH management.

Rye cover crop biomass before soybean was greater in RH than SH in 2010/2011 and the greatest rye biomass was observed in 2012 (7,876 kg ha^{-1} in RH and 4,940 kg ha^{-1} in SH) (Synder et al. 2016). Termination was intentionally delayed in RH during the first three years to increase weed suppression, but the increased cover crop biomass contributed to soybean establishment difficulties. Earlier termination of the cover crop, switching from a no-till drill to a no-till planter, and adding a residue manager to the planter appears to have been effective in counteracting the related establishment problems. In the second three years of the study, rye biomass was greatest in 2013, but no differences in plant soybean population were observed in 2013, only in 2015. The challenge of producing enough rye biomass to act as a weed suppressor, but to the extent where crop population and subsequent yield are affected is not unique to this study. Delaying cover crop termination decreases weed density (Mirsky et al. 2010) but too much residue creates difficulties in soybean planting (Nord et al. 2011; Synder et al. 2016).

Weed biomass was significantly higher in RH than SH across 2013-2015, but was relatively low in the soybean crop across the six years, even when biomass in RH-Cult was greatest in 2015 (Table 1-6). In 2015, the rye cover crop stand was reduced, coupled with abnormal weather patterns that rendered the inter-row cultivation less effective, and weed biomass was more expressed than it was in previous years. Previous studies (Mirsky et al. 2011) have shown that weed biomass is strongly influenced by cereal rye biomass; the more biomass, the greater the weed suppression. While having a cereal rye cover crop still benefitted weed management in 2015, it did not provide as great an advantage as the larger biomass in previous years. The negligible weed biomass in RH-POST and SH (38-cm and 76-cm) in 2015 was a result of the effectiveness of the foliar applied glyphosate.

Across years, SH treatment soybeans yielded 7% more than RH. Yields differed between sub-management treatments only in 2015 where population of the RH-Cult was 102,000 plants ha^{-1} fewer than SH-38 cm. Previous results from the 2010-2012 trial established that plant population and rye biomass were significant predictors of soybean yield (Synder et al 2016). Differences in yield in 2015 were reminiscent of yield disparities in 2012 that were attributed to population differences when SH soybean yields were higher after SH was replanted and RH was not. Dry spring weather conditions in 2015 in Pennsylvania resulted in spotty soybean emergence across the state (Roth 2015) and likely impacted soybean establishment in our experiment, particularly in the 76-cm row treatments. We speculate that the yield differences observed in 2015 were due to soybean population differences rather than other management factors. Previous research has demonstrated yield differences between narrower row-spacing (19 and 38 cm) and 76 cm when planting into a high-residue cover crop (Wells et al. 2014) as well as inconsistencies in soybean population establishment (Mischler et al. 2010), due to part to equipment selection and difficulty in achieving proper seed placement. High-residue cultivation can also reduce soybean yield in the absence of weed competition (Keene et al. 2016), and especially in a dry year. While high-residue cultivation did not negatively impact soybean population in this study, it is possible root-shearing or soil drying caused by cultivation exacerbated the already hindered RH-Cult soybean plants.

Rye biomass prior to corn did not differ between RH and SH in any year. Compared to rye before soybean, biomass was lower resulting from the later planting time and earlier termination. Corn plant populations did not vary between sub-management treatments, but year was a significant factor as population was lower in 2013 than in 2014/2015. We speculate that the lower population in 2013 was likely due to another factor and not rye biomass as it was relatively low that year. Corn planting in all three years was less challenging than soybean as thick rye residue was not an obstacle. Weed biomass and yield in corn silage were consistent with what was observed in 2010-2012 (Synder et al. 2016). Low weed biomass and similar corn yields across all management treatments indicates that weeds were effectively controlled within both the cash crops and over the span of the rotation. Weed biomass was greatest in 2015, after being exposed to the same weather-weed management timing difficulties and further reduction in rye biomass, as experience in soybean, although there was no impact on silage yield. This supports the results of other studies where weeds in corn were effectively controlled using mechanical weed control without sacrificing yield (Keene et al. 2016, Bates et al. 2012). Other studies of organic corn production, have found that mechanical weed control in corn in wet years was not as effective as chemical control, although N supply also appears to have limited corn yields and perhaps weed competitiveness (Posner et al. 2008; Cavigelli, et al. 2008). While corn silage yield was not impacted by weed biomass in any year, the addition of weed seed to the soil seedbank in 2015 could present additional weed management challenges in the future.

The RH-Cult generally resulted in greater weed biomass then the RH-POST and SH treatments without losing the integrity of the crop yield. Implementation of these IWM tactics reduced applied active ingredient use by up to 95% in soybean and 74% in corn compared to SH management. As the bulk of herbicide use in the rotation occurs with the rye cover crop-soy-rye cover crop-corn sequence, a reduction herbicide inputs can benefit the entire rotation. The RH-POST controlled weeds similarly to SH management in most years, while reducing herbicide active ingredient by 11% in soybean and 52% on average in corn. The use of an herbicide-based POST control is more palatable in areas where soil erosion and continuous no-till management are preferred and where high residue cultivation may not be allowed by the farm's conservation program. While not as effective at reducing herbicide application, RH-POST offers the benefit of complete weed control without the potential soil erosion that can occur during cultivation (Synder et al. 2016). Studies with comparable rotations have noted the same ability to reduce herbicide use, while controlling weed populations and maintaining yield (Liebman et al. 2008). These more diverse cropping systems were capable of reducing herbicide use by 88% over 9 years, compared to a higher-input, conventional system (Davis et al 2012). Cover crops were not incorporated between cash crops, eliminating planting complications like those observed in the NE SARE study. While greater input reductions were possible these systems were more reliant on tillage for crop seed bed preparation that provides some weed control, a practice that is not available under continuous no-till management.

The partial budget analysis of both crops was very similar to those noted by Synder et al. (2016). Greater net returns are observed in SH-38 cm than any other sub-management, as SH had greater returns than RH in 2010-2013. In corn silage, it was more profitable to employ RH-Cult than SH management and this was similar to what was reported in 2010-2013 (Snyder et al. 2016). The results of our research show that the profitability of corn managed with reduced herbicide inputs combined with cultural and mechanical tactics compared to herbicide-based weed management is similar to the analysis performed by Liebman et al. (2008). In the study by Liebman et al. (2008) soybean production was more profitable under a reduced herbicide management than a chemical approach, in contrast to our results. The discrepancy in profitability between RH-Cult and SH-38 cm was driven primarily by yield differences in our study likely due to plant population and row spacing. In the Liebman et al. (2008) study, soybean are planted on the same row spacing; so, that management factor was not compared. In addition, the Liebman et al. (2008) study did not include a rye cover crop and soil was tilled prior to planting soybean.

The practice of IWM allows for the selection of appropriate practices based on field conditions. By combining different non-herbicide based controls with appropriately selected herbicide applications, weed biomass can be limited and yield maintained while reducing the overall herbicide inputs necessary for weed control. Banding herbicide can reduce the total ai applied while providing adequate early season weed control. Banded herbicide paired with an effect postemergence control can drastically reduce ai inputs as demonstrated in corn silage. Managers facing challenging weather, sloped fields, or long-term no-till land may opt to replace cultivation with a POST application to maintain consistent weed control while still reducing herbicide use. Producers may also choose to apply practices where net returns would be greatest, such as using the RH-Cult management in corn silage, but using a chemical approach in soybean to allow for narrower row spacing.

Risk of developing herbicide resistant weed biotypes is reduced when a diverse suite of tactics is used each season. The combination of cultural, mechanical, and chemical controls used in this study not only effectively control weeds but also reduce the likelihood that a weed could develop resistance to any single tactic. By using mixes of ai both within and between crops, it is more likely that present herbicide resistant weeds will be controlled and no additional resistance will develop. In conclusion, IWM can be effectively employed to reduce herbicide application while maintaining adequate weed control, crop yield, and farm viability.

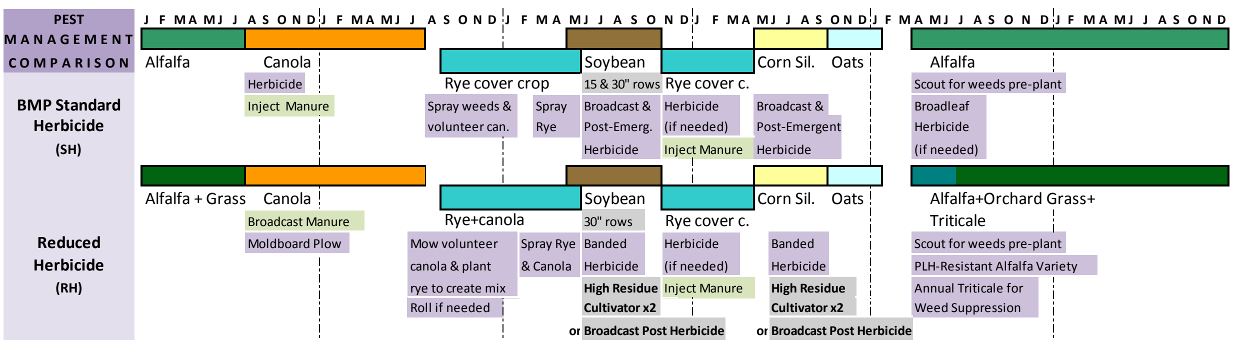

Figure 1-1 – Pest Management crop rotation comparison BMP is the Standard rotation that using more herbicide, while Reduced herbicide incorporates additional cultural and mechanical management tactics.

Table 1-1 – Cash crops (soybean and corn silage) planted variety, planting date, and harvest date for 2013-2015 in all managements.

Crop	Year	Variety	Planting Date	Harvest Date
Soybean	**2013**	Growmark HS28A12	5/20-21/2013	10/13/2013
	2014		6/2/2014	10/27/2014
	2015	TS2849-RS2	5/22/2015	10/8/2015
Corn Silage	**2013**	TA-290-08 LL	5/8, 14/ 2013	9/6/2013
	2014	304-02 ND RR	5/31/2014	9/19/2014
	2015	TA-089-00	5/15/2015	9/8/2015

Table 1-2 – Specific herbicides used in crop for soybean weed control. The PRE herbicides applied at planting and the POST applied about 5 WAP. The total active ingredient (ai) applied (excluding burndown) and % of the SH treatment are provided. The RH-Cult included two passes with the high residue cultivator at 5 WAP and 5 to 7 days later.

Management	PRE	Rate	POST	Rate	Total ai applied	% of SH
		———	———	kg ai ha^{-1}	———	
SH	Flumioxazin + pyroxasulfone	0.16	Glyphosate	0.85	1.01	100
RH-POST	Flumioxazin + pyroxasulfone	0.053 (banded)	Glyphosate	0.85	0.903	89
RH-Cult	Flumioxazin + pyroxasulfone	0.053 (banded)	--	0	0.053	5

Table 1-3 – Application rates of manure applied to corn silage in spring 2013 and to cereal rye cover crop before corn silage in fall 2013 and 2014 and fertilizer application rates made to corn silage in all years.

Management	Rate of Manure Application			Sidedress N as UAN			Post-fertilizer application as K_2O		
	——————kg ha^{-1}——————			————kg ha^{-1}————			——————kg ha^{-1}——————		
	2012	2013	2014	2013	2014	2015	2013	2014	2015
Standard Herbicide	42,144	43,937	39,230	0	100	84	235	0	0
Reduced Herbicide	42,144	43,937	39,230	0	100	84	168	101	0

Table 1-4 - Specific herbicides used in crop for corn weed control. The PRE herbicides applied at planting and the POST applied about 5 WAP. The total active ingredient (ai) applied (excluding burndown) and % of the SH treatment are provided. The RH-Cult included two passes with the high residue cultivator at 5 WAP and 5 to 7 days later.

Management	Year	PRE	Rate	POST	Rate	Total ai applied	% of SH
			——————kg ai ha $^{-1}$——————				
SH	2013	Pendimethalin + s-metolachlor	3.36	Diflufenzopyr + dicamba + glufosinate	0.79	4.15	100
	2014	Mesotrione + s-metolachlor	1.9	Diflufenzopyr + dicamba + glyphosate	1.05	2.95	100
	2015	Mesotrione + s-metolachlor	1.9	Diflufenzopyr + dicamba + nicosulfuron + rimsulfuron	0.24	2.14	100
RH-POST	2013	Pendimethalin + s-metolachlor	1.12 (banded)	Diflufenzopyr + dicamba + glufosinate	0.79	1.91	46
	2014	Mesotrione + s-metolachlor	0.64 (banded)	Diflufenzopyr + dicamba + glyphosate	1.05	1.69	57
	2015	Mesotrione + s-metolachlor	0.64 (banded)	Diflufenzopyr + dicamba + nicosulfuron + rimsulfuron	0.24	0.88	41
RH-Cult	2013	Pendimethalin + s-metolachlor	1.12 (banded)	--	0	1.12	27
	2014	Mesotrione + s-metolachlor	0.64 (banded)	--	0	0.64	22
	2015	Mesotrione + s-metolachlor	0.64 (banded)	--	0	0.64	30

Table 1-5 – Monthly total and season total rain fall during the growing season at for 2013-2015.

	2013	2014	2015
	———cm rainfall———		
April	7	7	9
May	5	13	3
June	15	12	17
July	11	9	16
August	4	12	5
September	5	3	7
Total	47	56	58

Table 1-6 – Soybean plant population, grain yield, and in-season weed biomass under the two main managements: Reduced Herbicide or Standard Herbicide for 2013-2015. Different letters (a,b) indicate a statistical significance at $p<0.05$ between managements.

	Cereal Rye Biomass			**Weed Biomass**	**Soybean Population**			**Grain Yield**
Main	———kg ha^{-1}———			kg ha^{-1}	———plant ha^{-1}———			kg ha^{-1}
Management	2013	2014	2015	2013-2015	2013	2014	2015	2013-2015
Reduced Herbicide	5,183.2 a	2,167.8 a	1,650.2 a	79.75 a	300,235 a	382,642 a	356,259 b	3,305 b
Standard Herbicide	5,395.2 a	3,046.4 a	1,576.0 a	3.01 b	257,304 a	325,447 a	431,324 a	3,523 a
Standard Error ±	1,107.3	463	463	22	21,469	21,469	21,469	89
					Significance of Fixed Effects			
				———Pr>F———				
Year	--	0.0034		0.08		<.0001		0.10
Main mgt	0.90	0.29		**0.0008**		0.60		**0.003**
Sub-mgt	--	--		**0.002**		0.22		0.14
Year*Main mgt	--	0.20		0.14		**0.006**		0.19
Year*Sub-mgt	--	--		0.13		0.74		0.63

Table 1-7 – Soybean grain yield, plant populations, and in-season weed biomass under the four unique sub-managements: Reduced Herbicide with inter-row cultivation or post-emergence herbicide and Standard Herbicide with two different row spacing for 2013-2015. Different letters (a,b) indicate a statistical significance at $p<0.05$ between sub-managements within a year.

		Weed Biomass			Plant Population			Grain Yield		
		kg ha^{-1}			kg ha^{-1}			kg ha^{-1}		
Main Management	**Sub-mgt**	2013	2014	2015	2013	2014	2015	2013	2014	2015
Reduced Herbicide	Cult	20.6 a	108.6 a	332.2 a	303,907 a	390,288 a	356,134 ab	3,121 a	3,347 a	3,472 b
	POST	5.5 a	4.3 a	7.3 b	296,563 a	374,996 a	356,383 ab	3,027 a	3,350 a	3,513 ab
Standard Herbicide	76cm	8.8 a	0.03 a	8.0 b	250,243 a	320,601 a	404,821 b	3,295 a	3,497 a	3,671 ab
	38cm	1.1 a	0 a	0.2 b	264,365 a	330,293 a	457,827 a	3,320 a	3,314 a	4,043 a
	Standard Error ±	10	43	137	22,212	29,840	21,882	238	119	136
					Significance of Fixed Effects					
				Pr>F						
	Main mgt	0.32	0.08	**<.0001**	0.17	0.16	0.05	0.12	0.72	**0.02**
	Sub-mgt	0.69	0.22	**0.0004**	0.72	0.89	0.01	0.64	0.35	0.19

Table 1-8 – Corn plant population, silage yield, and in-season weed biomass under the two main managements: Reduced Herbicide or Standard Herbicide for 2013-2015. Different letters (a,b) indicate a statistical significance at p<0.05 between managements.

	Cereal Rye Biomass			Weed Biomass			Corn Population			Corn Silage Yield		
	———kg ha^{-1}———			———kg ha^{-1}———			———plant ha^{-1}———			———DM kg ha^{-1}———		
Main Management	2013	2014	2015	2013	2014	2015	2013	2014	2015	2013	2014	2015
Reduced Herbicide	258 a	1,255 a	335 a	128 a	8 a	168 a	61,623 a	83,420 a	80,998 a	11,871 a	15,552 a	16,515 a
Standard Herbicide	197 a	1,019 a	404 a	7 b	0.03 a	0.7 b	69,158 a	80,191 a	80,998 a	14,144 a	15,454 a	17,422 a
Standard Error±	23	164	23	38	38	38	3,532	3,532	3,532	894	894	894
							Significance of Fixed Effects					
	2014	2013/2015					———Pr>F———					
Year	--	0.0006			0.07			**0.01**			**0.03**	
Main mgt (RH or SH)	0.33	0.91			<.0001			0.49			0.11	
Sub-mgt	--	--			<.0001			0.14			0.47	
Year*Main mgt	**--**	0.08			**0.01**			0.14			0.30	
Year*Sub-mgt	--	--			0.41			0.45			0.45	

Table 1-9 – Weed biomass in corn silage under Standard Herbicide or two sub-managements in the RH main management: inter-row cultivation and post-emergence herbicide for 2013-2015. Different letters (a,b) indicate a statistical significance at $p<0.05$ between three managements within a year.

	Weed Biomass		
	——kg ha^{-1}——		
Management	2013	2014	2015
Reduced Herbicide - Cult	188.8 a	16.0 a	302.7 a
Reduced Herbicide - POST	67.8 ab	0.005 b	34.3 b
Standard Herbicide	7.5 b	0.03 b	0.7 c
Standard Error ±	86	3	9
	Significance of Fixed Effects		
	——Pr>F——		
Main mgt	0.05	0.002	0.004
Sub-mgt	0.09	<.001	0.004

Table 1-10– Net returns to management and differences in returns under all sub-managements for corn silage and soybean production. The net returns are based on the average yield and cost of production from 2013-2015. Differences are determined by comparing RH returns to SH or SH-38cm returns.

Crop				
		Average total cost	Average net return	Average difference to SH[1]
Corn Silage			———$ ha^{-1}———	
	RH - Cult	$1,683	$670	-$182
	RH- POST	$1,646	$601	-$114
	SH	$1,760	$488	-
Soybean				Difference to SH-38 cm
	RH - Cult	$788	$637	$131
	RH - POST	$765	$653	$114
	SH - 76cm	$762	$738	$30
	SH - 38cm	$763	$767	-

[1]Negative values indicate higher net returns to management under RH management

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Chapter 2

Success of Cover Crop Species and Cultivar Interseeding in Corn and Soybean in the mid-Atlantic Region

Abstract

Cover crop adoption in the Northeast has been slowed due to a number of factors, despite having the highest adoption rate in the country. Commodity crop producers are faced with a short fall growing season for cover following harvest and before weather conditions prevent fall growth. Multiple methods have been evaluated to expand this restricted growing window, including aerial seeding, underseeding and relay intercropping. All of these methods face additional challenges in no-till production systems. Researchers at Penn State developed an innovative cover crop interseeder to address establishment restrictions in no-till grain production. After design of the machine was completed, a number of successful intseeder cover crops needed to be selected. A successful interseeded cover crop may require traits that are not normally associated with post-harvest established cover crops. These species need to tolerate low light and moisture conditions while being able to establish. Annual ryegrass (*Lolium multiflorum*) has been shown to be a strong candidate for interseeding in earlier studies and a trial was conducted to test different varieties for interseeding ability. A Species Trial was conducted to evaluate different grass and legume species in either corn or soybean. These trials were conducted in Pennsylvania (PA), New York (NY), and Maryland (MD). Several species were shown to be better candidates for interseeding based on fall and spring biomass. These species were: Medium Red Clover (*Trifolium pratense*), Annual ryegrass, and Orchardgrass (*Dactylis glomerata* L.). The annual ryegrass trial showed similar performance across varieties with few performing better than

others. A better understanding of appropriate cover crop selection can be used in conjunction with ongoing work with herbicide selection to create recommendations for farmers.

Introduction

Cover crops are a valuable tool in field crop production for contributions towards soil health, crop rotation diversity, pest, and weed control, along with land conservation. Adoption of cover crops across the US is steadily rising since 2011 (NC SARE 2016). Despite numerous studies supporting the use of cover crops and practices based in agroecology (Schipanski et al. 2014, Smith et al. 2008, Snapp et al. 2005), adoption of diverse cover crops is particularly slow among grain producers in the northern corn-belt. While an increasing number of producers are implementing cover crops as long-term practices, adoption by corn and soybean farmers is often constricted by the narrow growing window following grain harvest (NC SARE 2016). In spite of 11 of the top 18 cover crop planted states in the US being in New England and the mid-Atlantic, no state claims more than 27% adoption on available crop land and most states assert less than 15% adoption (Hamilton 2016).

A recent survey of Pennsylvania farmers reported that multiple ecosystem services from cover crops was the desired goal and these included erosion reduction, addition of organic matter, and winter hardiness (Hamilton 2016). A similar survey of NY dairy farmers showed similar farmer goals for cover crop use, but included interception of manure during application and nitrogen retention (Long et al. 2012). Cover crops that provide either living plant matter or residue in both the fall and spring are preferred for their benefits to erosion control and soil structure. Winter hardiness zones in the mid-Atlantic region range from Zone 7a in Maryland to Zone 5b in northern New York. Central Pennsylvania is generally between extremes of the region, at Zone 6a. In general, small grain cover crops such as cereal rye can be planted through early October in Central PA and produce greater than 1.5 Mg ha^{-1} of biomass by early May (Duiker 2013). Winter cereals planted in mid-October are less likely to produce the desired amount of spring biomass. The warmer planting zones in southern PA and MD have more flexibility in cover crop selection as more sensitive species, such as crimson clover, are able to over winter. Common legume cover crop species such as hairy vetch and crimson clover require earlier planting in southern PA, by mid-September, to produce sufficient growth and survive the winter (Duiker 2013).

The date of corn and soybean grain crop harvest, recommended cover crop planting date, and the increased likelihood of sub-optimal temperatures for cover crop growth can create a narrow window of only a few weeks for farmers to plant a cover crop that will have enough of a growing period to provide all the desired qualities. In conjunction with the narrow growing window, farmers are frequently challenged by other time consuming factors and the weather that work to delay cover crop planting. Fall planted cereal rye cover crops have been shown to be effective scavengers of residual nitrogen left from in season fertilization of corn (Ditsch et al. 1993). Cover crops that are planted as early as possible in the fall have been shown to have greater biomass production and nitrogen accumulation than later planting dates (Hasemi et al. 2013).

Earlier fall establishment of cover crops provides additional benefits including greater above and below ground growth which is more effective at holding soil and reducing the potential for erosion. Earlier establishment may allow for other cover crop species such as legumes, which normally do not survive the winter when establishment occurs after corn grain harvest. Forage radish and spring oats are often included in some cover crop mixes, but must be seeded by early September in central PA in order to provide meaningful fall growth. Establishment after corn grain is often too late to be of value.

Several methods of early planting have been attempted in order to address the growing window restriction and increase the benefits of cover crop use. Aerial over seeding of cover crops has become more common as it is an easy way to plant cover crops before grain crop harvest, but establishment is inconsistent and highly dependent on rainfall and the ability of the seed to penetrate the crop canopy (Wilson et al. 2014). Enterprising farmers have modified high-boy drop seeders to broadcast cover crops generally in late summer (Shipman 2010), but successful establishment is still very dependent on rainfall. Of the different cover crop establishment methods, drill-seeded and seeds that are incorporated via a light disk or other incorporation tool tend to have the best emergence and greatest potential to provide beneficial services (Fisher et al. 2011).

Interseeding cover crops into cash crops has already had some success in the mid-Atlantic region. Researchers in New York demonstrated that several cover crop species could be successfully established either before or after the last inter-row cultivation in organic soybean (Hively et al. 2001). Baributsa et al. (2008) showed that red clover interseeded into V5-V7 corn at populations up to 75,000 plants ha^{-1} did not reduce corn yield and could produce enough dry matter to provide N to a subsequent crop. In these studies, cover crops were often broadcast by hand or with a small hand-seeder to simulate commercial applications. In addition, much of this work was performed in tilled cropping systems rather than no-till.

In response to the need for a cost effective interseeding cover crop method suitable for no-till mid-Atlantic farmers, Penn State researchers developed a machine capable of planting cover crops into standing corn and other crops (Dillon 2013). This new high clearance drill is capable of seeding a cover crop into emerged no-till corn or other crops that are planted in 76-cm rows. The drill is also equipped to apply side-dress nitrogen and a postemergent herbicide at the time of interseeding, eliminating the need for additional trips through a field, and reducing the labor requirements for cover crop planting. Preliminary research with this machine has shown some success with mixtures of cover crop species interseeded in V5 to V7 corn (Dillon 2013). However, the previous research conducted at Penn State examined a limited number of species in corn and did not examine potential success across a geographic gradient. Therefore, the objective of our research was to evaluate different grass and legume cover crop species in corn and soybean grown for grain across a three-state region. In addition, we evaluated annual ryegrass cultivar performance in interseeded corn. From the preliminary research, we hypothesized that annual ryegrass and medium red clover would be the best suited for our region based on a number of considered indicators. Relative to ryegrass cultivar performance were hypothesized that cultivars more commonly being used for forage in our region would produce more biomass and have better winter survival than varieties that are less popular to our region.

Methods

Trials were conducted in no-till corn and soybean at a single location in three different states (Table 2-1). The trials used a high clearance drill manufactured by Interseeder Technologies (http://www.interseedertech.com/) to examine interseeded legume and grass cover crops for their suitability in corn or soybean. Cover crop species trials were conducted in both corn and soybean and compared 7 to 12 different grasses and legumes (Table 2-2). An additional trial compared the performance of up to 11 different annual ryegrass cultivars interseeded in corn (Table 2-3). The annual ryegrass cultivar trial included varieties that are commonly grown as forage in the region in addition to some varieties that were recommended by ryegrass seed producers. Both trials evaluated cover crop performance based on fall and spring cover crop biomass. In addition, the potential impact of the cover crop on corn and soybean grain yield was determined.

Much of the methodology was similar across trials and locations. The selected cover crop species and annual ryegrass cultivars were generally the same in the corn trials; the cover crop species comparisons in soybean varied somewhat between sites and years. Each location operated an independent drill that was 9-m wide and capable of operating in no-till conditions. The drill straddles four rows of corn or soybean and has three individual row units spaced 19-cm apart that operate between cash crop rows spaced 76-cm apart. The row units consist of a no-till coulter to expose the soil and prepare the seedbed, a double disk opener which deposits the seeds, followed by a packing or gauge wheel to close the planting slit and regulate seeding depth. The equipment is also capable of applying nitrogen fertilizer and herbicide at the same time as seeding, but these functions were not employed in these studies.

All trials were established as random complete block designs with four replications on two university research farms (Russel E. Larson Agriculture Research Center in Rock Springs and Musgrave Research Farm in Aurora, NY) and the USDA-ARS research facility near Beltsville, MD (Beltsville Agricultural Research Center) (Table 2-4). The soils textural classes were a mix of silt and sandy loam in MD and silt loams in PA and NY and pH ranged from 6.5 in MD up to 7.5 in NY. Individual plot size was 3 m wide by 15 m in length.

Corn and soybean were planted into a no-till seedbed at each of the trial locations. Variety varied by site (Table 2-4) and the targeted population was 69,300 (MD) to 79,100 (NY and PA) seeds ha^{-1} for corn and 432,000 seeds ha^{-1} for soybean. The previous crop before corn was soybean and vice versa. An herbicide application of glyphosate (0.88 kg ae ha^{-1}) and 2,4-D

LVE (0.56 kg ae ha$^-$1) was applied before cash crop planting to control emerged vegetation. In both corn and soybean trials, this application occurred at least 7 days prior to planting. Prior to corn planting in PA, urea treated with a urease inhibitor was broadcast applied at 150 kg N ha^{-1} with the intent to supply all the N needs for the corn. In MD and NY, 34 to 56 kg ha^{-1} N was applied at planting with an additional 112 to 134 kg/ha^{-1} applied as a side-dress treatment. Fields were fertilized with P_2O_5 and K_2O as recommended by soil testing prior to cash crop planting. Approximately one week prior to interseeding, or about V3 corn, glyphosate was broadcast applied at the same rate as the application prior to corn and soybean to control any emerged weeds before interseeding.

Cover crops were interseeded into the standing corn between the V5 and V8 stage and between V3 and R1 in soybean. Grass cover crops and hairy vetch were planted at 22 kg ha^{-1} and the clover cover crops were seeded at a rate of 25 kg ha^{-1}, except in NY where crimson clover was seeded at 50 kg ha^{-1} and cereal rye was seeded at 56 kg ha^{-1} (Table 2-2). All legumes were inoculated with the appropriate *rhizobia* strain prior to seeding and the same cover crop seed lots were used across sites by year.

Above ground cover crop biomass was collected in the fall to assess successful establishment. Cover crop biomass was generally collected just prior to or shortly after cash crop harvest (Table 2-4). Biomass was collected from two 0.5m^2 areas between the middle two rows by clipping and removing the cover crop to the ground level. Crop debris and any weeds were removed and the samples were dried for a minimum for 48 hours before being weighed to determine dry matter accumulation. Biomass was collected again in the spring using the same method. Spring collection was performed just prior to typical cover crop termination before corn for the three locations.

Analysis was completed in SAS v. 9.4 using a Mixed model. The Tukey adjustment was used to perform mean separations and alpha was set at 0.05. The control treatment of 'No Cover' was not included in the comparison of cover crop biomass but was included in the yield comparisons.

Results

Rainfall and temperature varied by both location and year. In season precipitation ranged from 47 cm to 65 cm over the three locations (Table 2-5). MD and PA had drier years in 2013, while NY had drier years in 2014. In season rainfall also varied between years with some years at a given location. Average daily temperature was similar across the three locations, but with MD having the warmest summer temperatures and NY reaching the coldest winter temperatures (Figure 2-1). The winter of 2013 was unusually cold and temperatures stayed at a lower temperature for additional days with limited snowfall. Temperatures over 2014 were more representative for the region.

Cover Crop Species trial in corn. The species trial in corn was conducted at four locations over two years (Table 2-1). A significant interaction was found between site, year, and cover crop, and the analysis was performed based on individual site-year. In the first year of the study at MD, interseeding difficulties occurred leading to poor cover crop establishment and reduced biomass production in both the fall and spring (Table 2-6). We speculate that cover crops were seeded too deep in the soil, leading to reduced emergence and establishment. In general, the target depth with smaller clover and grass seed is less than 0.5 inch due to seed size (The Pennsylvania State University 2011). When seeded correctly, interseeded cover crops emerge within 10 days of seeding, which did not occur in MD in 2013. The MD machine was newly acquired days before field use, not providing adequate time for accurate depth adjustment.

Failure in establishment led to low cover crop biomass and no differences between treatments either in the fall of 2013 or the following spring. The most successful legume in MD in 2013 was crimson clover, which produced 14 and 170 kg ha^{-1} dry matter, respectively, by the fall and spring harvest. Annual ryegrass produced 42 and 201 kg ha^{-1} dry matter in fall and spring, respectively. Corn grain yield was not harvested by individual plot in 2013 in MD, but rather the entire study area was collected and weighed providing an average yield. The 2013 season was productive with timely rainfall (Table 2-5) with the corn yield averaging 13,200 kg ha^{-1}.

The planting challenges that resulted in the poor establishment in 2013 were corrected in 2014 at MD. The cover crops emerged uniformly shortly after seeding with the crimson clover having the highest numerical fall biomass (404 kg ha^{-1}), but similar to medium red clover and hairy vetch (364 and 261 kg ha^{-1}, respectively) (Table 2-6). Of the grasses, perennial ryegrass had the highest numerical fall biomass (144 kg ha^{-1}), but it was not statistically different from the other grasses (Table 2-6). Spring biomass was similar across the all treatments with crimson clover, medium red clover, hairy vetch, tall fescue, and annual and perennial ryegrass producing similar amounts. Annual ryegrass had the numerically highest spring biomass (635 kg ha^{-1}) and ladino clover, Kentucky bluegrass and orchardgrass produced less than 300 kg ha^{-1} (Table 2-6). Corn yield in 2014 in MD ranged from 10,169 to 11,296 and did not differ between treatments including no cover (Table 2-6).

In PA, crimson clover produced 861 kg ha^{-1} fall biomass, which was greater than any other treatment in 2013 (Table 2-7). The other legumes produced less fall biomass than crimson clover with medium red and ladino clovers being similar followed by hairy vetch. Of the legumes, yellow sweet clover produced the least amount of fall growth (65 kg ha^{-1}). Annual ryegrass produced the greatest amount of fall biomass among the grasses (488 kg ha^{-1}) and

Kentucky bluegrass and perennial ryegrass the least (Table 2-7). Of the legumes, by spring only medium red clover achieved greater than 450 kg ha^{-1}, crimson clover failed to regrow due to winterkill and hairy vetch, yellow sweet clover, and ladino clover produced 110 kg ha^{-1} or less spring regrowth. The winter of the first year was reached uncommonly low temperatures for central PA (Figure 2-1) with minimal snow cover and cold sensitive cover crops such as crimson clover did not survive. Previous research has shown that crimson clover survival in central PA and north can be marginal (Duiker 2013). Although all grass species survived the winter, spring biomass ranged from 107 to 229 kg ha^{-1} by the time they were terminated in the spring. This amount of above ground dry matter would be considered relatively low compared to a cereal grain such as rye but still provided sufficient below ground biomass to achieve soil protection (Duiker 2013, Mirsky et al. 2011). In 2013, no differences were observed in corn grain yield between interseeded cover crops or the no cover treatment (Table 2-7).

Tall fescue was added as an additional grass species in 2014. In general cover crop growth by late fall in PA was lower than the previous year and no differences were observed between legume treatments. Legume cover crop biomass at corn harvest ranged from 36 kg ha^{-1} with hairy vetch up to 160 kg ha^{-1} with medium red clover (Table 2-7). As was observed the previous year in PA, annual ryegrass had the greatest amount of fall growth of the grasses (375 kg ha^{-1}), followed by orchardgrass, perennial ryegrass, and tall fescue. As in the previous year, Kentucky bluegrass was near the bottom relative to fall biomass production. Relative to corn yield, the tall fescue treatment yielded less than the orchardgrass or crimson clover treatments, although no cover crop treatment was different than the no cover control indicating that cover crops likely did not influence corn yield. We speculate that the differences in corn yield were likely due to field variability and not related to cover crop treatment.

Cover crop Species trial in soybean. The species trial in soybean was conducted at five locations over two years (Table 2-1) and not all treatments were the same at each location. A significant interaction was found between site, year, and cover crop for common treatments, and the analysis was performed based on individual site-year. In MD, the soybean trial was successfully conducted only in 2014 and fall cover crop biomass ranged from 8 to 33 kg ha^{-1} (Table 2-8). Cover crops emerged and established after interseeding, but by soybean grain harvest, cover crop growth was variable and generally inadequate to provide the desired benefits. All the cover crops winter killed in MD in 2014, resulting in no biomass collection the following spring. Soybean yield was not collected on a per plot basis but averaged 3,746 kg ha^{-1}. In general, the interseeded cover crops did not perform well when planted into soybean in Maryland.

In PA, the species trial in soybean also had limited success and some treatments were more successful than others. Some cover crops established by late fall of both years but that did not guarantee winter survival and spring regrowth. Hairy vetch was the most productive cover crop in 2013 producing aver 400 kg ha^{-1} fall biomass (Table 2-9), this was followed by crimson clover and annual ryegrass. All cover crops except crimson clover survived the winter. In 2014, results were different with annual ryegrass achieving the highest fall (406 kg ha^{-1}) and spring (803 kg ha^{-1}) dry matter yield with most other species producing less than 100 kg ha^{-1}. Unlike the previous year, hairy vetch growth was minimal in the fall and was not present the following spring. Medium red clover was the most successful legume across years with some fall production and increasing biomass by spring termination (Table 2-9). Soybean yield was only collected in PA in 2014 and no differences between treatments were identified.

Interseeded cover crop establishment in soybean was most successful in NY. Although cover crop establishment success varied by species in 2013, crimson clover had the numerically greatest biomass (1,391 kg ha^{-1}) and was statistically similar to cereal rye, annual ryegrass, perennial ryegrass, and the four species mix (Table 2-10). Kentucky bluegrass had the numerically least amount of dry matter (142 kg ha^{-1}) but was similar to some other species. By spring termination, cereal rye produced almost 2,300 kg ha^{-1} dry matter. It was followed by medium red clover, yellow sweet clover, orchardgrass and perennial ryegrass, which all had greater than 1,100 kg ha^{-1} in the spring. The only species that had no spring regrowth was forage radish, which winter killed both years. In 2014, fall cover crop biomass was not collected and spring biomass did not follow the same pattern as the previous year. Annual ryegrass had the greatest biomass (685 kg ha^{-1}) and was similar to medium red clover, orchardgrass, and the four species mix. The forage radish again winter killed. Unlike the previous year, the cereal rye produced less than 50 kg ha^{-1} and no treatment exceeded the 1,000 kg ha^{-1} mark (Table 2-10). Soybean in 2014 appeared more competitive than the previous year and the cover crops were not interseeded until late August. The combination of a competitive soybean crop and late interseeding likely reduced cover crop success. Soybean yields did not differ between cover crop treatments and the no cover control either year.

Annual ryegrass cultivar trial. The annual ryegrass cultivar trial was conducted at six locations over two years (Table 2-1). A significant interaction was found between site, year, and cultivar, so the analysis was performed based on individual site-year. In MD, ryegrass cultivar performance was similar in both fall and spring in both 2013 and 2014 (Table 2-11). Typical fall biomass ranged from as little as 39 kg ha^{-1} to as much as 182 kg ha^{-1} with no differences among cultivars. Unlike the species study conducted in MD in 2013, all ryegrass cultivars established, survived the winter and produced spring regrowth (Table 11). In 2014, fall biomass ranged from 53 to 142 kg ha^{-1}, while spring regrowth generally increased at least four times ranging from 388 up to 702 kg ha^{-1}. The mild winter in 2014/15 must have helped increase spring regrowth compared to the harsher winter of 2013/14 (Figure 2-1). As with the species trial in 2013 at MD, grain yield was collected across the entire trial and not by individual plots and yield averaged 13,221 kg ha^{-1}. In 2014, grain yield ranged from 10,858 up to 11, 998 kg ha^{-1} and there were no differences between ryegrass treatments (Table 2-8).

In PA, annual ryegrass fall biomass in 2013 ranged from 148 to 291 kg ha^{-1} with DH3 being numerically highest and greater than King with other cultivars yielding equivalent amounts to each other (Table 12). By spring termination, Rootmax and SBA22 yielded more than Green Spirit and MO1 with others being equal. Fall and spring biomass averaged 235 and 168 kg ha^{-1}, respectively. In 2014, fall biomass production averaged 367 kg ha^{-1} and was generally greater than the previous year, but did not differ among cultivars. By spring termination, Green Spirit was numerically highest at 768 kg ha^{-1} and greater than DH3 (311 kg ha^{-1}); all other cultivars were similar to both. Corn grain yield did not differ between cultivars or the no cover control in both years (Table 2-12)

The annual ryegrass cultivar trial was conducted in NY both years. Fall cover crop biomass was collected only in 2013 and spring biomass and corn yield was collected in both years. In 2013, fall biomass ranged from 484 to 294 kg ha^{-1}. Bounty and KB Royal had significantly greater biomass than DH3 (Table 2-13), all other cultivars were similar to these three. All cultivars survived the winter in NY, which has been shown to be problematic with southern bred cultivars (Brörkman et al. 2014). By spring termination, biomass ranged from 66 to 291 kg ha^{-1} and despite the larger numerical spread, biomass did not differ between cultivars. The cultivar Marshall was substituted for Green Spirit in 2014 and it produced 366 kg ha^{-1} spring biomass which was numerically highest and greater than MO1 (61 kg ha^{-1}) and DH3 (54 kg ha^{-1}).

All other cultivars were similar to these three (Table 2-13). Corn grain yield was not impacted from any cultivar treatment with all treatments having similar yields in both years.

Discussion

It is hard to draw a single conclusion about the most successful cover crop species from the wide variability between crops, sites, and years. Several legumes species significantly underperformed when interseeded, such as yellow sweet clover, across the entire region. This biennial clover is drought tolerant, but much of the first-year growth is in root development making it unsuited to the short window of growth between grain crops (SARE 2007). Lack of ideal growing environment or time could have attributed to why some species failed where other species succeeded, limiting the selection of well performing legumes. Crimson clover and medium red clover were the most successful legume species although crimson clover establishment was variable. Crimson clover was consistently able to establish and generate spring growth in MD, but was unreliable in PA and NY. In 2013, crimson clover did not survive the winter in both PA and NY. Producers looking to interseed a legume into corn would likely be most successful with medium red clover which established and survived at all three locations. As hypothesized, annual ryegrass was consistent across sites and years. The use of annual ryegrass as a cover crop has been increasing and can be used in the mid-Atlantic for fall grazing of cattle. However, management of annual ryegrass is a concern as successful termination with herbicides requires attention to the details and there is a growing risk of herbicide resistance (Legleiter et al. 2015, Mutch 2012). Perennial ryegrass, tall fescue and orchardgrass are potential alternatives to annual ryegrass, but were generally not as productive.

Cover crops interseeded into soybean were not as successful as those in corn. A south to north gradient became apparent, as interseeding in soybean was not successful in MD, had limited success in PA, and mostly proved successful in NY. Cover crops struggled to establish and survive in the more competitive and full soybean canopies in MD and PA. Other research in MD suggests that interseeding has greater potential for success in double-crop soybean, where plants do not produce as competitive of a growing environment as full-season soybean (Mirsky, personal communication). However, double-cropped soybeans are typically planted in narrower rows, not the necessary 76 cm spacing required for interseeding. Despite current conventions for soybean planting, the possibilities of additional benefits from interseeding merit further inquiry for this planting window. Interseeding in soybean was most successful in NY and like in corn, medium red clover was the most reliable legume tested. The results of the grass species were more mixed with two very different years. In 2013 cereal rye was very productive along both ryegrasses and orchardgrass. In 2014, annual ryegrass and orchardgrass successfully overwintered but cereal rye was less successful, likely due to the late seeding date. The best time for interseeding has been examined at trials in corn and the results show that seeding after V5 tends to be less successful (Curran and Lingenfelter, 2016). Similar trials have not been conducted in soybean.

Few consistent differences were observed between annual ryegrass cultivars. It was expected that a larger range of biomass would be observed based on breeding characteristics of cultivars. Ryegrass grown in the south is more likely to winterkill in our northern climate and later planting increases the risk of winterkill (SARE 2007) but these challenges were not observed. Differences were primarily observed in spring biomass but was rarely consistent across the two years. Producers interseeding annual ryegrass would be best of select seed that is adapted for the area and readily available. The annual ryegrass cultivars used in this study are marketed as forage types and seemed well adapted to the region.

Compared to post-harvest planted cover crops, the interseeded grass species do not always produce as much spring biomass. Annual ryegrass planted by early October in central PA is capable of producing 1,500 kg ha^{-1} by mid-May (Duiker 2014). Red clover is more typically seeded in the spring and not planted post-harvest. A recent Canadian study reported the success of seeding red clover into a small grain (Coombs et al. 2017) and this tactic has also been successful in the mid-Atlantic (Snyder et al. 2016). Interseeding red clover in corn in early summer presents a new opportunity to establish a legume that could benefit the subsequent crop in rotation or perhaps even be used as forage. Cereal rye was only included in soybean in NY and was successful in one of two years. Numerous studies have shown the effectiveness of cereal rye as a cover crop (Nord et al. 2012, Mischler et al. 2010) and the productive growth that can be achieved when planted before October in the mid-Atlantic (Mirsky et al. 2011). However, anecdotal evidence suggests that cereal rye and other small grains do not tolerate heat and shade as well as some other grasses, but additional research is needed to confirm its potential for interseeding.

In conclusion, cover crop adoption by mid-Atlantic farmers can be encouraged by the use of the Interseeder. Medium red clover and annual ryegrass established most consistently in our trials. The results from our research suggest that interseeding is generally more successful in corn than soybean but cover crop establishment in soybean merits further exploration. These studies relied on glyphosate resistant corn and did not use residual herbicides. Where weed infestations are severe and for certain late emerging species, residual herbicides may be necessary. Some research examining residual herbicides and interseeding has been conducted showing that certain herbicides can be used successfully (Curran et al. 2017). Producers should consider a number of factors including cover crop species selection and seeding rate, timing of interseeding, potential economic benefits, reduction of field activities, and residual herbicide use before adopting this new cover crop establishment tactic.

Table 2-1 – Location, year, and total site years of both the species study and ryegrass cultivar study. The ryegrass cultivar study was only performed in corn.

	Aurora, NY	Beltsville, MD	Rock Springs, PA	
Species - Corn	-	2013 and 2014	2013 and 2014	4
Species - Soybean	2013 and 2014	2014	2013 and 2014	5
Ryegrass cultivar	2013 and 2014	2013 and 2014	2013 and 2014	6

Table 2-2 – Cover crop common names, scientific names, and seeding rate for all species used in the species trial. Select species were planted at limited sites, the Species Mix was planted in NY soybean only.

Cover Crop	Species	Seeding rate
		kg ha^{-1}
Alfalfa	*Medicago sativa*	25
Clover, crimson	*Trifolium incarntum*	25
Clover, ladino	*Trifolium repens*	25
Clover, medium red	*Trifolium pratense*	25
Clover, yellow sweet	*Melilotus officinalis*	25
Vetch, hairy	*Vicia villosa*	50
Bluegrass, Kentucky	*Poa pratensis*	50
Fescue, tall	*Lolium arundinaceum*	50
Orchardgrass	*Dactylis glomerata*	50
Rye, cereal	*Secale cereal*	56
Ryegrass, annual	*Lolium multiflorum*	50
Ryegrass, perennial	*Lolium perenne*	50
Radish, forage	*Rapharius sativus*	25
Species Mix (2013)		50 (total)
	Vicia villosa,	16
	Trifolium incarntum,	22
	Trifolium pratense	11
Species Mix (2014)		36 (total)
	Lolium multiflorum	11
	Vicia villosa,	8
	Trifolium incarntum,	11
	Trifolium pratense	11

Table 2-3 – Ryegrass cultivars of *Lolium multiflorum* and seed sources used in the ryegrass cultivar trial. All cultivars were seeded at a rate of 50 kg ha^{-1}.

Ryegrass Cultivar	**Seed Source**
Bounty	Saddle Butte Ag Inc.
Bruiser	Ampac Seed Company
DH 3	Allied Seed, LLC
Green Spirit	Barenbrug
KB Royal/Supreme*	KB Seed Solutions
King	LaCrosse Seeds
MO 1	DLF International Seeds
Rootmax	Cover Crop Solutions
SBA 22	Unavailable
Winterhawk	OreGro Seeds Incorporated

*KB Royal was planted in 2013 and KB Supreme in 2014.

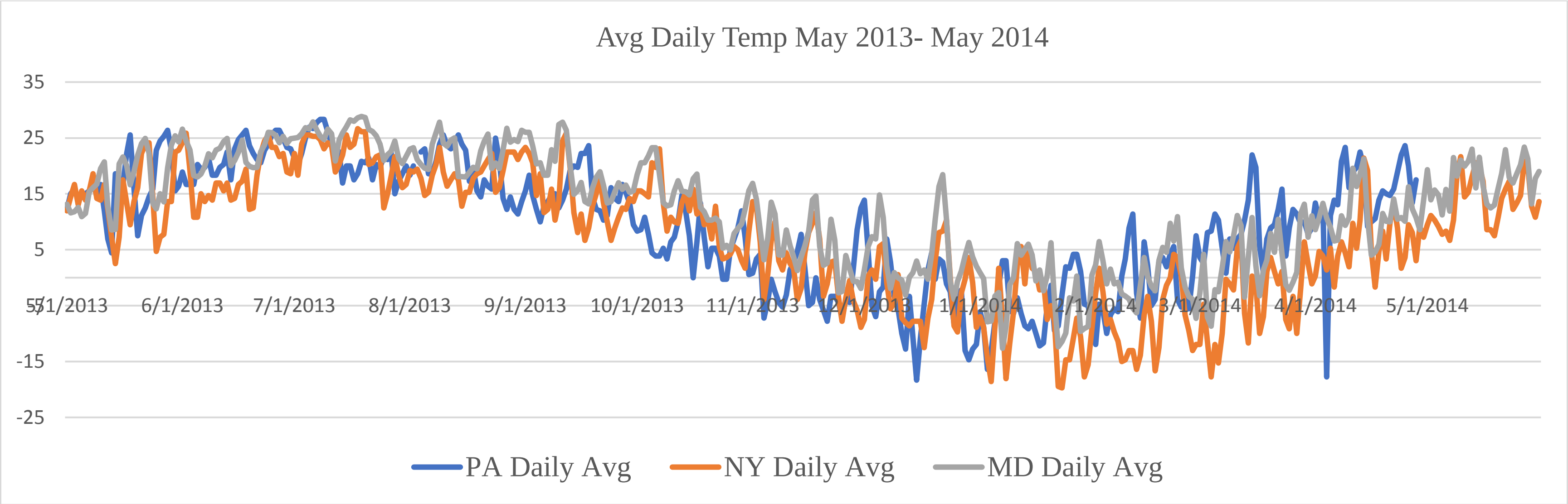
Table 2-4 – Dates for all sites and years of crop planting, interseeded cover crop planting, fall cover crop biomass collection, crop grain harvest and spring cover crop biomass collection. Species and ryegrass cultivar trials in corn were planted on the same day.

Site	Crop	Year	Seed Variety	Crop Planting Date	Interseeding Date	Fall Biomass Collection	Crop Harvest	Spring Biomass Collection*
PA	Corn	2013	DKC-46-61	5/15	6/25	11/20	10/15	5/12
		2014	DKC-47-35	5/9	6/18	10/28	10/31	5/2
	Soybean	2013	AG-2431	5/15	6/25	11/20	-	5/6
		2014	AG-2431	5/14	6/24	10/30	10/31	5/5
MD	Corn	2013	TA647-22DP	5/18	6/21	12/20	10/13	4/18
		2014	TA647-22DP	5/20	6/19	11/5	10/25	4/6
	Soybean	2014	TS3849R2S	5/20	6/19	12/20	10/8	4/6
NY	Corn	2013	DKC44-13S	5/15	6/25	11/20	11/12	5/22
		2014	DKC44-13S	5/27	7/2	11/25	12/2	5/15
	Soybean	2013	AG-2031	6/5	7/16	11/19	10/30	5/22
		2014	PIO-92Y12	5/29	8/11	-	11/4	5/19

*Spring biomass collection took place in the spring of the following year that the cover crop was established.

Table 2-5 – Monthly total and season total rain fall during the growing season at each research sites for 2013 and 2014.

	MD		**NY**		**PA**	
	2013	2014	2013	2014	2013	2014
	––––––––––––––––––––––cm rainfall––––––––––––––––––––––					
April	6	18	8	9	7	7
May	10	13	6	10	5	13
June	19	7	10	7	15	12
July	9	8	18	11	11	9
August	6	13	13	10	4	12
September	5	5	10	6	5	3
Total	54	64	65	53	47	56



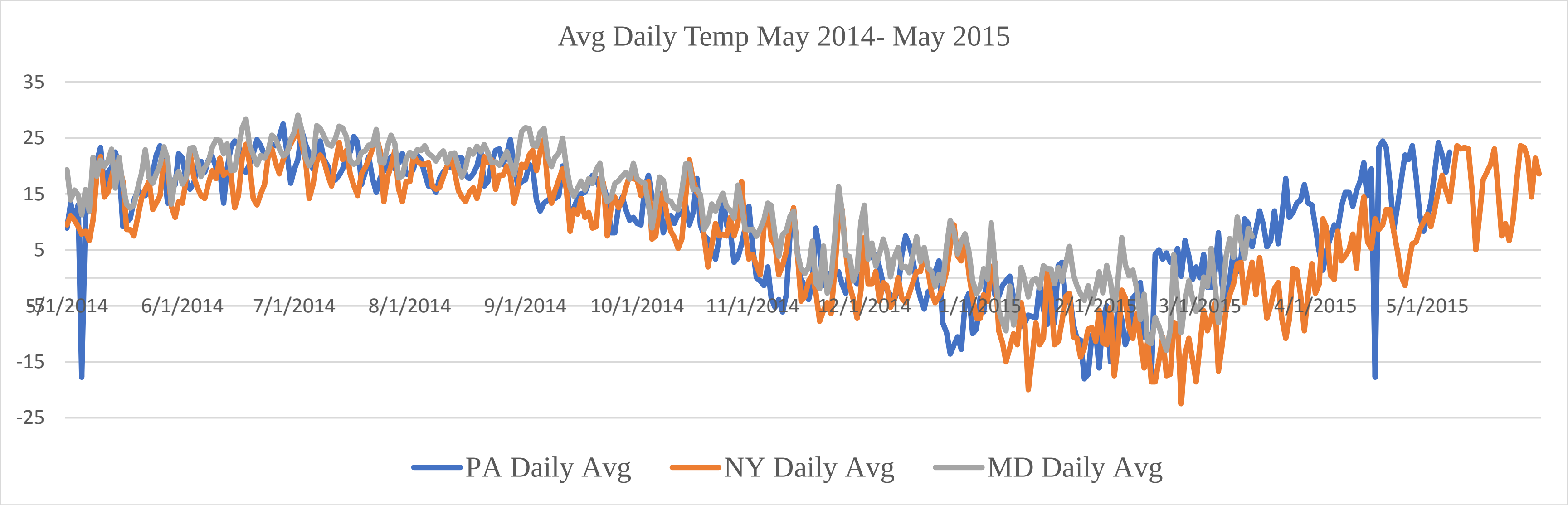


Figure 2-1 – Average daily temperatures (°C) for May 2013-May 2014 and May 2014- May 2015 at each of the three research location.

Table 2-6 – Interseeded cover crop biomass in the fall and spring and corn grain yield (2014 only) for the Species Trial conducted in Beltsville, MD in 2013 and 2014. Biomass and grain yield are reported in kg ha^{-1}. Letters (a,b) indicate a significant differences between values based on a p<0.05.

	2013				2014					
Cover Crop Species	**Cover Crop Biomass**				**Cover Crop Biomass**				**Corn Yield**	
	Fall		Spring		Fall		Spring			
	kg ha^{-1}									
Clover, crimson	14	a	170	a	404	a	398	ab	11,296	a
Clover, ladino	9	a	65	a	50	cd	201	b	10,646	a
Clover, medium red	0	a	0	a	364	ab	381	ab	10,865	a
Clover, yellow sweet	1	a	54	a	161	bcd	131	b	10,518	a
Vetch, hairy	5	a	84	a	261	abc	418	ab	10,757	a
Bluegrass, Kentucky	1	a	11	a	23	d	263	b	10,717	a
Fescue, tall	--		--		76	cd	370	ab	10,470	a
Orchardgrass	2	a	153	a	60	cd	268	b	11,142	a
Ryegrass, annual	42	a	201	a	96	cd	635	a	10,169	a
Ryegrass, perennial	0	a	37	a	144	bcd	384	ab	10,997	a
No cover	--		--		--		--		10,803	a

Table 2-7- Interseeded cover crop biomass in the fall and spring with corresponding corn grain yield for the Species Trial conducted in Rock Springs, PA in 2013 and 2014. Biomass and grain yield are reported in kg ha^{-1}. Letters (a,b) indicate a significant differences between values based on a $p<0.05$.

Cover Crop Species	2013						2014					
	Cover Crop Biomass				Corn Yield		Cover Crop Biomass				Corn Yield	
	Fall		Spring				Fall		Spring			
	kg ha^{-1}											
Clover, crimson	861	a	1	c	10,525	a	147	bc	16	c	14,228	a
Clover, ladino	395	bc	110	bc	10,082	a	55	bc	200	bc	11,714	ab
Clover, medium red	583	b	453	a	9,377	a	160	bc	588	a	13,619	ab
Clover, yellow sweet	65	d	85	bc	10,529	a	40	c	158	c	13,352	ab
Vetch, hairy	235	cd	78	bc	10,825	a	36	c	37	c	13,048	ab
Bluegrass, Kentucky	26	d	107	bc	10,437	a	33	c	216	bc	13,203	ab
Fescue, tall	--	--	--	--	--	a	112	bc	515	ab	11,125	b
Orchardgrass	216	cd	194	b	10,717	a	185	b	755	a	13,835	a
Ryegrass, annual	488	b	229	b	10,948	a	375	a	745	a	11,999	ab
Ryegrass, perennial	137	d	135	bc	10,852	a	183	b	615	a	13,270	ab
No cover	--		--		10,472	a	--		--		13,606	ab

Table 2-8 - Interseeded cover crop biomass in the fall and spring with corresponding soybean grain yield for the Species Trial conducted in Beltsville, MD in2014. Biomass and grain yield are reported in kg ha^{-1}. Letters (a,b) indicate a significant differences between values based on a $p<0.05$.

	2014	
	Cover Crop Biomass	
Cover Crop Species	Fall	
	———kg ha^{-1}———	
Clover, crimson	12	a
Clover, ladino	32	a
Clover, medium red	22	a
Clover, yellow sweet	20	a
Vetch, hairy	13	a
Rye, cereal	8	a
Ryegrass, annual	33	a
Radish, forage	21	a
No cover	--	

Table 2-9 – Interseeded cover crop biomass in the fall and spring with corresponding soybean grain yield (2014 only) for the Species Trial conducted in Rock Spring, PA in 2013 and 2014. Biomass and grain yield are reported in kg ha^{-1}. Letters (a,b) indicate a significant differences between values based on a $p<0.05$.

Cover Crop Species	2013 Cover Crop Biomass Fall		2013 Cover Crop Biomass Spring		2014 Cover Crop Biomass Fall		2014 Cover Crop Biomass Spring		2014 Soybean Yield	
	kg ha^{-1}									
Alfalfa	--		--		10	c	0	c	4,059	a
Clover, crimson	362	ab	0	b	70	bc	0	c	4,058	a
Clover, ladino	15	d	13	b	95	bc	0	c	4,058	a
Clover, medium red	101	c	226	b	147	b	240	b	4,057	a
Clover, yellow sweet	54	cd	259	ab	15	bc	0	c	4,063	a
Vetch, hairy	407	a	586	a	15	bc	0	c	4,050	a
Ryegrass, annual	300	b	179	b	406	a	803	a	4,050	a
No cover	--		--		--		--		4,058	a

Table 2-10 – Interseeded cover crop biomass in the fall and spring with corresponding soybean grain yield for the species trial conducted in Aurora, NY in 2013 and 2014. Biomass and grain yield are reported in kg ha^{-1}. Letters (a,b) indicate a significant differences between values based on a $p<0.05$.

Cover Crop Species	2013						2014			
	Cover Crop Biomass				Soybean Yield		Cover Crop Biomass		Soybean Yield	
	Fall		Spring				Spring			
	kg ha^{-1}									
Clover, crimson	1,391	a	32	e	2,860	a	90	b	2,782	a
Clover, ladino	147	ed	282	e	3,448	a	5	b	3,143	a
Clover, medium red	643	bcde	1,372	b	3,021	a	284	ab	2,858	a
Clover, yellow sweet	165	ed	1,128	bcd	3,776	a	98	b	3,195	a
Vetch, Hairy	--		--		--		52	b	3,061	a
Bluegrass, Kentucky	142	e	498	de	2,972	a	115	b	2,981	a
Orchardgrass	327	cde	1,158	bc	3,262	a	341	ab	3,159	a
Rye, cereal	856	abcd	2,281	a	2,959	a	40	b	2,847	a
Ryegrass, annual	815	abcde	585	cde	2,988	a	685	a	3,182	a
Ryegrass, perennial	899	abc	1,258	b	2,774	a	--		--	
Radish, forage	477	bcde	0	e	3,149	a	0	b	2,998	a
4 spp mix	1,143	ab	66	e	4,068	a	403	ab	3,061	a
No cover	--		--		3,090	a	--		2,955	a

Table 2-11- Interseeded cover crop biomass in the fall and spring with corresponding corn grain yield for the Ryegrass Cultivar Trial conducted in Beltsville, MD in 2013 and 2014. Biomass and grain yield are reported in kg ha^{-1}. Letters (a,b) indicate a significant differences between values based on a p<0.05.

Ryegrass Cultivar	2013 Cover Crop Biomass Fall		2013 Cover Crop Biomass Spring		2014 Cover Crop Biomass Fall		2014 Cover Crop Biomass Spring		Corn Yield	
	———————————————kg ha^{-1}———————————————									
Bounty	88	a	156	a	142	a	591	a	11,998	a
Bruiser	110	a	161	a	137	a	582	a	10,858	a
DH3	40	a	75	a	53	a	485	a	11,884	a
Green Spirit	140	a	97	a	131	a	584	a	11,323	a
KB Royal / Supreme*	80	a	64	a	110	a	609	a	11,899	a
King	182	a	164	a	99	a	405	a	11,237	a
MO 1	34	a	87	a	88	a	388	a	11,252	a
Rootmax	136	a	136	a	85	a	657	a	11,432	a
SBA 22	118	a	198	a	78	a	702	a	11,179	a
Winterhawk	75	a	118	a	106	a	620	a	11,277	a
No Cover	--		--		--		--		11,986	a

*KB Royal was planted in 2013 and KB Supreme was planted in 2014

Table 2-12- Interseeded cover crop biomass in the fall and spring with corresponding corn grain yield for the Ryegrass Cultivar Trial conducted in Rock Springs, PA in 2013 and 2014. Biomass and grain yield are reported in kg ha^{-1}. Letters (a,b) indicate a significant differences between values based on a p<0.05.

Ryegrass Cultivar	2013						2014					
	Cover Crop Biomass				Corn Yield		Cover Crop Biomass				Corn Yield	
	Fall		Spring				Fall		Spring			
	——kg ha^{-1}——											
Bounty	235	ab	177	ab	10,678	a	411	a	548	ab	14,051	a
Bruiser	219	ab	219	ab	10,616	a	355	a	463	ab	13,951	a
DH3	291	a	152	ab	10,099	a	393	a	311	b	14,470	a
Green Spirit	214	ab	78	b	10,018	a	355	a	768	a	14,065	a
KB Royal / Supreme	244	ab	152	ab	11,052	a	393	a	560	ab	13,472	a
King	149	b	148	ab	10,745	a	332	a	411	ab	14,016	a
MO 1	242	ab	71	b	10,826	a	362	a	369	ab	13,506	a
Rootmax	261	ab	282	a	10,353	a	360	a	665	ab	13,917	a
SBA 22	271	ab	296	a	9,410	a	384	a	582	ab	13,623	a
Winterhawk	225	ab	108	ab	10,673	a	321	a	608	ab	13,972	a
No Cover	--		--		10,669	a	--		--		13,995	a

*KB Royal was planted in 2013 and KB Supreme was planted in 2014

Table 2-13 - Interseeded cover crop biomass in the fall and spring with corresponding corn grain yield for the Ryegrass Cultivar Trial conducted in Aurora, NY in 2013 and 2014. Biomass and grain yield are reported in kg ha^{-1}. Letters (a,b) indicate a significant differences between values based on a $p<0.05$.

Ryegrass Cultivar	2013 Cover Crop Biomass Fall		2013 Cover Crop Biomass Spring		2013 Corn Yield		2014 Cover Crop Biomass Spring		2014 Corn Yield	
	——kg ha^{-1}——									
Bounty	484	a	219	a	6,609	a	252	ab	13,361	a
Bruiser	409	ab	187	a	5,476	a	174	ab	12,737	a
DH3	294	b	95	a	5,912	a	54	b	13,667	a
Green Spirit	446	ab	291	a	7,002	a	--		--	
KB Royal	359	a	67	a	7,342	a	235	ab	13,616	a
King	351	ab	194	a	7,181	a	126	ab	13,132	a
MO 1	367	ab	66	a	6,810	a	62	b	14,012	a
Marshall	--		--		--		366	a	13,471	a
Rootmax	387	ab	218	a	7,070	a	213	ab	12,492	a
SBA 22	415	ab	126	a	7,958	a	173	ab	12,916	a
Winterhawk	465	ab	137	a	7,091	a	276	ab	12,761	a
No Cover	--		--		7,553	a	--		13,068	a

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Epilogue

A number of conclusions may be drawn from the NE SARE Dairy Cropping Systems Study in regards to weed control and crop yield. The RH-Cult management in corn silage maintained yields and generated equal or more net returns than the SH management. Weed biomass was greater in RH-Cult, but this did not impact yield in any of the first three years (Synder et al. 2016) nor in the three-year results presented in Chapter 2. Despite the desire of some farmers for fields devoid of most weeds, this study demonstrates that under the conditions of this experiment, with consistent management herbicides can be reduced, weeds can be maintained below competitive thresholds and yields maintained. The IWM tactics used in this study including implementing a diverse rotation that includes cover crops, banding herbicides and using POST applications, and using mechanical controls such as inter-row cultivation could be adopted by conservation tillage farmers based on weed problems, farmer preferences and access to equipment.

Soybean did not perform as well under RH-Cult as the SH-38 cm row spacing. Previous studies have shown the impact of soybean row spacing on yield and antidotal evidence leads us to believe that many PA farmers today plant on 38-cm or less compared to 76-cm rows for the perceived yield advantage. While RH-Cult and RH-Post were both able to reduce herbicide inputs while maintaining a relatively low weed population, it is unlikely a producer would be willing to sacrifice higher yields and plant in 76-cm rows in order to adopt high-residue cultivation. In addition, this is not the first study to observe difficulties in soybean production when planting into a heavy cover crop residue. There is a need for further exploration into no-till soybean production in these systems and incorporate cover crops that can potentially impede crop establishment. With consistent soybean plant establishment, future studies could explore expanded ways of incorporating IWM.

A weed seedbank study was conducted in the fall of 2014 and the spring of 2015. The results of this work were not presented in this thesis. Future analysis of this data could provide additional insight into the impacts of the longer-term RH management over the six-year period. Preliminary analyses did not reveal significant differences in weed density between the two management systems which was not expected. Perhaps weed management was sufficiently effective in both systems to prevent significant seed rain that might have influenced the weed seedbank dynamics. Preliminary analysis did show an apparent difference in the species diversity between systems, but this requires additional analysis. A determination of how management impacts the weed seedbank could reveal opportunities to drive or shift seedbanks directionally based on management inputs. For example, does high residue cultivation or cover crop implementation cause a shift in dominant species?

This study evaluated weed biomass and yield in only two crops over the second three-year period of the rotation. Future work should evaluate weed populations over the entire six-years and across the entire rotation. Previous analysis determined that weed biomass was affected by the crop rotation and management. This should be further explored to include the impact of the three-year forage stand on weeds and the legacy effect to the seed bank.

The interseeder cover crop species trials revealed annual ryegrass and medium red clover as the most consistent cover crops to establish across the mid-Atlantic region. Other legumes such as crimson clover and hairy vetch or grasses including orchardgrass, perennial ryegrass, and tall fescue can also be successful, but additional research is necessary. The success of these cover crops, while perhaps not as dependable or productive to some producers in the southern mid-

Atlantic as some post-harvest planted species (e.g. cereal rye), can provide multiple benefits and an additional establishment options for farmers. In particular, the ability to establish a legume following corn should be explored more fully. Opportunities for consistent establishment and high biomass production should be further explored and factors such as optimum seeding time and effective herbicide programs must be identified. The ability of the interseeder drill to plant cover crops as well as apply herbicide and side-dress fertilizer should be explored more potentially making this a more viable option for mid-Atlantic producers.

In the end, strategies must be developed that integrate diverse approaches that include alternatives to herbicides and integration of cover crops. Both studies summarized in this thesis provide evidence for IWM and the use of cover crops. Certainly, a missing piece that should be a future focus is how interseeded cover crops could benefit weed management. A living growing cover would compete against weeds and this could be particularly important in reduced herbicide input systems. The knowledge gained in this research should contribute to recommendations made to producers to encourage practices that reduce environmental impact, reduce herbicide use, and benefit agriculture in the long run.

Appendix: Seedbank Study

A seedbank study was performed in the spring and fall of 2015 determine the composition of the germinable seed bank. Samples were taken from first year alfalfa, rye going to corn silage, and canola in the spring and following corn silage, third year alfalfa, and soybean in the fall. Samples were also taken from the Corn/Soy Rotation to act as a low diversity, conventional production comparison.

Soil cores were collected with a 2-inch auger. Cores were split from 0-15 cm and 15-30 cm. In order to prevent soil loss, the first 15 cm will be taken then removed from the auger. The next 15 cm were taken from the same hole as to obtain a continuous 30 cm from the same sampling point. There were 6, randomly sampled cores taken from each split-split plot. Cores were not taken from the yield strip (area dependent on the crop) or from the first 6 meters on the western half of the plot or from the first 6 meters of the south-eastern corner as to avoid any weed microplots from previous years.

Samples were only be taken from the fertilized plots in the C-S Rotation as to reduce the possibility of manure application confounding the controlled comparison. The two split-split plot samples were composited as it is acting as a sample of only the main effect.

Soil samples were grown out in the ASI greenhouses. Seeds were given approximately a month, before the germinated population was identified, counted, and removed from the tray. The soil was allowed time to dry out before it was watered and germination occurred again. This cycle was repeated three times for each sampling period.

Data was summarized by sampling period (Spring or Fall), average number of germinated weed seedlings, summer annual species, winter annual species, perennial species, and total number of species for each depth and crop.

Average number of germinated weeds by lifecycle (summer annual, winter annual, and perennial), total number of weed seedlings, and total number of different species based on crop, weed management, and sample depth for spring and fall of 2015.

Spring 2015								
Rotation	**Crop**	**Management**	**Depth**	**Summer Annual**	**Winter Annual**	**Perennial**	**Total weed seedlings**	**Number of Species**
Pest Rotation	Alfalfa	RH	6	32	5	18	44	11
			12	41	7	38	75	11
		SH	6	41	5	37	65	10
			12	28	4	10	48	7
	Corn Silage	RH	6	71	3	17	64	8
			12	65	5	19	90	9
		SH	6	48	8	14	90	8
			12	44	4	5	45	8
	Soybean	RH	6	57	3	37	122	11
			12	64	4	45	82	11
		SH	6	51	11	62	83	11
			12	39	8	24	86	9
Corn/Soy Rotation	Corn Grain		6	66	20	47	160	10
			12	37	5	44	75	9
	Soybean		6	58	20	37	115	10
			12	38	10	10	69	12

Fall 2015								
Rotation	**Crop**	**Management**	**Depth**	**Summer Annual**	**Winter Annual**	**Perennial**	**Total weed seedlings**	**Number of Species**
Pest Rotation	Alfalfa	RH	6	52	3	6	53	7
			12	22	0	4	31	5
		SH	6	29	1	12	42	5
			12	37	1	13	51	6
	Corn Silage	RH	6	31	1	14	47	4
			12	20	1	11	31	3
		SH	6	23	1	7	31	4
			12	40	0	8	34	6
	Soybean	RH	6	35	3	11	31	6
			12	15	1	6	19	2
		SH	6	29	1	4	33	5
			12	36	0	6	43	5
Corn/Soy Rotation	Corn Grain		6	31	1	2	19	4
			12	30	1	17	47	6
	Soybean		6	57	15	23	95	7
			12	23	2	3	40	5