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ALTERNATIVES FOR REDUCING TILLAGE IN AN ORGANIC GRAIN/SILAGE PRODUCTION SYSTEM: IMPLICATIONS FOR WEED MANAGEMENT

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ABSTRACT

Many organic farmers would like to reduce tillage to aid with soil conservation and decrease labor and fuel costs. However, tillage is still necessary for weed control and incorporation of nutrient amendments. One strategy for reducing tillage revolves around cover crop-based, organic rotational no-till, which employs cover crop mulches and no-till cash crop planting. Primary tillage occurs in the fall at cover crop establishment, and in-season weed control relies on suppression by the cover crop mulch along with supplemental inter-row cultivation. We initiated a cropping systems experiment to study several strategies for reducing tillage frequency and intensity within an organic grain/silage rotation in the Mid-Atlantic. Four cropping systems (S1-S4) were examined before soybean and corn crops. For soybean, either a cover crop mixture interseeded into corn harvested for grain or fall sown cereal rye after corn silage and before soybean was terminated via tillage or roller-crimper, respectively. Soybean were either seeded into the tilled cover crop mixture (S2 and S4) or no-till planted into the cereal rye mulch (S1 and S3). Cover crops preceding corn included two systems of hairy vetch/triticale sown after spelt harvest (S1 and S2) and primary tillage, and two systems of red clover/timothy frost-seeded into spelt in late winter (S3 and S4). One hairy vetch system was terminated via roller-crimping (S1), while the other three systems relied on spring tillage to incorporate the cover crop and livestock manure. One hairy vetch and red clover system were grown for corn silage (S1 and S3), while the other two were harvested as grain corn. The results showed that for the soybean crop, while the interseeded mix generally produced around 2,000 kg ha^{-1} biomass, cereal rye typically produced about 5,000 kg ha^{-1}, with upwards of 8,000 kg ha^{-1}. Weed suppression varied from year to year based on environmental conditions which sometimes hindered in-season cultivation. Weed control was good and subsequent biomass production was as low as 95 kg ha^{-1} in 2015, but reached upwards of 2,000 kg ha^{-1} in 2016, when weather conditions prevented effective mechanical weed control. Despite differences in both soybean stand and weed biomass, yields were comparable between the no-till and tilled soybean systems, ranging from 1,800-3,000 kg ha^{-1} across years. For the corn crop, red clover/timothy produced 3,300-4,500 kg ha^{-1} cover crop biomass, while hairy vetch/triticale was more variable, producing 3,600-7,500 kg ha^{-1} biomass over the three years. Although weed biomass at the time of corn planting was below 78 kg ha^{-1}, in-season weed control varied by both treatment and year depending on the effectiveness of in-season cultivation. Late-summer weed biomass levels ranged from 300 kg ha^{-1} up to 2,700 kg ha^{-1}, with less effective weed control resulting when environmental conditions prevented timely blind tillage and inter-row cultivation. Corn grain yields were not different from year to year; however, corn silage yields were different between systems every year likely due to later planted corn and a reduced nutrient supply. Finally, the weed seedbanks were measured to the plow layer each March preceding the cash crop growing season. Our results show that poor in-season weed control greatly drives the density of the weed seedbank, with seeds m^{-2} increasing after a droughty 2016 which hindered in-season cultivation efforts. Foxtail species dominated the seedbank in all three cash crops (corn, soybean, spelt), comprising at least 40% of the germinable seedbank. Other prevalent species included purslane speedwell, yellow woodsorrel, Eastern black nightshade, common lambsquarters, and redroot pigweed, among others. Seedbank trends showed that seed density increased after the corn and soybean phases, but decreased after the spelt phase. No-till corn and soybean systems tended to have lower seed density relative to tilled systems, but this was dependent on successful in-season weed control. Our results also show that interseeding a cover crop in corn can help reduce returns to the seedbank, with seed density being lower than corn systems which did not employ interseeding.

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LIST OF ABBREVIATIONS

1. ROSE- reduced-tillage organic systems experiment
2. HV- hairy vetch
3. TR- triticale
4. RC- red clover
5. TM- timothy
6. CR- cereal rye
7. INT- interseeded cover crop
8. IM- injected manure
9. BM- broadcast manure
10. MP- moldboard plow
11. CP- chisel plow
12. RELARC- Russell E. Larson Agricultural Research Center
13. WAP- weeks after planting
14. CBS- corn-soybean-spelt
15. BSC- soybean-spelt-corn
16. SCB- spelt-corn-soybean

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PROLOGUE

Organic agriculture prohibits the use of synthetic pesticides and fertilizers, and relies on a diverse cropping system to help manage pests and provide plant nutrients (Gomiero et al., 2011, NOP 2005). Per the National Organic Program standards, organic farmers must also use tactics which promote biodiversity and improve soil organic matter and soil quality while reducing runoff and erosion (NOP 2005). Concerns for the environment and increasing interest in organic food by the public have increased demand for organic food products every year (Dimitri and Oberholtzer, 2009). Organic farmers are looking for new and diverse ways to manage their systems with less tillage, including cultural methods such as cover cropping. Weed management in organic systems is of huge concern and generally very reliant on tillage (Bond and Grundy, 2000, Mohler and Baker, 2014), so identifying successful reduced tillage tactics for these systems is an important step toward greater sustainability. Over a decade ago, Barberi (2002) reported that weed control issues in organic systems have not been investigated nearly as much as in conventional farming research, and that a systems perspective is needed to identify successful solutions. Although some recent research has focused on organic crop production systems within the last 10 years (Keene 2015, Mirsky et al., 2013; Mirsky et al., 2012, Wallace et al., 2017), these systems are complex and require longer-term evaluation across ecological space and time (Barberi, 2002, Mohler and Baker, 2014).

Continuous no-till in organic annual row crop production is currently not feasible, as tillage remains critical for weed control and incorporating nutrients and residues (Peigné et al., 2007). Practices which help reduce this reliance on tillage for weed management in organic systems can promote soil health by decreasing both the frequency and intensity of soil disturbance. There are numerous benefits to reducing mechanical operations, including retention of soil moisture during times of water stress, and increased organic matter content (Berner et al., 2008, Kuepper 2001). No-till practices can also help decrease soil runoff and increase water infiltration through better soil aggregate stability (Uri 2000). Furthermore, fuel, energy, and labor are saved due to fewer tractor passes with equipment, which helps save money in the operation (Berner et al., 2008, Uri 2000).

Cover crop-based, rotational no-till is one method for reducing tillage in organic annual row crop production (Keene 2015, Mirsky et al., 2012, Wallace et al., 2017). This approach typically utilizes primary tillage in the fall following cash crop harvest to prepare a seedbed for cover crop seeding (Mirsky et al., 2012). Cover crops are terminated in the spring using a roller-crimper, which creates a weed-suppressive mulch to aid in summer annual weed control and enables no-till cash crop planting (Kornecki et al., 2006, Reberg-Horton et al., 2012, Wallace et al., 2017). The mulch can help conserve water and provide nutrients to the cash crop while the cover crop residue is decomposing (Mirsky et al., 2012). This approach eliminates the need for primary tillage in the spring, helping contribute to the goal of reduced erosion and increased soil conservation and quality (NOP 2005). Organic rotational no-till systems can achieve similar yields to tillage-based systems, but adequate weed suppression from the cover crop mulch is critical for this to happen (Mirsky et al., 2012, Teasdale et al., 2012).

While past research on cover crop-based, organic rotational no-till production has focused on ways to facilitate the adoption of no-till practices, several agronomic challenges have arisen which impede successful implementation. Termination of cover crops by use of the roller-crimper has been variable, with incomplete control arising when cover crops are not roll-crimped at the correct growth stage. Failure to control cover crops in this way results in subsequent weedy or "volunteer" cover crops which pose a problem in future cash crops (Keene 2015, Keene et al., 2017, Wallace et al., 2017). Inconsistent establishment of cash crops in high biomass of rolled cover crop residue continues to be of concern as well. While high amounts of residue are required to suppress weeds, there can be tradeoffs with sufficient cash crop establishment (Mirsky et al., 2012). Modifications to tillage equipment may be needed to achieve correct seed placement and furrow closure. Finally, a narrow window following corn grain harvest for cover crop establishment poses issues with successful cover crop establishment before winter (Keene 2015, Wallace et al., 2017). Many farmers in the Mid-Atlantic who wish to grow corn for grain cannot successfully seed a cover crop following corn harvest, resulting in either poor cover crops or fallow soil. These constraints to adoption of no-till are ones which require more research to better aid organic farmers in the Mid-Atlantic.

To address constraints to the adoption of organic rotational no-till production, we conducted the second phase of the Reduced-tillage Organic Systems Experiment (ROSE). In the first phase of the ROSE, we examined roll-crimped cover crops preceding no-till corn and soybean planting. We utilized a systems experiment approach to examine the effects of various management practices on weed management in a three year, corn (*Zea mays* L.) – soybean (*Glycine max* L. Merr.) –spelt (*Triticum spelta* L.) organic rotational no-till rotation. Additionally, we examined alternative reduced-tillage practices such as interseeding and frost-seeding to address the previously identified constraints (Keene

2015, Wallace et al., 2017). Cropping systems varied by cover crop species, their establishment and termination, manure application timing, as well as tillage frequency and intensity. The results from this research can aid farmers in the successful adoption of reduced-tillage practices in the Mid-Atlantic.

This thesis is comprised of three chapters, with each chapter addressing aspects of the second phase of the ROSE. Chapter one examines the components of the soybean cropping systems, including cover crop biomass, summer annual weed biomass, and soybean populations and yield. Chapter two addresses the same variables as chapter one, but focuses on the corn phase of the rotation. The first two chapters also examine a partial budget analysis of the different cropping systems to better understand the costs associated with different reduced-tillage practices. In chapter three, we interpret the weed seedbank findings, examining seedbank trajectories over the course of the rotation and the implications that different practices can have on seed density. This thesis concludes with an epilogue which provides a brief summary of the findings from each chapter, as well as the areas in which future research should focus to facilitate the successful adoption of reduced-tillage practices in Mid-Atlantic organic annual row crop production.

Literature Cited

Barberi, O. 2002. Weed management in organic agriculture: are we addressing the right issue? Weed Res. 42:177-193.

Berner, A., I. Hildermann, A. Fliebbach, L. Pfiffner, U. Niggli, and P. Mäder. 2008. Crop yield and soil fertility response to reduced tillage under organic management. Soil and Till. Res. 101:89-96.

Bond, W. and A.C. Grundy. 2001. Non-chemical weed management in organic farming systems. Weed Res. 41:383-405.

Dimitri, C. and L. Oberholtzer. 2009. Marketing U.S. organic foods. USDA ERS Economic Information Bulletin #58.

Gomiero, T., D. Pimentel and M.G. Paoletti. 2011. Environmental impact of different agricultural management practices: conventional vs. organic agriculture. Crit. Rev. in Plant Sci. 30:95-124.

Keene, C.L. 2015. Agronomic performance of a reduced-tillage organic grain crop rotation during the transition to organic production. Dissertation. University Park, PA: The Pennsylvania State University. 176 p.

Keene, C.L. and W.S. Curran. 2016. Optimizing high-residue cultivation timing and frequency in reduced-tillage soybean and corn. Agron. J. 108:1987-1906.

Keene, C.L., W.S. Curran, J.M. Wallace, M.R. Ryan, S.B. Mirsky, M.J. VanGessel and M.E. Barbercheck. 2017. Cover crop termination timing is critical in organic rotational no-till systems. Agron. J. 109:272-282.

Kornecki, T.S., A.J. Price and R.L. Raper. 2006. Performance of different roller designs in terminating rye cover crop and reducing vibration. Amer. Soc. of Agri. and Bio. Eng. 22:633-641.

Kuepper, G. 2001. Pursuing conservation tillage systems for organic crop production. ATTRA’s Organic Matters Series. https://attra.ncat.org/attrapub/download.php?id=107.

Mirsky, S.B., M.R. Ryan, W.S. Curran, J.R. Teasdale, J. Maul, J.T. Spargo, J.Moyer, A.M. Grantham, D. Weber, T.R. Way and G.G. Camargo. 2012. Conservation tillage issues: cover crop-based organic rotational no-till grain production in the mid-Atlantic, USA. Renew. Agric. and Food Syst. 27:31-40.

Mirsky, S.B., M.R. Ryan, J.R. Teasdale, W.S. Curran, C.S. Reberg-Horton, J.T. Spargo, M.S. Wells, C.L. Keene and J.W. Moyer. 2013. Overcoming weed management challenges in cover crop–based organic rotational no-till soybean production in the eastern United States. Weed Technol. 27:193-203.

Mohler, C.L. and B.P. Baker. 2014. Weed management by upstate New York organic farmers: strategies, techniques and research priorities. Renew. Agric. and Food Sys. 30:418-427.

[NOP] National Organic Program Handbook. 2005. Accessed September 2nd, 2017. https://www.ams.usda.gov/rules-regulations/organic/handbook.

Peigné, J., B.C. Ball, J. Roger-Estrade and C. David. 2007. Is conservation tillage suitable for organic farming? A review. Soil Use Manag. 23:129-144.

Reberg-Horton, S.C., J.M. Grossman, T.S. Kornecki, A. D. Meijer, A.J. Price, G.T. Place and T.M. Webster. 2012. Utilizing cover crop mulches to reduce tillage in organic systems in the southeastern USA. Renew. Agric. and Food Syst. 27:41-48.

Teasdale, J.R., S.B. Mirsky, J.T. Spargo, M.A. Cavigelli and J.E. Maul. 2012. Reduced-tillage organic corn production in a hairy vetch cover crop. Agron. J. 104: 621-628.

Uri, N.D. 2000. Perceptions on the use of no-till farming in production agriculture in the United States: an analysis of survey results. Agric. Eco. And Env. 77: 263-266.

Wallace, J.M., C.L Keene, W.S. Curran, S.B. Mirsky. M.R. Ryan and M.J. VanGessel. 2017. Integrated weed management strategies in cover crop-based, organic rotational no-till corn and soybean in the mid-Atlantic region. *In print.*

Chapter 1

Crop Performance and Weed Control in Rotational No-till vs. Tillage-based Organic Soybean

Abstract

Many organic farmers would like to reduce tillage in their operations to help with soil conservation and decrease labor and fuel costs. However, tillage is necessary for weed control and incorporation of nutrient amendments. One strategy for reducing tillage revolves around cover crop-based, organic rotational no-till, which employs cover crop mulches and no-till cash crop planting. Primary tillage occurs in the fall at cover crop establishment, and in-season weed control relies on suppression by the cover crop mulch along with supplemental inter-row cultivation. We initiated a cropping systems experiment to study several strategies for reducing tillage frequency and intensity within an organic grain and silage rotation to test the feasibility of organic reduced tillage production in the Mid-Atlantic U.S. Either a cover crop mixture interseeded into corn harvested for grain or fall sown cereal rye after corn silage and before soybean was terminated via tillage or roller-crimper, respectively. Soybean were seeded into the tilled cover crop mixture or no-till planted into the cereal rye mulch. While the interseeded mix generally produced approximately 2,000 kg ha^{-1} biomass, cereal rye typically produced about 5,000 kg ha^{-1}, with a maximum of approximately 8,000 kg ha^{-1}. Weed suppression varied annually based on environmental conditions which sometimes hindered in-season cultivation. Weed control was sufficient and subsequent biomass production was as low as 95 kg ha^{-1} in 2015, but approached 2,000 kg ha^{-1} in 2016 when weather conditions prevented effective

mechanical weed control. Despite differences in both soybean stand and weed biomass, yields were comparable between the no-till and tilled soybean systems, ranging from 1,800-3,400 kg ha^{-1} across years.

Introduction

While organic crop production has historically relied on tillage to control weeds and incorporate nutrient amendments, frequent and intensive tillage can lead to soil erosion and a decrease in soil quality (Teasdale et al., 2007, Uri et al., 1999). Reducing tillage has many benefits, including decreased need for labor and fuel, and decreases in greenhouse gas emissions (Mirsky et al., 2012). Reduced tillage practices can lead to improved soil functionality, including increases in soil aggregate stability, cation-exchange capacity and soil water-holding potential (Teasdale at al., 2007). Organic production practices also have numerous soil health and environmental benefits because these systems generally rely on many integrated, non-chemical, cultural methods including cover cropping and diverse crop rotations (Gomiero et al., 2011, Liebman and Davis, 2000). Compared to their conventional counterparts, organic farms tend to have higher soil organic matter, higher yields under drought stress through greater water conservation, and less reliance on chemical inputs (Pimentel et al., 2005). The overall goal of organic farming revolves around utilizing whole system approaches to produce long-term sustainability through a combination of soil conservation and soil building practices (Gomiero et al., 2011). Elimination of tillage from organic annual row crop production is currently not feasible because tillage remains the primary tool for weed control, crop residue management, and incorporation of nutrient amendments (Peigné et al., 2007). Greater utilization of cover crops and incorporation of other strategies that reduce tillage may help to alleviate some of the challenges faced by organic producers attempting to reduce their mechanical operations.

Research on reduction of tillage in organic annual grain production has focused on development of cover crop-based rotational no-till systems, in which cover crops are mechanically terminated and cash crops are no-till planted, while primary tillage is used at other points in the crop rotation (Mirsky et al., 2012, Reberg-Horton et al., 2012, Wallace et al., 2017) In this system, summer annual cash crops are no-till planted into a weed-suppressive, cover crop mulch that was terminated using a roller-crimper (Kornecki et al., 2006). Tillage is still used in the rotation, typically after cash crop harvest and prior to cover crop establishment to help manage weed seedbanks, as well as incorporate nutrient amendments and other crop residues (Gruber and Claupein, 2009, Mirsky et al., 2012). Past research has identified some agronomic challenges related to cover crop-based rotational no-till systems (Keene 2015). First, there is the potential for inconsistent termination of the rolled cover crop, which results in recovery and resumption of cover crop growth. This can result in both direct competition with the current cash crop as well as future crops through seed production and subsequent “volunteer” cover crops. Cash crop establishment in the rolled mulch can also be problematic because of difficulty slicing through cover crop residue with no-till planters, resulting in poor or uneven stands. Finally, the period between cash crop harvest, cover crop establishment and the onset of colder temperatures can be short, impacting cover crop establishment and performance. This can result in reduced spring cover crop growth, potential nutrient loss, and increased early season weed competition (Keene 2015).

Organic farmers and those transitioning to organic have expressed interest in implementing reduced-tillage practices and integrating cover crops to increase soil health and to reduce labor, time, and fuel costs (USDA NASS 2014). In particular, there is increasing demand for organic soybeans and high price premiums further increase incentive for transitioning to organic annual grain production (Cavigelli et al., 2008, Smith et al., 2011). Cover crop-based, organic no-till soybean production may facilitate greater organic soybean production, while providing soil conservation benefits such as reduced erosion and water retention (Huggins and Reganold, 2008). In this system, soybean is no-till planted into a rolled cereal rye (*Secale cereale* L.) cover crop, which creates a mat that helps conserve water and nutrients by reducing soil run-off, and smothers weeds. Furthermore, this system can produce competitive yields relative to organic tilled soybean (Mirsky et al., 2013, Wells et al., 2014). Although soybean populations can sometimes be lower compared to full-tillage systems because of issues related to planting into heavy cover crop residue, no-till yields have proven to be competitive because of the plasticity of soybean plants coupled with the other benefits to no-till production such as water conservation during periods of drought stress (Delate et al., 2012, Mirsky et al., 2013).

The success of organic rotational no-till systems depends on making decisions appropriate for the growing environment. It is important to select cover crop species that provide adequate weed control, while also being suitable for control by the roller-crimper (Ashford and Reeves, 2003). In the Mid-Atlantic, it is crucial to choose species which are winter hardy and can establish after cash crop harvest in the fall. Cereal rye is commonly planted as a cover crop after corn and before soybean because it is winter hardy and can be established relatively late in the fall (Bushuk 2001, Teasdale 1998). Rolled cereal rye before soybean can help suppress weeds, especially when high amounts of cover crop biomass are achieved (Mischler et al., 2010). Research has demonstrated that in order to adequately control cereal rye, it must be roll-crimped not earlier than at anthesis, which can provide up to 85% control (Mirsky et al., 2009). In the

Northeast, cereal rye can produce at least 6,000-8,000 kg ha^{-1} of aboveground biomass, which is crucial for early season weed control because the cover crop blocks light interception, competes for nutrients, and alters weed germination cues (Mirsky et al., 2012, Reberg-Horton et al., 2012, Wallace et al., 2017). Many farmers in the Mid-Atlantic cannot establish a fall cover crop after corn grain harvest because it is too late in the season to ensure cover crop establishment and winter survival. An alternative option to post-harvest cover crop establishment is relay cropping or interseeding, which involves establishing cover crops in a standing cash crop (Brooker et al., 2014). Interseeding cover crops helps ensure that they become well established by the time of cash crop harvest, and it also eliminates the need for fall tillage. Winter cover can help reduce soil erosion, scavenge nitrogen, and capture atmospheric carbon which can be converted to organic matter to help improve soil quality (Dabney et al., 2001, Meisinger et al., 1991, Staver and Brinsfield, 1998). Interseeding cover crops usually involves broadcasting seed into a standing crop using ground or aerial equipment. Cover crops can be seeded into standing corn early in the season around V5-V7 using a specialized drill (Dillon et al., 2012) or high-boy drop seeder (Shipman 2010). The successful establishment of cover crops with interseeding is dependent on timing of seeding and seed placement, as well as temperature and precipitation to promote germination, emergence, and survival (Dabney et al., 2001, Wilson et al., 2014).

Soil disturbance in agricultural systems can have both positive and negative effects on the weed community, subsequently affecting the local weed flora, the germination timing, and potential management decisions. Frequent and intense tillage in annual row crop production is common for weed control in organic crop production systems, but can also help select weed species that tolerate soil disturbance and can successfully establish over time in the agroecosystem (Smith and Mortensen, 2017). Additionally, tillage practices differing in frequency, intensity, and depth can stratify weed seeds in the soil profile, causing seed dormancy and shifts in emergence timing (Gruber and Claupein, 2009). Understanding how weeds adapt to tillage intensity and frequency is important for weed management in any cropping system and should influence management decisions in the farming operation.

Integrated weed management is critical for organic farmers, as they have few rescue options in the event that weed control tactics fail. Primary tillage typically occurs before each crop is established either in the fall and/or spring to create a seedbed for planting, which can help bury weed seeds. Increasing cash crop planting density may help reduce weed density in the crop row, as there will be direct competition from the cash crop (Ryan et al., 2011). Use of in-season cultivation, such as tine weeding and rotary hoeing, followed by inter-row cultivation is common in organic grain crop production to control weeds that germinate within and between the crop rows. However, frequent soil disturbance does not aid in soil building and conservation practices that many farmers are trying to achieve, and the effectiveness of tillage operations is highly dependent on environmental conditions (Peigné et al., 2007). When a farmer is unable to successfully cultivate in a timely manner due to weather, weeds can quickly approach thresholds that will negatively impact cash crop yield.

The concept behind our research was to analyze a suite of reduced-tillage practices within a cover crop-based, organic rotational no-till system to help organic farmers overcome the limitations to reducing tillage in their operations. To achieve this goal, we evaluated alternative crop management strategies for integrating cover crops and reducing tillage frequency in the corn to soybean phase of a small grain-corn-soybean rotation. To examine the effectiveness of weed control in organic tilled vs. no-till soybean, we employed different in-season methods. Tilled soybean systems received standard blind tillage followed by inter-row cultivation, while no-till systems relied on a higher soybean plant population and the rolled cover crop mulch and high-residue inter-row cultivation to manage weeds. We collected aboveground weed biomass in-row as well as between-row to determine the effects of the different weed management tactics described above and the subsequent effects on soybean yields.

Our objectives included evaluating the differences in cover crop performance, weed suppression, and yield limiting factors between conventionally tilled and no-till soybean to determine the feasibility of reducing tillage in organic production in the Mid-Atlantic. We hypothesized that: (1) use of a roller-crimper to create a weed-suppressive mulch and high-residue inter-row cultivator to control weeds in no-till soybean will result in similar late summer weed control compared to tilled soybean systems undergoing standard full inversion tillage in the spring followed by blind tillage and cultivation, and (2) grain yield in tilled and no-till soybean systems will be equal in value.

Materials and Methods

Site description. We conducted a cropping systems experiment on certified organic land at the Pennsylvania State University Russell E. Larson Agricultural Research Center (RELARC) at Rock Springs, Pennsylvania (40˚43´N, 77˚56´W) from 2014 to 2017. The soil at the site was comprised of mainly Hagerstown silt loam soil (fine, mixed, semiactive, mesic Typic Hapludalfs), with some Opequon-Hagerstown soils (clayey, mixed, active, mesic Lithic Hapludalfs). The RELARC resides in Zone 6b of the USDA Plant Hardiness Zones, with an average annual high/low temperature of 25/5.1˚C. Growing degree days (base 10˚C) are provided for April through October each year (Appendix D). Annual rainfall and snowfall average 1,006mm and 1,140mm, respectively.

Experimental design. This experiment implemented a three year rotation of corn (*Zea mays* L.)-soybean (*Glycine max* L. Merr.)-spelt (*Triticum spelta* L.) in a full entry design with cover crops preceding corn and soybean. A randomized complete block, split-plot design with four replications was used. Each block contained the three crop rotation entry points as main plots, with four cropping system treatments as the split-plot within each main plot. Cropping systems differed by cover crop species, their planting date and termination method, manure management, and tillage frequency and intensity (Figure 1-1). Split-plots measured 9m wide by 49m long, and all main plots were separated by grass alleyways. Prior to the initiation of the experiment, a three year rotation of corn-soybean-wheat with cover crops before corn and soybean was examined in main plots using organic rotational no-till practices. The experiment was managed organically from 2011-2014, gaining certification at the completion of the three years. Data collection for this project began fall 2014.

Crop rotation. In this paper, we focus on evaluating system performance within the soybean phase of the rotation, beginning with cover crop establishment preceding soybean. Four systems (S1 – S4) were examined. In systems one and three, a moldboard (S1) or chisel plow (S3) followed by multiple passes of secondary tillage were used to create a fine seedbed following corn silage harvest (Figure 1-1). Cereal rye (*Secale cereal* L.) ‘Aroostook’ was seeded using a Great Plains 1005NT drill on a 20-cm row spacing at 134 kg ha^{-1} (Appendix A). The cereal rye was terminated with a roller-crimper in the opposite direction that it was seeded the following spring at anthesis. Rolling occurred twice to achieve adequate cover crop control, first seven days before soybean planting and again immediately prior to soybean planting. Soybean was no-till planted at 555,750 plt ha^{-1} following the second pass with the roller-crimper in the same direction as rolling using a four-row John Deere 7200 planter on 76-cm rows equipped with

Dawn Biologic ZRX residue managers. In contrast, a cover crop mixture was interseeded the previous season in corn at V6 in S2 and S4 to allow for grain production (Figure 1-1). This cover crop mixture consisted of annual ryegrass (*Lolium perenne L. ssp. multiflorum.*) 'KB Supreme', orchardgrass (*Dactylis glomerata* L.) 'Potomac', and forage radish (*Raphanus sativus* L.) 'Tillage' drilled at 11, 11, and 3.4 kg ha^{-1} (Appendix A), respectively, which was designed to build soil organic matter, scavenge nutrients, prevent soil erosion, and possibly provide grazing opportunities for livestock. The cover crop mixture was terminated in the spring via moldboard plow and secondary tillage (Figure 1-1) to create a fine seedbed, and soybean was planted on 76-cm rows at 444,600 plt ha^{-1} approximately seven to ten days after plowing using the same planter as previously described. Soybean was seeded at a higher rate in the no-till systems to have a more competitive soybean crop and also to compensate for any challenges that could arise from planting into the rolled cover crop mulch (Mirsky et al., 2013).

Weed management differed between systems. The two tilled soybean systems relied on inversion and secondary tillage in the spring to control and incorporate the interseeded cover crop and control any emerged weeds prior to soybean planting. After planting, we used blind cultivation with a rotary hoe and flex-tine-weeder and two or more passes in-season with an inter-row cultivator (Appendix C). A rotary hoe was used only in 2017 to better control weeds, as weed suppression in 2016 was poor and weed emergence was anticipated to be very high. No-till systems relied on the rolled cover crop, and employed use of a John Deere 886 high-residue inter-row cultivator approximately four and five weeks after planting (WAP). This cultivator has a single 50-cm sweep between each soybean row that runs a few centimeters below the soil surface to uproot germinated weeds, while minimizing residue disturbance. The frequency of in-season tillage events varied from year to year based on environmental conditions and weed severity (Appendix C).

Data collection. We sampled aboveground cover crop biomass between late October and early November in each year using six randomly placed 0.25 m^2 quadrats in each split-plot. Cover crop biomass was sampled again in mid- to late-May just prior to cover crop termination using nine 0.25m^2 quadrats per split-plot, with three samples being collected from each transect (yield rows). We clipped biomass at the ground level and bagged and sorted the samples by species. All plant material was dried for at least five days at 65˚C and then weighed in the lab and averaged across subsamples prior to analysis.

We sampled weed biomass at the same time as cover crop biomass in the fall and spring, using the same protocols. We also sampled weed biomass in mid-August prior to soybean harvest. Nine 0.5 m^2 quadrats were sampled per split-plot, with three samples collected from each yield row. Within each of the nine samples, weeds were collected separately by their location (in-row and between row), allowing us to determine the effectiveness of the cover crop mulch in no-till systems and in-season cultivation frequency and intensity in the tilled systems. Weeds were clipped at ground level, separated by species, and dried for at least five days at 65˚C before weighing. We averaged biomass across subsamples and by location (in row and between row) before analysis.

Six weeks after planting (WAP; planting described in crop rotation), we assessed soybean populations by counting the number of plants in 5.3 meters of row at three random locations within each of the three transects per split-plot. Soybean yield data was collected by machine harvesting six rows from each split plot using a small plot combine and grain yield was adjusted to 13% moisture.

Economic analysis. An enterprise budget analysis was conducted to give an estimated economic comparison between cropping systems. This analysis can be used to estimate an operation's revenue and expenses based on certain practices, and used to make comparisons against alternative practices. Budgets were calculated for each cropping system using the Mississippi State Budget Generator v6.0 (Laughlin and Spurlock, 2008). Tractor and other implement sizes were based on typical size for farms in the Mid-Atlantic. Production costs were based on the previous year's input prices. A 6% interest rate for opportunity cost was factored in starting from the date of input use until harvest. The charges provided do not include land management charges. Additionally, net returns show an estimated income per cropping system and were calculated by multiplying system cash crop yields by expected soybean price and subtracting total production costs. Budgets were originally calculated on a dollars acre^{-1} basis, and converted to dollars hectare^{-1} for final analysis.

Statistical analysis. We evaluated system-level treatment effects including: 1) fall and spring cover crop biomass (kg ha^{-1}), 2) fall, spring, and late summer weed biomass (kg ha^{-1}), 3) soybean population (% of seed dropped), and 4) soybean yield (kg ha^{-1}) using ANOVA in SAS 9.4. We used linear mixed effects models (PROC MIXED) with system and location (in-row, between row) as fixed factors and block as a random factor. Weed biomass data were log-transformed to meet the assumptions of normality of variances. In-row and between row weeds and soybean populations were analyzed as proportions of the totals, and the arcsin square root transform function was used to normalize the data. We separated means using the Tukey-Kramer method at alpha=0.05. Transformed data was back-transformed and all data are presented in tables and figures as treatment means with standard errors.

Results and Discussion

Cover crop performance and weed biomass. Fall cereal rye (S1, S3) biomass, sampled in late October, ranged from 28 kg ha^{-1} in 2016 to 300 kg ha^{-1} in 2015 (Table 1-1). This was mostly the result of cover crop planting date; cereal rye was sown October 3 in 2014 and October 12 in 2016 following corn silage harvest compared to September 25 in 2015, giving it more time to establish before cover crop sampling (Appendix A). In contrast, the interseeded cover crop (S2, S4; annual ryegrass + orchardgrass + forage radish) produced over 700 kg ha^{-1} of fall biomass in 2014, but only about 400 kg ha^{-1} in 2015 and 100 kg ha^{-1} in 2016 (Table 1-1). Success of establishing an interseeded cover crop can be variable depending on environmental conditions following establishment, but these values are similar to previous research conducted in Pennsylvania (Curran et al., XXXX, Caswell 2017). Fall cover crop biomass responded to cropping system, year, and the interaction of system and year (Table 1-1). Interseeded cover crop biomass was greater than cereal rye biomass in fall 2014, but not in 2015 or 2016. The cereal rye biomass was greater than that of the interseeded mix because of earlier establishment and better fall growing conditions (Figure 1-2). Poor establishment of interseeded cover crops during dry weather also led to lower fall cover crop biomass in 2016.

Weed biomass data was not collected in the fall of 2014, but in 2015 and 2016, no weeds were present in cereal rye (Table 1-1), likely because primary tillage occurred just prior to cover crop seeding, controlling any emerged plants and burying any weed seeds that may have been present near the soil surface. Weed biomass in the interseeded cover crop was also minimal in the late fall, ranging from 14-107 kg ha^{-1} (Table 1-1). Although winter annual weed density at the time of fall sampling was relatively low in all three years of this study, under different circumstances, less successful cover crop establishment could allow for greater competition from winter annual weeds, having consequences for fall and spring weed biomass and weed seedbank inputs.

Spring cover crop biomass was affected by cropping system, year, and their interaction (Table 1-1). In the spring of 2015, cereal rye produced approximately 5,000 kg ha^{-1} above-ground dry matter, while the interseeded cover crop mix produced approximately 2,000 kg ha^{-1} (Figure 1-3). In spring of 2016, cereal rye biomass in the no-till systems was greater than 6,000 kg ha^{-1} in the S1 treatment and approximately 8,300 kg ha^{-1} in the S3 treatment (Figure 1-3). The difference in spring cover crop biomass between S1 and S3 may have resulted from the nutrient legacy of the previous corn crop. In S3, we applied manure to corn in spring 2015 just prior to corn planting, while the S1 corn manure application occurred in late summer 2014 prior to cover crop establishment. This enabled no-till planting of corn into rolled cover crop mulch in S1, while the manure and cover crop were incorporated with tillage in S3 (Figure 1-1). Cover crop biomass was also different between cropping system treatments in spring of 2017 (Figure 1-3). The interseeded systems 2 and 4 produced less than 700 kg ha^{-1} biomass or less due to poor interseeder establishment the previous summer, while S1 and S3 cereal rye produced approximately 6,000 kg ha^{-1} of biomass (Table 1-1).

Weed biomass in the spring was variable from year to year, resulting in a significant treatment interaction (Table 1-1). In spring 2015, weed biomass was relatively low, ranging from 5-69 kg ha^{-1} with no difference across cropping systems. In spring 2016, more weeds were present in the interseeded cover crop than in cereal rye, likely due to the large difference in spring cover crop growth between systems (Table 1-1, Figure 1-4). Although we observed more weeds in the interseeded systems in spring prior to soybean planting, both the cover crop and weeds were terminated via primary tillage, making it less of concern for cash crop performance as the weeds were killed by the tillage event. Spring sampled weeds included common chickweed [*Stellaria media (L.*) Vill.], dandelion (*Taraxacum officinale* F.H. Wigg.), Canada thistle [*Cirsium arvense (*L.) Scop.], and early-emerging common ragweed (*Ambrosia artemisiifolia* L.) and foxtail species (*Setaria spp.*). Common chickweed was the most frequently occurring winter annual at spring sampling, and by mid-May many had flowered and set seed. Production of viable seeds could negatively impact subsequent winter annual cash crops through competition for water and nutrients. Emerged summer annuals were still in the vegetative stage at cover crop termination, so recruitment of these individuals resulted in seedbank depletion. Despite lower levels of fall cover crop growth in 2016 compared to other years, cover crop growth in the spring increased and few weeds were present in spring 2017, resulting in no system level differences (Figure 1-4). Spring weed biomass in 2017 ranged from 3-16 kg ha^{-1} (Table 1-1).

The cereal rye cover crop biomass was consistent with other research in the mid-Atlantic, which report 5,000-9,000 kg ha^{-1} of biomass or greater, dependent on seeding date and soil fertility (Mirsky et al., 2012, Ryan et al., 2011). This amount of cereal rye biomass can result in adequate weed suppression in no-till soybean systems. Although interseeding has yet to be studied extensively in organic systems, our results suggest that it is a viable alternative to post-harvest cover crop establishment and would allow farmers to produce grain corn and provide winter ground cover that can potentially compete against winter annual weeds.

Late-summer weed biomass. In 2015, weed biomass did not differ between systems with relatively effective weed control across all four systems. Weed biomass ranged from 95 kg ha^{-1} to 424 kg ha^{-1} with the dominant species being mostly the foxtail species, Pennsylvania smartweed (*Polygonum pensylvanicum* L.), and yellow nutsedge (*Cyperus esculentus* L.) (Table

1-2, Figure 1-5). In 2015, a total of six primary, secondary, and in-season cultivation events occurred in the tilled systems (S2, S4) (Appendix C) and weather conditions permitted timely cultivation passes. In addition, the close to 5,000 kg ha^{-1} cereal rye biomass in 2015 and the use of two high-residue cultivator passes in the no-till planted systems (S1 and S3) adequately suppressed weeds. The weed flora in the no-till planted systems were dominated by common ragweed and some foxtail species that emerged through the rolled mulch early in the summer. To determine the effect of weed management tactics between no-till and tilled soybeans, weeds were sampled in and between the crop rows. In 2015, weed biomass did not respond to system and location. Although not significant, the proportion of weeds in-row in no-till S1 was only 25% of the total weed biomass (Table 1-2). In systems S2-S4, weed biomass was not different based on its location or across cropping system treatments and the in-row weed biomass ranged from 59 and 70% of the total (Table 1-2).

In 2016, late-summer weed biomass was generally greater than in the previous summer and differences were observed between some systems. While the no-till planted S1 produced only 283 kg ha^{-1} weed biomass, the other three systems produced 920-2,039 kg ha^{-1}. In 2016, a wet period occurred during cash crop establishment, followed by a mid-summer drought. The early summer wet period prevented timely blind and inter-row cultivation efforts and the mid-summer drought delayed soybean canopy closure. Tilled systems (S2, S4) received a total of five in-season cultivation passes, but because of weather related delays, this cultivation did not effectively control some of the established weeds. Furthermore, drought conditions caused the soil surface to be compacted, resulting in reduced cultivation efficacy in some cases. In the no-till systems (S1, S3), because of dry soil conditions, the high-residue cultivator sweeps were unsuccessful at penetrating the soil surface, resulting in the inability to use the high-residue cultivator in 2016. Therefore, weed biomass was a function of only the rolled cereal rye mulch. System 1 had fewer weeds than S3, and differences in late-summer weed biomass between the two no-till planted systems was likely a result of weed seedbank characteristics produced in the previous corn crop. Seedbank abundance likely resulted in the observed differences in weed biomass, since both of these no-till planted systems relied on cereal rye mulch to suppress weeds in soybean (Figure 3-3). System one was previously in rolled hairy vetch followed by no-till planted corn the prior year, while S3 employed a red clover cover crop and primary tillage before corn planting (Figure 1-1). A number of factors could help explain the differences between the resulting weed biomass in S1 vs. S3. First, fall tillage after corn harvest differed between systems, with S1 undergoing full inversion tillage with a moldboard plow, while S3 employed a chisel plow. Inversion tillage would have buried more weed seeds, resulting in fewer viable seeds near the soil surface relative to S3 in the following spring (Figure 1-1). Second, hairy vetch volunteered in S1 soybean that was not a factor in S3, which had been planted in a mixture of red clover-timothy. At 4 WAP, volunteer hairy vetch biomass averaged close to 1,000 kg ha^{-1} in S1 soybean, which likely suppressed summer annual weed growth. By the time weed biomass was sampled in late summer, the volunteer hairy vetch had matured and disappeared and was not part of the above-ground weed flora that was collected. Finally, a nitrogen legacy may have been a factor contributing to differences in weed biomass, with higher N fertility in S3 due to spring manure application to corn in the previous year. Manure application in S1 occurred in late summer prior to cover crop establishment rather than in the subsequent spring, likely leaving fewer available nutrients at soybean planting in S1 with the potential for greater nutrient uptake by weeds.

Weed biomass by location also differed in 2016. With the exception of S1, which had lower in-row weed biomass compared to between-row biomass by number and proportion,, the other three systems exhibited 62-81% of the total weed biomass in-row (Table 1-2). This showed the effectiveness of inter-row cultivation, especially in the tilled cropping systems and also the ability of the rolled cereal rye to help suppress weeds in-row in the no-till planted systems.

In 2017, total weed biomass differed between cropping systems, ranging from 110-251 kg ha^{-1} in the tilled systems and 944-1,062 kg ha^{-1} in the no-till systems (Table 1-2). Timely blind and inter-row cultivation occurred in 2017, which effectively reduced weed biomass in the tilled systems. Although cereal rye cover crop biomass was approximately 6,000 kg ha^{-1} in the no-till systems (Table 1-1), wet weather conditions allowed weeds to germinate and establish in the crop row and also in the cover crop mulch before high-residue cultivation was completed. Weed biomass in 2017 was different between cropping systems and by location, with in-row weed biomass being higher than between row weed biomass (Table 1-2). Very little weed biomass was observed between rows in S2 and S4 due to the effectiveness of in-season cultivation events; this was not true of S1 and S3, where weeds had successfully survived high-residue cultivation between the soybean rows. In-row weeds increased in 2017 compared to previous years, comprising 80-99% of total weed biomass across systems (Table 1-2). Due to high weed seed inputs into the seedbank in the previous year, we increased the number of both blind tillage and inter-row cultivation passes in S2 and S4 in 2017, with 6 total field operations occurring after soybean planting (Appendix C). This resulted in low levels of inter-row weed biomass observed, with a majority of weeds occurring in-row (Table 1-2). System one and S3 produced higher weed biomass than the tilled systems, and more weeds survived in-row (Table

1-2). The proportion of weeds in-row was not affected by the interaction of system and year, but some differences were observed between systems (p=0.0012) (Table 1-2).

In general, and as expected, more weeds tended to survive in-row compared to between row across all systems. Poor performance of the blind cultivation equipment due to wet and cloddy soils in 2016, almost complete reliance on the rolled cover crop mulch in no-till planted systems, and good performance of inter-row cultivation in the tilled systems, especially in 2017, help explain these results. These data show that weed control by rolled cover crop biomass can be variable. While the mulch can sometimes provide adequate weed control in row, variable aggressiveness of row cleaners during the planting operation and any patchiness in the rolled residue can allow weeds to emerge and survive. While in-season, inter-row cultivation can be very effective at controlling weeds between rows especially in tilled systems, blind cultivation before crop emergence should aim to be as timely as possible to help control in-row weeds to prevent yield losses from weed competition.

Our late-summer weed biomass results clearly indicate the implications that environmental conditions can have on mechanical cultivation and the resulting weed control. If cultivation is not timely, weeds can quickly approach levels that may be detrimental to crop yield, even with the presence of a rolled cover crop mulch. Weed biomass typically declines with increasing amounts of cereal rye biomass and supplemental weed control (Nord et al., 2011), and research by Mirsky et al. (2013) showed that in order to achieve good weed control, cereal rye biomass needs to reach at least 6,000 kg ha^{-1}. High-residue cultivation can supplement the cover crop mulch and is particularly important when weed density is high (Nord et al., 2011).

Although further research is needed, results from this research suggest that rolled cereal rye before soybean has the potential to decrease weed biomass in the crop row, resulting in weed suppression similar to that in a tillage-based soybean system. The goal of in-season cultivation and cultural weed management practices is to provide the cash crop with an advantage over growing weeds (Rasmussen 2004), so if levels of cover crop biomass are deemed insufficient to control weeds between the rows, the addition of supplemental high-residue cultivation can help. However this operation is highly weather dependent, and the success of cultivation efforts relies on proper equipment and operator ability (Bond and Grundy, 2001). Ensuring that cereal rye is seeded at the correct rate and time the previous fall to produce enough biomass to suppress weeds is key. Planting soybeans on narrower row spacing can also help by shading out weeds, but decreasing row spacing below 76-cm can limit the ability for inter-row cultivation.

Soybean populations and yields. Since no-till soybeans were seeded at a higher rate, soybean populations were analyzed as proportions of the total seeded rate (Appendix B). Populations were assessed after last cultivation at six WAP. Populations ranged from 79-85% of the total planted in 2015, 54-74% in 2016, and 57-73% in 2017. Populations responded to cropping system, year, and interaction in analysis (Table 1-3). Populations were not different across cropping systems in 2015, were higher in S1 compared to other systems in 2016, and lower in the no-till cropping systems (S1, S3) compared to tilled systems in 2017 (Table 1-3). The decrease in populations in 2016 compared to 2015 can likely be contributed to the wet conditions experienced at planting. Wet soil can cause improper furrow closer, and in the no-till systems, cutting through both cereal rye residue and the soil to create an opening for seed placement can prove problematic (Mirsky et al., 2012). Planter issues and high cereal rye biomass in 2017 led to lower soybean populations compared to 2015, as weather was not an issue. Increasing soybean seeding rates over 225,000 plt ha^{-1} may be a viable option, as this has shown to be more competitive against weeds; however, increased seeding rates should not be used as the single weed management tactic (Place et al., 2009).

Soybean grain yield differed across years, but was not different between systems in the first two years (Table 1-3). In 2015, yield ranged from 2,800-3,068 kg ha^{-1}. The drought conditions of 2016, coupled with decreased soybean populations and increased weed severity, likely resulted in lower yields, which ranged from 1,896-2,790 kg ha^{-1}. Although not statistically different from the other treatments, the highest grain yield occurred in no-till S1, which also had the highest soybean population and lowest weed biomass. Previous research has shown that no-till planted organic soybean yields have the potential to be competitive with tilled soybeans (Smith et al., 2011). In 2017, grain yield ranged from 2,445-3,463 kg ha^{-1}, but was lower in the no-till S1 and S3 systems. Soybean population was lower in these two systems, and late-summer weed biomass was higher relative to the tilled systems, and these factors likely contributed to lower yield. Although no-till soybean can sometimes yield higher than tilled systems during water-stressed conditions due to soil moisture conservation, this seemed to be offset by planting issues and lack of cultivation attempts to control in-season weed flushes (Delate et al., 2012, Mirsky et al., 2013). Planter technology may be a limitation to organic no-till soybean, as it can be difficult to achieve adequate down pressure to cut through heavy cover crop residue, while also reaching proper seed placement and furrow closure.

Enterprise budgets. Budget analysis showed that costs can be variable from year to year based on labor and tillage needs, which are largely driven by weed severity and the number of subsequent cultivation passes (Table 1-4). Net returns between no-till planted and tilled organic soybeans are generally comparable, except in years where soybean grain yield was lower due to weeds and /or soybean population issues (Table 1-4). Overall, no-till organic soybeans tend to have similar net returns (\$ ha^{-1}) compared to organic tilled systems, further demonstrating that no-till soybeans can be a viable option for organic growers.

Conclusions. The success of organic cover crop-based, rotational no-till relies on many management decisions. For no-till soybean to be integrated into an organic cropping system the preceding cover crop must be well established ahead of winter; in central PA, we believe that at least 6,000 kg ha^{-1} of biomass must be produced by cover crop termination time to successfully aid in weed suppression. Cereal rye should ideally be planted by early October and roll-crimped at anthesis to provide adequate control (Keene et al., 2017). Planting into heavy cover crop residue can be problematic at soybean planting, and adjustments to equipment should be considered to achieve proper planting depth and furrow closer. While rolled cereal rye does provide excellent early-season weed control, the effectiveness of the mulch diminishes 4 to 6 weeks after planting. Use of a high-residue cultivator can help control weeds between the crop rows, while providing minimal soil disturbance. Our research has shown that organic rotational no-till soybean yields are comparable to organic tilled systems, making them a viable option for growers who are interested in incorporating cover crops into their rotation and reducing their reliance on tillage.

Literature Cited

Ashford, D.L. and D.W. Reeves. 2003. Use of a mechanical roller-crimper as an alternative kill method for cover crops. Am. J. Altern. Agric. 18:37-45.

Bond, W. and A.C. Grundy. 2001. Non-chemical weed management in organic farming systems. Weed Res. 41:383-405.

Brooker, R.W., A. E. Bennett, W. F. Cong, T. J. Daniell, T.S. George, P.D. Hallett, C. Hawes, P.M. Iannetta, H.G. Jones, A.J. Karley, L. Li, B.M. McKenzie, R.J. Pakeman, E. Paterson, C. Schob, J. Shen, G. Squire, C.A. Watson, C. Zhang, F. Zhang, J. Zhang, and P.J. White. 2014. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phyt. 206:107-117.

Bushuk, W. 2001. Rye production and uses worldwide. Cer. Food. World. 46:70-73.

Caswell, K.E. 2017. Incorporating cover crops and diversified weed management to improve cropping system productivity. M.S. Thesis. University Park, PA: The Pennsylvania State University. 78 p.

Cavigelli, M.A., J.R. Teasdale, and A.E. Conklin. 2008. Long-term agronomic performance of organic and conventional field crops in the mid-Atlantic region. Agron. J. 100:785-794.

Curran, W.S, R.J. Hoover, S.B. Mirsky, G.W. Roth, M.R. Ryan, V.J. Ackroyd, J.M Wallace, M.A. Dempsey and C.J. Pelzer. XXXX. Evaluation of cover crops interseeded into corn (*Zea mays* L.) across the Mid-Atlantic region. Submitted to Agron. J. 7/17.

Dabney, S.M., J.A. Delgado and D.W. Reeves. 2001. Using winter cover crops to improve soil and water quality. Comm. in Soil Sci. and Plant An. 32:1221-1250.

Delate, K., D. Cwach and C. Chase. 2012. Organic no-tillage system effects on soybean, corn and irrigated tomato production and economic performance in Iowa, USA. Renew. Agric. Food Syst. 27:49-59.

Dillon, C.S., G. Roth, W.S. Curran and W. Harkcom. 2012. Development of a cover crop inter-seeder and applicator for no-till corn. Abstract. ASA Annual Meeting, #304.

Gomiero, T., D. Pimentel and M.G. Paoletti. 2011. Environmental impact of different agricultural management practices: conventional vs. organic agriculture. Crit. Rev. in Plant Sci. 30:95-124.

Gruber, S. and W. Claupein. 2009. Effect of tillage intensity on weed infestation in organic farming. Soil and Till. Res. 105:104-111.

Huggins, D.R. and J.P. Reganold. 2008. No-till: the quiet revolution. Sci. Amer. 299:70-77.

Keene, C.L. 2015. Agronomic performance of a reduced-tillage organic grain crop rotation during the transition to organic production. Dissertation. University Park, PA: The Pennsylvania State University. 176 p.

Keene, C.L., W.S. Curran, J.M. Wallace, M.R. Ryan, S.B. Mirsky, M.J. VanGessel and M.E. Barbercheck. 2017. Cover crop termination timing is critical in organic rotational no-till systems. Agron. J. 109:272-282.

Kornecki, T.S., A.J. Price and R.L. Raper. 2006. Performance of different roller designs in terminating rye cover crop and reducing vibration. Amer. Soc. of Agri. and Bio. Eng. 22:633-641.

Laughlin, D. and S. Spurlock. 2008. Mississippi State Budget Generator v 6.0. Software User's Manual. Accessed November 7th, 2017 from http://www.agecon.msstate.edu/whatwedo/budgets/generator/index.asp

Liebman, M. and A.S. Davis. 2000. Integration of soil, crop and weed management in low-external-input farming systems. Weed Res. 40: 27-47.

Meisinger, J.J., W.L. Hargrove, R.L. Mikkelsen, J.R. Williams and V.W. Benson. 1991. Effects of cover crops on groundwater quality. Soil and Water Cons. Soc. 57-68.

Mirsky, S.B., W.S. Curran, D.A. Mortensen, M.R. Ryan and D.L. Shumway. 2009. Control of cereal rye with a roller/crimper as influenced by cover crop phenology. Agron. J. 101:1589-1596.

Mirsky, S.B., M.R. Ryan, W.S. Curran, J.R. Teasdale, J. Maul, J.T. Spargo, J. Moyer, A. M. Grantham, D. Weber, T. Way and G.G. Camargo. 2012. Conservation tillage issues: cover crop-based organic rotational no-till grain production in the mid-Atlantic, USA. Renew. Agric. and Food Syst. 27:31-40.

Mirsky, S.B., M.R. Ryan, J.R. Teasdale, W.S. Curran, C.S. Reberg-Horton, J.T. Spargo, M.S. Wells, C.L. Keene, and J.W. Moyer. 2013. Overcoming weed management challenges in cover crop–based organic rotational no-till soybean production in the eastern United States. Weed Technol. 27:193-203.

Mischler, R.A, W.S. Curran, S.W. Duiker and J.A. Hyde. 2010. Use of a rolled-rye cover crop for weed suppression in no-till soybeans. Weed Technol. 24:253-261.

Nord, E.A., W.S. Curran, D.A. Mortensen, S.B. Mirsky and B.P. Jones. 2011. Integrating multiple tactics for managing weeds in high residue no-till soybean. Agron. J. 103:1542- 1551.

Peigné, J., B.C. Ball, J. Roger-Estrade and C. David. 2007. Is conservation tillage suitable for organic farming? A review. Soil Use Manag. 23:129-144.

Pimentel, D., P. Hepperly, J. Hanson, D. Douds and R. Seidel. 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. BioSci. 55:573-582.

Place, G.T., S.C. Reberg-Horton, J.E. Dunphy and A.N. Smith. 2009. Seeding rate effects on weed control and yield for organic soybean production. Weed Technol. 23:497-502.

Rasmussen, I.A. 2004. The effect of sowing date, stale seedbed, row width and mechanical weed control on weeds and yields of organic winter wheat. Weed Res. 44:12-20.

Reberg-Horton, S.C., J.M. Grossman, T.S. Kornecki, A. D. Meijer, A.J. Price, G.T. Place and T.M. Webster. 2012. Utilizing cover crop mulches to reduce tillage in organic systems in the southeastern USA. Renew. Agric. and Food Syst. 27:41-48.

Ryan, M.R., S.B. Mirsky, D.A. Mortensen, J.R. Teasdale and W.S. Curran. 2011. Potential synergistic effects of cereal rye biomass and soybean planting density on weed suppression. Weed Sci. 59:238-246.

Shipman, K. 2010. "High-rise highboy goes to extreme for cover crop project". Accessed August 27, 2017. http://farmweeknow.com/story-highrise-highboy-goes-to-extreme-for-cover-crop-project-0-40297.

Smith, A.N., S.C. Reberg-Horton, G.T. Place, A.D. Meijer, C. Arellano and J.P. Mueller. 2011. Rolled rye mulch for weed suppression in organic no-tillage soybeans. Weed Sci. 59:224-231.

Smith, R.G. and D.A. Mortensen. (2017). A disturbance-based framework for understanding weed community assembly in agroecosystems: Challenges and opportunities for agroecological weed management. In A. Wezel (Ed.), Agroecological practices for sustainable agriculture: Principles, applications, and making the transition (pp. 127-154). London, UK: World Scientific Publishing Europe Ltd.

Staver, K.W. and R. B. Brinsfield. 1998. Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. J. of Soil and Water Cons. 53:230-240.

Teasdale, J.R. 1998. Cover crops, smother plants, and weed management. In D.D. Buhler, J.L Hatfield and B.A. Stewart (Ed.), Integrated weed and soil management (pp.247-270). Chelsea, Michigan: Ann Arbor Press.

Teasdale, J.R., C.B. Coffman and R.W. Mangum. 2007. Potential long-term benefits of no-tillage and organic cropping systems for grain production and soil improvement. Agron. J. 99:1297-1305.

Uri, N.D., J.D. Atwood and J. Sanabria. 1999. The environmental benefits and costs of conservation tillage. Env. Geol. 38:111-125.

USDA NASS. 2014. Conservation. Consensus Highlights.

Wallace, J.M., C.L Keene, W.S. Curran, S.B. Mirsky. M.R. Ryan and M.J. VanGessel. 2017. Integrated weed management strategies in cover crop-based, organic rotational no-till corn and soybean in the mid-Atlantic region. *In print.*

Wells, M.S., S.C. Reberg-Horton and S.B. Mirsky. 2014. Cultural strategies for managing weeds and soil moisture in cover crop based no-till soybean. Weed Sci. 62:501-511.

Wilson, M.L., D.L. Allan and J.M. Baker. 2014. Aerial seeding cover crops in the northern US corn belt: limitations, future research needs, and alternative practices. J. of Soil and Water Cons. 69:67-72.

Table 1-1. 2014-2017 descriptive statistics for soybean. Cropping system means plus or minus standard error are presented for fall and spring cover crop and weed biomass in kg ha^{-1}. Significance of cropping system (S), year (Y), and their interaction (SxY) are shown. Non-significant results (p>0.05) are designated by "NS".

System (year)	**Fall cover crop**	**Fall weeds**	**Spring cover crop**	**Spring weeds**
2014-15	------------------------------- kg ha^{-1}	-------------------------------------		
S1	70 ± 8	N/A	4881 ± 452	28 ± 10
S2	774 ± 72	N/A	1927 ± 111	5 ± 2
S3	84 ± 6	N/A	4722 ± 410	69 ± 33
S4	739 ± 142	N/A	1824 ± 183	19 ± 7
2015-16				
S1	180 ± 26	0 ± 0	6115 ± 605	42 ± 13
S2	423 ± 30	67 ± 44	1299 ± 147	171 ± 21
S3	290 ± 18	0 ± 0	8281 ± 448	10 ± 3
S4	391 ± 105	14 ± 8	1426 ± 188	113 ± 35
2016-17				
S1	28 ± 4	0 ± 0	6219 ± 338	4 ± 1
S2	108 ± 56	107 ± 59	478 ± 200	16 ± 6
S3	41 ± 4	0 ± 0	6313 ± 346	3 ± 2
S4	70 ± 22	81 ± 28	662 ± 287	13 ± 7
ANOVA	----------------------------------- P value	--		
System (S)	<0.0001	NS	<0.0001	0.021
Year (Y)	<0.0001	NS	<0.0001	<0.0001
SxY	<0.0001	NS	<0.0001	<0.0001

Table 1-2. 2014-2017 descriptive statistics for soybean. Cropping system means plus or minus standard error are presented for total late-summer weed biomass and late-summer weed biomass by location (kg ha^{-1}) along with the proportion late-summer weed biomass in-row. Significance of cropping system (S), year (Y), and their interaction (SxY) are shown. Non-significant results (p>0.05) are designated by "NS". Different letters next to cropping system means represent systems differences between in-row versus between row weed biomass or between cropping systems for total weed biomass and proportion data at p<0.05.

System (year)	Total late-summer weeds	In-row weed biomass	Between-row weed biomass	Proportion in-row
2014-15		------------- kg ha^{-1} -------------		
S1	251 a (± 125)	57 a (± 30)	194 a (± 96)	0.26 a (± 0.097)
S2	424 a (± 170)	217 a (± 58)	207 a (± 152)	0.70 a (± 0.171)
S3	291 a (± 94)	197 a (± 102)	102 a (± 37)	0.59 a (± 0.171)
S4	95 a (± 35)	59 a (± 21)	37 a (± 14)	0.59 a (± 0.086)
2015-16				
S1	283 b (± 48)	67 c (± 9)	215 bc (± 55)	0.27 b (± 0.075)
S2	1675 a (±320)	1268 a (± 164)	407 b (± 165)	0.77 a (± 0.053)
S3	920 a (±132)	573 a (± 81)	346 b (± 78)	0.62 a (± 0.046)
S4	2039 a (±481)	1642 a (± 392)	397 b (± 143)	0.81 a (± 0.054)
2016-17				
S1	944 a (± 130)	822 a (± 129)	121 b (± 13)	0.85 b (± 0.017)
S2	251 b (± 126)	248 b (± 125)	2 c (± 1)	0.96 a (± 0.026)
S3	1062 a (± 225)	867 a (± 202)	194 ab (± 28)	0.80 b (± 0.018)
S4	110 b (± 28)	109 b (± 28)	1 c (± 0.5)	0.99 a (± 0.004)
ANOVA		------------- P value -------------		
System (S)	0.024	0.011		<0.0001
Year (Y)	<0.0001	<0.0001		<0.0001
SxY	<0.0001	<0.0001		NS
		2015		
System (S)		NS		
Location (L)		NS		
SxL		NS		
		2016		
System (S)		<0.0001		
Location (L)		0.005		
SxL		0.0004		
		2017		
System (S)		<0.0001		
Location (L)		<0.0001		
SxL		<0.0001		

Table 1-3. 2014-2017 descriptive statistics for soybean. Cropping system means plus or minus standard error are presented for soybean population as a proportion of the total planted and soybean grain yield in kg ha^{-1}. Significance of cropping system (S), year (Y), and their interaction (SxY) are shown. Non-significant results ($p>0.05$) are designated by "NS". Different letters next to cropping system means represent systems differences at $p<0.05$.

System (year)	**Soybean population proportion**	**Soybean yield**
2015		
S1	0.85 a (± 0.020)	2875 a (± 60)
S2	0.79 a (± 0.023)	2986 a (± 53)
S3	0.85 a (± 0.018)	2800 a (± 124)
S4	0.80 a (± 0.030)	3068 a (± 119)
2016		
S1	0.74 a (± 0.048)	2790 a (± 510)
S2	0.57 b (± 0.022)	2061 a (± 222)
S3	0.55 b (± 0.084)	1896 a (± 234)
S4	0.54 b (± 0.021)	2168 a (± 155)
2017		
S1	0.64 b (± 0.046)	2653 b (± 148)
S2	0.73 a (± 0.015)	3363 a (± 58)
S3	0.57 b (± 0.018)	2445 b (± 171)
S4	0.67 a (± 0.027)	3463 a (± 91)
ANOVA	---------------- P value -------------	
System (S)	0.046	0.013
Year (Y)	<0.0001	<0.0001
SxY	0.0093	0.0085

Table 1-4. Partial budget analysis for soybean in dollars ($) per hectare for each cropping system (S1-S4) in 2015-2017. Costs shown include cover crop and soybean seed cost, labor costs, fuel, and repairs/maintenance for no-till cereal rye (S1, S3) versus tilled interseeded cover crop (S2, S4). Fixed costs include implements and tractors. Income from soybean yield is shown in total dollars per hectare based on market price of $18 bu^{-1}. Costs of production estimates are based on the previous year's input prices.

Item	**S1**	**S2**	**S3**	**S4**
2015				
Income				
Grain	1907.33	1857.98	1980.69	2035.85
Variable costs				
Lime	44.46	44.46	44.46	44.46
Cover crop seed	85.96	118.12	85.96	118.12
Soybean seed	230.20	184.02	230.20	184.02
Labor	136.39	104.68	120.21	102.58
Fuel	112.80	92.01	101.49	91.49
Repairs & maintenance	69.80	62.29	60.05	62.27
Interest on capital	2.88	0.32	2.52	1.46
Total variable costs	682.51	605.89	644.89	604.38
Fixed costs	167.07	142.77	152.57	142.67
Total cost	849.58	748.66	797.46	747.05
Net returns	1057.75	1016.95	1183.23	1288.77
2016				
Income				
Grain	1851.31	1255.11	1428.50	1367.59
Variable costs				
Lime	0.00	0.00	0.00	0.00
Cover crop seed	85.96	118.12	85.96	118.12
Soybean seed	230.20	184.02	230.20	184.02
Labor	113.05	119.57	117.47	100.80
Fuel	103.37	115.52	114.93	92.92
Repairs & maintenance	59.82	68.54	68.52	50.81
Interest on capital	2.94	0.32	1.48	2.57
Total variable costs	595.34	606.09	604.53	607.72

Item	S1	S2	S3	S4
Fixed costs	146.20	156.03	155.93	133.11
Total cost	741.54	762.12	760.46	740.83
Net returns	1109.77	400.61	668.04	626.76
2017				
Income				
Grain	1900.09	2407.61	1753.30	2482.92
Variable costs				
Lime	0.00	0.00	0.00	0.00
Cover crop seed	85.96	118.12	85.96	118.12
Soybean seed	230.20	184.02	230.20	184.02
Labor	125.65	254.04	104.25	248.53
Fuel	68.83	162.11	58.35	159.30
Repairs & maintenance	61.32	122.38	53.03	123.78
Interest on capital	1.64	0.29	2.14	0.27
Total variable costs	572.34	839.74	532.66	834.02
Fixed costs	145.85	285.40	129.00	282.90
Total cost	718.19	1125.15	661.66	1116.92
Net returns	1181.90	1282.46	1091.64	1366.00

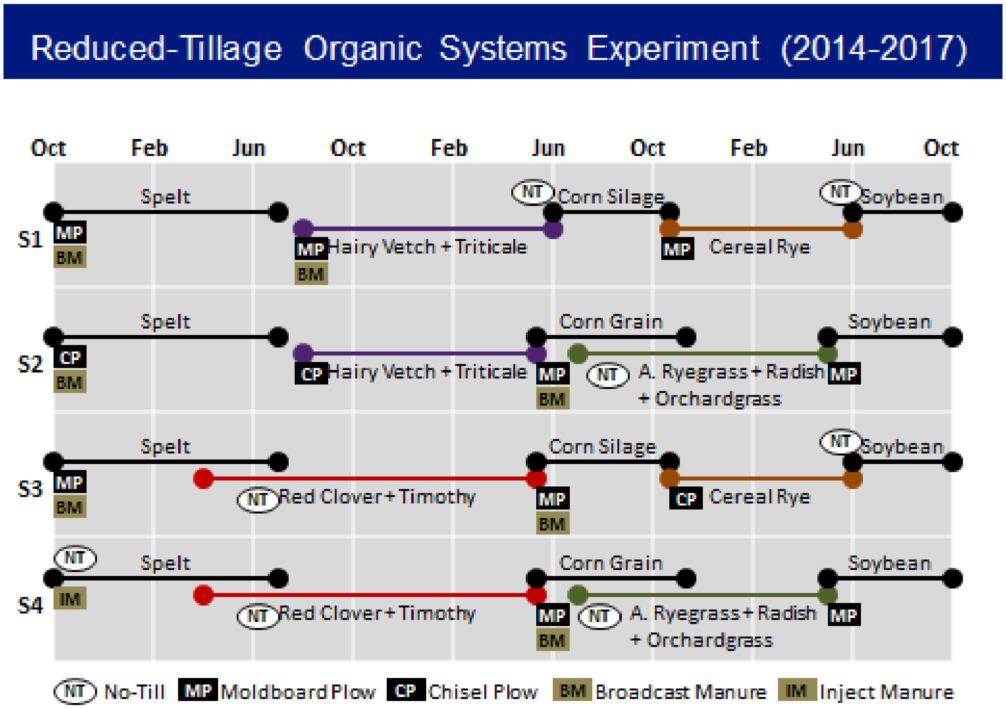

Figure 1-1. Comparison of four reduced-tillage cropping systems evaluated at Penn State's Russell E. Larsen Agricultural Research Center (RELARC) (2014 – 2017).

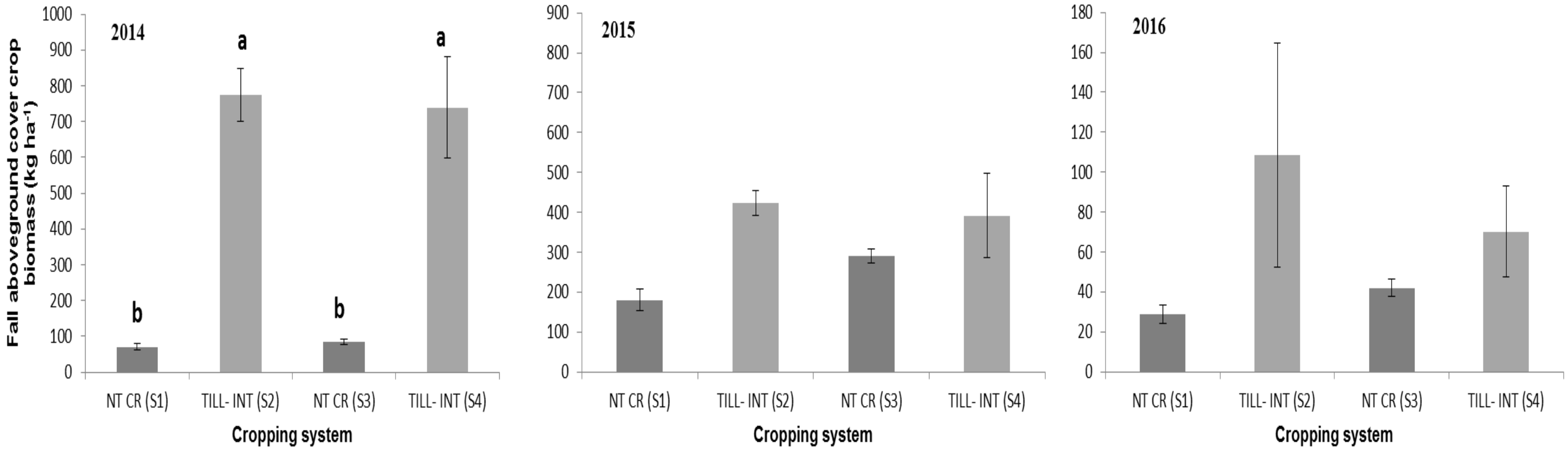

Figure 1-2. Effect of cropping system on total aboveground fall cover crop biomass (kg ha^{-1}) in the fall of 2014-2016. Cropping systems differ by tillage regime (dark grey= no-till (NT); light grey= till) and cover crop species and establishment method (CR = cereal rye established after corn harvest; INT = cover crop mixture interseeded into corn grain). Cropping system*year effect: $F_{6,33}$ = 10.89; p= <0.0001. 2014 cropping system effect: $F_{3,9}$ = 23.96; p= 0.0001. 2015 cropping system effect: $F_{3,9}$ = 3.34; p= 0.069. 2016 cropping system effect: $F_{3,9}$ = 1.77; p= 0.22. Different letters above bars indicate system differences at p<0.05.

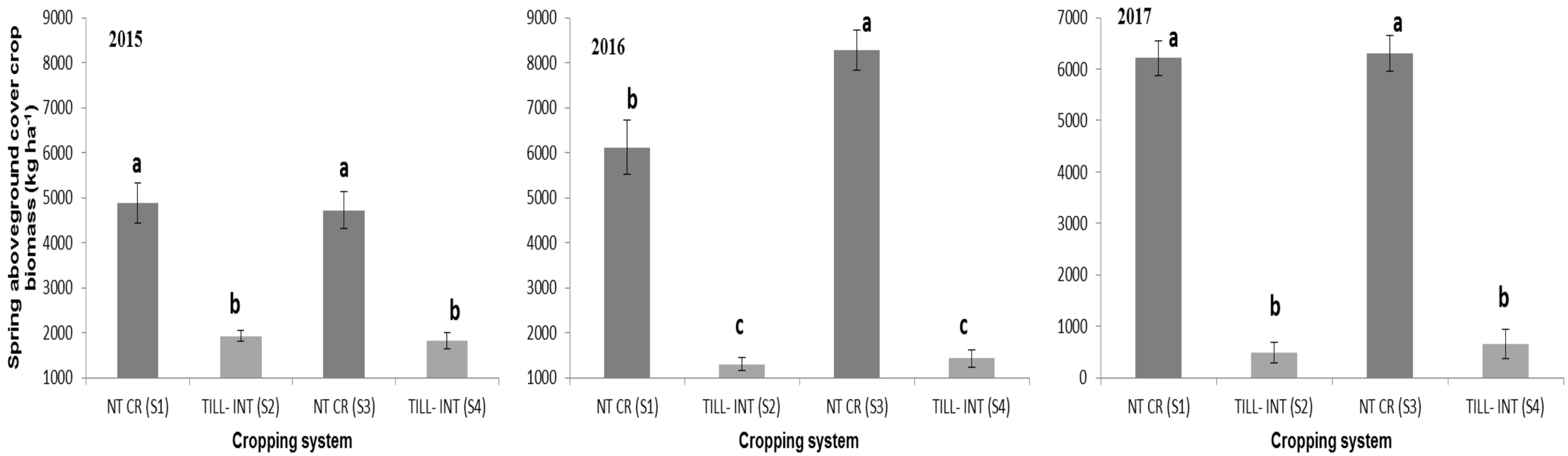

Figure 1-3. Effect of cropping system on total aboveground spring cover crop biomass (kg ha^{-1}) prior to termination in the spring of 2015-2017. Cropping systems differ by tillage regime (dark grey= no-till (NT); light grey= till) and cover crop species and establishment method (CR = cereal rye established after corn harvest; INT = cover crop mixture interseeded into corn grain). Cropping system*year effect: $F_{6,33} = 9.65$; p= <0.0001. 2015 cropping system effect: $F_{3,9} = 30.84$; p= <0.0001. 2016 cropping system effect: $F_{3,9} = 80.10$; p= <0.0001. 2017 cropping system effect: $F_{3,9} = 111.58$; p= <0.0001. Different letters above bars indicate system differences at $p<0.05$.

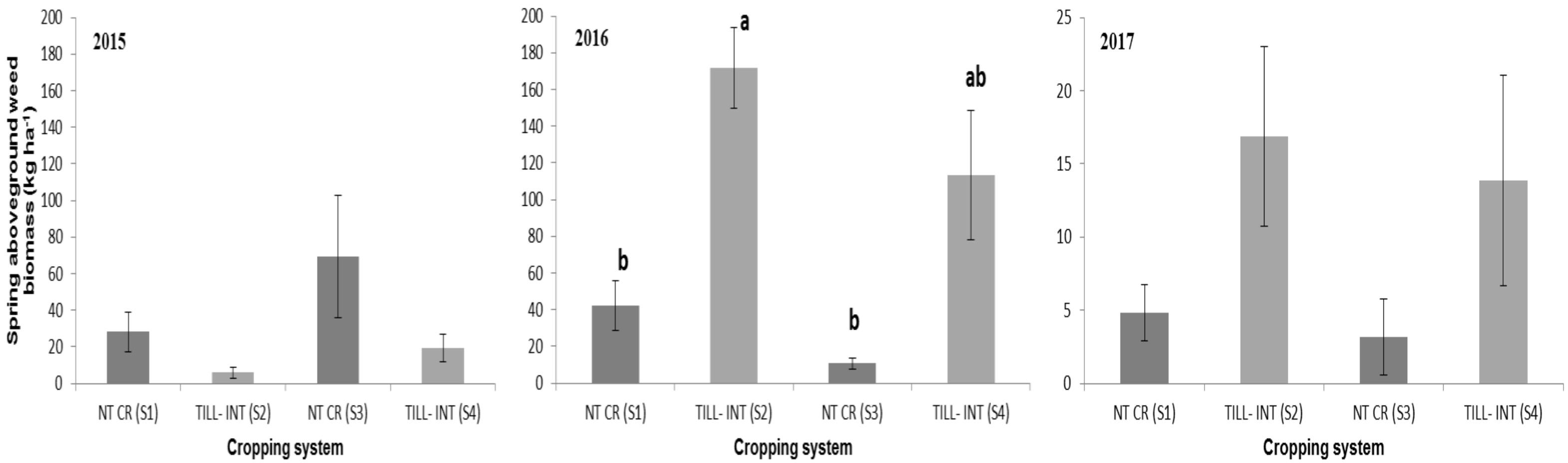

Figure 1-4. Effect of cropping system on total aboveground spring weed biomass (kg ha^{-1}) prior to cover crop termination in the spring of 2015-2017. Cropping systems differ by tillage regime (dark grey= no-till (NT); light grey= till) and cover crop species and establishment method (CR = cereal rye established after corn harvest; INT = cover crop mixture interseeded into corn grain). Cropping system*year effect: $F_{6,33}$ = 8.59; p= <0.0001. 2015 cropping system effect: $F_{3,9}$ = 2.85; p= 0.097. 2016 cropping system effect: $F_{3,9}$ = 9.05; p= 0.0044. 2017 cropping system effect: $F_{3,9}$ = 1.68; p= 0.24. Different letters above bars indicate system differences at p<0.05.

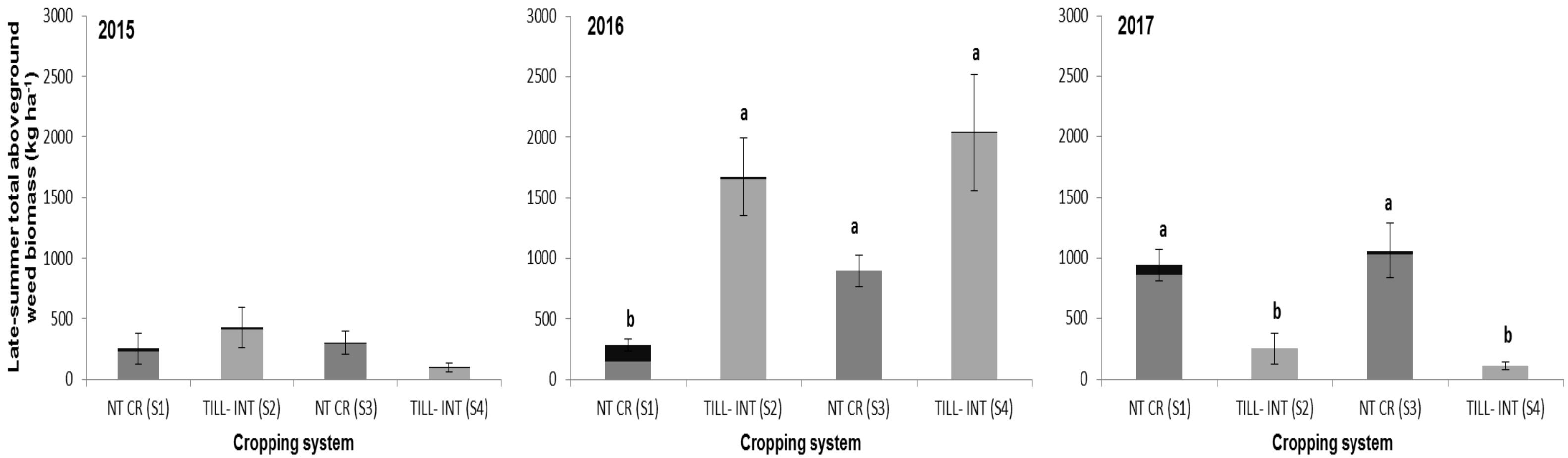

Figure 1-5. Effect of cropping system on total aboveground late-summer weed biomass (kg ha^{-1}) in summer 2015-2017. Cropping systems differ by tillage regime (dark grey= no-till (NT); light grey= till) and cover crop species and establishment method (CR = cereal rye established after corn harvest; INT = cover crop mixture interseeded into corn grain). Stacked bars indicate total cropping system biomass by annual species (bottom; gray bars) and perennial species (top; black bars). Cropping system*year effect: $F_{6,33}$ = 8.65; p= <0.0001. 2015 cropping system effect: $F_{3,9}$ = 1.37; p= 0.31. 2016 cropping system effect: $F_{3,9}$ = 24.71; p= 0.0001. 2017 cropping system effect: $F_{3,9}$ = 11.81; p= 0.0018. Different letters above bars indicate system differences at p<0.05.

Chapter 2

Crop Performance and Weed Control in Rotational No-till vs. Tillage-based Organic Corn Grain and Silage

Abstract

While many organic farmers would like to reduce their reliance on tillage, it still remains critical for weed control and incorporation of amendments such as manure. Cover crop-based, organic rotational no-till, which utilizes cover crop mulches and no-till cash crop planting, may be a strategy to lessen this reliance on tillage. We initiated a three year cropping systems experiment to examine alternative strategies for reducing tillage frequency and intensity within an organic grain/silage rotation to determine the feasibility of organic reduced tillage production in the Mid-Atlantic. Four different cropping systems were evaluated for three years. Cover crops preceding corn included two systems of hairy vetch/triticale sown after spelt harvest, and two systems of red clover/timothy frost-seeded into spelt in late winter. Hairy vetch in system 1 was terminated via roller-crimping, while the cover crops in the other three systems relied on spring tillage to incorporate the cover crop and livestock manure. Two systems were harvested as corn silage while two others were harvested for grain. Red clover/timothy produced 3,300-4,500 kg ha^{-1} above-ground cover crop biomass, while hairy vetch/triticale was more variable, producing 3,600-7,500 kg ha^{-1} of aboveground biomass over the three years. Although weed biomass at the time of corn planting was below 78 kg ha^{-1}, in-season weed control varied by both treatment and year depending on the

effectiveness of in-season cultivation. Late-summer weed biomass ranged from 300 kg ha^{-1} up to 2,700 kg ha^{-1}, with less effective weed control resulting when weather conditions prevented timely blind tillage and inter-row cultivation. Corn grain yields were not different between systems from year to year; however, no-till planted corn silage yielded lower than the tilled silage system, likely due to later planting of corn and potentially lower soil fertility.

Introduction

When practiced as a whole systems approach with the goal of increasing long-term sustainability, organic crop production can benefit both soil conservation and improved soil quality (Gomiero et al., 2011). Organic farms do not use synthetic inputs, and rely more on cultural practices such as crop rotation and cover cropping for pest management, which increases the diversity and overall stability of the agroecosystem (Gomiero et al., 2011). Organic farms tend to have higher soil organic matter and better water conservation, which aids in yield stability during times of water shortage (Pimentel et al., 2005). However, organic row crop farmers are generally very dependent on tillage for weed control and to incorporate manure and other amendments. This reliance can contribute to soil degradation and does not aid an overall goal of organic farming to build soil quality (NOP 2005, Teasdale et al., 2007, Uri et al., 1999).

The benefits of reducing tillage are numerous and include soil moisture retention, better moderation of soil temperature through increased soil stability, and increased soil organic matter content (Berner et al., 2008, Kuepper 2001). Practicing no-till can lessen sediment runoff and erosion, as well as improve water infiltration and surface water quality (Uri 2000). Reducing tillage can also conserve energy because of fewer trips or passes with equipment through the field, resulting in decreased fuel use (Berner et al., 2008). Economically, no-till reduces labor and machinery needs, thereby saving energy and money for the operation (Uri 2000). Although use of tillage in organic systems for weed control and amendment incorporation remains critical, there are practices that can be utilized to help decrease the overall frequency and intensity of such practices (Peigné et al., 2007).

One approach to reducing tillage in organic annual crop production is the use of cover crop-based, rotational no-till (Keene 2015, Mirsky et al., 2012, Wallace et al., 2017). This approach uses a roller-crimper to terminate cover crops at the time of cash crop planting to create a cover crop mulch which aids in the control of summer annual weeds (Kornecki et al., 2006, Reberg-Horton et al., 2012, Wallace et al., 2017). To maintain adequate weed control in this system and potentially incorporate green and livestock manures, primary tillage is often used after cash crop harvest in the fall, creating a seed bed for establishment of either a cover crop or another cash crop (Mirsky et al., 2012). This practice can eliminate the need for spring tillage and facilitate no-till establishment of the subsequent crop, contributing to the goal of increased soil conservation.

With the increasing demand for organic dairy products in the Mid-Atlantic, many farmers are interested in the addition of organic feed grain in their rotations (Smith et al., 2011). Cover crop-based, organic no-till corn has the potential to foster greater implementation of organic silage/grain production to meet market needs, while also facilitating soil conservation and increased soil quality (Huggins and Reganold, 2008). Typically, corn is no-till planted into a cover crop terminated via roller-crimper, which smothers weeds, conserves water during times of drought, and provides nutrients as the cover residues decompose (Mirsky et al., 2012). Compared to traditional tillage-based organic corn, reduce tillage systems can achieve similar yields; however, effective weed suppression from the rolled cover crop mulch is considered critical for maintaining yield (Mirsky et al., 2012, Teasdale et al., 2012). Both research and farmer experience has revealed that adoption of organic no-till corn continues to be challenging and more work is needed to overcome several potential yield limiting constraints (Mirsky et al., 2012, Mischler et al., 2010, Reberg-Horton et al., 2012, Wallace et al., 2017).

Successful adoption of organic no-till corn production is dependent on cover crop species selection, performance, and control. The cover crop must be winter hardy, accumulate sufficient biomass to suppress weeds, and provide timely release of nutrients to the cash crop. In the mid-Atlantic region, hairy vetch (*Vicia villosa Roth*) is a suitable legume cover crop that meets these requirements by providing up to 150 kg ha^{-1} of plant available nitrogen, and as much as 8,000 kg ha^{-1} above-ground dry matter to aid in the control of weeds (Mirsky et al., 2012, Mischler et al., 2010). Research has demonstrated that hairy vetch is best controlled using a roller-crimper during late flowering or early pod set, providing around 80% control (Hoffman et al., 1993, Mischler et al., 2009). Delaying cover crop termination in the spring until hairy vetch accumulates maximum above-ground biomass also aids in increased weed suppression (Wallace et al., 2017). However there can be tradeoffs associated with delaying cover crop termination, such as decreased nutrient availability and issues with direct seeding into rolled cover crop residue related to difficulties slicing through the cover crop mulch and achieving accurate seed placement (Keene 2015, Parr et al., 2011). These tradeoffs should be considered in making cover crop management decisions.

Frost seeding a legume in the spring is an alternative practice to tilling and planting a cover crop such as hairy vetch after small grain harvest. This practice involves broadcasting or drill seeding a cover crop in early spring into an established small grain cash crop such as wheat (*Triticum aestivum* L.) or spelt (*Triticum spelta* L.) (Mutch et al., 2003). The partially frozen soil can support machinery while still allowing good stand establishment of the cover crop as the soil warms in the spring (Stute and Shelley, 2016.) This is most often done with a biennial or perennial legume that will help suppress weeds after small grain harvest and also fix and capture nitrogen for the subsequent crop. Research from the Northeast and upper Midwest show that frost-seeded legumes can establish well and do not interfere with small grain crop yield or harvest (Snyder et al., 2016, Stute and Shelley, 2016). There is also the potential to take a forage cutting in the late summer or fall if sufficient dry matter is produced to increase profitability (Singer et al., 2005).

Agricultural systems frequently undergo soil disturbance, which can have both positive and negative effects on the weed community. This subsequently affects the local weed flora, the germination timing, and potential management decisions. Organic annual row crop production systems rely on frequent and intense tillage for weed control; however, this can help select weed species that tolerate soil disturbance and can successfully establish over time in the agroecosystem (Smith and Mortensen, 2017). Additionally, tillage practices differing in frequency, intensity, and depth can stratify weed seeds in the soil profile, causing seed dormancy and shifts in emergence timing (Gruber and Claupein, 2009). Understanding how weeds adapt to tillage intensity and frequency is important for weed management in any cropping system and should influence management decisions in the farming operation.

Controlling weeds is a continual challenge for organic farmers and growers must stay alert to a changing pest dynamic. The idea of "many little hammers," or combining weed suppressive tactics (Fisher 2012, Liebman and Gallandt, 1997), is an approach to insure a low and stable pest population over time (Liebman et al., 2001). Crop rotation is a powerful weed management tool that introduces different crop sequences within and between years that can potentially create an unfavorable environment for weeds (Liebman and Dyck, 1993). Increasing the diversity of a crop rotation by sowing cover crops between cash crops can aid in weed management. Actively growing cover crops or dead residues can act as a weed suppressive mulch (Clark 2007, Hartwig and Ammon, 2002, Snapp et al., 2005), and cover crops with high growth rates and foliar ground cover such as hairy vetch can result in weed suppression by competing for resources like sunlight, moisture, nutrients, and ecological space (Moonen and Barberi, 2004). The addition of cover crops into a rotation may also aid in reducing tillage either before the cover crop is established or at the time of termination. Typically in organic systems, weed control is achieved through fall and spring primary tillage, as well as several in-season cultivation events to control flushes of emerged weeds. However, these practices do not aid in soil conservation, and their effectiveness can be very dependent on air temperature and soil moisture, making consistent weed control difficult (Peigné et al., 2007). By increasing the use of diverse strategies, farmers can employ tactics such as crop rotation, selective tillage, and cover cropping to minimize the selection pressure that a single tactic employs and reduce the potential for population shifts and pest outbreaks (Fisher 2012).

In this research, we aimed to study a number of reduced-tillage practices within a cover crop-based, organic rotational no-till system. In this study, we investigated two different strategies for integrating cover crops in the corn phase of a three-year rotation. No-till corn planted into a rolled cover crop mulch along with subsequent high-residue inter-row cultivation was compared to three tillage-based systems that incorporated green manure cover crops and relied on standard mechanical weed control. The objectives of our study were to compare cover crop performance, weed suppression, and yield limiting factors between conventionally tilled and no-till organic corn systems. We hypothesized that: (1) use of a roller-crimper to create a weed-suppressive no-till mulch and high-residue inter-row cultivator to supplement weed control will result in similar weed control to a tilled corn system subjected to standard spring inversion tillage and in-season cultivation, and (2) organic no-till corn will produce similar yield to tillage- based organic corn systems.

Materials and Methods

Site description. An organic cropping systems experiment was conducted on certified organic land from 2014-2017 at the Pennsylvania State University Russell E. Larson Agricultural Research Center (RELARC) at Rock Springs, Pennsylvania (40˚43´N, 77˚56´W). Hagerstown silt loam was the dominant soil (fine, mixed, semiactive, mesic Typic Hapludalfs), with scattered zones of Opequon-Hagerstown soil (clayey, mixed, active, mesic Lithic Hapludalfs). The research center resides in Zone 6b of the USDA Plant Hardiness Zones, and temperate humid climatic conditions result in annual rainfall and snowfall averages of 1,006mm and 1,140mm, respectively. Growing degree days (base 10˚C) are provided for April through October each year (Appendix D). Annual temperature averages between 5 and 25˚C across the year.

Experimental design. A three year rotation of corn (*Zea mays* L.)-soybean (*Glycine max* (L.) Merr.)-spelt (*Triticum spelta* L.) was implemented using a full entry design with cover crops preceding corn and soybean cash crops. We used a randomized complete block, split-plot design with four replications. Within each block resided the three cash crop rotation entry points as main plots, with four cropping system treatments as the split-plot within each main plot. Cropping systems differences included cover crop species, their planting date and termination method, manure management, and tillage intensity and frequency (Figure 2-1). Split-plots measured 9m wide by 49m long, and main plots were separated by grass alleyways. Prior to experiment initiation, a three year rotation of corn-soybean-wheat with cover crops before corn and soybean was examined in main plots using organic rotational no-till practices. The experiment was managed organically from 2011-2014, and organic certification was awarded in 2014. Data collection for this project began fall 2014 after organic certification.

Crop rotation. In this paper, we focus on evaluating the performance of four systems (S1-S4) within the corn phase of the rotation, beginning with cover crop establishment preceding corn. In all four systems, corn ‘MC4050’ was planted on 76-cm rows at 81,510 plt ha^{-1} using a four-row John Deere 7200 planter equipped with Dawn Biologic ZRX residue managers. In system one (S1), liquid dairy manure was broadcast at 74,831 L ha^{-}

^{1} and incorporated via moldboard plow following spelt harvest (Figure 2-1). Hairy vetch (*Vicia villosa Roth*) ‘Groff’ plus triticale (*Triticosecale*) ‘815’ were seeded in late August at 34 kg ha^{-1} each in 19-cm rows using a Great Plains 1005NT drill following disking and s-tining. The following spring at hairy vetch early pod set (Mischler growth stage 7), the cover crop was terminated using a roller-crimper to create a weed suppressive mulch (Mischler et al., 2010). Corn was no-till planted for silage immediately after rolling and rolling was repeated a second time approximately one week after corn planting to ensure complete cover crop control (Appendix B). High-residue cultivation (John Deere 886) occurred in season twice about four and five weeks after planting (WAP) to supplement weed control in S1. The cultivator has a 50-cm sweep between each corn row that runs just a few centimeters below the soil surface to sever germinated weeds while still keeping the cover crop mulch relatively intact.

System two (S2) followed the same cover crop establishment protocol as described in S1; however, manure was not applied after spelt harvest and a chisel plow rather than the moldboard plow was used as the primary tillage implement before cover crop establishment (Figure 2-1). Manure application and incorporation and cover crop termination was achieved by moldboard plow before corn planting in the spring, using the same manure rates and planter as previously described. Corn for grain was planted using the same variety as S1 approximately seven to ten days following primary tillage and planting occurred one to two weeks earlier than the no-till S1 system (Appendix B). System 2 relied on blind (flex-tine weeder and rotary hoe) and inter-row cultivation for weed control in corn. In-season tillage events varied by year, and were driven by weed severity and environmental conditions (Appendix C).

Systems three (S3) and four (S4) used frost-seeded medium red clover (*Trifolium pratense* L.) ‘VNS’ and timothy (*Phleum pratense* L.) ‘King’s’ instead of hairy vetch-triticale (Figure 2-1). The cover crop was drill seeded into standing spelt on 19-cm rows using the same Great Plains drill as previously described in late winter at 12 and 4.5 kg ha^{-1}, respectively (Appendix A). Following spelt harvest, the legume-grass cover crop was allowed to grow into the fall and was harvested for forage in early to mid-October. Forage yield was determined by harvesting three subsamples the entire length of each split-plot using a small plot forage harvester. Samples were oven dried at 65˚C for at least five days before weighing. The following spring before corn planting, manure was broadcast applied over the growing cover crop and incorporated via the same primary and secondary tillage as described in S2. Corn was grown for silage in S3 and for grain in S4 and planting and weed control followed the same protocol as S2 (Figure 2-1).

In the silage systems (S1 and S3), a cereal rye (*Secale cereale* L.) ‘Aroostook’ cover crop was seeded after corn harvest. To enable corn grain production (S2 and S4) and still allow for cover crop establishment, a cover crop mixture of annual ryegrass (*Lolium perenne L. spp. multiflorum*) ‘KB Supreme’, orchardgrass (*Dactylis glomerata* L.) ‘Potomac’, and forage radish (*Raphanus sativus* L.) ‘Tillage Radish’ were drill seeded at 11, 11, and 3.4 kg ha^{-1} (Appendix A), respectively, into standing corn at V5-V7. This mixture was chosen primarily for building soil organic matter, scavenging nutrients, and the potential to provide grazing opportunities for livestock. These cover crops proceeded soybean in the rotation and the results are described in Chapter 1.

Data collection. We sampled aboveground cover crop biomass in late October to early November in each year using six randomly placed $0.25m^2$ quadrats in each split-plot.

Cover crop biomass was sampled again in mid- to late-May just prior to cover crop termination using nine 0.25m^2 quadrats per split-plot, with three samples being collected from each transect (yield rows). We collected spring biomass just prior to cover crop termination, with S2-S4 being sampled about seven to ten days prior to S1. Biomass was clipped at the ground level and bagged, sorted in the lab by species, and dried for at least five days at 65˚C. Once dried, biomass was weighed and averaged across subsamples before analysis.

We sampled weed biomass at the same time as cover crop biomass collection in the fall and spring, using the same protocols. We also sampled weed biomass in mid-August prior to corn harvest. During this sampling period, nine 0.5m^2 quadrats were sampled per split plot, with three samples being taken from each yield row. Within each sample, weeds were sampled separately in-row and between row, allowing us to determine the effectiveness of the cover crop mulch in no-till systems and in-season cultivation frequency and intensity in the tilled systems. We clipped weeds at ground level, and bagged them by location (in-row or between row). Biomass was averaged across subsamples and by location before analysis.

We assessed corn populations after last cultivation at six WAP by counting the number of plants in 5.3 meters of row. Assessments occurred at three random locations within each of the three transects per split-plot, resulting in a total of nine population assessments. Corn yield data was collected by harvesting six rows for the entire length in each split-plot using either a small silage harvester or small plot combine, and averaged prior to analysis.

Economic analysis. A budget analysis was conducted to give an estimated economic comparison between cropping systems. This analysis can be used to estimate an operation's revenue and expenses based on certain practices, and used to make comparisons against alternative practices. Enterprise budgets were calculated for each cropping system using the Mississippi State Budget Generator v6.0 (Laughlin and Spurlock, 2008). Tractor and other implement sizes were based on typical size for farms in the Mid-Atlantic. Production costs were based on the previous year's input prices. A 6% interest rate for opportunity cost was factored in starting from the date of input use until harvest. The charges provided do not include land management charges. Additionally, net returns show an estimated income per cropping system and were calculated by multiplying system cash crop yields by expected corn silage and grain prices and subtracting total production costs. Budgets were originally calculated on a dollars acre^{-1} basis, and converted to dollars hectare^{-1} for final analysis.

Statistical analysis. We evaluated system-level effects on: 1) fall and spring cover crop biomass (kg ha^{-1}), 2) fall, spring, and late summer weed biomass (kg ha^{-1}), 3) corn population (% of planted), and 4) corn yield (kg ha^{-1}) using ANOVA in SAS 9.4. We used linear mixed effects models (PROC MIXED) with system, year, and system*year as fixed factors. Block was used as a random factor. For late summer weed biomass, we additionally evaluated system effects on in-row vs. between row weeds. Fixed effects included system, location (in-row, between row), and their interaction. To meet the assumptions of normality of variances, we log-transformed total late summer weed biomass and weed biomass by location. In-row weeds and corn populations were analyzed as proportions of the totals, and the arcsin square root transform function was used to normalize the data. We separated means using the Tukey-Kramer method at alpha=0.05. Transformed data was later back-transformed and all data are presented in tables and figures with treatment means and standard errors.

Results and Discussion

Cover crop performance and weed biomass. Fall cover crop biomass was different across years and sometimes systems, but there was no system*year interaction (Table 2-1). Hairy vetch/triticale (S1, S2) cover crop biomass in late fall averaged around 1,500 kg ha^{-1} and 2,400 kg ha^{-1} in 2014 and 2015, respectively, but averaged only 900 kg ha^{-1} in 2016 (Table 2-1). Red clover/timothy (S3, S4) produced approximately 1,900, 3,200, and 1,200 kg ha^{-1} of fall cover crop biomass in 2014, 2015, and 2016 respectively (Table 2-1). These values do not include the forage harvest that occurred about four weeks prior, so total fall biomass is considerably higher than for S1 and S2. Forage yield averaged around 5,600 kg ha^{-1}, making total biomass much greater before clover haylage harvest. Establishment dates for the cover crops within each system were similar for each year, so differences in growth and biomass accumulation between years can be attributed to differences in rainfall and temperature (Appendix A). Fall weed biomass was not collected in 2014 and in 2015 and 2016, weed biomass did not differ due to cropping system (Table 2-1). Fall weed biomass was variable and relatively low, ranging from 15-221 kg ha^{-1}. Weed biomass was low because of tillage at hairy vetch/triticale seeding in S1 and S2 and also because of the competitive ability of red clover in S3 and S4. Mowing of the red clover cover crop also helped keep weed biomass low, as this operation removed weeds and prevented them from setting seed. Common weed species included foxtail species (*Setaria spp.*), common lambsquarters (*Chenopodium album* L.), yellow nutsedge (*Cyperus esculentus* L.), as well as winter annual species like common chickweed [*Stellaria media* (L.) Vill.] and henbit (*Lamium amplexicaule* L.). While fall weed biomass at the time of sampling was low across years, different circumstances could result in decreased establishment of cover crops and subsequent competition from weeds. This would provide consequences for spring biomass and future weed seedbanks.

Spring cover crop biomass was different across systems and years, but there was not a system*year interaction (Table 2-1). Across the three years, S1 hairy vetch/triticale accumulated as much as 2,500 kg ha^{-1} more spring biomass or about 1,800 kg ha^{-1} on average than S2 at termination (Table 2-1). This difference was likely caused by manure application at cover crop establishment in S1, whereas S2 manure application occurred at termination just prior to cash crop planting. In addition, S1 was sampled seven to 10 day later in the spring than S2 due to delay in termination that occurred because of no-till management (Figure 2-1). Red clover/timothy spring cover crop biomass ranged from 3,300-4,500 kg ha^{-1} across the three years, and was not different between S3 and S4 (Table 2-1). Red clover/timothy spring biomass was not different from S2 hairy vetch/triticale in any year, however it was lower than S1 biomass in two of three years (Figure 2-2).

The growth habit of the cover crop species and timing of manure application likely contributed to these differences in biomass across systems. System one spring cover crop biomass was likely greater because of higher fertility due to manure application at the time of cover crop planting as well as the delay in termination timing. Hairy vetch also tends to grow more quickly than red clover in late spring, as it is an annual species while clover is biennial that has a slower growth habit. Despite some cropping systems differences in spring cover crop biomass, all systems had few weeds in the spring (78 kg ha^{-1} or less) and no cropping system or year differences were observed in spring weed biomass (Table 2-1). Although winter annual weeds were scattered throughout the treatment plots, they tended to be relatively low in both density and biomass, with some common chickweed and henbit as well as early emerging foxtail species and common ragweed (*Ambrosia artemisiifolia* L.) making up the majority of what was observed.

Our cover crop biomass results are consistent with other research in the Mid-Atlantic, which showed that hairy vetch before corn can produce at least 6,000 kg ha^{-1} of biomass (Mirsky et al., 2012, Teasdale et al., 2012). Red clover frost-seeded into spelt the year prior to corn is also a viable option, as it is a competitive biennial species that can fix nitrogen and produce 3,000-5,000 kg ha^{-1} of biomass (Liebman et al., 2012, Snyder et al., 2016). Both species provided excellent fall and early-season weed suppression, either with the help of pre-plant tillage at cover crop establishment (hairy vetch-triticale) or by the competitive growth of the cover in the spring. Farmers wishing to incorporate these species into their operations should be careful to seed these cover crops at the optimal time and rate to ensure proper biomass accumulation for weed suppression.

Late-summer weed biomass. Late summer weed biomass responded to the system*year interaction and large year to year differences were observed, but system was not a significant factor in two of three years. All systems were dominated by summer annuals including foxtail species, along with common lambsquarters, pigweed species (*Amaranthus spp.*), and yellow woodsorrel (*Oxalis stricta* L.), among others. In 2015, weed biomass ranged from 725-964 kg ha^{-1} with the S1 no-till system being equal to the tilled systems (Table 2-2, Figure 2-3). Primary and secondary tillage events took place at either cover crop establishment (S1) or at termination (S2-S4), as well as a number of in-season cultivations, particularly in the tilled systems. A total of 7-11 primary, secondary, and in-season cultivations took place in 2015 in S2-S4, which would have controlled many emerged weeds (Appendix C).

Late-summer weed biomass was segregated spatially within and between the corn rows to help assess the efficacy of the weed control tactics in no-till versus tilled corn systems. Weed biomass by location did not respond to cropping system, or the interaction of system*location; however, location was significant for in-row versus between row weed biomass across years (Table 2-2). We also tested the data by the proportion of weeds in-row relative to the total weed biomass to confirm spatial differences. The proportion of total weed biomass in-row did not respond to cropping system or the interaction, but was different across years (Table 2-2).

The proportion analysis showed that in all three years and across systems, more weeds tended to survive in the crop row. In 2015, the proportion of biomass in-row comprised 79-91% of the total (Table 2-2). In 2016, a wet May and early June followed by low rainfall during the summer led to inadequate weed control and greater amounts of weed biomass compared to the other years (Table 2-3). Late-summer weed biomass ranged from 1,223-2,753 kg ha^{-1}, with no difference between no-till and the tilled systems (Figure 2-3). In-season cultivation attempts in June and July were not successful at controlling weed flushes, as the soil was dry and compact, resulting in fewer cultivation attempts compared to the previous year. In the no-till system (S1), high-residue cultivation was completed once compared to twice in 2015 because of compacted dry soil, putting more of a reliance on the rolled cover crop mulch. Weed biomass by location differed in 2016, with a significant system, location, and interaction effect (Table 2-2). In-row weed biomass comprised 74-88% of the total, and was higher in-row than between row in all four cropping system treatments (Table 2-2).

In 2017, environmental conditions allowed for better in-season mechanical weed control, particularly in the tilled systems. Late-summer weed biomass ranged from 339-712 kg ha^{-1} in the three tilled (S2 - S4) systems, to over 2,700 kg ha^{-1} in the no-till (S1) system (Table 2-2, Figure 2-3). Weed biomass in S1 was higher than the other three systems ($p= 0.003$), with all four systems having more weeds in-row than between-row (Table 2-2). Across cropping systems, the proportion of in-row weeds ranged from 91-98% of the total weed biomass (Table 2-2). Although the proportion of in-row weeds in S1 did not differ from S2-S4, the total amount was 3.5 to 7.5X greater (Table 2-2). The efficacy of both the no-till cover crop mulch and high residue cultivation was not as effective as the multiple mechanical weed control operations in the tilled systems. The less effective weed control in the no-till S1 was likely a result of both attaining lower amounts of cover crop biomass compared to previous years along with some survival of weeds in-row which re-rooted after high-residue cultivation.

While the spatial separation of weed biomass between and within the crop row has not been thoroughly examined, our results suggest that rolled hairy vetch before no-till corn has the potential to decrease weed biomass both within and between the crop row comparable to tilled systems. In two of three years, weed control both between and within row was the same or even greater in the no-till system compared to the three tilled systems. In both tilled and no-till systems, in-row weed control can fail either because the cover crop mulch alone is inadequate for weed suppression or the performance of blind cultivation in tilled systems is variable and highly dependent on environmental conditions, resulting in weed survival in-row. Other options to ensure better in-row weed suppression can include planting corn at a higher seeding rate to provide more competition against emerging weeds, seeding cover crops at the appropriate time and rate based on production guide recommendations to ensure maximum biomass accumulation, and having skilled tractor operators that know when crop, weed, and environmental conditions are optimum to achieve effective mechanical weed control (Mirsky et al., 2012, Weiner et al., 2001).

The variable weed control experienced over the three years of the study show that weed management in organic cover crop-based rotational no-till systems continues to be challenging, especially when environmental conditions impede the success of mechanical operations. Most weed biomass consisted of annual species, and although perennials were present more so in the no-till S1 system, they constituted a minor component of the weed flora. In the Mid-Atlantic, it is crucial that rolled cover crops achieve 6,000-8,000 kg ha^{-1} of biomass to ensure weed suppression (Mirsky et al., 2012). If inadequate levels of cover crop biomass are achieved, high-residue cultivation can be used as a supplemental weed management tool, but this operation is only effective on between-row weeds. In tilled organic corn systems, it is important to perform in-season cultivation frequently with new weed flushes so as not to let the emerged weeds get too large to control.

Cover crop interseeding may influence late season weed control, but it has yet to be studied extensively in either conventional or organic systems. Our results suggest that interseeding did not help suppress weeds, as weed biomass was similar across tilled systems both overall and spatially (Table 2-2). The intent of interseeding in our study was not targeting weed suppression but rather helping to diversify the crop rotation and establish a winter cover crop, while also eliminating the need for fall tillage after corn harvest. Because neither tillage nor mowing occurred in the fall, any mature weeds present would likely set seed; however, spring tillage before soybean planting would have buried seeds below the soil surface.

Corn populations and yields. In all four systems, corn was planted at 81,510 plants ha^{-1}, and the population data were analyzed as a proportion to the planted population (Appendix B). Corn populations did not differ between systems, but were affected by year (Table 2-4). In 2015, populations ranged from 82-88% of the total planted (Table 2-4). Wet conditions at planting in 2016 resulted in lower plant populations in all systems compared to the prior year, and ranged from 61-74% (Table 2-4). Wet conditions at planting can make establishment more difficult because it can result in seed furrows that do not completely close as well as cloddy conditions that impair the performance of the planting operation (Unger and Kaspar, 1994). Although plant populations were similar across systems, greater amounts of cover crop biomass can also contribute to lower rates of establishment in the no-till system (Table 2-1) (Mirsky et al., 2012, Mischler et al., 2010). Greater amounts of cover crop biomass can make it more difficult to slice through and achieve proper seed placement and furrow closure. In 2017, corn populations ranged from 65-83% of the total planted and again were not different between systems (Table 2-

4). A number of factors likely reduced plant populations including variable soil conditions at planting that can be typical following incorporation of green manure cover crops as well as multiple passes after planting with mechanical weed control implements that may injure or remove some plants due to inexact row spacing, particularly when doubling back on the guess rows. Use of blind tillage to control early weed flushes can be successful if done at the proper time and with precision, however inaccurate operation can result in removal of young cash crop plants, reducing populations and therefore potentially yield (Martens and Martens, 2005).

Corn yields were analyzed separately by grain or silage depending on the system. Corn grain yields (S2, S4) were not different in any year, although yields were lower in 2016 due to environmental conditions that led to reduced corn populations and greater weed biomass. Grain yields averaged 9,100 kg ha^{-1}, 8,400 kg ha^{-1}, and 10,100 kg ha^{-1} in 2015, 2016, and 2017, respectively (Table 2-4). In these corn grain systems, a cover crop was interseeded at V5-V7 to eliminate the need for fall tillage and post-harvest cover crop establishment. This tactic could be promising for organic systems because it would allow a farmer in the Mid-Atlantic to grow grain corn, while also eliminating a tillage entry in the fall. Previous research in conventional corn has demonstrated cover crops interseeded after V4 do not affect corn yield and may help suppress late emerging weeds (Baributsa et al., 2008, Dillon et al., 2012). While there are many benefits to interseeding cover crops, they do not produce biomass equivalent to cover crops such as cereal rye, so it is crucial to seed at the correct corn growth stage and cover crop seeding rate to ensure establishment and winter survival (Baributsa et al., 2008, Wilson et al., 2014).

Corn silage yields differed from year to year, and were lower in the no-till system (S1) compared with the tilled system (S3) in the first two years. System 1 silage produced around 25,000 kg ha^{-1} in 2015, while S3 yielded just over 38,000 kg ha^{-1} (Table 2-4, Figure 2-4). In 2016, S1 yielded just under 21,000 kg ha^{-1} and S3 almost 35,000 kg ha^{-1} (Table 2-4, Figure 2-4). However in 2017, S1 yielded higher than S3, averaging 37,000 kg ha^{-1} and 33,000 kg ha^{-1}, respectively (Table 2-4, Figure 2-4). Corn was successfully planted in the rolled vetch in 2017, and although summer weed biomass was high, the cash crop was able to get enough of a head start on weed growth for yield to be unaffected. Yield was lower in S3 in 2017 likely due to decreased plant populations. Although not statistically different from any other system, populations were reduced from blind tillage events. The number of in-season tillage events was increased in the tilled S3 system in 2017 to better control weeds (Appendix C); however, research has shown that increasing tillage can lead to quicker N degradation by microbes compared to no-till systems because of the increased break-up of soil aggregates which hold N (Kristensen et al., 2000). The tilled system produced higher yields than the no-till system in 2015-2016 and several reasons may be responsible for these results. High late-summer weed biomass may have affected yield in 2016 in both tilled and no-till systems, as well as low plant populations. However, weed biomass and corn populations were not different between these two systems, potentially pointing to other factors that could impact yield. Manure management could be a contributing factor behind these yield differences, as S1 received a late summer manure application to enable the no-till rolling of the cover crop in the spring, while S3 received spring broadcast manure at cover crop termination prior to inversion tillage (Figure 2-1). Nutrient availability may have differed between the systems based on manure application timing as well as differences in the rate of cover crop decomposition between no-till and tilled systems. Cover crop decomposition can be driven by temperature and moisture, with higher temperatures and greater rainfall resulting in quicker N release (Ranells and Wagger, 1996). Nutrients, and especially nitrogen, may have become available to the corn at a slower rate in the no-till system because the no-till terminated cover crop delayed decomposition and N mineralization (Drinkwater et al., 2000) compared to the tilled red clover in S3 which was incorporated into the soil with manure immediately before corn planting. Planting date differences may have also contributed to yield differences, as S3 was planted one- to two weeks earlier than S1 (Appendix B). System one was planted later than S3, as it was dependent upon hairy vetch growth stage for roller-crimper control. Optimum planting for corn in central Pennsylvania is usually mid-May, or 10-14 days before the last frost when soil temperatures reach at or above 10˚C early in the morning. It is common to see a yield loss of around 60 kg ha^{-1} day^{-1} with each day that planting is delayed past this period (Roth and Beegle, 2017).

While grain corn yields proved to be similar in the tilled (S2, S4) systems, challenges remain with the performance of no-till corn silage. Other research has shown that corn yields can be decreased by planting issues, weed competition, and availability of nitrogen (Mischler et al., 2010, Teasdale et al., 2012). It is possible to produce corn for silage in a rolled cover crop, no-till planted system, but these are several tradeoffs that remain to be addressed. Organic tillage-based corn for grain is commonly grown in the region, and interseeding a cover crop between V5 and V7 could provide a farming operation with more diversity in their rotation and the ability to seed a cover crop prior to grain harvest.

Enterprise budgets. Net returns varied across cropping systems from year to year, but were consistently higher in S3 and S4 where income was obtained from a clover forage harvest (Table 2-5). Lower yields in S1 silage from 2015 and 2016 was mirrored in the net returns, which were lower in 2016 compared to 2015. This shows that lack of weed control and insufficient nutrient availability can have great effects on farm profitability. Because of the consistently higher yield obtained in S3 corn silage and the addition of income from clover forage, net returns were approximately three times greater than in S1 (Table 2-5). When comparing corn grain systems, S4 net returns were approximately two and a half times that of S2 (Table 2-5). Although grain yields were similar between systems and in both years; the addition of clover forage income in S4 put profitability well above that of S2. Previous research has shown the benefit of the clover-corn system compared to hairy vetch, as the red clover is easier to manage than vetch while still providing ground cover and N sequestration (Snyder et al., 2016).

Conclusions. Organic cover crop-based, rotational no-till corn has several challenges that remain to be addressed. While a hairy vetch cover crop can produce over 6,000 kg ha^{-1} of biomass and smother early-season weeds, it is generally roll-crimped at early pod set (Mischler et al., 2010) which delays planting beyond the optimum time for central Pennsylvania. In addition, increased cover crop biomass can aid weed suppression, but can hinder corn establishment, especially during wet or dry springs (Mirsky et al., 2012). Adjustments to planting equipment should be considered so that the cash crop can be direct seeded into the rolled mulch with accurate seed placement and furrow closure. In this research, we employed aggressive zone residue managers that helped roll down the cover crop and slice through the residue. This helped achieve more ideal seed placement, but also tends to displace cover crop residue from the crop row, potentially allowing greater weed establishment. Weed control can be variable in the no-till system and high-residue cultivation is an option to control weeds between crop rows. Previous research showed that two passes with the high residue cultivator was necessary to successfully control weeds between the crop rows (Keene et al., 2016). In the tilled systems, in-season cultivation is critical for weed control, but efficacy is highly weather dependent and our research showed variable success across years. Although no advantage to weed control was observed in our research, interseeding into standing corn after last cultivation could benefit late season weed control, but more importantly it allows for corn grain production and cover crop establishment in shorter season environments. Finally, corn silage yield differences could be related to delayed planting in the no-till system, or availability of nutrients (Drinkwater et al., 2000). Future research should aim to address these agronomic challenges to enable more successful adoption of organic no-till corn. Organic farmers in the Mid-Atlantic should consider these challenges and make management decisions appropriate for their operation.

Literature Cited

Baributsa, D.N., E.F. Foster, K.D. Thelen, A.N. Kravchenko, D.R. Mutch and M. Ngouajio. 2008. Corn and cover crop response to corn density in an interseeding system. Agron. J. 100:981-987.

Berner, A., I. Hildermann, A. Fliebbach, L. Pfiffner, U. Niggli, and P. Mäder. 2008. Crop yield and soil fertility response to reduced tillage under organic management. Soil and Till. Res. 101:89-96.

Clark, A. (2007). Managing cover crops profitably (3rd ed.). Sustainable Agriculture Network. United Book Press, Inc.

Drinkwater, L.E., RR. Janke and L. Rossoni-Longnecker. 2000. Effects of tillage intensity on nitrogen dynamics and productivity in legume-based grain systems. Plant and Soil. 227:99-113.

Fisher, M. 2012. Many little hammers. Science. 337:4-10.

Gomiero, T., D. Pimentel and M.G. Paoletti. 2011. Environmental impact of different agricultural management practices: conventional vs. organic agriculture. Crit. Rev. in Plant Sci. 30:95-124.

Gruber, S. and W. Claupein. 2009. Effect of tillage intensity on weed infestation in organic farming. Soil and Till. Res. 105:104-111.

Hartwig, N.L. and H.A. Ammon. 2002. Cover crops and living mulches. Weed Sci. 50:688-699.

Hoffman, M.L., E.E. Regnier and J. Cardina. 1993. Weed and corn (*Zea mays* L.) responses to a hairy vetch (*Vicia villosa*) cover crop. Weed Technol. 7:594-599.

Huggins, D.R. and J.P. Reganold. 2008. No-till: the quiet revolution. Sci. Am. 299:70-77.

Keene, C.L. 2015. Agronomic performance of a reduced-tillage organic grain crop rotation during the transition to organic production. Dissertation. University Park, PA: The Pennsylvania State University. 176 p.

Keene, C.L. and W.S. Curran. 2016. Optimizing high-residue cultivation timing and frequency in reduced-tillage soybean and corn. Agron. J. 108:1987-1906.

Kornecki, T.S., A.J. Price and R.L. Raper. 2006. Performance of different roller designs in terminating rye cover crop and reducing vibration. Amer. Soc. of Agri. and Bio. Eng. 22:633-641.

Kristensen, H.L., G.W. McCarthy and J.J. Meisinger. 2000. Effects of soil structure disturbance on mineralization of organic soil nitrogen. Soil Sci. Soc. of Amer. J. 64:371-378.

Kuepper, G. 2001. Pursuing conservation tillage systems for organic crop production. ATTRA's Organic Matters Series. https://attra.ncat.org/attra-pub/download.php?id=107.

Laughlin, D. and S. Spurlock. 2008. Mississippi State Budget Generator v 6.0. Software User's Manual. Accessed November 7th, 2017 from http://www.agecon.msstate.edu/whatwedo/budgets/generator/index.asp.

Liebman, M. and E. Dyck. 1993. Crop rotation and intercropping strategies for weed management. Ecol. App. 3:92-122.

Liebman, M. and E.R. Gallandt. 1997. Many little hammers: ecological management of crop-weed interactions. In L. E. Jackson (Ed.), Ecology in Agriculture (pp.291-343). Academic Press: San Diego, California.

Liebman, M., C.L. Mohler and C.P. Staver. 2001. Ecological Management of Agricultural Weeds. Cambridge University Press: Cambridge, United Kingdom.

Liebman, M., R.L. Graef, D. Nettleton and C.A. Cambardella. 2012. Use of legume green manures as nitrogen sources for corn production. Renew. Agric. and Food Syst. 27:180-191.

Martens, K. and M.H. Martens. 2005. In-row cultivation. Rodale Institute. Accessed October 19, 2017. http://newfarm.rodaleinstitute.org/features/2005/0305/earlyweeds/index3.shtml.

Mirsky, S.B., M.R. Ryan, W.S. Curran, J.R. Teasdale, J. Maul, J.T. Spargo, J.Moyer, A.M. Grantham, D. Weber, T.R. Way and G.G. Camargo. 2012. Conservation tillage issues: cover crop-based organic rotational no-till grain production in the mid-Atlantic, USA. Renew. Agric. and Food Syst. 27:31-40.

Mischler, R.A., S.W. Duiker, W. S. Curran and D. Wilson. 2009. Hairy vetch management for no-till organic corn production. Agron. J. 102:355-362.

Moonen, A.C. and P. Barberi. 2004. Size and composition of the weed seedbank after 7 years of different cover-crop-maize management systems. Weed Res. 44:163-177.

Mutch, D.R., T.E. Martin and K.R. Kosola. 2003. Red clover (*Trifolium pratense*) suppression of Common ragweed (*Ambrosia artemisiifolia*) in winter wheat (*Triticum aestivum*). Weed Technol. 17:181-185.

[NOP] National Organic Program Handbook. 2005. Accessed September 2nd, 2017. https://www.ams.usda.gov/rules-regulations/organic/handbook.

Parr, M., J.M. Grossman, S.C. Reberg-Horton, C. Brinton and C. Crozier. 2011. Nitrogen delivery from legume cover crops in no-till organic corn production. Agron. J. 103: 1578-1590.

Peigné, J., B.C. Ball, J. Roger-Estrade and C. David. 2007. Is conservation tillage suitable for organic farming? A review. Soil Use Manag. 23:129-144.

Pimentel, D., P. Hepperly, J. Hanson, D. Douds and R. Seidel. 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. BioSci. 55:573-582.

Ranells, N.N. and M.G. Wagger. 1996. Nitrogen release from grass and legume cover crop monocultures and bicultures. Agron. J. 88:777-782.

Reberg-Horton, S.C., J.M. Grossman, T.S. Kornecki, A. D. Meijer, A.J. Price, G.T. Place and T.M. Webster. 2012. Utilizing cover crop mulches to reduce tillage in organic systems in the southeastern USA. Renew. Agric. and Food Syst. 27:41-48.

Roth, G.W. and D.B. Beegle. 2017. Corn. *In* The Agronomy Guide, 2017-2018 (AGRS-026), Penn State College of Agricultural Sciences, University Park, PA.

Singer, J.W., M.D. Casler and K.A. Kohler. 2005. Wheat effect on frost-seeded red clover cultivar establishment and yield. Agron. J. 98:265-269.

Smith, R.G., M.E. Barbercheck, D.A. Mortensen, J. Hyde and A.G. Hulting. 2011. Yield and net returns during the transition to organic feed grain production. Agron. J. 103: 51-59.

Smith, R.G. and D.A. Mortensen. (2017). A disturbance-based framework for understanding weed community assembly in agroecosystems: Challenges and opportunities for agroecological weed management. In A. Wezel (Ed.), Agroecological practices for sustainable agriculture: Principles, applications, and making the transition (pp. 127-154). London, UK: World Scientific Publishing Europe Ltd.

Snapp, S.S., S.M. Swinton, R. Labarta, D. Mutch, J.R. Black, R. Leep, J. Nyiraneza and K. O'Neil. 2005. Evaluating cover crops for benefits, costs, and performance within cropping system niches. Agron. J. 97:322-332.

Snyder, E.M., H.D. Karsten, W.S. Curran, G.M. Malcolm and J.A. Hyde. 2016. Green manure comparison between winter wheat and corn: weeds, yields, and economics. Agron. J. 108:2015-2025.

Stute, J. and K. Shelley. 2016. Frost seeding red clover in winter wheat. University of Wisconsin Extension Nutrient and Pest Management Program. Accessed September 4th, 2017. www.ipcm.wisc.edu.

Teasdale, J.R., C.B. Coffman and R.W. Mangum. 2007. Potential long-term benefits of no-tillage and organic cropping systems for grain production and soil improvement. Agron. J. 99:1297-1305.

Teasdale, J.R., S.B. Mirsky, J.T. Spargo, M.A. Cavigelli and J.E. Maul. 2012. Reduced-tillage organic corn production in a hairy vetch cover crop. Agron. J. 104: 621-628.

Unger, P.W. and T.C. Kaspar. 1994. Soil compaction and root growth: a review. Agron. J. 86:759-766.

Uri, N.D. 2000. Perceptions on the use of no-till farming in production agriculture in the United States: an analysis of survey results. Agric. Eco. And Env. 77: 263-266.

Uri, N.D., J.D. Atwood and J. Sanabria. 1999. The environmental benefits and costs of conservation tillage. Env. Geol. 38:111-125.

Wallace, J.M., C.L Keene, W.S. Curran, S.B. Mirsky. M.R. Ryan and M.J. VanGessel. 2017. Integrated weed management strategies in cover crop-based, organic rotational no-till corn and soybean in the mid-Atlantic region. *In print.*

Weiner, J., H.W. Griepentrog and L. Kristensen. 2001. Suppression of weeds by spring wheat *Triticum aestivum* increases with crop density and spatial uniformity. J. of App. Ecol. 38:784-790.

Table 2-1. 2014-2017 descriptive statistics for corn. Cropping system means plus or minus standard error are presented for fall and spring cover crop and weed biomass in kg ha^{-1}. Significance of cropping system (S), year (Y), and their interaction (SxY) are shown. Non-significant results (p>0.05) are designated by "NS". [1]

System (year)	**Fall cover crop**	**Fall weeds**	**Spring cover crop**	**Spring weeds**
2014-15		kg ha^{-1}		
S1	1765 ± 64	N/A	6678 ± 512	19 ± 10
S2	1384 ± 105	N/A	4866 ± 551	78 ± 44
S3	1946 ± 338	N/A	3748 ± 214	17 ± 13
S4	1925 ± 458	N/A	3842 ± 284	23 ± 16
2015-16				
S1	2142 ± 155	221 ± 108	7561 ± 750	2 ± 1
S2	2676 ± 495	169 ± 90	4955 ± 620	28 ± 21
S3	3151 ± 302	15 ± 5	4104 ± 372	7 ± 7
S4	3372 ± 557	205 ± 156	4559 ± 197	2 ± 1
2016-17				
S1	847 ± 149	37 ± 14	5528 ± 191	18 ± 14
S2	955 ± 197	32 ± 11	3642 ± 271	51 ± 15
S3	1640 ± 112	77 ± 6	4184 ± 253	38 ± 8
S4	783 ± 211	204 ± 27	3335 ± 636	65 ± 31
ANOVA		P value		
System (S)	0.045	NS	<0.0001	NS
Year (Y)	<0.0001	NS	0.0054	NS
S × Y	NS	NS	NS	NS

[1] S3 and S4 red clover-timothy biomass is based upon biomass at time of data collection in late fall. About four weeks prior, a clover haylage cutting was made in every year. Clover haylage plus fall cover crop biomass collected in S3 equaled 7617 kg ha^{-1} in 2014, 8493 kg ha^{-1} in 2015, and 10100 kg ha^{-1} in 2016. For S4 total biomass equaled 9872 kg ha^{-1} in 2014, 8365 kg ha^{-1} in 2015 and 5938 kg ha^{-1} in 2016.

Table 2-2. 2014-2017 descriptive statistics for corn. Cropping system means plus or minus standard error are presented for total late-summer weed biomass and late-summer weed biomass by location (kg ha^{-1}) along with the proportion late-summer weed biomass in-row. Significance of cropping system (S), year (Y), and their interaction (SxY) are shown. Non-significant results (p>0.05) are designated by "NS". Different letters next to cropping system means represent systems differences between in-row versus between row weed biomass or between cropping systems for total weed biomass and proportion data at p<0.05.

System (year)	**Total late-summer weeds**	**In-row weed biomass**	**Between-row weed biomass**	**Proportion in-row**
2014-15	-------------------	kg ha^{-1}	-------------------	
S1	725 a (± 278)	610 a (± 243)	114 a (± 45)	0.83 a (± 0.050)
S2	964 a (± 240)	700 a (± 75)	268 a (± 199)	0.79 a (± 0.10)
S3	826 a (± 112)	764 a (± 140)	62 a (± 29)	0.89 a (± 0.050)
S4	731 a (± 39)	676 a (± 57)	54 a (± 24)	0.91 a (± 0.030)
2015-16				
S1	1223 a (± 214)	1050 c (± 133)	173 bc (± 94)	0.88 a (± 0.050)
S2	2165 a (± 354)	1657 a (± 370)	508 b (± 87)	0.74 a (± 0.060)
S3	2753 a (± 589)	2324 ab (± 509)	429 b (± 156)	0.85 a (± 0.050)
S4	1370 a (± 415)	1181 a (± 364)	169 b (± 72)	0.85 a (± 0.040)
2016-17				
S1	2720 a (± 401)	2490 a (± 367)	230 b (± 143)	0.91 a (± 0.040)
S2	339 b (± 14)	326 ab (± 25)	13 c (± 12)	0.95 a (± 0.040)
S3	712 b (± 395)	702 ab (± 386)	9 c (± 8)	0.98 a (± 0.002)
S4	544 b (± 168)	534 ab (± 164)	10 c (± 9)	0.98 a (± 0.010)
	-------------------	P value	-------------------	
ANOVA				
System (S)	NS	NS		NS
Year (Y)	<0.0001	0.0013		0.0007
SxY	<0.0001	NS		NS
		2015		
System (S)		NS		
Location (L)		NS		
SxL		NS		
		2016		
System (S)		<0.0001		
Location (L)		0.005		
SxL		0.0004		
		2017		
System (S)		<0.0001		
Location (L)		<0.0001		
SxL		<0.0001		

Table 2-3. Monthly total precipitation (mm) for April-October, 2015-2017. Taken from NRCS Rock Springs, PA Weather Station data.

Month	2015	2016	2017
April	90.68	43.94	114.81
May	34.80	87.12	176.78
June	166.37	78.99	101.85
July	158.24	85.09	195.83
August	50.80	111.25	107.44
September	74.68	82.80	41.66
October	107.19	78.49	176.78
Total	682.75	567.69	915.16

Table 2-4. 2014-2017 descriptive statistics for corn. Cropping system means plus or minus standard error are presented for corn population as a proportion of the total planted and corn silage/grain yield in kg ha^{-1}. Significance of cropping system (S), year (Y), and their interaction (SxY) are shown. Non-significant results ($p>0.05$) are designated by "NS". Different letters next to cropping system means represent systems differences at $p<0.05$ for corn populations, or between silage or grain system mean comparisons.

System (year)	**Corn population proportion**	**Silage yield**	**Grain yield**
2015			
S1	0.88 a (± 0.020)	24815 b (± 3317)	-
S2	0.85 a (± 0.010)	-	9051 a (± 403)
S3	0.83 a (± 0.040)	38489 a (± 1053)	-
S4	0.82 a (± 0.010)	-	9223 a (± 3317)
2016			
S1	0.74 a (± 0.060)	20758 b (± 1143)	-
S2	0.72 a (± 0.030)	-	8122 a (± 549)
S3	0.69 a (± 0.090)	34903 a (± 2107)	-
S4	0.61 a (± 0.060)	-	8791 a (± 194)
2017			
S1	0.83 a (± 0.030)	37760 a (± 829)	-
S2	0.80 a (± 0.010)	-	10031 a (± 221
S3	0.65 a (± 0.030)	33682 b (± 1299)	-
S4	0.80 a (± 0.030)	-	10296 a (± 773)
ANOVA	---------------- P value -------------		
System (S)	NS	<0.0001	NS
Year (Y)	<0.0001	0.040	0.0036
SxY	NS	NS	NS

Table 2-5. Partial budget analysis for corn in dollars ($) per hectare for each cropping system (S1-S4) in 2015-2017. Costs shown include manure, cover crop and corn seed cost, labor costs, fuel, and repairs/maintenance for hairy vetch/triticale (S1, S3) versus red clover/timothy cover crop (S2, S4). Fixed costs include implements and tractors. Income from corn grain/silage yield is shown in total dollars per hectare based on market price of \$10 bu^{-1} or \$90 ton^{-1}, respectively, and for \$250 ton^{-1} for clover forage yield where applicable. Costs of production estimates are based on the previous year's input prices.

Item	**S1**	**S2**	**S3**	**S4**
2015				
Income				
Grain/Silage	2878.20	2986.44	3874.50	3043.02
Clover forage	0.00	0.00	1555.95	1801.95
Variable costs				
Lime	44.28	44.28	44.28	44.28
Liquid manure	649.44	649.44	649.44	649.44
Cover crop seed	168.26	168.26	81.92	81.92
Corn seed	211.56	211.56	211.56	211.56
Labor	149.91	167.50	147.80	147.80
Fuel	125.09	155.29	136.31	136.31
Repairs & maintenance	84.89	129.96	116.75	116.75
Interest on capital	10.79	10.01	0.74	0.30
Total variable costs	1444.24	1536.31	1388.79	1388.35
Fixed costs	164.82	249.91	222.33	222.33
Total cost	1609.06	1786.23	1611.13	1610.69
Net returns	1269.13	1200.20	3819.32	3233.40
2016				
Income				
Grain/Silage	2045.16	3173.40	3447.19	3419.40
Clover forage	0.00	0.00	1906.50	1783.50
Variable costs				
Lime	0.00	0.00	0.00	0.00

Item	S1	S2	S3	S4
Liquid manure	649.44	649.44	649.44	649.44
Cover crop seed	168.26	168.26	81.92	81.92
Corn seed	211.56	211.56	211.56	211.56
Labor	100.34	159.09	143.30	143.30
Fuel	100.42	164.45	145.53	145.53
Repairs & maintenance	81.48	126.25	113.78	113.78
Interest on capital	9.91	9.54	0.81	0.32
Total variable costs	1321.41	1488.60	1346.33	1345.84
Fixed costs	153.21	242.33	216.16	216.16
Total cost	1474.62	1730.93	1562.49	1562.00
Net returns	562.26	1442.47	3791.20	3640.90
2017				
Income				
Grain/Silage	2694.31	3525.35	2403.29	3618.34
Clover forage	0.00	0.00	1107.00	848.70
Variable costs				
Lime	0.00	0.00	0.00	0.00
Liquid manure	649.44	649.44	649.44	649.44
Cover crop seed	168.26	168.26	81.92	81.92
Corn seed	211.56	211.56	211.56	211.56
Labor	143.46	254.16	226.59	222.75
Fuel	81.67	149.17	134.85	132.71
Repairs & maintenance	96.38	140.56	132.61	132.79
Interest on capital	10.13	2.87	0.41	0.19
Total variable costs	1360.92	1576.04	1437.40	1431.37
Fixed costs	189.54	290.84	267.05	261.57
Total cost	1550.46	1866.88	1704.46	1692.94
Net returns	1143.85	1658.47	1805.83	2774.10

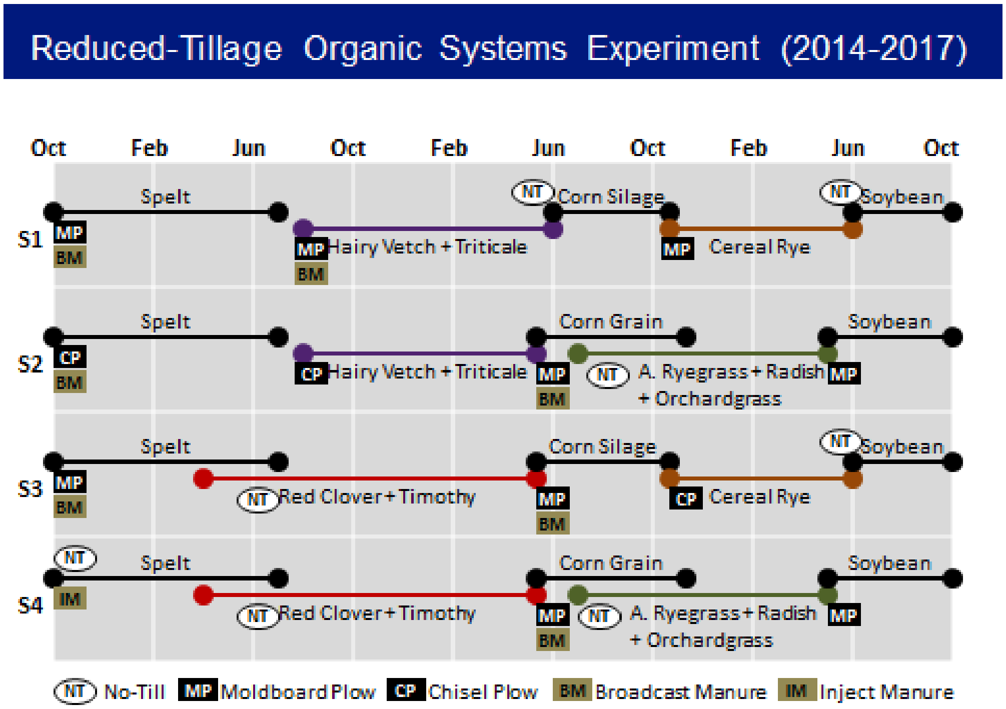

Figure 2-1. Comparison of four reduced-tillage cropping systems evaluated at Penn State's Russell E. Larsen Agricultural Research Center (RELARC) (2014 – 2017).

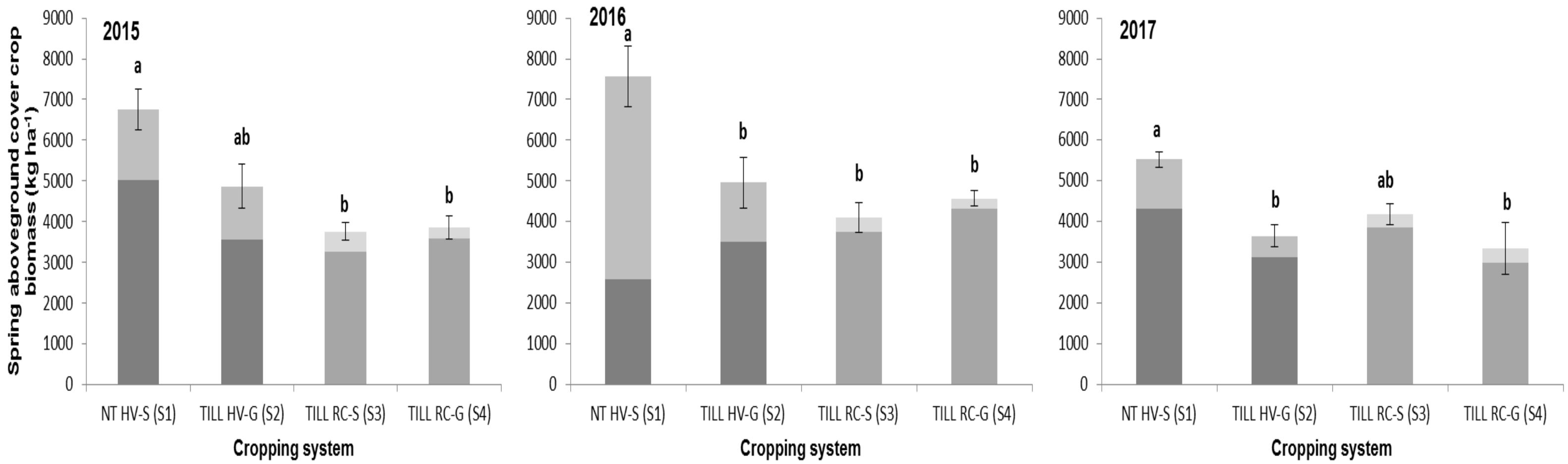

Figure 2-2. Effect of cropping system on total aboveground spring cover crop biomass (kg ha^{-1}) prior to termination in the spring of 2015-2017. Cropping systems differ by tillage regime (no-till (NT); till) and cover crop species and establishment method (HV = hairy vetch established after spelt harvest; RC = red clover frost seeded into spelt). Stacked bars indicate total cropping system biomass by cover crop species. Bottom, darker bars= HV or RC; top, lighter bars= triticale (TR) above HV or timothy (TM) above RC. Cropping system*year effect: $F_{6,33} = 1.21$; p= 0.32. 2015 cropping system effect: $F_{3,9} = 10.0$; p= 0.0032. 2016 cropping system effect: $F_{3,9} = 8.90$; p= 0.0047. 2017 cropping system effect: $F_{3,9} = 7.76$; p= 0.0072. Different letters above bars indicate system differences at $p<0.05$.

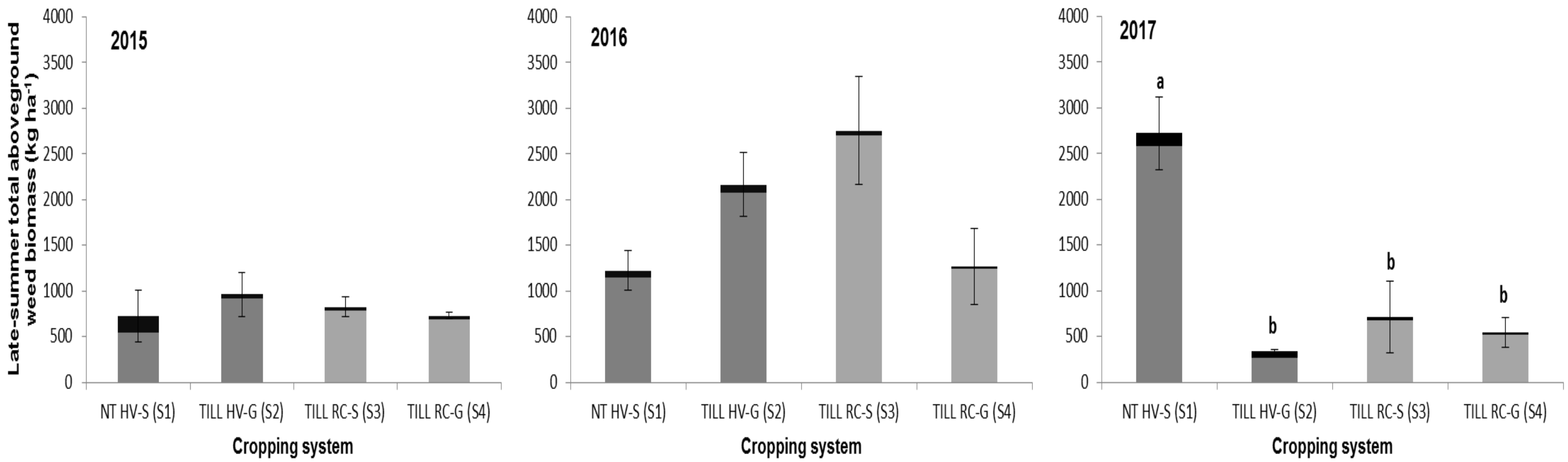

Figure 2-3. Effect of cropping system on total aboveground late-summer weed biomass (kg ha^{-1}) in summer 2015-2017. Cropping systems differ by tillage regime (no-till (NT); till) and cover crop species and establishment method (HV = hairy vetch established after spelt harvest; RC = red clover frost seeded into spelt). Stacked bars indicate total cropping system biomass by annual species (bottom; gray bars) and perennial species (top; black bars). Cropping system*year effect: $F_{6,33} = 7.44$; p= <0.0001. 2015 cropping system effect: $F_{3,9} = 0.66$; p= 0.59. 2016 cropping system effect: $F_{3,9} = 3.49$; p= 0.063. 2017 cropping system effect: $F_{3,9} = 10.2$; p= 0.003. Different letters above bars indicate system differences at p<0.05.

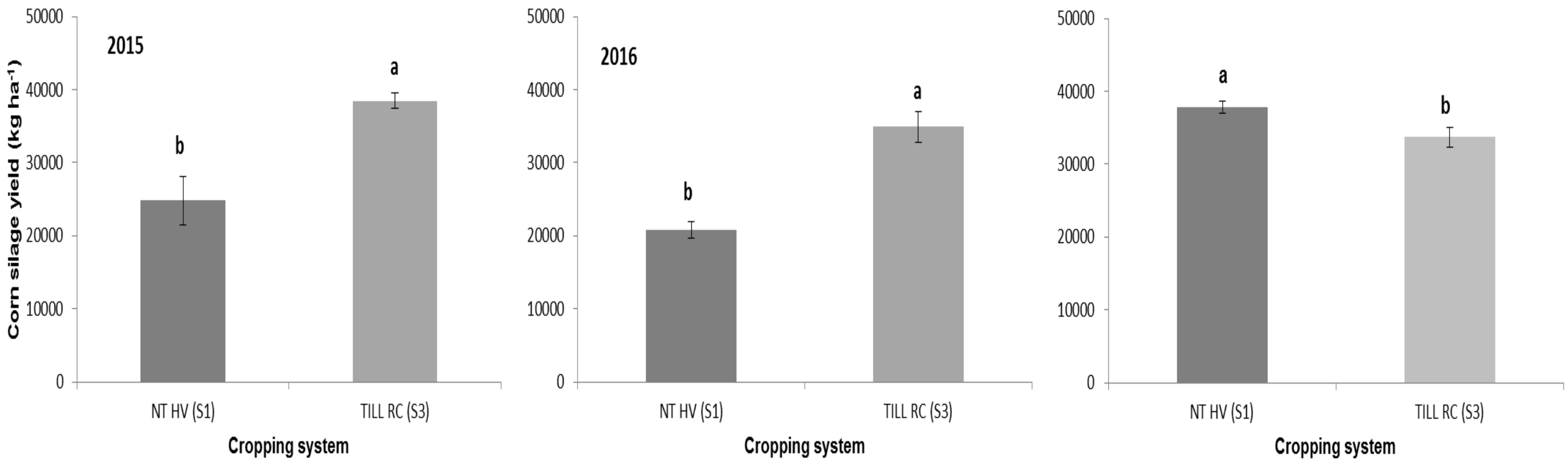

Figure 2-4. Effect of cropping system on corn silage yield (kg ha^{-1}) in 2015 and 2016. Cropping systems differ by tillage regime (no-till (NT); till) and cover crop species and establishment method (HV = hairy vetch established after spelt harvest; RC = red clover frost seeded into spelt). 2015 cropping system effect: $F_{1,3}$ = 26.58; p= 0.014. 2016 cropping system effect: $F_{1,3}$ = 34.28; p= 0.0099. 2017 cropping system effect: $F_{1,3}$ = 24.19; p= 0.016. Different letters above bars indicate system differences at p<0.05.

Chapter 3

Poor In-Season Weed Control Drives Weed Seedbank Abundance in Organic Cover Crop-based Rotational No-till Systems

Abstract

Reducing tillage is a common goal of many organic farmers who would like to reduce fuel and labor needs while also building soil quality and decreasing erosion. However tillage remains critical, especially for weed control and nutrient incorporation. We conducted a multi-year grain/silage cropping systems experiment to analyze a suite of reduced-tillage practices which organic farmers in the mid-Atlantic could incorporate into their operations to help reduce both the frequency and intensity of tillage. This research built off the existing principles behind organic cover crop-based, rotational no-till, which utilizes roll-crimped cover crops ahead of no-till cash crop planting. One of the factors examined during this research was the seed density of the weed seedbank, measured to the depth of the plow layer each March preceding the cash crop growing season. Poor in-season weed control greatly drives the density of the weed seedbank, with seeds m^{-2} increasing after a droughty 2016 which hindered in-season cultivation efforts. Foxtail species (*Setaria spp.*) dominated the seedbank in all three cash crops (corn, soybean, spelt), and other prevalent species included purslane speedwell (*Veronica peregrina* L.), yellow woodsorrel (*Oxalis stricta* L.), Eastern black nightshade (*Solanum ptychanthum Dunal*), common lambsquarters (*Chenopodium album* L.), and pigweed species

(*Amaranthus spp.*), among others. Seedbank trends showed that seed density increased after the corn and soybean phases, but decreased after the spelt phase. Reduced tillage corn and soybean systems tended to have lower seed density relative to tilled systems, but this was dependent on successful in-season weed control. Our results also show that interseeding a cover crop in corn can help reduce returns to the seedbank, with seed density being lower than corn systems which did not employ interseeding.

Introduction

Consumer demand for organic dairy and meat products continues to increase, but there are many agronomic challenges to producing organic grain and feed. Farmers are interested in transitioning to organic production, but organic production requires more tillage operations to control weeds and incorporate manures and residues in comparison to conventional, no-till production. Organic cover crop-based rotational no-till systems can reduce the need for tillage at points in the crop rotation, as these systems rely on roll-crimped cover crops for within-season weed suppression in no-till planted corn and soybean (Wallace et al., 2017). Tillage is used in the fall to incorporate residues and manures, and to prepare a seedbed for cover crop seeding. The following spring, the cover crop is roll-crimped to form a mulch, which competes against germinating weeds. While this system does eliminate the need for spring tillage, there can be challenges related to planting into the mulch, volunteer cover crops, and insufficient nutrient availability from cover crop breakdown (Keene 2015, Wallace et al., 2017).

Keene (2015) showed the need for the integration of alternative strategies into organic, cover crop-based rotational no-till annual grain production. High amounts of cover crop biomass are important for weed suppression. However, high biomass on the surface can pose a problem for successful crop establishment with no-till planters. Cash crop populations can be decreased due to difficulties slicing through residue and achieving adequate seed placement and furrow closure (Keene 2015, Mirsky et al., 2012, Ryan et al., 2011). Roll-crimping cover crops at the incorrect growth stage can challenge the success of these systems as well, resulting in subsequent weedy or “volunteer” cover crops that compete with the growing cash crop (Keene 2015, Wallace et al., 2017). Additionally, nitrogen availability from the breakdown of the rolled cover crops can be of concern in no-till corn production, as nitrogen may not be readily available for uptake by corn during periods of high nitrogen demand. These findings suggest the need for other strategies in organic rotational no-till to address the constraints to adoption.

Cover cropping strategies that help diversify the crop rotation, while also reducing the frequency and intensity of tillage in organic annual grain production, may aid in addressing the constraints to cover crop-based rotational no-till production. In the Mid-Atlantic, organic cover crop-based no-till soybean production requires corn silage production in the previous year because of the need to optimize cereal rye establishment before winter. Interseeding a cover crop after last in-season cultivation when corn is at V5-V7 can enable grain production, though cover crop establishment rates may vary using this approach (Dillon et al., 2012). Interseeding cover crops also helps eliminate fall tillage, which is usually carried out when seeding a fall cover crop. Frost-seeding cover crops is another alternative practice that can help reduce tillage intensity and frequency in organic cover crop-based rotational no-till. By drilling a cover crop into a standing winter grain such as spelt or wheat in late-winter, tillage after small grain harvest is eliminated and ground cover is maintained until corn planting the next year (Snyder et al., 2016, Stute and Shelley, 2016). These alternative practices can be integrated into a rotational no-till system to help reduce the intensity and frequency of tillage events while also eliminating the need for fall tillage.

No-till establishment of cover crops, including interseeding or frost-seeding practices, not only diversifies annual grain rotations, but also helps reduce the intensity and frequency of tillage. Understanding how alternative reduced-tillage strategies, including cover crop management and associated tillage intensity and timing, affect weed seedbank trajectories is critical for determining the viability of cover crop-based, reduced-tillage organic production practices for annual grain crops. Organic rotational cover crop-based no-till corn and soybean systems must rely on the cover crop mulch and subsequent use of a high-residue cultivator for weed suppression. Tilled systems rely on primary tillage before cash crop planting, as well as use of multiple cultivation passes in-season, including blind cultivation and inter-row cultivation. However, mechanical operations are heavily dependent on weather and soil conditions, making complete reliance on these tactics undesirable. Integrated weed management tactics are needed for reducing tillage in organic row crop production to lessen this reliance on mechanical operations.

An understanding of weed seedbank dynamics is critical to the design of integrated weed management practices in reduced-tillage organic production systems. In agroecosystems, weeds adapt to environments that promote disturbance and increased availability of resources (Smith and Mortensen, 2017). Because of this, weed control during the cash crop growing season remains one of the most critical challenges in agriculture, as weeds can cause crop yield losses. Different agricultural management decisions influence the assembly of local weed communities, including crop rotation, crop type, cover crop management, and the frequency and intensity of tillage operations (Booth and Swanton, 2002, Menalled et al., 2001).

In organic systems, weed communities tend to shift towards greater species diversity and increased seed density, with a majority of the seedbank dominated by annual species that have germination periods that extend over the growing season due to frequent disturbances (Ryan et al., 2010). Crop rotation is a powerful tool for organic weed management because different crop sequences within and between years can potentially create an unfavorable environment for weeds (Liebman and Dyck, 1993, Murphy et al., 2006, Teasdale et al., 2004). Greater crop diversity and the addition of forage or pasture crops in a rotation has shown to interrupt weed lifecycles and reduce weed seed production over time compared to monocultures (Kegode et al., 1999, Teasdale et al., 2004). A diverse crop rotation also requires different management practices that change from crop to crop, resulting in differing weed management strategies that can change the trajectory of weed seedbanks (Cardina et al., 2002). When different management tactics are combined, weed species population densities are reduced by decreasing the amount of viable weed seeds returned to the soil seedbank, and crop rotation combined with other strategies such as reducing tillage and cover cropping can help increase the decay of weed seeds in the soil (Anderson 2015, Ball 1992, Shrestha et al., 2002).

The addition of cover crops in a rotation can help influence weed seedbanks. Actively growing and dead cover crop mulches influence weed life cycles through both suppression and modifications to germination cues by actively growing plant competition and through physical interference by mulches (Mirsky et al., 2013, Moonen and Barberi, 2004). Cover crop establishment can also aid in seedbank reductions, as tillage is often used when seeding a cover crop in the fall or when terminating it in the spring. Any weeds that are present at these times usually have not reached maturity, so few weed seeds are returned to the seedbank (Gallandt 2006).

Different tillage practices distribute weed seeds throughout the soil profile, causing shifts to the germinable weed seedbank (Buhler at al., 1997, Cardina et al., 2002). Primary tillage can turn up seeds from the plow layer that were lying dormant and initiate germination cues such as changes in light quality, an increases in temperature and oxygen (Gallandt 2006). However minimal disturbance systems such as no-till can also promote weed seed germination, as annual seed rain causes weed seeds to gather near the surface of the soil, making germination conditions optimal (Barberi and Cascio, 2000, Cardina et al., 2002).

Our objective in this paper is to evaluate the effects of organic cropping systems that employ various reduced-tillage practices on weed seedbank dynamics in a corn – soybean - spelt annual grain rotation. In addition, we identify dominant weed species and life-history traits observed in each cash crop across different reduced-tillage systems. We hypothesize that: (1) the cropping system employing no-till corn and soybean production will exhibit the lowest weed seed density compared to tilled summer annual cropping systems due to comparatively greater weed-suppression using rolled cover crops, (2) weed seed density will decrease after the spelt phase in each system due to relative lack of soil disturbance and persistent ground cover in-season, and (3) annual species will comprise a majority of the seedbank as these species are better adapted to tillage- based systems.

Materials and Methods

Site description. An organic cover crop-based, rotational no-till cropping systems experiment evaluating multiple reduced-tillage strategies was conducted on certified organic land in Rock Springs, Pennsylvania (40˚43´N, 77˚56´W) at the Pennsylvania State University Russell E. Larson Agricultural Research Center (RELARC) from 2014 to 2017. The experiment was conducted on Hagerstown silt loam soil (fine, mixed, semiactive, mesic Typic Hapludalfs), as well as some Opequon-Hagerstown soils (clayey, mixed, active, mesic Lithic Hapludalfs). The RELARC is in USDA Plant Hardiness Zone 6b and has an average annual high temperature of 25°C and an average annual low temperature of 5.1˚C. Rainfall averages 1,006 mm annually, with annual snowfall reaching 1,140mm.

Experimental design. We implemented a three year rotation of corn (*Zea mays* L.)-soybean (*Glycine max* L. Merr)-spelt (*Triticum spelta* L.) in a full entry design with cover crops preceding corn and soybean cash crops (Figure 3-1). We used a randomized complete block, split-plot design with four replications. Each replication consisted of the three cash crop rotation entry points as main plots, with four cropping system treatments as the split-plot within main plots for each cash crop. Cover crop species, their planting date and termination method, manure management, and tillage intensity and frequency varied between cropping systems (Figure 3-1). Split-plots measured 9 m wide by 49 m long, with grass alleyways separating main plots. Prior to experiment initiation, organic rotational, no-till practices were examined using a three year rotation of corn-soybean-wheat with cover crops roll-crimped before no-till planting of corn and soybean. This project was managed organically from 2011, and organic certification was received in 2014 at project completion. Data collection to study alternative strategies in the corn-soybean-spelt project began fall 2014 after cover crop planting.

Crop rotation. In this paper we examine cropping system level effects on weed seedbank dynamics. Each system is described below, starting with manure application and spelt planting. Cropping systems and rotations are also described visually in Figure 3-1. In system one (S1), manure was broadcast at 74,831 L ha^{-1} and incorporated via moldboard plow before spelt planting. Following spelt harvest, manure was applied and incorporated as described above. A cover crop mixture containing hairy vetch (*Vicia villosa Roth*) ‘Groff’ and triticale (*Triticosecale*) ‘815’ was planted at a rate of 34 kg ha^{-1} per species. The cover crop mixture was terminated by a roller-crimper at full flowering of hairy vetch, allowing for no-till planting of corn grown for silage. Corn ‘MC4050’ was planted at 81,510 plt ha^{-1}. Following silage harvest in the fall, a seedbed was prepared through use of primary and secondary tillage. Cereal rye (*Secale cereal* L.) ‘Aroostook’ was sown at 134 kg ha^{-1} and terminated with the roller-crimper the following spring at full anthesis. Soybean ‘Growmark HS21C40’ was no-till planted into the rolled mulch at 555,750 plt ha^{-1}. In-season weed management in both the no-till corn and soybean phase was achieved with a high-residue cultivator at four and six weeks after planting (WAP). The high-residue cultivator has single 50-cm sweeps that run between cash crops rows at a shallow depth (5 cm), severing roots of established weeds.

System two (S2) replicated S1 management in the spelt phase and cover crop seeding after spelt harvest. However, after spelt harvest no manure was applied at hairy vetch and triticale planting. Manure was instead applied in the spring and incorporated with the cover crop mixture with a moldboard plow 7-10 days before corn planting. Corn was planted for grain at the same seeding rate using the same variety as above. To allow for grain production, while also establishing a cover crop before winter, a mixture of annual ryegrass (*Lolium perenne* L. *ssp. multiflorum*) 'KB Supreme, orchardgrass (*Dactylis glomerata* L.) 'Potomac', and forage radish (*Raphanus sativus* L.) 'Tillage' was interseeded into the standing corn at V5-V7 after last cultivation. The cover crop was drilled at 11, 11, and 3.4 kg ha^{-1}, respectively. The following spring, the interseeded cover crop was terminated with a moldboard plow, and soybean was planted using the same variety as S1 at 444,600 plt ha^{-1}. Blind cultivation and inter-row cultivation were used as in-season weed management tactics.

System three (S3) established spelt in the same manner as described above. In early March, a Great Plains Drill was used to frost-seed a cover crop of red clover (*Trifolium pratense* L.) 'VNS' and timothy (*Phleum pratense* L.) 'King's' into the established spelt at 12 and 4.5 kg ha^{-1}, respectively. After spelt harvest, the frost-seeded cover crop was managed adaptively by either mowing in late summer for weed control or by harvesting for forage in early fall if biomass production was sufficient. The following spring, manure was broadcast over the cover crop at the rate described in S1, and both were incorporated by primary tillage. Corn was planted for silage following the same protocol as S1 and weeds were managed with blind and inter-row cultivation. After silage harvest, a seedbed was prepared using primary and secondary tillage and cereal rye was sown at the same seeding rate as S1. Cereal rye was roll-crimped the next spring to enable no-till planting of soybean, following the same protocol as S1. In-season weed management in no-till soybean include use of a high-residue cultivator described in S1.

System four (S4) was the least tillage-intensive. Before spelt planting, manure was injected on 37-cm bands using a high-residue, shallow manure injector at the same rate as the broadcast method to enable no-till drilling of spelt. As in S3, red clover and timothy were frost-seeded into the spelt in late winter. The following spring, manure was broadcast and incorporated with the cover crop with a moldboard plow. Corn grain, interseeding, and soybean planting followed the guidelines outlined for S2. In-season weed management for corn and soybean was achieved following the same protocols described in S2.

Data collection. Soil cores were taken from all split-plots in mid- to late-March each spring. Twelve cores measuring 5-cm wide by 20-cm deep were taken randomly throughout the plot and composited into one sample in a paper bag. The bags were placed on greenhouse benches and allowed to thoroughly air dry for several days before being sieved. Sieving broke up soil aggregates, and exposed seeds to light and mechanical scarification. After sieving, 4,000 cm^3 of soil was spread over a thin layer of 500 cm^3 vermiculite in a black, plastic flat. The flats were randomly placed on one of two greenhouse benches. An automatic watering system (Rainbird) was set to water the flats three times a day, for two to three minutes each time. Temperature and light within the greenhouse were regulated by greenhouse fans and automatic shade cloths. After 30 days, flats were removed from the greenhouse and weed seedlings were identified by species, counted, and removed. The soil was once again sieved, returned to the flats, and the process was repeated two more times for a total of three rounds of germination identification and counting.

Statistical analysis. All analyses were run using R.3.2.4. Rank abundance was examined at the species level for each cash crop, as well as within each cropping system for each cash crop. We also examined rank abundance for the three cash crops by weed life history traits, which were categorized as: 1) annual monocot, 2) annual dicot, 3) perennial, 4) biennial, 5) volunteer cover crop. Seedbank density trajectories (seeds m^{-2} to the plow layer) were examined graphically by year in each cropping system as well as across systems by cash crop entry point using the GGPLOT function. Descriptive data is presented in tables and figures by volume scaled to seeds m^{-2} to the plow layer.

Results and Discussion

Crop rotation effects on weed seedbanks. Seedbank density (seeds m^{-2} to the plow layer) was analyzed for each system (S1-S4) across the cash crop rotation by entry point, labeled CBS (corn-bean-spelt), BSC (bean-spelt-corn), and SCB (spelt-corn-bean). In S1, seed density increased after the corn and soybean phases, but decreased after spelt (Figure 3-2). The corn and soybean phases of this system both utilized rolled cover crops and no-till cash crop planting, with high-residue cultivation for additional in-season weed control. While this was effective for inter-row weed control, a majority of weeds germinated, set seed in-row (Table 1-2, Table 2-2), and were incorporated into the soil after cash crop harvest. The same trend was observed in S2, with seedbank increases seen after corn and soybean planting and a seedbank decrease observed after the spelt phase. A larger seedbank increase was observed in 2017 in S2 after the soybean phase relative to S1, corresponding with observed trends in weed biomass production in the 2016 cash crop (Table 1-2), which we attribute to poor cultivation performance due to environmental conditions (Figure 3-2, Appendix C). While the same trend was also seen in S3, there was a sharper decrease in the seedbank after the spelt phase. The same overall trend was observed in S4 (Figure 3-2). This system had the lowest frequency of tillage relative to the other three systems, utilizing injected manure in order to no-till plant spelt. Frost-seeding occurred in the spelt phase, which would have provided continuous soil cover and a lack of soil disturbance. Reductions in seedbank abundance following spelt are consistent across cropping systems despite S4 no-till planting spelt.

Cash- and cover-crop effects on weed seedbanks. Weed seedbank sampling occurred each March to measure the cumulative effects of the different reduced-tillage strategies and corresponding within-season weed management in the previous cash crop. Cropping systems varied by cover crop species, cover crop planting and termination timing, tillage timing and intensity, as well as in-season weed management. Each panel of Figure 3-3 represents the cumulative effect of these practices for each cash crop across the four cropping systems, labeled by the legacy of the cash crop a panel represents. In general, weed seedbank density increased across cash crops from 2015-2017, which we attribute to poor weed control in 2016 that led to high levels of late-summer weed biomass and weed seed rain. The legacy of the corn to soybean transition, measured in spring 2016, indicated that no-till corn production followed by full inversion-tillage and cereal rye planting reduced weed seedbank density prior to the soybean phase compared to other reduced-tillage management strategies (Figure 3-3a). However, this trend was not observed in the corn to soybean transition measured in spring 2017 (Figure 3-3f). This could have resulted from the increased seedbank from poor weed control during 2016.

The legacy of the soybean to spelt transition, measured in spring 2016, indicated that no-till soybean production (S1, S3) lowered weed seedbank densities compared to full-tillage soybean production followed by till- (S2) or no-till spelt (S4), which illustrates the viability of rolled cover crops for weed suppression (Figure 3-3b). This trend was only consistent for S1 no-till planted soybean to spelt transition measured in 2017 (Figure 3-3d), which corresponds to the lower amount of late-summer weed biomass observed in S1 soybean in 2016 (Table 1-2). We suggest that weed biomass may have been higher in S3 compared to S1 because of the nutrient legacy from the previous year's corn crop and the use of less intensive tillage at cereal rye seeding, which would not have buried seeds as deep into the soil (Figure 3-1).

The spelt to corn legacy in 2016 was not as variable across cropping systems, but seed density was highest in S1 (Figure 3-3c). Seed density was likely lower in the S3 and S4 spelt cropping systems due to frost seeding a cover crop which helped provide continuous soil cover after spelt harvest and competition against germinating weeds which helped reduce seed rain (Figure 3-1). In 2017, the seedbank density from the spelt to corn transition was below 10,000 seeds m^{-2} and consistent among the four cropping systems, suggesting that frost-seeded versus non-frost seeded systems will result in similar seedbank returns (Figure 3-3e). Additionally, the potential for extra farm income from a clover haylage harvest combined with the soil benefits outweighs not employing this practice.

The legacy of soybean to spelt in 2016-2017 showed variability across systems, with S1 exhibiting the lowest seed density (Figure 3-3). This system had the lowest amount of late-summer weed biomass in 2016, which we suggest led to lower seedbank returns compared to the other three systems. Seed density was low and did not vary appreciably across spelt systems before corn in 2016-2017 (Figure 3-3). The legacy of corn to soybean from 2016-2017 showed that interseeding a cover crop in S2 and S4 helped decrease seed density compared to S1 and S3 which did not interseed, which may have been caused by cultivation before interseeding which uprooted germinated weeds before they set seed (Figure 3-3). This shows that interseeding can help decrease returns to the weed seedbank while also diversifying a crop rotation and eliminating the need for fall tillage while allowing for corn grain production.

Spelt to corn weed community. The weed seedbank transitioning to corn systems across the three years was comprised mostly of annual dicots and monocots, which represented 85-95% of the seedbank across cropping systems, respectively (Table 3-1). Annual dicots or monocots represented 45-57% of the total seedbank depending on system, with a combined 85-95% accumulated frequency of the weed seedbank. Perennial and biennial species comprised 5-14% and 0.1%, respectively, of the total seedbank and were likely controlled by tillage events throughout the course of the entire crop rotation (Table 3-1). Volunteer species monitored in seedbank growouts included annual ryegrass, orchardgrass, red clover, cereal rye, and hairy vetch. These species were included because of the potential for them to become weedy in subsequent cash crops upon incomplete termination. The proportion of potential volunteer cover crop seed in corn only reached 0.1-0.3% across cropping systems, and contributed very little to the seedbank (Table 3-1).

Rank abundance of the top five species in each of the systems was analyzed. Foxtail species (SETSPP) were the most abundant species in all four systems, ranging from 29-45% of the total seedbank (Table 3-2). Foxtail species are prolific seed producers, and likely set seed before harvest in the previous crop. Foxtail species can shift emergence patterns to be before the time of roller-crimping, making them well adapted to rotational no-till systems (Teasdale and Mirsky, 2015, Wallace et al., 2017) Other species included purslane speedwell (VERPG), yellow woodsorrel (OXAST), Eastern black nightshade (SOLPT), horseweed (CONCA), common lambsquarters (CHEAL), redroot pigweed (AMACH), and Pennsylvania smartweed (POLPY). The top five species made up 74.1-82.5% of the total observed seedlings (Table 3-2).

Corn to soybean weed community. The corn to soybean weed seedbank across the three years was also comprised mostly of annual monocots or dicots. Accumulated frequency varied across cropping systems, but annual species comprised 87-94% of the total weed seedbank (Table 3-1). Perennial species and volunteers comprised 5-12% and 0.1-0.2%, respectively, of the total seedbank and, as with the corn systems, were likely controlled by tillage which occurred at different points in the rotation (Table 3-1). No biennial species were observed in soybean.

Foxtail species were also the most frequent species in all systems, which demonstrates the ability of this weed species to persist in reduced-tillage organic annual crop production systems. The proportion of foxtail species ranged from 36-69% (Table 3-

3). Other species observed in soybean systems included yellow woodsorrel, purslane speedwell, redroot pigweed, horseweed, and Eastern black nightshade. The top five species comprising 76.6-86.1% of the total observed seedlings (Table 3-3).

Soybean to spelt weed community. Annual monocots represented 48-69% of the seedbank across cropping systems in the soybean to spelt phase of the rotation, and combined with annual dicots, annual species represented 90-95% of the total spelt weed seedbank (Table 3-1). Perennial species made up 3-9% of the seedbank, with volunteers and biennial species representing an even smaller proportion of the total seedbank at 0.1-0.2% and 0.1%, respectively (Table 3-1).

Many of the top five species observed before the corn and soybean systems were also observed in the transition to the spelt phase of the rotation. Again, foxtail species ranked first in all four systems, with abundance ranging from 46-64% of the total weed seedbank (Table 3-4). Other species in the top five observed included yellow woodsorrel, redroot pigweed, purslane speedwell, common lambsquarters, and Pennsylvania smartweed. The top five species in spelt comprised 76.9-82.7% of the observed species (Table 3-4).

Conclusions. Our results clearly indicate the implications that poor in-season weed control can have on weed seedbanks. Weeds that escape within-season weed control can result in high-levels of seed rain, which becomes incorporated into the plow layer following a tillage event (Ball 1992). Seed density increased from 2015 to 2017 because of the drought conditions in 2016, which led to poor in-season weed control with cultivation tools. The integration of winter grains continues to be a critical strategy for decreasing weed seedbank density, as this component of the rotation provides temporal diversity and lack of soil disturbance (Liebman and Dyck, 1993). Organic cover crop-based rotational no-till research in the Mid-Atlantic has also demonstrated the need for the addition of a winter grain in the rotation, as this phase helped decrease returns to the seedbank by decreasing summer annual weed biomass relative to other cash crops (Wallace et al., 2017). Although seedbank dynamics were strongly influenced by weather events that hindered cultivation efforts, our research suggests that rolled cover crop, no-till planted systems are comparable to tillage-based systems for weed seedbank management within an annual crop rotation. Previous studies on organic cover crop-based, rotational no-till have focused around in-season weed competition, however this study provides new data on seedbank dynamics over the entire rotation.

Weed seedbanks were largely dominated by foxtail species across systems and cash crops. Foxtail likely set seed before cash crop harvest, where the seed was incorporated into the soil by tillage events either in the fall or spring. This species is highly adaptive of different cropping systems and can shift its germination time to earlier in the season to escape successful control (Teasdale and Mirsky, 2015). Furthermore, foxtail seeds in rotational no-till systems are subject to varying factors which can interrupt or impose dormancy. Tillage events which bury seeds expose them to low oxygen conditions and inducing dormancy, while practices which leave the seeds near the soil surface subject the seeds to cold weather and moisture which can facilitate stratification to break dormancy and encourage germination as temperatures increase in the spring (Teasdale and Mirsky, 2015). Other research has shown that annual grass weeds tend to increase under systems that reduce tillage (Davis et al., 2005). Weed species populations are also greatly affected by the conditions of the soil in which they reside, so different tillage management will result in changes to the seedbank over time, selecting for or against certain species (Ngouajio and McGiffen Jr., 2002). Our study demonstrates that cover crop-based no-till and tillage-based summer annual cash crop production are both susceptible to high seedbank returns. The adoption of alternative reduced-tillage strategies may consider a suite of grower objectives, in addition to weed control, such as cash crop yields, profitability, and soil quality.

Literature Cited

Anderson, R.L. 2015. Integrating a complex rotation with no-till improves weed management in organic farming. A review. Agron. for Sust. Devel. 35:967-974.

Ball, D.A. 1992. Weed seedbank response to tillage, herbicides, and crop rotation sequence. Weed Sci. 40:654-659.

Barberi, P. and B.L. Cascio. 2001. Long-term tillage and crop rotation effects on weed seedbank size and composition. Weed Res. 41:325-340.

Booth, B.D. and C.J. Swanton. 2002. Assembly theory applied to weed communities. Weed Sci. 50:2-13.

Buhler, D.D., R.G. Hartzler and F. Forcella. 1997. Implications of weed seedbank dynamics to weed management. Weed Sci. 45:329-336.

Cardina, J. C.P. Herms and D.J. Doohan. 2002. Crop rotation and tillage system effects on weed seedbanks. Weed Sci. 50:448-460.

Davis, A.S., K.A. Renner and K.L. Gross. 2005. Weed seedbank and community shifts in a long-term cropping systems experiment. Weed Sci. 53:296-306.

Dillon, C.S., G. Roth, W.S. Curran and W. Harkcom. 2012. Development of a cover crop inter-seeder and applicator for no-till corn. Abstract. ASA Annual Meeting, #304.

Gallandt, E.R. 2006. How can we target the weed seedbank? Weed Sci. 54:588-596.

Keene, C.L. 2015. Agronomic performance of a reduced-tillage organic grain crop rotation during the transition to organic production. Dissertation. University Park, PA: The Pennsylvania State University. 176 p.

Kegode, G.O., F. Forcella and S. Clay. 1999. Influence of crop rotation, tillage, and management inputs on weed seed production. Weed Sci. 47:175-183.

Liebman, M. and E. Dyck. 1993. Crop rotation and intercropping strategies for weed management. Ecol. App. 3:92-122.

Menalled, F.D., K.L. Gross and M. Hammond. 2001. Weed aboveground and seedbank community responses to agricultural management systems. Ecol. App. 11:1586-1601.

Mirsky, S.B., M.R. Ryan, J.R. Teasdale, W.S. Curran, C.S. Reberg-Horton, J.T. Spargo, M.S. Wells, C.L. Keene and J.W. Moyer. 2013. Overcoming weed management challenges in cover crop-based organic rotational no-till soybean production in the eastern united states. Weed Technol. 27:193-203.

Moonen, A.C. and P. Barberi. 2004. Size and composition of the weed seedbank after 7 years of different cover-crop-maize management systems. Weed Res. 44:163-177.

Murphy, S.D., D.R. Clements, S. Belaoussoff, P.G. Kevan and C.J. Swanton. 2006. Promotion of weed species diversity and reduction of weed seedbanks with conservation tillage and crop rotation. Weed Sci. 54:69-77.

Ngouajio, M. and M.E. McGiffen Jr. 2002. Going organic changes weed population dynamics. Hort. Technol. 12:590-596.

Ryan, M.R., R.G. Smith, S.B. Mirsky, D.A. Mortensen and R. Seidel. 2010. Management filters and species traits: weed community assembly in long-term organic and conventional systems. Weed Sci. 58:265-277.

Ryan, M.R., S.B. Mirsky, D.A. Mortensen, J.R. Teasdale and W.S. Curran. 2011. Potential synergistic effects of cereal rye biomass and soybean planting density on weed suppression. Weed Sci. 59:238-246.

Shrestha, A., S.Z. Knezevic, R.C. Roy, B.R. Ball-Coelho and C.J. Swanton. 2002. Effect of tillage, cover crop and crop rotation on the composition of weed flora in a sandy soil. Weed Res. 42:76-87.

Smith, R.G. and D.A. Mortensen. (2017). A disturbance-based framework for understanding weed community assembly in agroecosystems: Challenges and opportunities for agroecological weed management. In A. Wezel (Ed.), Agroecological practices for sustainable agriculture: Principles, applications, and making the transition (pp. 127-154). London, UK: World Scientific Publishing Europe Ltd.

Snyder, E.M., H.D. Karsten, W.S. Curran, G.M. Malcolm and J.A. Hyde. 2016. Green manure comparison between winter wheat and corn: weeds, yields, and economics. Agron. J. 108: 2015-2025.

Stute, J. and K. Shelley. 2016. Frost seeding red clover in winter wheat. University of Wisconsin Extension Nutrient and Pest Management Program. Accessed October 9th, 2017. www.ipcm.wisc.edu.

Teasdale, J.R., R. W. Mangum, J. Radhakrishnan and M.A. Cavigelli. 2004. Weed seedbank dynamics in three organic farming crop rotations. Agron. J. 96:1429-1435.

Teasdale, J.R. and S.B. Mirsky. 2015. Tillage and planting date effects on weed dormancy, emergence, and early growth in organic corn. Weed Sci. 63:477-490.

Wallace, J.M., C.L Keene, W.S. Curran, S.B. Mirsky. M.R. Ryan and M.J. VanGessel. 2017. Integrated weed management strategies in cover crop-based, organic rotational no-till corn and soybean in the mid-Atlantic region. *In print.*

Table 3-1. Rank abundance of seedbank life history traits listed from highest to lowest. Proportions and accumulated frequency are shown for each life history trait, in each cropping system (S1-S4) for each cash crop, from 2015-2017.

Crop	System	Life history trait	Proportion	Accumulated frequency
Corn	S1	Annual dicot	47.4	47.4
		Annual monocot	42.8	90.2
		Perennial	9.5	99.7
		Volunteers	0.3	100.0
	S2	Annual dicot	45.4	45.4
		Annual monocot	40.2	85.6
		Perennial	14.2	99.8
		Biennial	0.1	99.9
		Volunteers	0.1	100.0
	S3	Annual monocot	48.0	48.0
		Annual dicot	47.0	95.0
		Perennial	5.0	100.0
	S4	Annual dicot	57.4	57.4
		Annual monocot	34.7	92.1
		Perennial	7.8	99.8
		Volunteers	0.2	100.0
Soybean	S1	Annual monocot	65.7	65.7
		Annual dicot	27.3	93.0
		Perennial	7.0	100.0
	S2	Annual dicot	49.8	49.8
		Annual monocot	37.8	87.6
		Perennial	12.2	99.8
		Volunteers	0.2	100.0
	S3	Annual monocot	74.0	74.0
		Annual dicot	20.9	94.9
		Perennial	5.0	99.9
		Volunteers	0.1	100.0
	S4	Annual dicot	50.3	50.3
		Annual monocot	42.7	93.0
		Perennial	6.7	99.8
		Volunteers	0.2	100.0
Spelt	S1	Annual monocot	56.8	56.8
		Annual dicot	33.5	90.3
		Perennial	9.5	99.8
		Volunteers	0.2	100.0
	S2	Annual monocot	51.2	51.2
		Annual dicot	42.0	93.2
		Perennial	6.6	99.8

Crop	System	Life history trait	Proportion	Accumulated frequency
		Volunteers	0.1	99.9
		Biennial	0.1	100.0
	S3	Annual monocot	69.8	69.8
		Annual dicot	26.1	95.9
		Perennial	3.9	99.8
		Volunteers	0.2	100.0
	S4	Annual monocot	48.9	48.9
		Annual dicot	44.5	93.4
		Perennial	6.4	99.7
		Volunteers	0.2	99.9
		Biennial	0.1	100.0

Table 3-2. Rank abundance, proportion, and accumulated frequency of top five species in all corn cropping systems (S1-S4) from 2015-2017. Species are listed from highest to lowest, and listed by Bayer Code and common name.

System	Species	Common name	Proportion	Accumulated frequency
S1	SETSPP	Foxtail spp.	39.7	39.7
	VERPG	Purslane speedwell	13.5	53.2
	OXAST	Yellow woodsorrel	8.7	61.9
	CONCA	Horseweed	8.6	70.5
	SOLPT	Eastern black nightshade	6.4	77.0
S2	SETSPP	Foxtail spp.	37.1	37.1
	OXAST	Yellow woodsorrel	13.6	50.8
	VERPG	Purslane speedwell	10.7	61.4
	SOLPT	Eastern black nightshade	9.6	71.0
	CHEAL	Common lambsquarters	7.1	78.1
S3	SETSPP	Foxtail spp.	45.2	45.2
	VERPG	Purslane speedwell	13.1	58.3
	SOLPT	Eastern black nightshade	11.5	69.8
	AMACH	Pigweed spp.	7.5	77.3
	POLPY	Pennsylvania smartweed	5.2	82.5
S4	SETSPP	Foxtail spp.	29.5	29.5
	VERPG	Purslane speedwell	14.1	43.5
	SOLPT	Eastern black nightshade	13.4	57.0
	CONCA	Horseweed	9.5	66.5
	OXAST	Yellow woodsorrel	7.6	74.1

Table 3-3. Rank abundance, proportion, and accumulated frequency of top five species in all soybean cropping systems (S1-S4) from 2015-2017. Species are listed from highest to lowest, and listed by Bayer Code and common name.

System	Species	Common name	Proportion	Accumulated frequency
	SETSPP	Foxtail spp.	62.6	62.6
	OXAST	Yellow woodsorrel	6.9	69.5
S1	VERPG	Purslane speedwell	6.5	76.0
	AMACH	Pigweed spp.	6.0	82.0
	CONCA	Horseweed	4.1	86.1
	SETSPP	Foxtail spp.	36.4	36.4
	CONCA	Horseweed	13.0	49.4
S2	OXAST	Yellow woodsorrel	11.5	60.9
	VERPG	Purslane speedwell	9.3	70.2
	SOLPT	Eastern black nightshade	8.9	79.2
	SETSPP	Foxtail spp.	69.1	69.1
	CONCA	Horseweed	5.3	74.4
S3	OXAST	Yellow woodsorrel	4.5	78.8
	VERPG	Purslane speedwell	4.0	82.8
	AMACH	Pigweed spp.	3.3	86.1
	SETSPP	Foxtail spp.	39.3	39.3
	VERPG	Purslane speedwell	13.3	52.5
S4	CONCA	Horseweed	9.8	62.4
	SOLPT	Eastern black nightshade	7.8	70.2
	OXAST	Yellow woodsorrel	6.3	76.6

Table 3-4. Rank abundance, proportion, and accumulated frequency of top five species in all spelt cropping systems (S1-S4) from 2015-2017. Species are listed from highest to lowest, and listed by Bayer Code and common name.

System	Species	Common name	Proportion	Accumulated frequency
	SETSPP	Foxtail spp.	48.5	48.5
	OXAST	Yellow woodsorrel	9.1	57.6
S1	AMACH	Pigweed spp.	7.6	65.2
	PANDI	Fall panicum	7.4	72.6
	VERPG	Purslane speedwell	7.1	79.6
	SETSPP	Foxtail spp.	48.2	48.2
	CHEAL	Common lambsquarters	13.1	61.3
S2	AMACH	Pigweed spp.	8.4	69.7
	OXAST	Yellow woodsorrel	6.1	75.8
	SOLPT	Eastern black nightshade	4.3	80.1
	SETSPP	Foxtail spp.	64.6	64.6
	AMACH	Pigweed spp.	6.4	71.0
S3	PANDI	Fall panicum	4.1	75.1
	POLPY	Pennsylvania smartweed	3.9	79.1
	OXAST	Yellow woodsorrel	3.7	82.7
	SETSPP	Foxtail spp.	46.9	46.9
	POLPY	Pennsylvania smartweed	8.8	55.7
S4	AMACH	Pigweed spp.	7.6	63.3
	CONCA	Horseweed	7.4	70.7
	OXAST	Yellow woodsorrel	6.2	76.9

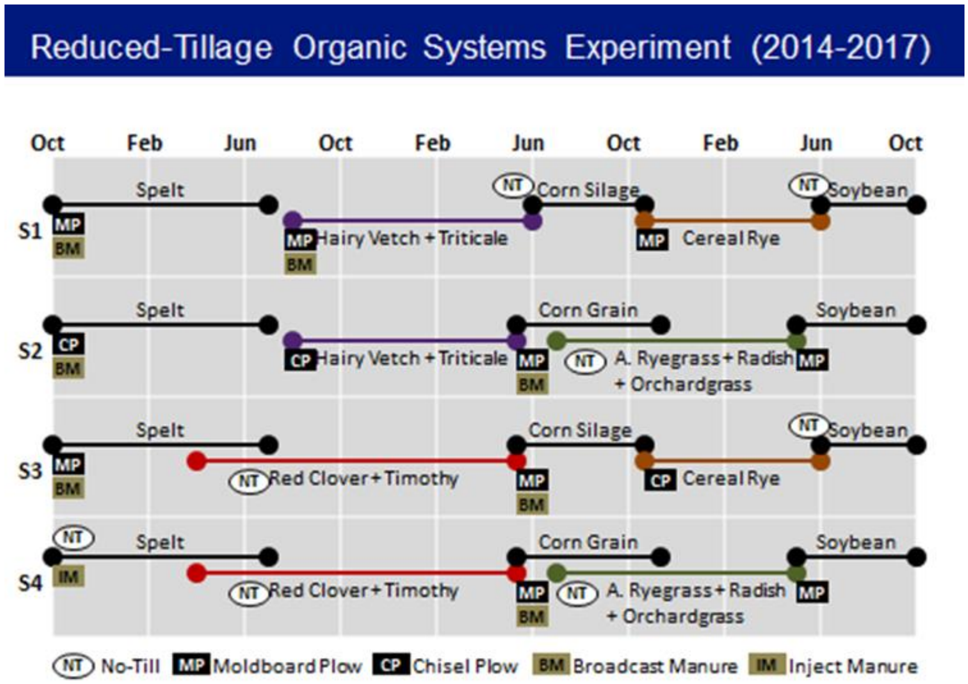

Figure 3-1. Comparison of four reduced-tillage cropping systems evaluated at Penn State's Russell E. Larsen Agricultural Research Center (RELARC) (2014 – 2017).

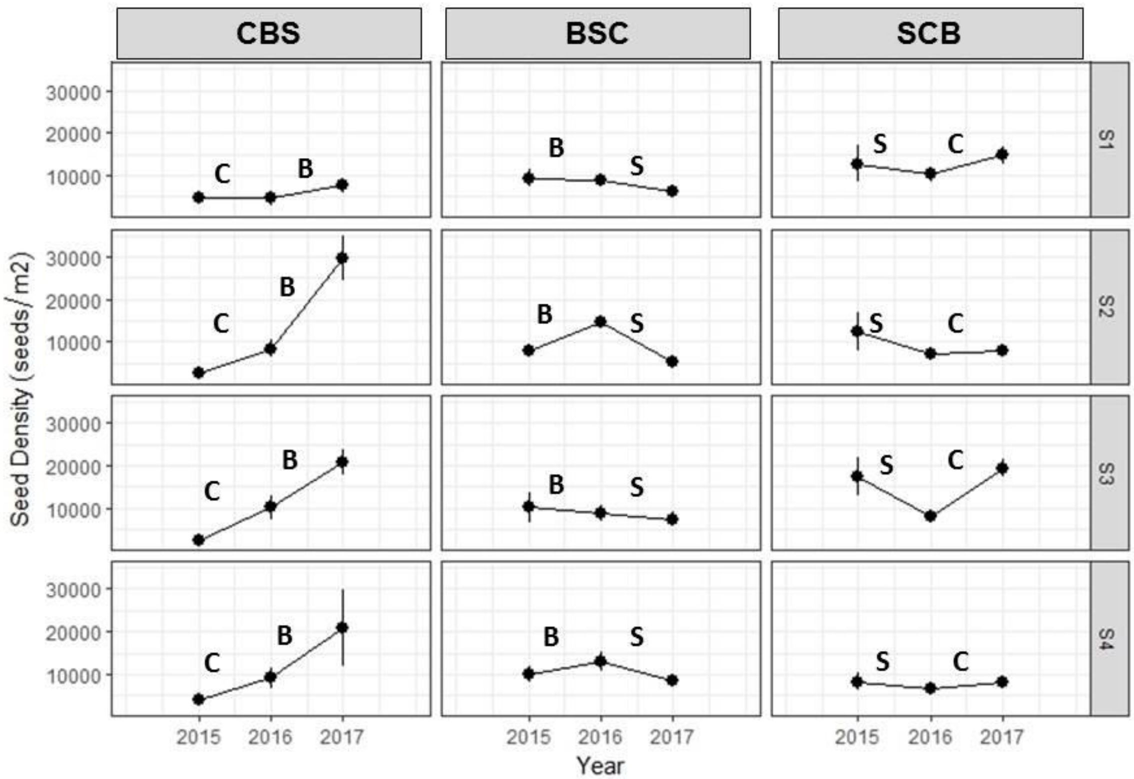

Figure 3-2. Seed density in seeds m^{-2} to the plow layer in each cropping system (S1-S4) across the cash crop rotation. Year represents in which year that cash crop was planted. Points on the graph represent seedbank soil sampling. C= corn, B= soybean, S= spelt.

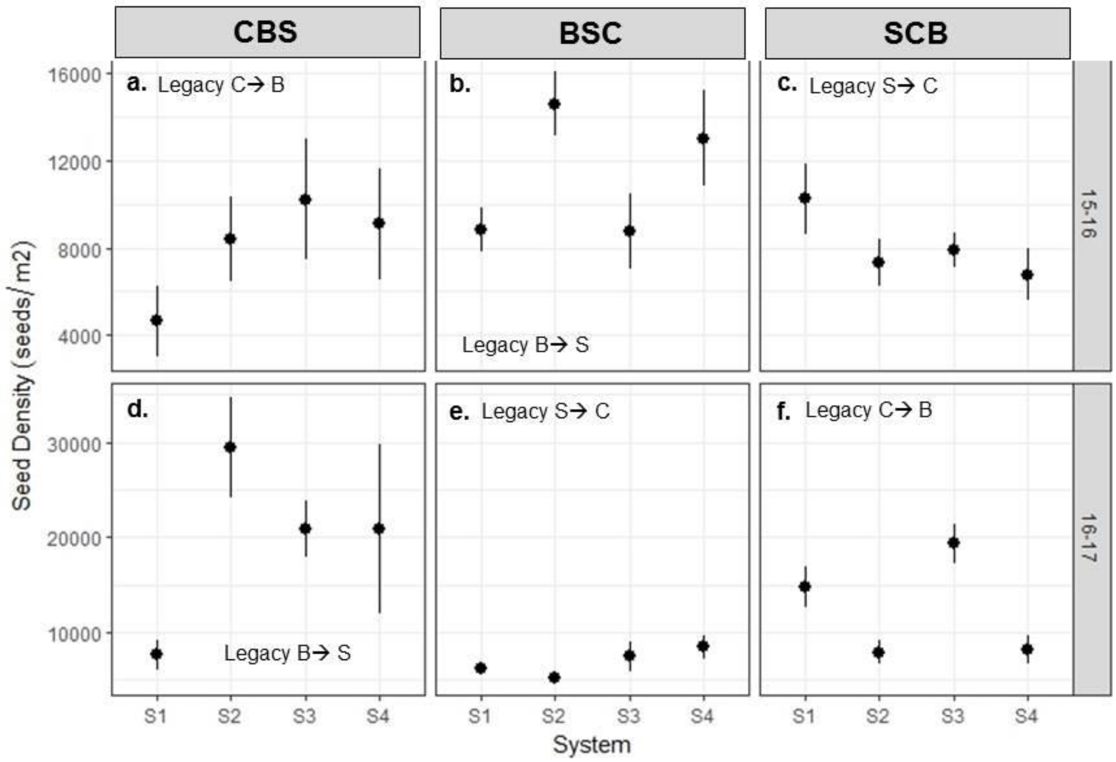

Figure 3-3. Legacy of cropping system from 2015-2016 and 2016-2017. Values represent seed density in seeds m^{-2} to the plow layer. C= corn, B= soybean, S= spelt.

Epilogue

This research has helped develop a more complete understanding of different reduced-tillage strategies and their implications on organic rotational no-till grain/silage production and weed management. We determined that the interseeded mix generally produced around 2,000 kg ha^{-1} spring cover crop biomass, while cereal rye spring cover crop biomass generally reached around 5,000 kg ha^{-1}, with biomass reaching approximately 8,000 kg ha^{-1}. While this level of biomass provided excellent early-season weed control, crop populations were reduced in some years due to wet soil at planting or difficulty slicing through residue. Summer annual weed control varied from year to year, with biomass as low as 95 kg ha^{-1} and as high as 2,000 kg ha^{-1}. The success of weed suppression in the tillage-based systems was highly dependent on mechanical operations which were hindered in 2016 due to wet conditions at planting and a mid-summer drought. Although the rolled cereal rye mulch provided good weed suppression, supplemental high-residue cultivation is still necessary for more complete control. Despite differences in both soybean stand and weed biomass, soybean grain yields were comparable between the no-till and tilled systems, ranging from 1,800-3,000 kg ha^{-1} across years. This is promising for growers who wish to adopt reduced-tillage strategies in their operations.

No-till organic corn production proved to be not as manageable compared to no-till organic soybean. Hairy vetch/triticale before corn averaged just over 5,000 kg ha^{-1} spring cover crop biomass, while red clover/timothy produced around 3,500 kg ha^{-1}. The no-till hairy vetch system consistently produced more spring biomass relative to the tillage-based systems, as roller-crimping of the cover crop was contingent upon hairy vetch growth stage. Manure was also applied at cover crop seeding in this system, providing more nutrients compared to the spring manure application in the other cropping systems. Although cash crop populations were reduced in some years because of soil conditions at planting, corn populations were not different between cropping systems in any year. Summer annual weed biomass was as low as 300 kg ha^{-1} but due to poor weed control in 2016, biomass reached well over 1,000 kg ha^{-1}, with some systems experiencing around 2,700 kg ha^{-1}. Weed biomass was higher in the no-till system only during 2017, when false seed-bedding was utilized and in-season cultivation was increased in the tillage-based systems. Corn grain yields were comparable in all years, however corn silage continues to have problems which should be addressed. No-till silage consistently produced less than the tillage-based silage system, with several factors pointing to this yield difference. Planting date was about seven to ten days later in the no-till system, as termination of the cover crop was reliant on hairy vetch growth stage for adequate control. Nutrient availability may have also led to reduced yield relative to the tilled system, as the rolled hairy vetch decomposed on the soil surface while the red clover was incorporated into the soil by moldboard plow with manure at corn planting. Research should aim to address these issues for better adoption of no-till corn in the Mid-Atlantic United States.

The impact of poor weed control was observed when analyzing weed seedbank trends across the three years. Weed seedbank levels quickly increased after the droughty conditions in 2016 led to ineffective in-season cultivation. Several trends were observed during the course of the rotation, mainly the increase in the seedbank after corn and soybean and a decrease after the spelt phase. Although weed biomass was not analyzed in the spelt phase, tillage after spelt harvest to establish hairy vetch/triticale likely buried weed seeds well below the soil surface. Spelt systems which frost seeded red clover/timothy helped to reduce seed rain by providing continuous soil cover, physical impedance on weed seed germination, and lack of tillage after spelt harvest. Seed abundance was generally lower in no-till planted corn and soybean systems and in systems which interseeded in corn at V5-V7, however this changed after poor weed suppression in 2016 increased seed abundance across all cropping systems. Annual monocots and dicots represented a majority of the seedbank, as annual species are well adapted to systems which integrate tillage at cover crop seeding or before cash crop planting. Across all three cash crops, foxtail species were the dominant weed species. This species can shift its germination to earlier in the season in order to germinate and become well established before mechanical operations. Future work should examine ways to control this species so it is not as successful in organic systems.

Although this research has helped with the challenges faced with reducing tillage in organic systems, there are still issues which future research should aim to examine in order for better adoption of cover crop-based, organic rotational no-till. Organic no-till soybeans have shown to be comparable to tillage-based organic soybean systems, however no-till corn silage continues to yield lower to tillage-based silage. Later planting date in this no-till system is unavoidable, as roller-crimping is contingent upon cover crop growth stage. Future research could aim to analyze different cover crops to roll-crimp before no-till corn planting, and should also examine ways to solve slower nutrient availability from rolled versus tilled cover crops. The addition of perennial forage crops such as alfalfa could be examined to help diversify the crop rotation, break weed pest cycles, and provide additional organic forage needs. Despite the challenges that still remain, there are a number of reduced-tillage practices a farmer in the mid-Atlantic could employ to help make their operation more diverse and sustainable.

Appendix A

Cover crop varieties, planting rates, and planting dates at RELARC, 2015-2017.

Cover Crop	Variety	Seeding Rate	Planting date 2014-2015	2015-2016	2016- 2017
		kg ha^{-1}			
Hairy vetch + Triticale	Groff + 815	34 + 34	Aug. 27	Aug. 28	Aug. 30
Red clover + Timothy	VNS + King's	12 + 4.5	Mar. 27	Mar. 23	Mar. 4
Cereal Rye	Aroostook	134	Oct. 3	Sept. 25	Oct. 12
Annual Ryegrass + Orchardgrass + Radish	KB Supreme + Potomac + Tillage	11 + 11 + 3.4	July 18	July 8	June 29

Appendix B

Corn and soybean varieties, planting rates, and planting dates at RELARC, 2015-2017.

Cash Crop	Variety	Seeding Rate	Planting date 2015	Planting date 2016	Planting date 2017
		plt ha^{-1}			
Corn (till)	Master's Choice 4050 (90 d)	81,510	May 29	May 26	June 2
Corn (no-till)	Master's Choice 4050 (90 d)	81,510	June 5	June 9	June 13
Soybean (till)	Growmark HS21C40 (2.1)	444,600	June 4	May 19	June 5
Soybean (no-till)	Growmark HS21C40 (2.1)	555,750	June 7	May 27	June 5

Appendix C

Number of tillage events each year in all corn and soybean systems. Soil disturbance was counted when cover crops preceding cash crops were planted, when they were terminated, and any in-season cultivation events. Tillage is broken into primary (moldboard or chisel plow), secondary (disc, s-tine, or cultimulch), or in-season (tine weed, rotary hoe, standard cultivation, high-residue cultivation). P=primary, S=secondary, I=in-season, Total=sum of all tillage events.

	2014-2015				2015-2016				2016-2017			
Corn	P	S	I	Total	P	S	I	Total	P	S	I	Total
S1	1	3	2	6	1	3	1	5	1	4	2	7
S2	2	5	4	11	2	6	4	12	2	10	6	18
S3	1	2	4	7	1	3	4	8	1	6	6	13
S4	1	2	4	7	1	3	4	8	1	6	6	13
Bean												
S1	1	3	2	6	1	3	0	4	1	2	2	5
S2	1	2	3	6	1	3	5	9	1	7	6	14
S3	1	3	2	6	1	3	0	4	1	2	2	5
S4	1	2	3	6	1	3	5	9	1	7	6	14

Appendix D

Cumulative monthly growing degree days (base 10˚C) for April through October at RELARC, 2015-2017.