ADAPTING REDUCED TILLAGE SYSTEMS FOR ORGANIC PRODUCTION: UTILIZING STRIP-TILLAGE AND ALTERNATIVE COVER CROP SPATIAL ARRANGEMENTS TO ADDRESS FARMERS’ PERCEIVED BARRIERS TO ADOPTION

By

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A DISSERTATION

Submitted to Michigan State University in partial fulfillment of the requirements for the degree of Horticulture—Doctor of Philosophy

2015
ABSTRACT

ADAPTING REDUCED TILLAGE SYSTEMS FOR ORGANIC PRODUCTION: UTILIZING STRIP-TILLAGE AND ALTERNATIVE COVER CROP SPATIAL ARRANGEMENTS TO ADDRESS FARMERS’ PERCEIVED BARRIERS TO ADOPTION

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Reduced tillage (RT) practices provide a number of ecological and agronomic benefits, but may also result in reduced inorganic nitrogen (N) availability and greater weed competition. These challenges are especially difficult on organic farms, where fertilizer and herbicide options are limited. My dissertation aims to adapt RT systems for organic production by addressing critical barriers to adoption: N deficiency and weeds. First, I conducted a survey to determine Michigan organic farmers’ current tillage practices and attitudes towards RT. Second, I evaluated the effect that one form of reduced tillage, strip-tillage (ST), has on N dynamics within an organic system. Finally, I evaluated how varying cover crop spatial arrangements within ST might mediate RT challenges; specifically how strip-intercropping of cereal rye and hairy vetch affects cover crop biomass and N, soil and sweet corn N, and weeds.

Our survey documented a wide range of current tillage frequencies associated with production of specific organic crops. Despite an overall high level of awareness of the benefits of RT, interest in adoption of specific RT practices among organic farmers was fairly low. Among RT options, vegetable farmers were most interested in permanent beds and strip-tillage and field crop producers in rotational tillage, followed by strip-tillage. The greatest perceived barriers to RT adoption were weeds, residue management, crop establishment, impact on yields and obtaining RT equipment.
Strip-tillage (ST) confines soil disturbance and incorporation of organic residues to a narrow strip directly within the crop row. We conducted field studies in southwest Michigan from 2011 to 2014 to examine the effects of tillage (ST vs full-width tillage [FWT]), on soil N and weeds under various levels of cover cropping and weed management. Compared to FWT, ST had lower inorganic N availability both within and between crop rows. Additionally, ST increased the concentration of N within the soil leachate and the potential for N to be lost through denitrification. Despite lower soil N, ST only negatively impacted sweet corn biomass and N uptake in 1 out of 3 years and increased yields in 1 out of 3 years. ST had varying effects on weed emergence and biomass, which was largely dependent on cover crop biomass. In 2012, rye-vetch biomass was between 7.0 and 8.0 Mg ha⁻¹, and reduced weed emergence and biomass within ST, resulting in greater sweet corn yield under low weed management. However, in 2013 rye-vetch biomass was approximately 35% lower, weed biomass higher, and yields reduced in ST compared to FWT.

To address the challenges of residue management and N deficiency within organic RT, we compared standard full-width mixtures of rye and vetch cover crops, to a novel “strip-intercropping” arrangement in which rye was planted only between future crop rows, and vetch planted only in-line with future crop rows. Strip-intercropping resulted in a lower C:N ratio of residue and higher N mineralization within the crop zone, but had no effect on weeds, or corn yield, biomass, or N uptake. To increase the potential benefits of strip-intercropping, future research efforts should focus on cover crop mixtures and termination methods which minimize the movement of shoot tissue across zones.
ACKNOWLEDGEMENTS

This work would not have been possible without the help of many people. First, I must thank my advisor, Dan Brainard for putting up with me over the past 5.5 years and for teaching me, among other things, the value of a good topic sentence. From carrot musical instruments to carpetweed wigs, you definitely made things fun. I look forward to our future collaborations.

Second, I must thank the members of my advisory committee, Mathieu Ngouajio, Phil Robertson, Sasha Kravchenko, and John Kerr. I feel very fortunate to have chosen some of the five kindest people to comprise my committee. You have all made stressful situations much easier, and this work would not have been possible without your thoughtful advice and encouragement.

I owe a huge debt to the members of the Brainard lab for all their help over the years. Particular thanks to Erin Haramoto, for taking me under her wing and being my go to troubleshooter, as well as to Zack Hayen. You both gave me an inflated idea of what a graduate student should strive to accomplish, but your examples inspired me to work both harder and smarter. I would like to thank our lab technician, Corey Noyes, for laboratory and field assistance. This work would have been impossible without the small army of rotating Brainard lab undergrads that have helped me over the years.

I also received both field and laboratory advice from a number of people throughout MSU including Joe Simmons, and the entire staff at the KBS Farming Systems Center, as well as Todd Martin, Kevin Kahrmark, and John Dahl.
I am also in debt to a number of graduate students for professionally and personally enriching my years at MSU. I would particularly like to thank Christine Sprunger, Bonnie McGill, Brendan O’Neill, Erin Hill, and Aaron Yoder.

I would also like to thank my family, especially my parents for all their love and support, and for their constant reminder that at some point in my life I will eventually need to get a real job. I am fortunate to have many other family members who without their love and support this would not be possible, particularly my grandparents.

Finally, I would like to thank my wonderful partner Jason Keagy. The best part about coming to MSU was meeting you, and I am very fortunate to have you in my life.
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KEY TO ABBREVIATIONS

RT: Reduced tillage

ST: Strip-tillage

FWT: Full-width tillage

RV: Rye-vetch mixture

NoRV: No rye-vetch

MIX: Mixed rye and vetch spatial arrangement

SEG: Rye and vetch segregated into strips

WR: Within the crop row

BR: Between crop rows

N: Nitrogen
INTRODUCTION

Reducing the frequency and intensity of tillage can lead to improvements in soil health, a critical objective in organic cropping systems. Frequent and intense tillage disrupts soil aggregates and macropores, resulting in increased carbon dioxide emissions (Grandy and Robertson, 2006), reduced infiltration rates (Franzluebbers, 2002), soil crusting (Awadhwal and Thierstein, 1985), and increased risk of erosion (Karlen et al 1994, Triplett and Dick, 2008). Reduced-tillage (RT) practices are also being promoted as an effective strategy to both mitigate and adapt to climate change (Pittelkow et al. 2014) due to their potential for C sequestration (Lal and Kimble, 1997), as well as increased soil water infiltration and holding capacity (Franzluebbers, 2002; Mahli and O'Sullivan 1990). For these reasons, interest is growing in adapting reduced tillage (RT) for organic production.

A common critique of organic farming is that it is very tillage intensive. Despite widespread adoption within conventional systems (Triplett and Dick, 2008), reduced-till practices have rarely been adopted by organic farmers, due in part to the challenges created for nitrogen (N) and weeds. Tillage performs several important functions on organic farms. Primary tillage incorporates crop residues to stimulate decomposition and facilitate mechanical cultivation (Peigné et al. 2007). When left on the soil surface rather than incorporated, organic amendments have a slower rate of decomposition and mineralization, leading to reduced N availability (Dou et al. 1994). Without the use of herbicides, tillage is the dominant form of weed control in organic systems (Peigné et al. 2007, Dedecker et al. 2014; Jabbour et al. 2013). Mechanical cultivation controls weeds
either via burying weeds through soil inversion or by severing them at the soil surface (Bond and Grundy, 2001).

N deficiency and weed competition are the two greatest challenges to achieving maximum yields in organic systems (Clark et al. 1999; Bond and Grundy, 2001; Poudel et al. 2002; Posner et al. 2008). Cavigelli et al. (2008) found that N deficiency accounted for between 70 to 75% of the yield reductions in organically grown field corn, while weed competition accounted for the entire 19% yield reduction in organic soybeans. In a long-term comparison trial of organic and conventional production systems, mechanical weed control was sufficient to suppress weeds in 66% of site-years within organic treatments, but when wet conditions prevented cultivation the subsequent high weed pressure led to yield reductions (Posner et al. 2008). Improving N and weed management in organic cropping systems is essential for enhancing crop productivity. The cost of N inputs and labor required for mechanical weed control represent significant expenses within organic production (Archer et al. 2007), and the challenges of weed control and N deficiency are likely to be exacerbated by tillage reductions.

This goal of my dissertation is to improve our understanding of tillage within organic systems, especially with respect to the critical barriers to RT adoption: N deficiency and weeds. In accordance with this goal we addressed the following research questions. First, what is the current level of tillage being utilized on organic farms, and what are organic farmers perceptions regarding RT practices? Second, how does RT affect the N dynamics within organic production, including N losses to the environment? And finally, how can winter cover crops, such as rye and vetch, be more efficiently
utilized within organic RT to maximize N availability, weed suppression, and crop yields?

For research on organic RT systems to be both useful and effective, it needs to accurately take into account the knowledge and situations currently present on organic farms. Little information is currently available on the amount and intensity of tillage currently used on organic farms, as well as organic farmers’ interest in, and attitudes toward reduced tillage (RT). To address these knowledge gaps, we conducted a survey of field crop and vegetable growers in Michigan who follow organic production guidelines (Chapter 1). The overall goal of the survey was to evaluate attitudes and perspectives of organic farmers regarding RT systems in order to guide future research and education programs. Specific objectives were to: 1) document the extent and type of current tillage practices employed by organic farmers; 2) determine the forms of reduced tillage that organic farmers are currently most interested in adopting or learning more about; 3) examine perceptions among organic farmers regarding the barriers and benefits of RT adoption.

Thus far, much of the research on reduced-till in organic production has looked at no-till or rotational till systems. However, other reduced till techniques are available that may be more applicable to an organic system. For example, strip-tillage has several distinct advantages relative to both conventional full-width tillage and no-till. Strip-tillage utilizes a combination of narrowly placed disks and rotary baskets (often attached to a shank), which confines tillage to a narrow strip where the crop will be planted (Luna and Staben, 2002). This divides the cropping system into two distinct yet adjacent zones: tilled and untilled. The tillage zone enhances soil aeration and creates a finer seedbed
into which the crop will be planted (Licht and Al-Kaisi, 2005). The untilled zone between-row (BR) maintains some of the benefits of no till, such as improved water infiltration, organic matter retention, and decreased erosion (Johnson and Hoyt, 1999). Strip-tillage enables a greater level of control over organic matter turnover. Incorporating crop residue in-row (WR) enables faster decomposition and mineralization of organic matter to increase nutrient availability to the crop. When combined with a preceding cover crop, residue is preserved on the soil surface BR to provide a number of ecosystem services throughout the growing season, such as suppressing weed germination, reducing soil erosion and conserving soil moisture (Mohler and Teasdale, 1993; Unger and Vigil, 1998).

Few studies have examined the effect that strip-tillage has on N availability within a legume-based system. Organic systems are already prone to N deficiency (Clark et al. 1999; Poudel et al. 2002; Cavigelli et al. 2008), and previous work has shown that N mineralization from legume residue is reduced when residues are left on the surface compared to incorporated into the soil (Mulvaney et al. 2010). Therefore, RT may exacerbate the problem of N deficiency. Understanding how tillage influences the fate of N within an organic system is important to develop strategies to reduce N deficiency and increase N use efficiency within organic RT systems. To enhance our understanding on N dynamics within a legume based ST system, we examined the effects of strip-tillage and a rye and vetch cover crop on 1) season long inorganic N availability, 2) the potential for N mineralization, and 3) the potential for N losses through denitrification and leaching (Chapter 2).
The final three chapters of this dissertation utilize target placement of N resources to address the critical barriers to organic-RT adoption: N deficiency and weeds. In conventional systems, N use efficiency has been improved with targeted placement of N fertilizers, such as banding N. Targeted placement of nitrogen has the potential to mitigate inefficiencies in nutrient management, which are profuse throughout agricultural production. Blanket applications of nutrient amendments incorporated across an entire field often place nutrients outside the access zone of crop roots. When nutrient availability does not coincide with root location, nutrients are subject to being lost (Robertson, 1997). In conventional crop production, banding synthetic N fertilizers increased crop nitrogen use efficiency and reduced nitrogen losses (Maddux et al. 1991; Waddell and Weil, 2006; Nash et al. 2012). In addition to decreasing N losses, targeted placement of N may also have distinct advantages for weed management. For example, banding synthetic N has been shown to increase the crop’s competiveness against weeds, and may decrease emergence and growth of annual weeds by decreasing their ability to access N (Kirkland and Beckie, 1998; Blackshaw et al. 2004).

In organic cropping systems, few attempts have been made to improve N use efficiency through more precise placement of N sources, including legume cover crops. We investigate one approach to achieve targeted N placement, via strip-intercropping of functionally diverse grass and legume cover crops within an organic ST system. This research also evaluates potential synergistic benefits of combining strip-intercropping with strip-tillage. By targeting tillage to the planting zone, problems associated with hairy vetch re-growth and crop interference are minimized, while benefits associated with surface retention of rye are maximized.
Strip-intercropping involves separating component species within a mixture into distinct alternate strips with the ultimate aim of delaying the onset of competition (Ofori and Stern, 1987; Midmore, 1993). Legume and cereal grass cover crops are utilized in cropping system to meet distinct objectives: legumes serve to provide N to the system, and cereal grasses are utilized to suppress weeds and return large quantities of carbon to the soil. By segregating these species into distinct zones, their functions can be targeted efficiently to maximize benefits to the crop while minimizing problems associated with interspecific competition in traditional full-width mixtures. Hairy vetch (Vicia villosa Roth.) planted and incorporated solely in the WR zone provides N directly to the crop. Cereal rye (Secale cereal L.) planted only in the BR zone, reduces interspecific competition with vetch, creates a zone of initial N immobilization to tie up excess N and suppress weeds, as well as provides other ecosystems services such as improvements in soil quality.

In Chapter 3, we examine how strip-intercropping of rye and hairy vetch affects i) the overall productivity of a rye-vetch mixture, as well as the relative biomass of each component; and ii) the spatial distribution and C:N ratio of rye-vetch residues between zones. We hypothesized that compared to full-width rye-vetch mixtures, strip-intercropping of cereal rye and hairy vetch would result in a greater proportion of vetch biomass and a lower C:N ratio of cover crop residues within the vetch zone (VZ); in line with future crop establishment.

Subsequently, Chapter 4 reports whether strip-intercropping of cereal rye and hairy vetch can increase potentially mineralizeable N and N availability within the crop row of strip-tillage, as well as the subsequent effects on sweet corn biomass, N uptake,
and yields. Additionally, we examined whether rye and vetch spatial arrangement and strip-tillage effects on sweet corn were mediated through differences in root mass and morphology.

Chapter 5 reports the effect of cover crop spatial arrangement, tillage, and weed management intensity on weeds, soil N, and crop biomass and yields within organic sweet corn production. We hypothesized that soil inorganic N would be greater within the crop row (WR) of ST when rye and vetch (RV) are segregated into strips, and lower between crop rows (BR). Additionally, we hypothesized that the number of weeds emerging BR will be lower in strip-tillage compared to full-width tillage, and that weed biomass and N content, as well as sweet corn yield loss due to weeds, will be reduced when cereal rye and hairy vetch are segregated into strips in combination with strip-tillage.
LITERATURE CITED


CHAPTER ONE

Michigan organic farmer perceptions of the barriers and benefits of reduced-tillage: Results from a farmer survey.

ABSTRACT

A common critique of organic farming is that it relies heavily on tillage practices with known negative effects on soils. However, little information is currently available on organic farmers’ current tillage practices and attitudes toward reduced tillage (RT). To address these knowledge gaps, we mailed a written survey to 337 Michigan farmers who follow organic production guidelines, and received 39 completed surveys from vegetable growers and 65 from field crop growers. Respondents reported a wide range in tillage frequency and intensity, both across and within production of specific crops. Tillage operations were fairly evenly split between field preparation and cultivation. The most commonly used primary tillage was moldboard and chisel plow for field crops, and rototiller for vegetables. Interest in adoption of RT practices among respondents was overall fairly low, but farmers did express a high level of interest for a few forms of RT. Vegetable farmers reported an overall greater interest in adoption compared to field crop producers and were most interested in permanent beds and strip-tillage. Field crop producers were most interested in rotational tillage, followed by strip-tillage. The greatest perceived benefits to adoption were improved soil quality and fuel savings. Vegetable producers were more likely to perceive obtaining RT equipment as a greater barrier to RT adoption compared to field crop producers. Both groups ranked weeds, impacts on yields, residue management, and crop establishment as high barriers to adoption. Survey results suggest that future research efforts should focus on: i)
developing low cost adaptable RT equipment for organic vegetable producers; ii) identifying the optimal level of tillage that balances weed and soil management tradeoffs; and iii) developing strategies that maximize cover crop residue weed suppression, while avoiding crop interference.

INTRODUCTION

A common critique of organic farming is that it is very tillage intensive. Frequent and intense tillage disrupts soil aggregates and macropores, resulting in increased carbon dioxide emissions (Grandy and Robertson, 2006; Grandy et al. 2006), reduced infiltration rates (Franzlubbers, 2002), soil crusting (Awadhwal and Thierstein, 1985), and increased risk of erosion (Karlen et al 1994, Triplett and Dick, 2008). Several long-term studies comparing agricultural management have found that although organic systems may improve soil quality indicators compared to conventional systems (Pimentel et al. 2005; Teasdale et al. 2007), they may fail to provide soil quality improvements equal to no-till (Bhardwaj et al. 2011). For example, a long-term study in Michigan found that organically managed soils had a lower soil stability ratio and reduced volume of drainable pores compared to no-till (Bhardwaj et al. 2011).

Although excessive tillage can be detrimental to soil health, tillage performs several important functions on an organic farm. Primary tillage is helpful for incorporation of cover crop residues to stimulate decomposition and facilitate mechanical cultivation (Peigné et al. 2007). When left on the soil surface rather than incorporated, organic amendments have a slower rate of decomposition and mineralization, leading to reduced N availability (Dou et al. 1994). Without the use of herbicides, tillage is the dominant form of weed control in organic systems (Peigné et al.
Tillage is also an important tool for disease management because incorporating crop residues can increase the mortality of disease propagules (Bailey and Lazarovits, 2003). Despite the important role of tillage for organic production, and the negative consequences resulting from too much tillage, very little information is currently available on the amount and intensity of tillage currently used on organic farms.

The type of tillage implement, as well as the number of tillage operations performed at any one time and across the season, vary between organic farms as well as by year on any one farm. In certain years, limited time or wet soil conditions may prohibit the ideal number of tillage operations for optimum planting conditions and effective weed control (Posner et al. 2012). Additionally, tillage practices may vary by farm due to soil type, crops grown, or farmer preferences with respect to crops grown and acceptable level of weed control.

Access to high-quality and locally adapted information is a key factor that influences farmer adoption of conservation practices (Llewellyn, 2007; Baumgart-Getz et al. 2012). Currently a number of researchers are working to adapt reduced tillage (RT) systems for organic production (Carr, et al. 2012; Luna et al. 2012; Mirsky et al. 2012; Brainard et al. 2013). However, without adequate information regarding farmers' perceptions of the barriers to and benefits of RT practices, it is unknown whether researchers are providing organic farmers with the most relevant and useful information. Research is unlikely to be either effective or useful if it demonstrates an idea or principle that is already well-known (Llewellyn 2007). For example, it is well known that a major benefit of RT adoption is improvements in soil quality. But common organic practices,
such as cover cropping and additions of manures and compost, are already meeting many of the same ecological objectives of no-till farming by promoting building of soil organic matter (Fleiβach et al. 2007). Information on further improvements in soil quality could be a major incentive to encourage organic farmer adoption of RT. If so, it would be important for research efforts on organic RT systems to focus on providing new information to farmers demonstrating other potential benefits of RT adoption. One such example is the role that RT systems can play in facilitating adaptation to the erratic precipitation events predicted by climate change models (Hayhoe et al. 2010) by increasing water infiltration and soil water holding capacity (Mahli and O'Sullivan, 1990; Franzlubbers, 2002).

For agronomic research to be effective at enhancing farmer decision-making on farm and resource management, research must consider farmers’ existing knowledge, beliefs, and attitudes (Ahnström et al. 2009; Andrews et al. 2013). Farmers’ existing attitudes influence both their likelihood of adoption as well the likely success of those practices (Ahnström et al. 2009). Organic farmers tend to place a higher value on their own knowledge and the knowledge of other farmers compared to knowledge generated from scientific research (Jabbour et al. 2013). Incorporating farmer knowledge into agronomic research will assist scientist in tailoring research to address the specific interests and needs of farmers. Information is lacking on organic farmers knowledge and attitudes regarding the costs and benefits of RT adoption.

The actual and perceived costs and benefits of RT adoption may be influenced by internal characteristics of the farm. For example, smaller farms generally have less access to capital to invest in machinery that may be required for some forms of RT
Investment in new machinery may be inappropriate to smaller diversified farms when RT equipment may only be suitable for a small portion of the total crops produced. RT practices may only be suitable to specific crops, so which crops are utilized within a rotation may greatly impact the perceived costs and benefits. For example, Mirsky et al. (2013) found that the performance of field corn in organic no-till was more variable than soybean. Additionally, certain soil types and climates may be more suitable to RT (Rahm and Huffman, 1984). Other socio-economic factors such as farmer experience and access to information may also impact management decisions (Saltiel et al. 1994; Knowler and Bradshaw et al. 2007; Prokopy et al. 2008). While a number of studies have examined how the context of a farming operation impact management decisions (Beedell and Rehman, 1999; Knowler and Bradshaw et al. 2007; Ahnström et al. 2009), few studies have examined these relationships exclusively within organic farms.

The overall goal of this study was to evaluate attitudes and perspectives of organic farmers regarding RT systems in order to guide future research and education programs. Specific objectives are: 1) document the extent and type of tillage practices currently employed by organic farmers, as well as their access to equipment necessary for RT; 2) determine the forms of reduced tillage that organic farmers are currently most interested in adopting or learning more about; 3) examine perceptions among organic farmers regarding the costs and benefits of RT practices; 4) determine how farm and farmer characteristics influence their expressed interest in reduced tillage.
Study system: Organic agriculture in Michigan

We conducted a survey of organic farmers in Michigan. Michigan has a diversity of soil, topography, and climate due to its unique geographical position within the Great Lakes region (MDARD, 2012). Due in part to proximity to major cities and vegetable and fruit processing plants, Michigan farmers have a diversity of markets. These factors contribute to Michigan’s being the second most agriculturally diverse U.S. state (MDARD, 2012; USDA 2012). Michigan contains 332 organically certified or exempt farms (USDA, 2014), up 62% from 2005 (Bingen et al. 2007). In 2012, Michigan had over 58,000 acres of organic production, and organic sales totaled $124 million (USDA, 2014). Michigan is an important contributor in organic production of fruit, vegetable and field crops. Michigan ranks number 1 in the county in organic production of dry beans, popcorn, and tart cherry, and is a major organic producer of grain corn (#3), snap beans (#3), and blueberries (#4) (USDA, 2008).

MATERIALS AND METHODS

Survey development

In 2014, we conducted a written survey of field crop and vegetable growers in Michigan who follow organic production guidelines. Because a large portion of small farmers that follow organic guidelines are not certified, we did not make certification a prerequisite for survey completion. Respondents were asked to verify that they meet USDA’s National Organic Program (NOP) guidelines on the survey waiver form with return of the survey instrument. In Fall 2013, survey participants were identified through the NOP. The Local Harvest (http://www.localharvest.org) farm database, a commonly used website to identify sources of local food, was utilized to identify Michigan farmers.
that were not certified but self-identified as using organic practices. We separated all farm participants into either field crop or vegetable producer by their primary crops listed within NOP or Local Harvest.

Prior to survey administration, we obtained feedback on the survey instrument through an advisory group of farmers, researchers, and extension personnel. Once the survey was developed it was tested on a subgroup of 5 organic farmers to check reliability of responses, and feedback was incorporated. This research was conducted in accordance with the Michigan State University Human Research Protection Program and was deemed exempt (IRB# x14-041e).

**Survey content**

Two forms of the survey instrument were created: one for field crop growers and one for vegetable growers (see Supplemental File for survey example). The survey was organized into four sections, and included questions on demographic and farm characteristics (Section 1); crop specific questions (Section 2); and attitudes towards reduced tillage (Section 3); and questions related to agricultural research priorities (Section 4). Section 2 was the only section that differed between field crop and vegetable crop respondents. Results from Section 4 are not included.

Section 1 included questions on respondent demographics and characteristics of the farm, and was the same for both survey versions. Demographic questions included information on years farming, years farming organic, percent of the workweek spent farming, and percent of family income from farming. Farm characteristics included questions on principal crops, acreage, land tenure, soil type, organic certification, and equipment access on the farm.
The focus of Section 2 was to gather specific information from each respondent on the practices employed for the production of a specific crop on their farm. Production practices vary considerably by crop, therefore requiring respondents to answer questions targeted to a specific crop helped to control for crop-specific variability in responses. Field crop producers were asked to choose either field corn, soybeans, or dry beans. Vegetable producers were asked to select either winter squash or broccoli; but if neither of these crops were grown they could select tomato (tomato data not shown). These crops were selected because they were widely grown in the region, and because they represented crops known from previous research to be relatively amenable to RT practices. Section 2 included both open-ended questions and questions asking respondents to “check all that apply.” Questions focused on the type and frequency of tillage used for soil preparation and weed cultivation, type and quantity of soil amendments, organic herbicide or pesticide applications, cover crop species, and crop rotation. Surveys included figures illustrating different types of tillage equipment (see Supplemental File), in order to minimize errors associated with equipment terminology (Figures obtained from Grubinger, 1999; Bowman, 2002).

Section 3 consisted of a series of 0 to 7 Likert scales asking respondents to rank their interest in adoption of specific RT practices, knowledge of RT practices, as well as their perceptions of potential benefits and barriers to RT adoption. For Likert scales, 0 represented no interest or knowledge of RT, or not a potential benefit or barrier to RT adoption; 7 represented extremely interested in or knowledgeable about RT adoption, or extremely likely to be a potential barrier or benefit to RT adoption.
**Survey implementation**

Prior to the survey we sent an announcement by mail in January 2014, providing basic information on the timing and purpose of the survey. Survey packets were mailed in February 2014. Within the survey packet, we included a letter explaining the importance and purpose of the survey, survey instructions, a survey waiver form, as well as a pre-paid return envelope. The instruction letter also emphasized that a $15 check would be mailed following receipt of their completed survey. A reminder postcard was sent four weeks after the survey packet, encouraging recipients to complete the survey to receive their $15 check. To increase survey publicity, we put announcements in local Michigan organic agriculture emailing listserves.

Once a list of respondents was generated, each respondent was given a numbered code which corresponded to their survey instrument. The coded sheet was used to create a list of respondents to receive compensation. The coded identifiers were completely separated from the return and completed surveys to ensure anonymity.

The survey was sent to 337 Michigan farmers (178 field crop producers, and 159 vegetable producers); 12 surveys were returned unopened because they were no longer operating farms. 120 completed surveys were returned, and of these, 1 survey was incomplete and 14 additional surveys were excluded because respondents were primarily dairy or livestock operations with less than 15% of their operations dedicated to vegetable or field crop production. Therefore, a total of 105 surveys were included in analyses, for a final response rate of 34%. The response rate by region varied between 29 and 38% (Figure 1.1).
To evaluate the soil disturbance intensity of the varying tillage practices used on organic farms, we calculated cumulative STIR (soil tillage intensity rating) values for the tillage operations reported for each respondent (USDA NRCS, 2008). A soil tillage intensity rating (STIR) is a numerical value for a specific tillage operation used to estimate erosion potential in RUSLE2 (Revised Universal Soil Loss Equation Version 2). STIR values are calculated based on tillage type, depth, and percent of soil surface area disturbed, and can be found within RUSLE2. For each respondent, we multiplied the number of operations for each tillage implement by its specific STIR value (Table 1.1), and then summed across tillage types to get a cumulative STIR value according to:

\[ \text{Cumulative STIR} = \sum (STIR \text{ tillage operation} \times \# \text{ tillage passes}) \]

A distribution of cumulative STIR values for each of the five crops was then generated using cumulative STIR values for all respondents growing that crop.

**Statistical analyses**

Survey data were analyzed using SPSS (Windows version 22). Descriptive statistics (means, medians, frequencies) were calculated for demographic data and summaries of production practices, as well as Likert responses. Because Likert responses did not follow a normal distribution, we reported the median responses instead of the mean, and nonparametric tests (Kruskal-Wallis) were used when comparing categorical groups. Spearman correlation coefficients were used to evaluate the relationship between continuous variables and Likert responses. All figures were made using the GGPPLOT2 package in R (Wickham, 2009).

Factor analysis was used as a data dimensionality reduction method to evaluate the underlying relationships between perceived barriers, benefits, and interest in RT
adoption. Factor analysis utilizes the patterns of covariation among measured variables in a data set to infer latent variables, and these latent variables represent potential relationships that exist within the observable variables (Johnson and Wichern, 2007; O’Connell et al. 2014). Two methods were used to determine whether the original measured data variables could be reduced into a smaller number of factors: the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett’s test of sphericity (Leech et al. 2005). We used a principal component extraction method, with list-wise deletion of missing data, Varimax rotation, and a Kaiser normalization. To determine the appropriate number of factors we used the following criteria: 1) theoretical meaningfulness of appropriate factors, 2) scree plots, 3) total percent variance explained, and 4) eigenvalues that are at or near 1. Initially the factor analysis of barriers to RT adoption returned three factors in the exploratory approach using the criteria of factors having eigenvalues greater than 1. This model lacked interpretability, however, so we included a fourth factor because it had an eigenvalue close to 1 (0.89) and improved separation of factors and loadings of variables onto meaningful constructs. We selected a 0.6 cutoff for rotated factor loadings onto factor constructs.

RESULTS

Demographics

Demographic characteristics of vegetable and field crop survey respondents can be found in Table 1.2. Field crop producers made up 62% of survey respondents, and vegetable producers made up 38%.

Field crop growers tended to be more experienced, with 65% of field crop respondents having farmed for more than 20 years, compared to only 31% for vegetable growers. Among vegetable farmers, 40% had been farming for 10 years or
fewer. However, field crop and vegetable producers had similar levels of experience with organic production practices: 48% of field crop growers and 56% of vegetable growers had been farming organically for fewer than 10 years.

Field crop and vegetable growers also differed in several other important respects. Organic field crop respondents farmed much larger acreage (70% of vegetable growers farmed 10 acres or less, while 63% of field crop growers farmed over 100 acres). Field crop respondents also earned a higher proportion of their income from the farm business; 46% of field crop producers earned over 75% of their income from farming, while only 39% of vegetable producers earned over 75% of their family income from farming. Finally, field crop respondents were more likely to be organically certified; 90% of field crop growers were organically certified compared to only 40% of vegetable growers.

In terms of land ownership and time dedicated to farming, field and vegetable crop growers were fairly similar. The majority of both field crop (66%) and vegetable (72%) producers owned both their land and farm. Thirty percent of field crop owners rented some portion of their land, while only 20% of vegetable producers rented some portion of all of their land. For both vegetable and field crop producers, approximately 60% of respondents spent over 75% of their workweek farming. All vegetable producers spent greater than 25% of their workweek on farming, while 15% of field crop producers spent less than 25% of their workweek on farming.

**Farm geographic distribution and soil types**

Regional representation of survey respondents, and regional variation of farm type, soil type and farm size can be found in Figure 1.1. Vegetable farms tended to
have sandier soils, such as sandy loams, while field crop farms tended to have heavier textured soils such as clay loams. The regional response rate was between 29 and 38%, and the percent of respondents from each region closely reflected the percent of farms within the initial population. Survey respondents represented the entire state of Michigan, with the largest concentration (27%) within the “Thumb” region (see Figure 1.1). The Thumb region was largely dominated by field crop growers, and is especially known for its organic dry bean production. Approximately 10% of respondents were from Northern Michigan and the Upper Peninsula, and responses were dominated by vegetable producers. Central East and West regions comprised approximately 20% of respondents and were approximately evenly split between vegetable and field crop producers. The Central region comprised approximately 14% of respondents and was largely dominated by field crop growers. Southwest and Southeast Michigan comprised 29% of respondents and was largely dominated by vegetable producers, with Southeast Michigan having a larger median acreage compared to Southwest.

**Tillage and cultivation equipment**

Vegetable and field crop producers varied in the type of tillage equipment they could access (Figure 1.2). Ninety-two percent of field crop and 70% of vegetable growers reported access to a tractor. The most common primary tillage implements available to field crop producers were a moldboard plow (83%), followed by a chisel plow (73%), and then rototiller (54%). In contrast, almost all vegetable growers had access to a rototiller (82%), with fewer reporting access to a moldboard plow (62%) or chisel plow (36%).
Field crop and vegetable growers also reported key differences in their access to secondary tillage and cultivation equipment. Field crop growers had access to a number of secondary tillage implements including discs (89%), field cultivators (80%), harrows (65%), and soil finishers (45%). Vegetable growers had lower reported access to these implements, including discs (74%), harrows (51%), row cultivators (49%) and field cultivators (41%). However, some vegetable growers had access to bed formers (20%) which were less common on field crop farms. Field crop producers reported access to cultivation equipment, including the row cultivator (86%), rotary hoe (72%), and flextine weeders (55%). For vegetable producers, the most common cultivation tool was a row cultivator (49%).

**Tillage and cultivation practices**

Tillage practices employed for specific vegetable and field crops are recorded in Tables 1.3 and 1.4, and generally follow the patterns seen for equipment availability. The most commonly used primary tillage implement was the moldboard plow for both field corn (61%) and dry bean (71%); however for soybean the predominant primary tillage implement was the chisel plow (47%) (Table 1.3). The most commonly used implements used for forms of secondary tillage were disc (field corn=61%, dry bean=14%, soybean=41%), field cultivator (field corn= 35%, dry bean=43%, soybean=29%), harrow (field corn= 22%, dry bean= 14%, soybean= 6%), and soil finisher (field corn= 30%, dry bean= 43%, soybean= 77%). Table 1.3 shows the most commonly used combinations of primary and secondary tillage implements.

For both broccoli and winter squash, the most dominant form of primary tillage was rototilling (65%) (Table 1.4). In contrast, moldboard plowing was used by only 35%
of winter squash producers and 29% of broccoli producers. The most commonly used implements for secondary tillage were the disc (winter squash=50%, broccoli=35%), harrow (winter squash=30%, broccoli=24%), and bed former (winter squash=19%, broccoli=18%).

The dominant implements used for weed cultivation used for field crops were the row crop cultivator, rotary hoe, and flextine cultivator (Table 1.3). Row crop cultivators target weeds between crop rows and were used extensively (91-100%) in all three field crops. Rotary hoes and flextine cultivators are typically used for “blind cultivation” of small weeds either before crop emergence or 2-3 weeks after emergence. For field crop producers, rotary hoes were more frequently used (73-100%) then flextine cultivators (45-71%) for this purpose. Interestingly, flextine cultivation was more common for weed management in beans (71.4%) then in field corn (45.5%).

For broccoli and winter squash production the dominant implements used for cultivation were the row crop cultivator (winter squash= 46%, broccoli= 24%) and the rototiller (18-19%) (Table 1.4). In contrast to field crops, flextine and rotary hoe cultivation were very rarely used in these crops. Cultivation tools that were rarely used by vegetable producers included the tine cultivator (5.9% of broccoli) and the finger weeder (3.8% of winter squash). The Regiweeder™, Buffalo cultivator™, basket-weeder, rolling cultivator, and tine cultivator were never used by survey respondents for any of the field or vegetable crops.

Tillage frequency and intensity

The distribution for the number of tillage operations used for field preparation, cultivation, and total tillage operations for each of the specified crops can be found in
Figure 1.3. The mean number of total tillage operations was 8, 9.2, and 9.1 for field corn, dry beans, and soybeans, respectively. This included approximately 4 tillage operations for field preparation, and 4-5 operations for cultivation. The range in the total number of tillage operations was smallest for dry beans (5), followed by field corn (7) and soybean (11).

For winter squash, the mean number of total tillage operations was 6.6 with an average of 3.5 for field preparation, and 3.1 for cultivation. For broccoli, 7.9 total tillage operations were used on average, with 4.5 for field preparation and 3.4 for weed cultivation. Variability in tillage operations was much higher for production of broccoli and winter squash compared to the field crops, especially for broccoli. Total tillage operations of broccoli ranged from 0 to 26.5, while for winter squash total operations ranged from 2 to 14.5.

The vegetable crops, broccoli (mean=130, std. dev=121) and winter squash (mean=143, std. dev=99; Figure 1.4) had lower total STIR values compared to field crops, but had higher variance. Dry bean had the highest cumulative STIR with a mean of 224, and the lowest variance (std. dev=33); followed by field corn (mean=210, std.dev=69) and then soybean (mean=203, std.dev=65). Both vegetables crops were skewed right, while the field crops had more of a normal distribution.

**Grower interest and knowledge of RT**

Figure 1.5 shows the distributions of vegetable and field crop producer interest in adoption of specific forms of RT. Overall, interest in adoption of RT practices among organic farmer respondents was fairly low, and vegetable farmers reported an overall greater interest in adoption compared to field crop producers.
Vegetable producers were most interested in permanent beds (median=4 on Likert scale) and strip tillage (median=3), and least interested in ridge-till adoption (median=0) (Figure 1.5). Field crop producers were most interested in adopting rotational tillage (median=3), followed by strip tillage (median=2). Organic field crop growers had little interest (median=0) in permanent beds, no-till, and ridge-till. For some forms of RT, the median expressed interest was low or at zero, but the other 50% of responses were fairly evenly distributed from 1 to 7. For example, 25% of field-crop respondents answered at or above 6, 5, and 4 for rotational, strip-till, and no-till, respectively. And 25% of vegetable producer respondents expressed interest at or above 6, 5.5, and 5 for permanent beds, strip-till, and no-till, respectively.

Organic producers reported a median knowledge of RT practices at 4 or lower (Figure 1.5). Field crop producers reported the greatest knowledge of rotational tillage (median=4), followed by no-till (median=3) and strip-till (median=3). Vegetable producers reported the greatest knowledge of permanent beds (median=4), followed by no-till (median=3), strip-till (median=3), and rotational till (median=3). Vegetable producers reported the lowest knowledge of ridge-till (median=1), and field crop producers reported the lowest knowledge of permanent beds (median=1).

**Perceived costs and benefits of RT**

Vegetable and field crop producers had very similar perceptions of the benefits of RT adoption (Figure 1.6). The greatest perceived benefits to adoption were improved soil quality (reduced soil compaction, increased soil organic matter, reduced soil erosion, improved soil tilth, increased soil water infiltration and water holding capacity).
and fuel savings. Factors that scored fairly low on the perceived benefits included reduced labor, reduced pest pressure (from disease, insects, and weeds) and yields.

Perceived barriers to adoption were also similar for vegetable and field crop growers, with a few notable exceptions (Figure 1.7). Vegetable producers were more likely to perceive obtaining RT equipment—both obtaining scale-appropriate equipment ($P=0.001$) and the cost of new equipment ($P=0.045$)—as greater barriers to RT adoption compared to field crop producers. Both groups ranked weeds, impacts on yields, residue management, and crop establishment as high barriers to adoption. Lowest ranked barriers to adoption included labor costs, soil fertility, and learning new practices.

**Factors associated with attitudes towards RT**

Interest in RT adoption was correlated with several farm characteristics and farmer demographics (Table 1.5). The maximum expressed interest in RT adoption (maximum Likert value for interest in any form of RT) was negatively correlated with years farming and acres farmed. Greater reported knowledge of RT practices was positively correlated with interest in adopting no-till, strip-till, rotational till, and permanent beds. Demographic factors that did not correlate with interest in adoption were percent of week spent farming, land tenure, and organic certification (data not shown). The maximum percent clay and percent silt that respondents recorded for soil types that exist on their farm were both negatively correlated with interest in adoption.

Not surprisingly, farmer perceptions of RT barriers and benefits were often related to interest in adoption (Table 1.5). The perceived barriers to RT adoption that were negatively correlated with interest in adoption were weeds, insect, residue
management, yields, and a lack of information. Perception of crop establishment as a barrier was negatively correlated with interest in adoption of no-till and permanent beds. All perceived benefits of RT were positively correlated with the maximum expressed interest in adoption.

Our analysis showed that the Likert responses of perceived benefits were all highly correlated with each other and with expressed interest in adoption and the factor reduction did not yield interpretable constructs. Both the KMO value and Bartlett’s test of sphericity indicate that the barriers data was amenable to factor reduction. A KMO value of 0.7 or greater ensures that the factors explain an adequate proportion of variance among the measured variables, and we found a KMO of 0.79 for perceived barriers to adoption. The Bartlett’s test of sphericity was significant for (Approx Chi. Square=621, $P<0.001$), indicating that significant relationships existed between the perceived barriers to adoption.

We reduced the perceived barriers to adoption of RT practices into four factors (Table 1.6). The four factors generated from this model explained 76% of the total variance. The factor loading cutoff we used was 0.6, and each variable clearly loaded onto one of the four factors, with the one exception being yield, which had 0.5 onto Factor 1 and 0.59 onto Factor 2. The communalities were mostly all above 0.6, except for soil fertility, at 0.56. This indicates that the model explained a significant amount of variation for each individual variable. Factor 1 consisted of disease and insect pressure, labor costs, and soil fertility. Factor 2 consisted of weed competition, residue management, and crop establishment. Factor 3 consisted of equipment costs and obtaining scale-appropriate equipment. Factor 4 consisted of information lacking and
challenges with learning a new practice. Factor 2 was negatively correlated with maximum expressed interest in RT adoption \( r = -0.247 \).

**DISCUSSION**

**Survey scope**

While the scope of our survey was limited to Michigan, demographic information shows that the respondents within our survey closely resemble organic farmers surveyed elsewhere. For example, compared to a national survey of organic farmers (Walz, 2004; Dedecker et al. 2014), our survey respondents had similar: i) acreage (50% of respondents farmed 50 acres or less); ii) land tenure (approximately 65% of farmers owned all their farmed land); and iii) farming experience (approximately 50% farmed for 20 years or more) (Table 1.2). We had a larger percentage of non-certified farmers in our study compared to other organic surveys that specifically targeted certified organic farmers (Walz, 2004; Dedecker et al. 2014).

Our survey was different from other surveys of organic farmers because we restricted it to field crop and vegetable producers, and excluded fruit, dairy, livestock, and other types of farming operations. We had a greater response rate of field crop (40%) compared to vegetable (26%) farmer respondents, so it is possible that field crop producers were slightly over represented in our sample. Alternatively, it could be that some of the uncertified vegetable farms we identified via farm marketing websites were actually not following organic guidelines, and thus did not participate due to this requirement.
Factors influencing interest in adoption of RT

More experienced farmers with larger acreage expressed less interest in RT adoption (Table 1.5). To determine whether these relationships were driven by differences between field crop and vegetable producers, we tested these correlations within each farm type separately (data not shown). We did not find any significant relationship but we saw a similar negative trend between interest in RT and years farming and acres. This suggests that we had insufficient power to detect the negative relationship within each farm type (vegetable or field crop) separately (and that this relationship was independent of farm type. However, it is possible that field crop farmers are less interested in RT for reasons unrelated to farm experience. Farmers’ decisions on management and technology adoption rely heavily on their own experiences and prior held beliefs (Wilson et al. 2009; Jabbour, et al. 2013). Experienced farmers may have previously tried reducing their tillage, or have had to miss a cultivation window due to wet soil conditions, and may have had negative experiences with tillage reduction. Therefore, experienced farmers may feel strongly that their current level of tillage is required to maintain weed control and crop productivity. In contrast, farmers that expressed greater knowledge of RT practices also expressed greater interest in adoption. This suggests that either those interested in RT are more likely to seek out information, or that farmers become more interested in RT the more they learn.

Constraints to adoption and implications for research and extension

Our survey results suggest that availability of small-scale, affordable equipment is a major constraint to adoption of RT, especially among vegetable growers (Figures 1.7). Research and extension efforts should thus emphasize scale- and resource-
appropriate adaptations to maximize the potential adoption and impact of RT. Approximately 30% of vegetable respondents did not have access to a tractor, and likely rely on walk-behind rototillers. Rototiller based RT practices including strip-tillage have been explored for small-scale resource-poor farmers in the developing world (Krupnik et al. 2013), and may have useful applications for small-scale organic producers in the US. Similarly, permanent bed systems—which entail wider disturbed and undisturbed zones compared to strip tillage (Morrison and Gerik, 1983)—may provide greater flexibility for RT of diverse vegetables using existing farm equipment. Certainly, relatively strong grower interest in permanent bed systems among vegetable growers (Figure 1.5) reflects their perceived appropriateness.

Among organic field crop growers, larger-scale approaches to RT may be feasible. For example, greater than 70% of field crop producers, (compared to only 35% of vegetable producers), reported having access to a chisel plow, and over 90% had access to a tractor. Large-scale strip-tillage equipment is readily available because of its extensive use on conventional field crop farms. Such equipment may also be appropriate for organic production of field crops with minor modifications. This may explain greater interest among organic field crop producers in strip-tillage compared to other forms of RT other than rotational tillage (Figure 1.5).

**Current level of tillage on organic farms**

The type and number of tillage operations employed for crop production varied by crop and farm type. The dominant form of tillage for field crop producers was moldboard plowing, followed by chisel plowing and discing. These forms of tillage have high STIR values, which is partially why field crops had a greater cumulative STIR value.
compared to vegetable crops. Vegetable producers predominantly relied on the rototiller, which despite being fairly destructive to soil has a STIR value of only 18 because it is typically fairly shallow. Many small seeded vegetable crops, such as carrots, require the fine seedbed provided by rototilling. If an organic vegetable farmer invested in any one piece of equipment, the rototiller is valuable because it can be used for both large and small seeded crops. Vegetable farms have more limited access to equipment (Figure 1.2), but typically grow a diversity of crops and require versatile equipment.

Despite organic agriculture being criticized for being tillage intensive, there was little previous information on the number and types of tillage used on organic farms. By asking detailed questions about tillage practices utilized for specific crops, we establish a baseline for what routine tillage, in both number of operations and disturbance intensiveness, currently is on organic farms in Michigan. Soil tillage intensity ratings (STIR) are used within RUSLE2 to estimate the effect that soil management operations have on soil, particularly with regards to increasing susceptibility to erosion. Few have applied STIR values as an index of soil disturbance intensity to organic or conventional farms. However, Karlen et al. (2008) compared various soil quality indicators including STIR values for the South Fork Watershed in Iowa. The STIR values within our study were significantly higher than the STIR values reported for their study, which consisted of conventional farms that relied predominantly on chisel plowing and disking. However their study did not include an assessment of secondary tillage.

We found that a wide range of tillage frequencies and intensities are used on organic farms for all crops other than dry bean (Figures 1.3 and 1.4). In this context,
“reduced tillage” may be thought of as any frequency or intensity below some threshold (e.g. 1 standard deviation below the mean). This implies that some farmers’ are already employing reduced tillage compared to the general population. However, we currently have little information to compare farms that vary in tillage frequency and intensity (STIR adjusted tillage intensity; x-axis, Figure 1.4) based on weed control, crop establishment, and crop yields.

Research has shown that despite heavy reliance on tillage, organic farming can increase soil organic matter (Teasdale et al. 2007), and improve aggregate structure (Pulleman et al. 2003; Papadopoulos et al. 2009; Bhardwaj et al. 2011), presumably due to higher inputs and quality of organic matter such as compost, manures and cover crops. However, it is not yet clear to what extent routine tillage on organic farms impacts other characteristics of soil quality, such as water infiltration and soil crusting. More research is needed to determine the effect that the routine frequency and intensity of tillage used on organic farms has on soil quality characteristics, particularly characteristics that will be important for climate change adaptation, like water infiltration and water holding capacity. Additionally, future research is needed on the balance between the intensity and frequency of tillage and its effectiveness for weed control.

**Perceptions of RT benefits**

Determining the awareness of organic farmers regarding the benefits of RT adoption could point to areas where more extension and education efforts are needed. No-till systems have been widely publicized because of their potential for sequestering carbon and reducing soil erosion (Phillips et al. 1980; Johnson and Hoyt, 1999; Triplett and Dick, 2008). Traditional organic practices (ie. applying compost, manure and cover
cropping) will also achieve these outcomes. Given that complete elimination of tillage in organic systems is likely not feasible, it is unclear to what extent RT systems that utilize some periodic tillage would result in economic or ecological benefits. This lack of information could be responsible for low overall interest. We wondered whether organic farmers perceived improved water dynamics as being a likely benefit from RT adoption. Our results show that improved water infiltration and increased water holding capacity ranked equally high as the more publicized benefits of RT, such as increased organic matter and decreased erosion (Figure 1.6). Therefore, education and extension efforts aimed at these issues likely will have little effect on organic farmer attitudes towards RT adoption.

Perceived benefits to RT adoption were almost all positively correlated with interest in adoption. Why were some farmers more likely to perceive benefits from RT adoption than others? One explanation could be that RT is more aptly suited to certain soil type and climates. This is supported by the negative correlation between percent silt and clay with interest in adoption. Heavier soils that have poor drainage and take longer to warm in the spring experience additional problems with RT (Peigné et al. 2007). On the other hand, changes in physical properties associated with RT may be greater on silt and clay soils compared to sand (Peingé et al. 2007). Correlations between soil type and interest in adoption may also be driven by cropping system; since field crops were associated with heavier soils, we cannot rule out the possibility that this correlation reflects lower interest among field crop growers. Some farmers may not be aware of the benefits of RT, and these farmers may benefit from increased education and extension.
**Perceived barriers to RT adoption**

The perceived barriers to adoption reduced to four factors, only one of which FACTOR 2 (residue management, crop establishment, weeds, and to a lesser extent yields), was negatively correlated with interest in adoption (Table 1.6). This is consistent with researchers’ perceptions of the key to successful organic RT: developing residue-mulch systems that are able to suppress weeds without suppressing the crop (Mirsky et al. 2012; Brainard et al. 2013). Utilizing cover crop residue as a mulch to suppress weeds is thought to be the key to successful implementation of organic RT (Carr et al. 2012; Brainard et al. 2013). However, cover crop residue can also negatively affect crop establishment by interfering with planting equipment, immobilizing N, and releasing allelopathic compounds (Price and Norsworthy, 2013). Planting in high residue environments may cause hair pinning of residue within the seed furrow, decreasing soil-seed contact, and inhibiting germination (Mirsky et al. 2013). Cover crop biomass production is highly variable from year to year, and in years when cover crop biomass is low, there may not be sufficient residue for weed suppression. Low levels of residue used as a mulch can stimulate weed emergence (Mohler and Teasdale, 1993). High levels of residue create challenges for mechanical cultivation, which is likely to be necessary for control of escaped weeds.

**Implications for future research**

The goals of adapting reduced tillage systems to organic farms are to improve soil health, decrease soil erosion, and offer organic farmers options for adapting to climate change. In place mulch, combined with intact macropores, can buffer against extreme precipitation events. Complete elimination of tillage on organic farms is likely
not feasible. However, “Reduced Tillage” is any decrease in the soil disturbance intensity that farmers are currently using, and it may look very different on organic farms compared to the RT practices developed for conventional systems. Given the relatively low interest in the narrow forms of RT presented in the survey (no-till, rotational till, strip-till, permanent beds, ridge-till) the goal of future research and extension programs should perhaps be on decreasing the number of tillage operations and intensity (shifting the distribution to the left on the x-axes in Figures 1.3 and 1.4) without sacrificing weed control, crop yield, and profitability. Given the constraints expressed by growers, the most promising avenues for doing so are likely identification of more effective weed management strategies, including cultural weed management, and identifying low cost adaptable cultivation equipment capable of controlling weeds in high residue environments.

Our goal in research and extension is not to promote adoption of any one specific practice or technology, but to improve the decision-making ability of farmers. We should strive to provide them with information that is both useful and relevant. There has been much interest recently in the need to better frame our research and information to more accurately reflect farmers’ beliefs, perceptions, and attitudes (Ahnström et al. 2009; Wilson et al. 2009; O’Connell et al. 2014). Our research shows that many organic farmers are already aware of the benefits of RT adoption, therefore to promote RT adoption future research efforts should likely focus more on alleviating the barriers to adoption, rather than reiterating RT benefits. For example, future research efforts must evaluate the level of tillage that optimally balances weed control and soil quality.
objectives. Additional research is needed to maximize cover crop residue weed suppression, while avoiding crop interference.

**SUMMARY AND CONCLUSION**

Organic farms in Michigan exhibited a wide variation in tillage frequency and intensity. The number of total tillage operations was between 8 and 9 for field crops, and approximately 6.5 for vegetables. Tillage operations were fairly evenly split between field preparation and cultivation. The most commonly used primary tillage implements were moldboard and chisel plows for field crops, and rototiller for vegetables. Vegetable farmers reported an overall greater interest in adoption compared to field crop producers. Interest in adoption of RT practices among organic farmer respondents was overall fairly low, but farmers did express a high level of interest for a few forms of RT. Field crop producers were most interested in rotational tillage, followed by strip-till age, while vegetable growers were most interested in permanent beds and strip-tillage. Future efforts in adapting RT systems for organic production would likely be more successful if they focused on these forms of RT, or if they developed RT strategies specifically for organic production that targeted more incremental movements in the distribution and intensity of tillage to the left.

This survey suggests that organic farmers in Michigan are aware of the general benefits to RT adoption. The greatest perceived benefits to adoption were improved soil quality and fuel savings. Vegetable producers were more likely to perceive obtaining RT equipment as a greater barrier to RT adoption compared to field crop producers. Both groups ranked weeds, impacts on yields, residue management, and crop establishment as high barriers to adoption. Potentially fruitful avenues of future research might include
identification of low cost adaptable RT equipment for organic producers, and
identification of crop-specific levels of tillage that balance weed control and soil quality
objectives, while maintaining crop yield and profitability. For example, research aimed at
improving the efficiency of mechanical weed control (e.g. more efficient cultivation tools
that reduce the frequency or intensity requirements) or replacing tillage and cultivation
with non-mechanical forms of weed management such as cover cropping, may help
organic growers build long-term soil health, while avoiding short-term crop interference.
APPENDIX
Table 1.1. STIR values used for tillage operations reported by organic farmer respondents for crop production.

<table>
<thead>
<tr>
<th>Survey Option</th>
<th>RUSLE Tillage Operation</th>
<th>STIR value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spader</td>
<td>Spader</td>
<td>18.00</td>
</tr>
<tr>
<td>Fingerweeder</td>
<td>Weeder, fingerweeder</td>
<td>0.49</td>
</tr>
<tr>
<td>Striptiller</td>
<td>Subsoiler, in row strip conditioner, 40 in row</td>
<td>11.00</td>
</tr>
<tr>
<td>Bed former</td>
<td>Bed shaper</td>
<td>20.00</td>
</tr>
<tr>
<td>Flextine</td>
<td>Harrow coiled tine</td>
<td>16.00</td>
</tr>
<tr>
<td>Harrow</td>
<td>Spike tooth</td>
<td>16.00</td>
</tr>
<tr>
<td>Rotary hoe</td>
<td>Rotary cultivator</td>
<td>6.60</td>
</tr>
<tr>
<td>Row cultivator</td>
<td>Field cultivator 6-12 sweeps</td>
<td>26.00</td>
</tr>
<tr>
<td>Disc</td>
<td>Plow Disc</td>
<td>39.00</td>
</tr>
<tr>
<td>Field cultivator</td>
<td>Cultivator, with spike and coil tines</td>
<td>34.00</td>
</tr>
<tr>
<td>Rototiller</td>
<td>Rototiller (with adjusted depth)</td>
<td>18.00</td>
</tr>
<tr>
<td>Chisel plow</td>
<td>Chisel plow</td>
<td>53.00</td>
</tr>
<tr>
<td>Moldboard plow</td>
<td>Moldboard plow</td>
<td>65.00</td>
</tr>
<tr>
<td>Soil finisher</td>
<td>Combination of:</td>
<td>25.80</td>
</tr>
<tr>
<td></td>
<td>Coulter tiller and spike harrow</td>
<td>19.00</td>
</tr>
<tr>
<td></td>
<td>Rolling basket</td>
<td>6.80</td>
</tr>
</tbody>
</table>

Source: Revised Universal Soil Loss Equation 2
<table>
<thead>
<tr>
<th></th>
<th>Field Crop</th>
<th>Vegetable</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of Respondents</strong></td>
<td>65</td>
<td>39</td>
</tr>
<tr>
<td><strong>Years Farming</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 years or less</td>
<td>4.6</td>
<td>7.7</td>
</tr>
<tr>
<td>6 to 10 years</td>
<td>10.8</td>
<td>33.3</td>
</tr>
<tr>
<td>11 to 15 years</td>
<td>7.7</td>
<td>10.3</td>
</tr>
<tr>
<td>16 to 20 years</td>
<td>7.7</td>
<td>17.9</td>
</tr>
<tr>
<td>21 to 30 years</td>
<td>12.3</td>
<td>10.3</td>
</tr>
<tr>
<td>31 to 40 years</td>
<td>32.3</td>
<td>10.3</td>
</tr>
<tr>
<td>41 to 50 years</td>
<td>12.3</td>
<td>7.7</td>
</tr>
<tr>
<td>over 50 years</td>
<td>10.8</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>Years Farming Organic</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 years or less</td>
<td>7.7</td>
<td>17.9</td>
</tr>
<tr>
<td>6 to 10 years</td>
<td>40.0</td>
<td>38.5</td>
</tr>
<tr>
<td>11 to 15 years</td>
<td>20.0</td>
<td>12.8</td>
</tr>
<tr>
<td>16 to 20 years</td>
<td>16.9</td>
<td>10.3</td>
</tr>
<tr>
<td>21 to 30 years</td>
<td>12.3</td>
<td>5.1</td>
</tr>
<tr>
<td>31 to 40 years</td>
<td>1.5</td>
<td>7.7</td>
</tr>
<tr>
<td>41 to 50 years</td>
<td>0.0</td>
<td>5.1</td>
</tr>
<tr>
<td><strong>Owner of Land</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>owner of farm, own land</td>
<td>66.2</td>
<td>71.8</td>
</tr>
<tr>
<td>owner of farm, rented land</td>
<td>3.1</td>
<td>10.3</td>
</tr>
<tr>
<td>manager of farm</td>
<td>1.5</td>
<td>7.7</td>
</tr>
<tr>
<td>owner of farm, partial land owner</td>
<td>27.7</td>
<td>10.3</td>
</tr>
<tr>
<td><strong>Organically Certified</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no</td>
<td>10.8</td>
<td>61.5</td>
</tr>
<tr>
<td>yes</td>
<td>89.2</td>
<td>38.5</td>
</tr>
<tr>
<td></td>
<td>Field Crop</td>
<td>Vegetable</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>------------</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>Percent income from farming</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 to 25</td>
<td>18.5</td>
<td>38.5</td>
</tr>
<tr>
<td>26 to 50</td>
<td>10.8</td>
<td>15.4</td>
</tr>
<tr>
<td>51 to 75</td>
<td>23.1</td>
<td>7.7</td>
</tr>
<tr>
<td>76 to 100</td>
<td>46.2</td>
<td>38.5</td>
</tr>
<tr>
<td><strong>Percent of work week spent farming</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 to 25</td>
<td>15.3</td>
<td>0</td>
</tr>
<tr>
<td>26 to 50</td>
<td>9.1</td>
<td>20.5</td>
</tr>
<tr>
<td>51 to 75</td>
<td>13.8</td>
<td>7.7</td>
</tr>
<tr>
<td>76 to 100</td>
<td>59.9</td>
<td>66.7</td>
</tr>
<tr>
<td><strong>Farm acreage breakdown in here</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 and under</td>
<td>10.8</td>
<td>71.8</td>
</tr>
<tr>
<td>10 to 50</td>
<td>10.8</td>
<td>23.1</td>
</tr>
<tr>
<td>50 to 100</td>
<td>13.8</td>
<td>2.6</td>
</tr>
<tr>
<td>100 to 500</td>
<td>43.1</td>
<td>2.6</td>
</tr>
<tr>
<td>500 and higher</td>
<td>20.0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Percent of sales of farm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vegetables</td>
<td>8.7</td>
<td>86.1</td>
</tr>
<tr>
<td>treefruit</td>
<td>5.9</td>
<td>2.1</td>
</tr>
<tr>
<td>small fruit</td>
<td>4.4</td>
<td>4.9</td>
</tr>
<tr>
<td>hay</td>
<td>4.9</td>
<td>0.3</td>
</tr>
<tr>
<td>livesotck</td>
<td>6.1</td>
<td>3.1</td>
</tr>
<tr>
<td>beans</td>
<td>21.9</td>
<td>0.3</td>
</tr>
<tr>
<td>grains</td>
<td>41.1</td>
<td>1.0</td>
</tr>
<tr>
<td>dairy</td>
<td>1.4</td>
<td>0.0</td>
</tr>
<tr>
<td>other</td>
<td>5.7</td>
<td>2.4</td>
</tr>
</tbody>
</table>
Table 1.3. Tillage and cultivation practices employed for the production of field corn, dry bean, and soybean.

<table>
<thead>
<tr>
<th>Tillage Type</th>
<th>Field Corn (%)</th>
<th>Dry Bean (%)</th>
<th>Soybean (%)</th>
<th>Mean number of tillage operations (#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field preparation*</td>
<td>60.9</td>
<td>71.4</td>
<td>35.3</td>
<td>1.0 1.0 1.0</td>
</tr>
<tr>
<td>Moldboard plow (MP)</td>
<td>4.3</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>MP+ Rototiller</td>
<td>39.1</td>
<td>0.0</td>
<td>11.8</td>
<td></td>
</tr>
<tr>
<td>MP+ Disc</td>
<td>21.7</td>
<td>14.3</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>MP+ Harrow</td>
<td>13.0</td>
<td>28.6</td>
<td>11.8</td>
<td></td>
</tr>
<tr>
<td>MP+ Soil finisher</td>
<td>21.7</td>
<td>28.6</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td>Chisel plow (CP)</td>
<td>34.8</td>
<td>14.3</td>
<td>47.1</td>
<td>1.4 1.0 1.2</td>
</tr>
<tr>
<td>CP+ Rototiller</td>
<td>8.7</td>
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<td>0.0</td>
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</tr>
<tr>
<td>CP+ Disc</td>
<td>17.4</td>
<td>0.0</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td>CP+ Harrow</td>
<td>4.3</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>CP+ Soil finisher</td>
<td>13.0</td>
<td>14.3</td>
<td>23.5</td>
<td></td>
</tr>
<tr>
<td>CP+ Field cultivator</td>
<td>17.4</td>
<td>0.0</td>
<td>11.8</td>
<td></td>
</tr>
<tr>
<td>Rototiller</td>
<td>13.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.7 - -</td>
</tr>
<tr>
<td>Disc</td>
<td>60.9</td>
<td>14.3</td>
<td>41.2</td>
<td>1.4 1.0 1.6</td>
</tr>
<tr>
<td>Harrow</td>
<td>21.7</td>
<td>14.3</td>
<td>5.9</td>
<td>1.0 3.0 1.0</td>
</tr>
<tr>
<td>Soil finisher</td>
<td>30.4</td>
<td>42.9</td>
<td>76.5</td>
<td>2.1 2.7 1.6</td>
</tr>
<tr>
<td>Field cultivator</td>
<td>34.8</td>
<td>42.9</td>
<td>29.4</td>
<td>2.4 3.0 1.9</td>
</tr>
<tr>
<td>Other</td>
<td>4.3</td>
<td>0.0</td>
<td>5.9</td>
<td>2.0 — 3.0</td>
</tr>
<tr>
<td>Weed cultivation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flextine</td>
<td>45.5</td>
<td>71.4</td>
<td>64.7</td>
<td>1.3 1.4 1.5</td>
</tr>
<tr>
<td>Rotary hoe</td>
<td>73.9</td>
<td>100.0</td>
<td>100.0</td>
<td>1.9 1.5 1.7</td>
</tr>
<tr>
<td>Row Crop Cultivator</td>
<td>91.3</td>
<td>100.0</td>
<td>100.0</td>
<td>2.3 2.9 2.6</td>
</tr>
<tr>
<td>Buffalo Cultivator</td>
<td>4.3</td>
<td>0.0</td>
<td>0.0</td>
<td>2.0 — —</td>
</tr>
</tbody>
</table>

*Tillage combinations may not necessarily be in order of tillage operations.
Table 1.4. Tillage and cultivation practices employed for the production of winter squash and broccoli.

<table>
<thead>
<tr>
<th>Tillage Type</th>
<th>Respondents that used the following tillage (%)</th>
<th>Mean number of tillage operations (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter Squash</td>
<td>Broccoli</td>
</tr>
<tr>
<td>Field Preparation*</td>
<td>n=26</td>
<td>n=17</td>
</tr>
<tr>
<td>Rototiller (RT)</td>
<td>65.4</td>
<td>64.7</td>
</tr>
<tr>
<td>RT+ Disc</td>
<td>26.9</td>
<td>11.8</td>
</tr>
<tr>
<td>RT+ Harrow</td>
<td>7.7</td>
<td>0.0</td>
</tr>
<tr>
<td>RT+ Soil finisher</td>
<td>3.8</td>
<td>0.0</td>
</tr>
<tr>
<td>RT+ Field cultivator</td>
<td>3.8</td>
<td>5.9</td>
</tr>
<tr>
<td>Moldboard plow (MP)</td>
<td>34.6</td>
<td>29.4</td>
</tr>
<tr>
<td>MP+ Rototiller</td>
<td>15.4</td>
<td>5.9</td>
</tr>
<tr>
<td>MP+ Disc</td>
<td>26.9</td>
<td>29.4</td>
</tr>
<tr>
<td>MP+ Harrow</td>
<td>7.7</td>
<td>23.5</td>
</tr>
<tr>
<td>MP+ Soil finisher</td>
<td>3.8</td>
<td>5.9</td>
</tr>
<tr>
<td>MP+ Field cultivator</td>
<td>3.8</td>
<td>5.9</td>
</tr>
<tr>
<td>Chisel plow (CP)</td>
<td>23.1</td>
<td>11.8</td>
</tr>
<tr>
<td>CP+ Disc</td>
<td>7.7</td>
<td>7.7</td>
</tr>
<tr>
<td>CP+ Harrow</td>
<td>7.7</td>
<td>7.7</td>
</tr>
<tr>
<td>CP+ Soil finisher</td>
<td>7.7</td>
<td>3.8</td>
</tr>
<tr>
<td>CP+ Field cultivator</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Disc</td>
<td>50.0</td>
<td>35.3</td>
</tr>
<tr>
<td>Harrow</td>
<td>26.9</td>
<td>23.5</td>
</tr>
<tr>
<td>Bed former</td>
<td>19.2</td>
<td>17.6</td>
</tr>
<tr>
<td>Soil finisher</td>
<td>7.7</td>
<td>0.1</td>
</tr>
<tr>
<td>Field cultivator</td>
<td>7.7</td>
<td>0.1</td>
</tr>
<tr>
<td>Other</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Weed Cultivation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexine</td>
<td>7.7</td>
<td>0.0</td>
</tr>
<tr>
<td>Rotary hoe</td>
<td>7.7</td>
<td>0.0</td>
</tr>
<tr>
<td>Fingerweeder</td>
<td>3.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Tine cultivator</td>
<td>0.0</td>
<td>5.9</td>
</tr>
<tr>
<td>Row Crop Cultivator</td>
<td>46.2</td>
<td>23.5</td>
</tr>
<tr>
<td>Rototiller</td>
<td>19.2</td>
<td>17.6</td>
</tr>
</tbody>
</table>

*Tillage combinations may not necessarily be in order of tillage operations.
Table 1.5. Spearman correlation of farm and farmer characteristics, as well as perceived barriers and benefits of RT adoption, with expressed interest in adoption of specific reduced till practices.

<table>
<thead>
<tr>
<th>Farm and Farmer Characteristics</th>
<th>No-till</th>
<th>Rotational</th>
<th>Strip-till</th>
<th>Permenant Beds</th>
<th>Ridge-till</th>
<th>Max interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years Farming</td>
<td>-0.226*</td>
<td>-0.140</td>
<td>-0.283**</td>
<td>-0.344**</td>
<td>-0.042</td>
<td>-0.242**</td>
</tr>
<tr>
<td>Percent of week spent farming</td>
<td>0.142</td>
<td>0.120</td>
<td>0.170</td>
<td>0.007</td>
<td>0.154</td>
<td>0.081</td>
</tr>
<tr>
<td>Percent of income from farming</td>
<td>-0.037</td>
<td>-0.014</td>
<td>-0.003</td>
<td>-0.199**</td>
<td>-0.086</td>
<td>-0.139</td>
</tr>
<tr>
<td>Acres farmed (2013)</td>
<td>-0.136</td>
<td>-0.036</td>
<td>-0.114</td>
<td>-0.391**</td>
<td>-0.079</td>
<td>-0.201*</td>
</tr>
<tr>
<td>Total number of tillage operations</td>
<td>-0.158</td>
<td>0.012</td>
<td>-0.046</td>
<td>-0.356**</td>
<td>0.014</td>
<td>-0.171</td>
</tr>
<tr>
<td>Percent clay†</td>
<td>-0.266**</td>
<td>-0.080</td>
<td>-0.074</td>
<td>-0.247*</td>
<td>0.122</td>
<td>-0.218*</td>
</tr>
<tr>
<td>Percent silt†</td>
<td>-0.304**</td>
<td>-0.050</td>
<td>-0.129</td>
<td>-0.333**</td>
<td>-0.008</td>
<td>-0.241*</td>
</tr>
<tr>
<td>Knowledge of Specific RT Practices</td>
<td>0.275**</td>
<td>0.304**</td>
<td>0.394**</td>
<td>0.460**</td>
<td>0.183</td>
<td>—</td>
</tr>
<tr>
<td>Barriers to Adoption</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment Cost</td>
<td>-0.006</td>
<td>0.180</td>
<td>0.088</td>
<td>0.075</td>
<td>0.135</td>
<td>0.144</td>
</tr>
<tr>
<td>Scale Appropriate Equipment</td>
<td>-0.019</td>
<td>0.063</td>
<td>0.111</td>
<td>0.147</td>
<td>0.180</td>
<td>0.117</td>
</tr>
<tr>
<td>Information is lacking</td>
<td>0.100</td>
<td>0.168</td>
<td>0.069</td>
<td>0.260**</td>
<td>0.184</td>
<td>0.218*</td>
</tr>
<tr>
<td>Learning new practice</td>
<td>0.082</td>
<td>0.040</td>
<td>0.021</td>
<td>0.112</td>
<td>0.012</td>
<td>0.055</td>
</tr>
<tr>
<td>Labor costs</td>
<td>-0.099</td>
<td>-0.104</td>
<td>-0.071</td>
<td>-0.101</td>
<td>0.010</td>
<td>-0.143</td>
</tr>
<tr>
<td>Decreased Yields</td>
<td>-0.265**</td>
<td>-0.113</td>
<td>-0.276**</td>
<td>-0.194</td>
<td>-0.084</td>
<td>-0.230*</td>
</tr>
<tr>
<td>Soil Fertility</td>
<td>-0.174</td>
<td>-0.082</td>
<td>-0.132</td>
<td>-0.063</td>
<td>-0.114</td>
<td>-0.183</td>
</tr>
<tr>
<td>Residue management</td>
<td>-0.297**</td>
<td>-0.133</td>
<td>-0.227*</td>
<td>-0.198</td>
<td>-0.303**</td>
<td>-0.230*</td>
</tr>
<tr>
<td>Crop Establishment</td>
<td>-0.275**</td>
<td>-0.159</td>
<td>-0.117</td>
<td>-0.241*</td>
<td>-0.187</td>
<td>-0.146</td>
</tr>
<tr>
<td>Insect Pressure</td>
<td>-0.115</td>
<td>-0.070</td>
<td>-0.131</td>
<td>-0.212*</td>
<td>-0.082</td>
<td>-0.236*</td>
</tr>
<tr>
<td>Disease Pressure</td>
<td>-0.089</td>
<td>0.0191</td>
<td>-0.112</td>
<td>-0.182</td>
<td>-0.012</td>
<td>-0.165</td>
</tr>
<tr>
<td>Weed Competition</td>
<td>-0.340**</td>
<td>-0.217*</td>
<td>-0.314**</td>
<td>-0.347**</td>
<td>-0.163</td>
<td>-0.349**</td>
</tr>
<tr>
<td>Benefits to Adoption</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Savings</td>
<td>0.481**</td>
<td>0.325**</td>
<td>0.367**</td>
<td>0.368**</td>
<td>0.235*</td>
<td>0.469**</td>
</tr>
<tr>
<td>Labor Reduction</td>
<td>0.472**</td>
<td>0.351**</td>
<td>0.347**</td>
<td>0.301**</td>
<td>0.202*</td>
<td>0.467**</td>
</tr>
<tr>
<td>Increased Yields</td>
<td>0.564**</td>
<td>0.399**</td>
<td>0.439**</td>
<td>0.310**</td>
<td>0.255**</td>
<td>0.521**</td>
</tr>
<tr>
<td>Decreased Erosion</td>
<td>0.362*</td>
<td>0.350**</td>
<td>0.315**</td>
<td>0.192</td>
<td>0.161</td>
<td>0.420</td>
</tr>
<tr>
<td>Increased Soil Organic Matter</td>
<td>0.483**</td>
<td>0.415**</td>
<td>0.418**</td>
<td>0.294*</td>
<td>0.307*</td>
<td>0.544**</td>
</tr>
<tr>
<td>Improved Soil Tilth</td>
<td>0.536**</td>
<td>0.440**</td>
<td>0.425**</td>
<td>0.322**</td>
<td>0.303**</td>
<td>0.564**</td>
</tr>
<tr>
<td>Reduced Compaction</td>
<td>0.514**</td>
<td>0.390**</td>
<td>0.375**</td>
<td>0.351**</td>
<td>0.215*</td>
<td>0.538**</td>
</tr>
<tr>
<td>Improved Water Infiltration</td>
<td>0.423**</td>
<td>0.390**</td>
<td>0.273**</td>
<td>0.251**</td>
<td>0.312**</td>
<td>0.460**</td>
</tr>
<tr>
<td>Increased Water Holding Capacity</td>
<td>0.484**</td>
<td>0.341**</td>
<td>0.342**</td>
<td>0.289**</td>
<td>0.248*</td>
<td>0.487**</td>
</tr>
<tr>
<td>Lower Insect Pressure</td>
<td>0.584**</td>
<td>0.379**</td>
<td>0.404**</td>
<td>0.316**</td>
<td>0.330**</td>
<td>0.550**</td>
</tr>
<tr>
<td>Reduced Disease Pressure</td>
<td>0.545**</td>
<td>0.289**</td>
<td>0.336**</td>
<td>0.281**</td>
<td>0.243*</td>
<td>0.457**</td>
</tr>
<tr>
<td>Reduced Weed Pressure</td>
<td>0.589**</td>
<td>0.330**</td>
<td>0.220**</td>
<td>0.316**</td>
<td>0.132</td>
<td>0.433**</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).
† Percent clay and percent silt are the maximum of all soil types responents stated were present on their farm. See Appendix 1.2 for coding.
Table 1.6. Results from a factor analysis of the perceived barriers to adoption of RT, as well as correlation with maximum expressed interest in RT adoption.

<table>
<thead>
<tr>
<th>Perceived Barriers</th>
<th>Factor Loadings</th>
<th>Community Loadings</th>
<th>% Variance Explained</th>
<th>Correlation with Maximum Expressed Interest in RT adoption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Factor 1</td>
<td>Factor 2</td>
<td>Factor 3</td>
<td>Factor 4</td>
</tr>
<tr>
<td>Disease Pressure</td>
<td>0.85</td>
<td>0.37</td>
<td>-0.02</td>
<td>0.14</td>
</tr>
<tr>
<td>Insect Pressure</td>
<td>0.73</td>
<td>0.48</td>
<td>-0.04</td>
<td>0.25</td>
</tr>
<tr>
<td>Labor costs</td>
<td>0.73</td>
<td>0.11</td>
<td>0.33</td>
<td>0.17</td>
</tr>
<tr>
<td>Soil Fertility</td>
<td>0.65</td>
<td>0.27</td>
<td>0.25</td>
<td>-0.01</td>
</tr>
<tr>
<td>Weed Competition</td>
<td>0.19</td>
<td>0.83</td>
<td>0.03</td>
<td>-0.06</td>
</tr>
<tr>
<td>Residue management</td>
<td>0.23</td>
<td>0.76</td>
<td>0.13</td>
<td>0.03</td>
</tr>
<tr>
<td>Crop Establishment</td>
<td>0.24</td>
<td>0.77</td>
<td>0.16</td>
<td>0.09</td>
</tr>
<tr>
<td>Decreased Yields</td>
<td>0.50</td>
<td>0.59</td>
<td>-0.07</td>
<td>0.23</td>
</tr>
<tr>
<td>Equipment Cost</td>
<td>0.20</td>
<td>0.02</td>
<td>0.92</td>
<td>0.06</td>
</tr>
<tr>
<td>Scale Appropriate Equipment</td>
<td>0.06</td>
<td>0.20</td>
<td>0.86</td>
<td>0.31</td>
</tr>
<tr>
<td>Information is lacking</td>
<td>0.03</td>
<td>0.06</td>
<td>0.28</td>
<td>0.89</td>
</tr>
<tr>
<td>Learning new practice</td>
<td>0.29</td>
<td>0.03</td>
<td>0.07</td>
<td>0.88</td>
</tr>
</tbody>
</table>

| Eigenvalue                 | 5.11    | 1.97    | 1.22    | 0.87    | —               |
| % variance explained       | 22.65   | 45.36   | 61.1    | 76.37   | —               |
| Correlation with Maximum Expressed Interest in RT adoption | -0.151 | -0.247 | 0.170  | 0.132  | —               |
Table 1.7. Coding used for percent clay and percent silt soil types for correlations in Table 1.4.

<table>
<thead>
<tr>
<th>Percent Clay §</th>
<th>Percent Silt §</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 sand</td>
<td>sand</td>
</tr>
<tr>
<td>2 loamy sand</td>
<td>loamy sand</td>
</tr>
<tr>
<td>3 sandy loam</td>
<td>sandy loam</td>
</tr>
<tr>
<td>4 loam</td>
<td>sandy clay loam</td>
</tr>
<tr>
<td>5 silt loam</td>
<td>sandy clay loam</td>
</tr>
<tr>
<td>6 silt</td>
<td>clay</td>
</tr>
<tr>
<td>7 sandy clay loam</td>
<td>clay loam</td>
</tr>
<tr>
<td>8 clay loam</td>
<td>loam</td>
</tr>
<tr>
<td>9 silty clay loam</td>
<td>silty clay</td>
</tr>
<tr>
<td>10 sandy clay</td>
<td>silty clay loam</td>
</tr>
<tr>
<td>11 silty clay</td>
<td>silt loam</td>
</tr>
<tr>
<td>12 clay</td>
<td>silt</td>
</tr>
</tbody>
</table>

§ Numbers based on responses in soil texture triangle in Appendix 1.1.

*Muck or other soil types were eliminated from
Demographics by Region

North & Upper Peninsula
- N=10
- Response rate= 31%
- 30% Field crops (median acreage= 20)
- 70% Vegetables (median acreage= 4)
- Dominant soil: sandy loam, sandy clay

Central West
- N=13
- Response rate= 33%
- 54% Field crops (median acreage= 70)
- 46% Vegetables (median acreage= 4)
- Dominant soil: clay, clay loam, sandy loam

Southwest
- N=15
- Response rate= 38%
- 33% Field crops (median acreage= 43)
- 66% Vegetables (median acreage= 3)
- Dominant soil: sandy loam, sandy clay loam

Central
- N=15
- Response rate= 37%
- 80% Field crops (median acreage= 210)
- 20% Vegetables (median acreage= 8)
- Dominant soil: clay loam, sandy loam

Thumb
- N=27
- Response rate= 34%
- 93% Field crops (median acreage= 350)
- 7% Vegetables (median acreage= 13)
- Dominant soil: clay loam, clay, sandy loam

Southeast
- N=15
- Response rate= 33%
- 27% Field crops (median acreage= 269)
- 67% Vegetables (median acreage= 8)
- Dominant soil: sandy loam

Figure 1.1. Principle crop, acreage and soil type of survey respondents by Michigan region.
Figure 1.2. Percentage of organic field crop and vegetable producers in Michigan that have access to tillage and agricultural equipment.
Figure 1.3. Distributions of the number of tillage passes utilized for cultivation (A), field preparation (B), and cumulative total (C) for broccoli, winter squash, field corn, dry bean, and soybean. The y-axis is the probability density of a given number of tillage passes, and was determined using kernel density estimation.
Figure 1.4. Distributions of the cumulative STIR values for tillage utilized in the production of broccoli, winter squash, field corn, dry bean, and soybean. The y-axis is the probability density of a given number of tillage operations, and was determined using kernel density estimation.
Figure 1.5. Distribution and median (●) of survey respondents' expressed interest in adoption (left) and perceived knowledge of specific RT practices (right) on a 0 to 7 Likert scale. The width of violin plots represents the range of interest, and the height at any point represents the proportion of respondents with that score. 0 = No interest/ knowledge, 7 = Extremely interested/ knowledgeable.
Figure 1.6. Distribution and median (●) of survey respondents perceptions of the benefits to RT adoption on a 0 to 7 Likert scale. The width of violin plots represents the range of interest, and the height at any point represents the proportion of respondents with that score. 0=Not a likely benefit, 7=Extremely likely benefit.
Figure 1.7. Distribution and median (●) of survey respondents perceptions of the barriers to RT adoption on a 0 to 7 Likert scale. The width of violin plots represents the range of interest, and the height at any point represents the proportion of respondents with that score. 0= Not a likely barrier, 7= Extremely likely barrier.


CHAPTER TWO
Strip-tillage influences N availability and losses in an organic system

ABSTRACT
Developing reduced-tillage systems that increase inorganic N (IN) availability while decreasing N losses, is important for increasing nitrogen-use efficiency within legume-based systems. We conducted a field study from 2011 to 2014 in southwest Michigan to examine the effects of strip-tillage and a cereal rye and hairy vetch cover crop mixture (RV) on 1) season long IN availability, 2) N mineralization potential (PMN), and 3) the potential for N losses through denitrification and leaching. Treatments consisted of tillage (full-width tillage [FWT] and strip-tillage [ST]) and cover crop (RV and no cover crop [NoRV]). ST had no effect on PMN in the first half of the sweet corn season, but reduced PMN in the second half of the season when combined with RV. ST decreased IN availability 16 to 40% compared to FWT. Within ST, IN was higher in the in-row zone compared to the undisturbed between-row zone in 1 out of 3 years. The RV cover crop did not provide any consistent increase in soil IN. Across the three years of this study, ST increased the concentration of N within the soil leachate by approximately 50% and increased the potential for denitrification by 18%. However, despite lower soil IN, ST only resulted in negative effects on corn biomass and N content in 2013, the year with the lowest hairy vetch biomass. ST increased soil gravimetric moisture in 2012 and 2014, which may have compensated for the lower IN. More research is needed to determine strategies to increase nitrogen use efficiency and decrease N losses in legume-based reduced-till systems.
INTRODUCTION

Reducing tillage can provide a number of ecological and agronomic benefits, including increased soil aggregation and organic matter accumulation (Wander and Bollero, 1999; Franzluebbers 2002; West and Post, 2002; Bhardwaj et al. 2011), as well as reduced soil erosion (Karlen et al 1994, Triplett and Dick, 2008) and fuel use (Phillips et al. 1980; Gebhardt et al. 1985). Reduced-tillage (RT) practices are also being promoted as an effective strategy to both mitigate and adapt to climate change (Pittelkow et al. 2014) due to their potential for C sequestration (Lal and Kimble, 1997), as well as increased soil water infiltration and water holding capacity (Franzluebbers, 2002; Mahli and O’Sullivan 1990). However, tillage performs a number of important services to a cropping system, such as weed control and the incorporation of plant residues. Reducing or eliminating tillage may result in poor crop establishment due to reduced soil temperatures and residue interference (Mahli and O’Sullivan 1990; Mirsky et al. 2012), greater weed competition (Brainard et al. 2013, Mirsky et al. 2012), and reduced inorganic N availability (Dou et al. 1994; Doane et al. 2009).

Tillage stimulates N mineralization by incorporating plant residues (Varco et al. 1993), increasing soil aeration, and exposing occluded soil organic matter via aggregate fragmentation (Grandy and Robertson, 2006). In the absence of tillage, reduced plant available N has been widely reported in both legume and fertilizer based systems (Dou et al. 1995; Johnson and Hoyt, 1999). In legume-based no-till systems, residues remain on the soil surface, resulting in lower soil-residue contact and reduced rates of decomposition and N mineralization (Varco et al. 1993; Dou et al. 1994; Drinkwater et al. 2000). For example, hairy vetch residues left on the soil surface lost
45% of their original weight over 30 days, compared to 77% decomposition when residues were buried in the soil (Varco et al. 1993). Lower N mineralization from legume residues within RT systems is especially problematic in years or sites with cool or dry soil conditions (Dou et al. 1995; Rannells and Wagger, 1996; Ruffo and Bollero, 2003; Cook et al. 2010).

Despite having lower pools of inorganic N, no-till systems can result in equal or greater N uptake and productivity (Reeves et al. 1997), and may (Drinkwater et al. 2000; Doane et al. 2009) or may not (Cline and Silvernail et al. 2002; Cook et al. 2010) lead to decreased yields. Sustained N recovery despite lower soil inorganic N may be the result of greater synchronization between N availability and crop N demand. Conventionally tilled legume-based systems generally exhibit a large pulse of inorganic N early in the season, prior to crop exponential growth (Dou et al. 1994; Kuo et al. 1996). The slower period of N mineralization within RT may more closely reflect the timing of crop N demand. Slower decomposition and mineralization of plant residues may contribute to the build-up of organic pools of N and other nutrients (Kuo et al. 1997; Sainju et al. 2002).

Lower pools of inorganic N in no till systems may decrease reactive N lost to the environment through leaching or denitrification (Dinnes et al. 2002; Constantin et al. 2010). A long-term comparison of no-till to conventional tillage within a corn-soybean-winter wheat rotation found that no-till resulted in approximately 35% lower leaching compared to conventional tillage (Syswerda et al. 2012). However, no-till systems have greater intact soil pores, which can increase hydraulic conductivity and soil water drainage (Benjamin, 1993; Odgen et al. 1999). Thus, even if the concentration of N
within the soil leachate is equal to or lower than conventional tillage, no till may increase N leaching when differences in water drainage are taken into account (Izaurralde at al. 1995; Syswerda et al. 2012).

Tillage elimination can also have varying effects on N lost to denitrification. No-till is often associated with increased soil moisture and bulk density, factors that promote denitrification via reductions in oxygen levels (Smith and Tiedje, 1979; Groffman 1985; Palma et al. 1997). Denitrification is often carbon limited in agricultural systems (Luo et al. 1998 Kennedy et al. 2013), and when crop residues are incorporated into the soil they result in a pulse of high initial denitrification (Aulakh 1991). Residue mulches often decrease soil temperatures, which may also decrease rates of denitrification (Keeney et al. 1979; Maag and Vinther, 1996).

Developing reduced-tillage systems that increase inorganic N availability while decreasing N losses is essential to increasing nitrogen use efficiency, and may increase productivity, especially in organic or legume-based systems. Strip-tillage (ST) utilizes a combination of narrowly placed disks and rolling baskets (often attached to a shank) to confine tillage to a narrow strip where the crop will be planted (Luna and Staben, 2002). This divides the cropping system into two distinct adjacent zones: tilled and untilled. Tillage within the crop row creates a finer seedbed into which the crop will be planted (Licht and Al-Kaisi, 2005). The untilled zone between-row (BR) maintains the benefits of no till, such as improved water infiltration, organic matter retention, and decreased erosion (Karlen et al. 1994; Johnson and Hoyt, 1999; Franzluebbers, 2002). Strip-tillage enables a greater level of control over organic matter turnover. Incorporating crop residue within-row (WR) enables faster decomposition and mineralization of organic
matter to increase nutrient availability within the crop rooting zone. The BR zone is left undisturbed, and when combined with a preceding cover crop, residue is preserved on the soil surface for weed suppression, soil moisture conservation, and reduced soil erosion (Mohler and Teasdale, 1993; Unger and Vigil, 1998).

Compared to no-till and conventional systems, strip-tillage effects on soil N dynamics have been much less studied. Haramoto and Brainard (2012) found that in the absence of a cover crop, ST decreased inorganic N within the crop row compared to full-width tillage; however, when an oats cover crop was present, N availability was equivalent in the two tillage systems. Compared to no-till, Sainju et al. (2007) found ST increased inorganic N compared to no-till. Al-Kaisi and Licht (2004) found few significant differences in N concentration of soil leachate between no-till, strip-till, and conventional till, however, they did find that like no-till, strip-tillage resulted in lower N accumulation within the soil profile at deeper depths. Sainju et al. (2007) did not find any difference in N accumulated in the soil profile between ST and full-width tillage (FWT). Thus far, research on strip-tillage effects on inorganic N and N losses has been confined to conventional systems. It is not yet clear how ST may affect the fate of N in a legume-based organic system.

The objectives of this study were to examine the effects that strip-tillage has on 1) season long inorganic N availability, 2) the potential for N mineralization, 3) crop N uptake, and 4) the potential for N losses through denitrification and leaching. In addition, we evaluated whether these effects varied between zones (within- and between-crop rows) within the cropping system. We hypothesized that strip-tillage would have lower total inorganic N availability, but a greater proportion of its available N concentrated
within the crop row (WR) and thus result in a lower potential for N losses, and greater N uptake by the crop. A secondary objective was to examine how a rye and vetch cover crop interacts with strip-tillage to affect inorganic N availability, potentially mineralizeable N, sweet corn biomass and N uptake, and the potential for N losses.

**MATERIALS AND METHODS**

**Site description and experimental design**

The experiment was conducted between 2011-2014 on organically managed (approximately 5-7 years, depending on field) Kalamazoo (fine-loamy, mixed, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, mesic Typic Hapludalfs) loams (Crum and Collins, 1995), at the Kellogg Biological Station in Hickory Corners, MI (85° 24’W, 42° 24’ N).

Treatments were arranged in a split plot, randomized complete block design with four replicates. Main plots consisted of a 2 X 2 factorial of cover crop (Rye-vetch [RV] and no cover crop [NoRV]) and tillage (Strip-tillage [ST] and Full-width tillage [FWT]). The split plot factor was crop (sweet corn [CORN] or no crop [NOCORN]). Zones within the cropping system were also treated as subsubplots. The zone within the crop row (WR) was defined as the 25 cm zone where the crop was planted and where tillage occurred within strip-tilled treatments. The between-row (BR) zone was defined as the 50 cm zone between crop rows that was left untilled in strip-tilled treatments. The area of the sub-plots with corn (CORN) was 27.3 m² (9.1 m X 3.0 m), 37.2 m² (6.1 m X 6.1 m), and 41.0 m² (9.1 m X 4.5 m) in 2012, 2013, and 2014 respectively. Subplots without corn were 9.0 m² (3.0 m X 3.0 m) in 2012 and 2013, and 20.3 m² (4.5 m X 4.5 m) in 2014.
Field activities were performed according to Table 2.1. Both cereal rye and hairy vetch seeds were “Variety Not Stated” and organically certified across all three years. Cereal rye was planted with a grain drill at 62.7 kg ha\(^{-1}\). Hairy vetch was planted with a Jang push-seeder at 22.4 kg ha\(^{-1}\). Between-row spacing for rye and vetch was 19 cm. No N fertilizers were added prior to cover crop establishment. Additional organic forms of P and K were added according to soil tests, and consisted of: 34 kg K and P ha\(^{-1}\) of NOP certified Potassium Sulfate Plus and Tennessee Brown Phosphate in 2012 and 34 kg K ha\(^{-1}\) of Potassium Sulfate Plus in 2013.

Cover crops were flail mowed twice once vetch had reached approximately 50% flowering in mid- to late-May of 2012, 2013, and 2014. Full-width tillage treatments were chisel plowed, and then rototilled to break up cover crop residue. A Hiniker Model 6000 two-row strip tiller (equipped with cutting-coulters, shank point assembly, berming discs, and rolling basket) was used for WR tillage in zone tilled treatments. To improve soil tilth for planting in ST treatments, a walk behind rototiller was used for WR secondary-tillage. The resulting WR zone was approximately 25 cm wide and 25-30 cm deep. Two weeks after tillage, sweet corn was planted in all treatments using a high residue planter (Monosem vacuum seeder) at a between-row spacing of 76 cm and in-row spacing of 10 cm. Once sweet corn emerged, population density was thinned to an in-row spacing of 16.5 cm in CORN treatments, and removed via hoeing from NOCORN subplots. Weeds were controlled through a combination of hand weeding and hoeing. Sweet corn was irrigated during low-rainfall periods in 2012 and 2014, totaling 62.2 and 46.8 mm of irrigated water, respectively throughout the sweet corn season. In 2013, rainfall was sufficient so we did not provide any additional irrigation.
Data collection

Potentially mineralizable N. In situ N mineralization assays were employed to evaluate the potential for N release from cover crop residues within each tillage system (Robertson, et al. 1999). In situ or in field mineralization incubations incorporate effects that tillage and cover crop mulch have on soil structure, moisture, and temperature, as well as the subsequent effect these differences have on N mineralization. Incubations were initiated at two time points: 7 and 35 days after tillage. Five cm internal diameter (24 cm depth) PVC pipes were installed in both the WR and BR zones (3 cores per zone and tillage combination) within the sweet corn subplots and capped until core removal. At installation, we collected two soil samples directly adjacent to installed cores at the start of incubation and extracted for inorganic N to determine initial inorganic N. We removed soil cores after 30 to 35 days and measured soil for gravimetric moisture and inorganic N.

Mineralization per day was calculated according to the following equation:

\[
N_{\text{mineralized}} = \frac{(\text{Nitrate}_{\text{final}} + \text{Ammonium}_{\text{final}}) - (\text{Nitrate}_{\text{initial}} + \text{Ammonium}_{\text{initial}})}{T_{\text{days}}}
\]

Bulk density. Upon mineralization tube extraction, soil cores removed from the same plot and zone (WR and BR) were pooled, homogenized, and weighed. Two 10 g subsamples were then removed for gravimetric soil moisture to determine soil dry weight (see Equation 2.2). Bulk density was then calculated by dividing soil dry weight by soil volume (total volume of the pooled cores). If soil was missing from the tube bottom, we measured the length of tube with soil missing to estimate the volume of each soil core for calculation of bulk density.
Soil sampling - Inorganic N and gravimetric soil moisture. Soil samples were collected every 7-14 days (totaling 8 sampling times in 2012 and 2013, and 9 sampling points in 2014), throughout the growing season in all treatments and subplots in both the WR and BR. At each sampling date, approximately 12 cores (2.5 cm diameter and 20 cm deep) were taken from each plot and zone. Soil samples were dried at 38°C for 2 to 3 days, and ground. Fifty milliliters of 1M KCl were used to extract soil inorganic N on 10 g of dry soil and samples were analyzed on a QuikChem 8500 Flow Injection Analyzer (Gelderman and Beegle, 1998). Two 10 g subsamples of moist soil were dried at 100°C and reweighed for gravimetric soil moisture. Gravimetric water content (GWC) was calculated according to the following:

\[
GWC = \frac{(g\ moist\ soil - g\ dry\ soil)}{g\ dry\ soil}
\]

To calculate the soil inorganic N and gravimetric moisture across the whole plot, we used weighted means of the measured values from the WR and BR zones adjusted by their respective areas. For example, for inorganic N (IN) we used:

\[
IN_{whole\ plot} = IN_{WR} \times 1/3 + IN_{BR} \times 2/3
\]

Where the within-row (WR) zone is the 25 cm zone where the crop is planted (and where tillage occurs within strip-tilled treatments), and the between-row (BR) zone is the 50 cm zone between crop rows and also is untilled in strip-tilled treatments.

Sweet corn biomass and N content. At harvest, we removed all primary ears from sweet corn plants in a designated harvest area of 9.3, 14, and 22.3 m² in 2012, 2013, and 2014, respectively. Secondary corn ears were grouped in with nonharvested biomass and consisted of no greater than 5% of total non-harvested biomass. To obtain plant dry weight and percent N, we collected the non-harvested aboveground portion of 5...
randomly sampled plants from each plot, and 5 representative corn ears. We removed a 2.5 cm section from corn ears (taken 2.5 cm away from the base of the ear), dried to determine a fresh to dry weight ratio, and multiplied this ratio by total fresh weight to estimate total ear dry weight. Both nonharvested corn biomass and corn ear sections were dried at 60°C and ground to pass through a 1 mm screen. A Kjehldahl digest (Kalra, 1998) was performed on 0.15 g samples of nonharvested corn biomass and corn ears (2 lab replicates per sample) and analyzed for total Kjehldahl nitrogen with a QuikChem 8500 Flow Injection Analyzer.

Leachate inorganic N. Suction lysimeters (Soil Moisture Corps model no. 1920) were installed to a depth of 1.2 m to examine the effects of tillage (FWT vs ST) on inorganic N concentration of the soil leachate within sweet corn subplots, and only within treatments with a rye and vetch cover crop. In Year 1, lysimeters were installed in November 2011, during cover crop growth, but damage to cover crops was minimized. In both Years 2 and 3, lysimeters were installed in early Fall, prior to cover crop planting (Table 2.1). A 5 cm auger was used to hollow out the lysimeter cavity. We then inserted lysimeters into the hole and a silica-sand slurry was used to fill the gap between the cavity wall and the lysimeter. Once lysimeters were in place soil was sieved and the hole was refilled, and bentonite clay was added to minimize preferential flow. Trenches (30 to 35 cm depth) were created to run sample collection tubes outside of the plot. Soil water samples were collected within 48 hours of every significant rainfall (when precipitation exceeded approximately 2 cm) or irrigation event to determine the concentration of nitrate present in the soil water below the rooting zone of the crop.
Vacuum pressure was applied to approximately 60 psi and left overnight; samples were collected within 48 hours of vacuum pressure being applied.

**Volumetric soil moisture.** A Sentek™ Diviner 2000 capacitance probe was used to estimate the volumetric water content (VWC) of the soil in 10 cm increments to a depth of 1 m in 2013 and 2014. Diviner tubes (5 cm diameter X 100 cm deep) were installed within sweet corn subplots on the border of WR/BR zone. VWC measurements were used to evaluate differences in water content within the soil profile of tillage and cover crop treatments to help determine if differences in the concentration of nitrate in soil leachate samples were due to differences in quantity of nitrate or to water moving though the soil profile.

**Denitrification potential.** The denitrification enzyme assay (Groffman et al. 1999) was utilized to evaluate the potential for denitrification in ST and FWT, with and without a RV cover crop, at three time points during the season in 2013 and 2014. Soil was collected at planting, midseason and harvest. Soil samples were collected from each tillage, zone (WR and BR), and cover crop combination taken in subplots with sweet corn present. Separate soil cores were taken for WR and BR zones down to 20 cm, aggregated, and kept at field moisture in 4°C conditions until time of enzyme assay. Soil was passed through a 4 mm sieve, and 25 g of moist soil was weighed into 125 ml Erlenmeyer flasks and used for incubation. Soil was combined with 25 mL of a 2X DEA media (1.44 g/L \(\text{KNO}_3\), 0.02 g/L chloramphenicol, and 0.5 g/L dextrose), and flasks were sealed and flushed with \(\text{N}_2\) gas. Thirteen ml of acetylene gas was added (approximately 10% of headspace), and flasks were placed on an orbital shaker for 90 minutes. Headspace samples were collected at 30, 60, and 90 min and stored in evacuated glass exetainers,
Samples were analyzed using a gas chromatograph equipped with a 63Ni electron capture detector operating at 350°C. The N₂O dissolved in the slurry was calculated using the Bunsen coefficient of 0.632 for 20°C (Groffman et al. 1999). Denitrifying enzyme activity was calculated from N₂O accumulation over time using linear regression.

**Statistical analysis**

All data were analyzed using mixed models ANOVA with MIXED procedures in SAS (Version 9.3, SAS Institute, Cary, NC). Year was initially treated as a fixed factor to determine if fixed effects interacted with year to affect response variables, and if there was no difference year was pooled. In all cases, block was nested in year, and block and interactions of block with fixed factors were treated as random effects. We evaluated assumptions of normality and homogenous variances, and used unequal variance models where appropriate. All inorganic N data were log-transformed.

The fixed effects of tillage (FWT vs ST), cover crop (RV vs NoRV), zone (WR vs BR), crop (sweet corn vs none), and their interactions on N mineralization potential, N availability, and potential denitrification were analyzed. For N leachate data, only the fixed effects of tillage were analyzed, since leachate was collected only from corn subplots in treatments with rye and vetch. For corn N uptake and N partitioning, only the effects of tillage and cover crop were examined. For N leachate, IN, and gravimetric and volumetric soil water content, date was included as a repeated factor and repeated measures mixed models were performed and AIC and BIC values were compared to determine the best model fit. When significant treatment effects were detected, means were separated using Fisher's protected LSD $P < 0.05$. In cases where $P$-values were
between 0.05 and 0.10, differences are reported as “marginally significant” with the P-value presented parenthetically. All figures were made using the GGPlot2 package in R (Wickham, 2009).

RESULTS

Cover crop and weed biomass and C:N ratio

The RV cover crop mixtures contained approximately 2.7, 1.3, and 3.0 Mg ha\(^{-1}\) of hairy vetch above-ground biomass, and 5.5, 4.7 and 4.7 Mg ha\(^{-1}\) of cereal rye above-ground biomass in 2012, 2013, and 2014, respectively (Table 3.5, Figure 3.4). Total biomass in these treatments was therefore 8.2, 5.9, and 7.7 Mg ha\(^{-1}\) in 2012, 2013, and 2014, respectively. The C:N ratio of this RV aboveground biomass was approximately 43, 40, and 31 in 2012, 2013, 2014, respectively. Winter annual weed biomass within the NoRV treatments was approximately 3.0, 2.0, and 2.2 Mg ha\(^{-1}\) in 2012, 2013, and 2014. Winter annual weed biomass within the RV treatments was 1.5, 0.42, and 0.58 Mg ha\(^{-1}\) in 2012, 2013, and 2014, respectively. The mean C:N ratio of winter annual weeds was 37, 28, and 23 in 2012, 2013, and 2014, respectively. Winter annual weed C:N was only measured in NoRV treatments.

Potentially mineralizable N

Potentially minearizable N (PMN) was measured from planting to mid-season (Early) and mid-season to harvest (Late) in 2012, 2013, and 2014 (Figure 2.1). For both Early and Late N mineralization potentials, there were no interactions of year with either the cover crop or tillage factors. RV increased Early N mineralization potential by 23% compared to the NoRV control \((P = 0.03)\) but no significant tillage main effects or interactions were detected. For Late N mineralization, the effect of the RV cover crop
depended on tillage system (Till*Cover, \( P = 0.009 \)); RV increased Late N mineralization potential by 50% within FWT, but had no detectable effect within ST.

**Inorganic N availability**

The NOCORN subplots allow us to examine patterns in IN availability without crop interference. The effects of tillage on soil inorganic N (IN) in the absence of sweet corn varied with sampling time in two of three years, but rarely varied with cover crop (Table 2.2, Figure 2.2). In 2013 and 2014, ST reduced total IN availability by approximately 40% compared to FWT, with the greatest differences occurring after mid-July in both years. In 2012, a much smaller and only marginally significant \( P=0.088 \) reduction in IN in ST compared to FWT was observed (Table 2.2, Figure 2.2).

In the presence of sweet corn, IN was also lower in ST compared to FWT in 2013 and 2014, with the effect in both years depending strongly on sampling date (Table 2.2, Figure 2.2). Due to crop depletion of IN, fewer and smaller tillage differences in IN were observed, especially at later planting dates; the effect of tillage tended to increase until mid-July to August when soil inorganic N peaked, and then decrease until the end of the season during corn exponential growth and peak N demand (Figure 2.2). In all three years, no differences in IN were observed at the time of crop harvest, suggesting that the potential for post-harvest differences in leaching due to different residual N levels were minimal.

The rye and vetch cover crop had minimal effects on IN, which varied by year. In 2012, in both CORN and NOCORN plots, cover crop had no detectable effect on IN (Table 2.2, Figure 2.2). In 2013 within NOCORN subplots, there was a marginal interaction of cover crop, tillage, and sampling date \( P=0.059 \). Within ST, RV increased
inorganic N compared to NoRV early in the season, but lowered IN throughout the month of August; however under FWT, RV only increased IN at sweet corn harvest. In 2013 with sweet corn present, RV increased inorganic N within FWT during the month of July, but RV had no effect on IN within ST. In 2014, RV increased IN at planting in NOCORN subplots, (Table 2.2, Figure 2.3), and at one time-point in early August in the presence of sweet corn (Figure 2.2).

Within NOCORN subplots, tillage effects on IN availability within tillage zones (WR vs BR) differed by year, but did not interact with cover crop and rarely interacted with date (Table 2.3, Figure 2.3). In 2012, we detected no significant effect of tillage or cover crop on IN by zone. In 2013, the WR zone had significantly greater IN availability than the BR zone within ST plots, and both the WR and BR within FWT were greater than ST ($P = 0.028$). In 2014, IN was higher in both the WR and BR of FWT than ST, but the WR zone of ST was higher than the BR only on the last sampling date, and this effect was only marginally significant (Till*Zone*Date, $P = 0.094$).

**Gravimetric soil moisture**

In all three years we analyzed the effects of zone (WR and BR) on gravimetric soil moisture in CORN subplots, and found no interactions with tillage, cover crop, and date in any year (data not shown) so the data was used to calculate gravimetric moisture across the whole plot. The BR zone had approximately 1 to 2% greater gravimetric moisture compared to the WR.

Tillage effects on gravimetric soil moisture did not interact with cover crop in any of the three years, but did interact with date in 2012, and there was a marginal interaction with date in 2013 and 2014 (Table 2.4, Figure 2.4). In 2012, ST increased
gravimetric soil moisture by approximately 9%, and the difference between ST and FWT was greatest in mid-July. In 2013, FWT resulted in a marginal increase in soil moisture at sweet corn planting, but we found no detectable difference between tillage systems throughout the rest of the sweet corn season. In 2014, ST increased gravimetric moisture by an average of 7% throughout the sweet corn season, and this difference was greater at the end of July and end of August.

Cover crop effects on gravimetric soil moisture interacted with date in 2012 and 2014, but did not interact with tillage in any year (Table 2.4, Figure 2.4). RV increased gravimetric soil moisture by 5, 12, and 6% compared to NoRV in 2012, 2013, and 2014, respectively. In 2012, the greatest increase in soil moisture due to RV was in mid-July, while in 2014 the difference was greatest at the end of July and end of August.

**Volumetric soil moisture**

Volumetric soil moisture in both 2013 and 2014 can be found in Table 2.5 and Figure 2.5. ST increased soil moisture in 2013 at the 0.1 to 0.3 m depth (Till, P=0.012), and marginally increased soil moisture in 2014 at the 0.8 to 0.9 m depth. We found no effect of cover crop, and no interactions of tillage or cover crop with date.

**Sweet corn biomass and N content**

Tillage effects on sweet corn ear and nonharvested biomass interacted with cover crop in 2012, but did not interact with cover crop in 2013 and 2014 (Table 2.6, Figure 2.6). In 2012, tillage had no effect on sweet corn ear weight, however ST increased sweet corn nonharvested biomass by 44% within RV but not when combined with NoRV. In 2013, ST decreased nonharvested biomass by 11% compared to FWT, but had no effect on sweet corn ear weight. In 2014, ST increased sweet corn ear weight,
but had no effect on nonharvested biomass. Tillage had no effect on biomass partitioning in 2012 and 2013, and sweet corn ear biomass constituted approximately 46% and 32% in 2012 and 2013, respectively. In 2014, ST increased biomass partitioned to sweet corn ears, and sweet corn ear weight was 32 and 37% in ST and FWT, respectively.

Tillage effects on total sweet corn aboveground N content interacted with cover crop in 2012, but not in 2013, and we found no detectable effect of tillage in 2014. (Table 2.6, Figure 2.6). In 2012, ST+RV increased sweet corn N content compared to FWT+RV within RV, but tillage had no effect within NoRV. In 2013, ST reduced N uptake by 25%.

In 2012, RV increased sweet corn ear weight across both tillage systems; RV also increased sweet corn nonharvested biomass by 70% in ST, but had no effect within FWT (Table 2.6, Figure 2.6). In 2013, RV increased sweet corn nonharvested biomass, but had no effect on sweet corn ear weight. In 2014, RV increased sweet corn nonharvested biomass and sweet corn ear dry weight. Cover crop had no effect on biomass partitioning in any of the three years.

RV effects on sweet corn N content interacted with tillage in 2012, but not in 2013 or 2014. In 2012, RV increased sweet corn N content by approximately 65% in ST, but only 22% in FWT. In 2013, RV increased N content of nonharvested biomass, but had no effect on N content of sweet corn ears or total plant N. In 2014, RV increased total N content by 24% compared to NoRV.

Neither tillage nor cover crop affected N partitioning to sweet corn nonharvested biomass or corn ears in any of the three years. In 2012, 50-60% of N was partitioned to
the sweet corn ear. In 2013 and 2014, there was lower N partitioned to the corn ear, constituting 41 and 33% of total aboveground sweet corn N uptake in 2013 and 2014, respectively.

**Soil leachate N**

Strip tillage increased the concentration of N within the soil leachate by approximately 50% compared to FWT (Till, $P=0.0113$; Figure 2.7). In 2012 and 2014, N concentration within the soil leachate of ST systems tended to increase throughout the season, peaking at 20 mg L$^{-1}$ in 2012 and 25 mg L$^{-1}$ in 2014, while the FWT peaked in mid-August at 10 mg L$^{-1}$ in 2012 and 17 mg L$^{-1}$ in 2014. In 2013, in both FWT and ST leachate N concentration peaked in early August at 25 mg L$^{-1}$ in ST and 20 mg L$^{-1}$ in FWT, and then sharply declined till leachate N concentration was approximately 7 mg L$^{-1}$ in both tillage systems. N concentration in the soil leachate was measured within the spring of 2013 and 2014, but leachate N concentration during cover crop growth was negligible so spring data was not included in the analysis.

**Denitrification potential**

Tillage effects on denitrification potential across the whole plot did not interact with cover crop, year, or time-point (Figure 2.8). ST increased denitrification potential by 18% compared to FWT (Till, $P=0.024$). When we analyzed denitrification potential within zones of ST and FWT, we found that the two tillage systems showed different patterns in denitrification potential between the WR and BR zones (Figures 2.9-A and 2.9-B). At planting, ST resulted in 90% greater denitrification potential in the BR compared to the WR zone (Figure 2.9-A, Till*Zone, $P<0.016$), and 33% greater denitrification potential in the BR compared to the WR at later sampling dates (Fig 2.9-B). In contrast, FWT
resulted in 30% greater denitrification potential within the WR compared to the BR at the late sampling points (Figure 2.9-B, Till*Zone, $P < 0.0001$).

Cover crop effects on denitrification potential varied with zone at late (Mid-Season and Harvest combined) sampling points (Figures 2.9-D). Denitrification potential was lower in the WR zone of NoRV treatments compared to the BR zone and compared to the RV WR and BR (Cover*Zone, $P = 0.0226$), but we detected no zonal differences between the WR and BR of RV.

**DISCUSSION**

**Potentially mineralizable N and soil inorganic N**

Residues tend to decompose slower when left on the soil surface, compared to when incorporated into the soil (Mulvaney et al. 2010). Therefore, we expected to find lower PMN in ST compared to FWT. However, we only found lower PMN within ST in the latter part of the sweet corn season, when RV offered no additional N mineralization compared to the NoRV within ST. This is consistent with other studies that found mineralization of legume-cereal mixtures in RT decreases PMN in second half of season (Rannells and Wagger, 1996).

Contrary to our expectations, we found no consistent benefit in IN from a RV cover crop (Figure 2.2). Legume-cereal mixtures are often highly variable in the proportion of each species within the mixture, which determines the C:N ratio of the mixture and ultimately the release of N (Kuo and Sainju 1998; Hayden et al. 2014). Within our study, the C:N ratio of RV varied between 30 to 40, and a C:N ratio of 25 or below is believed to be required for net N mineralization (Allison, 1966). The NoRV consisted of winter annual weeds which had a lower C:N ratio than the RV mixture.
across all three years. In both 2012 and 2014, the C:N ratio of the winter weeds was close to 25, while in 2013 it was 38. This likely explains why we did not see more of an increase in inorganic N due to RV.

We expected that tillage within the WR of ST would stimulate N mineralization by incorporating RV residues and result in greater inorganic N compared to the BR. However, we only found greater inorganic N in one out of the three years (2013). One reason for the lower inorganic N within ST-WR could be that strip-tillage is less intense disturbance compared to conventional tillage. This is consistent with Haramoto and Brainard (2012) who also found lower inorganic N within the crop row of ST. Additionally, although the BR of ST had not been tilled, there were frequent hand-weeding events and the shallow disturbance resulting from weed control may have contributed to N mineralization.

**Sweet corn biomass and N uptake**

Despite ST’s having lower inorganic N availability across all three years, ST only resulted in lower sweet corn yields and biomass in 2013. Hairy vetch biomass within 2013 was less than 50% of 2012 and 2014 levels, and within NOCORN subplots, ST reduced IN by approximately 65% compared to FWT when combined with RV, and ST reduced IN by 20% lower when combined with NoRV. Therefore, N deficiency may explain lower sweet corn biomass and N uptake in ST in 2013. 2013 was the only year in which we did not see increased gravimetric soil moisture within ST+RV compared to FWT and ST+NoRV. It is possible that increased moisture compensated for lower inorganic N in 2012 and 2014. Alternatively, it may be that in both 2012 and 2014, rye and vetch cover crop biomass was sufficient so that N was not limiting within the strip-
tilled system. For example, in 2014 inorganic N was 30% lower in ST that FWT, yet this had no effect on sweet corn N uptake and yields.

**Soil leachate N and denitrification potential**

When analyzed across all three years, ST resulted in greater concentration of N within the soil leachate compared to FWT with a RV cover crop and equal or greater volumetric water content within the soil within 2013 and 2014. Greater leachate N concentration, combined with greater water throughout the soil profile, strongly suggests that ST increased the amount of N that leached from the soil profile during sweet corn growth. This is contrary to other studies that found ST either had no effect (Al-Kaisi and Licht 2004; Haramoto, 2014) or decreased (Haramoto, 2014) N leaching potential. However, both these studies used inorganic N fertilizer as the primary source of N. To our knowledge, ours is the first study that has examined ST effects on N leaching in a legume-based system.

Numerous studies have compared N leaching within no-till and conventional tilled systems, and have found varying results. Some studies have found a lower concentration of N within the soil leachate in no-till, but a greater total amount of N leaching due to increased soil water drainage (Izaurralde et al. 1995). Other studies have found a greater concentration of N within the soil leachate of no-till, with or without an increase in water drainage (Thomas et al. 1973; Tyler and Thomas, 1977).

One explanation for greater leachate N concentration within no-till concerns the difference in soil water movement through the rooting zone of undisturbed versus disturbed soils. No-till soil contains a greater proportion of macropores compared to conventional tillage (Thomas et al. 1973; Wu et al. 1992), resulting in greater infiltration
rates and the channeling of water through the rooting zone (Ogden et al. 1999). When water travels through macropores, it bypasses much of the soil matrix and has less contact with micropores and lower replacement of initial soil water (Quisenberry and Phillips, 1976; Bandaranayake et al. 1998; Tyler and Thomas, 1977). In a legume-based no-till soil system, organic residues remain upon the soil surface, resulting in a stratification of N mineralization (Logan et al. 1991; Johnson and Hoyt, 1999). Mineralized N is initially concentrated in the top few centimeters of the soil, and must percolate down through the soil profile. Precipitation infiltrating the soil likely captures recently mineralized N at the soil surface, causing mineralized N to bypass the soil matrix as it travels through the rooting zone through preferential flow pathways. In the disturbed soils of FWT, incorporated rye and vetch residues are distributed throughout the top soil layer. As water slowly percolates through the soil matrix within FWT, recently mineralized N has a greater chance of entering and being stored in soil micropores.

In FWT, greater denitrification potential was found in the WR zone compared to the BR. That the cover crop and tillage treatments between the WR and BR zones of FWT were equivalent suggests that any WR/BR differences within FWT are due to the presence of the crop WR. The sloughing off of corn root cells and root exudates likely provided a labile carbon source to enhance denitrification (Prade et al. 1988; Mahmood et al. 1997). Mahmood et al. (1997) found that maize plants stimulated denitrification at both high and low water-filled pore space, and attributed the stimulative effects to increased C availability with maize roots present. Previous studies have found that denitrification is often limited by carbon in agricultural systems, and may be more limited
by carbon than nitrogen (Kennedy et al. 2013, and Luo et al. 1998). These results reinforce the importance of considering WR and BR differences when sampling soil within agricultural systems. Often researchers take measurements across the entire plot, and do not report the influence that the crop has within the crop row.

ST increased denitrification potential across the whole plot, and also affected the zonal patterns (WR and BR) of denitrification differently within the two tillage systems. As opposed to FWT, ST had a higher denitrification potential in the BR compared to the WR. Given that the same mechanisms by which the crop enhanced denitrification potential within the WR of FWT are also operating in the WR of ST, this suggests that the mechanisms enhancing denitrification potential in the BR of ST were greater. The greater bulk density and increased soil moisture in 2014 likely increased water-filled pore space in the BR of ST, thereby increasing denitrification potential (Aulakh et al. 1991; Weier et al. 1993). On average, bulk density within the BR of ST was approximately 7% greater than tilled areas. Alternatively, Overstreet and Hoyt (2008) found greater microbial biomass within the untilled zone of ST. Therefore greater denitrification potential could be due to a greater overall microbial mass, and not to factors promoting denitrification per se.

Within this study we found that ST within a legume-based systems increased the potential for N losses to the environment. Increased reactive N lost through leaching and denitrification is concerning because of the potential for negative environmental ramifications. Leached N is a major contributor to hypoxic zones within marine systems, and denitrified-N lost as N$_2$O is a potent greenhouse gas with a CO$_2$ equivalent of 300 (Robertson and Vitousek, 2009). Additionally, increased N losses are especially
problematic in legume-based organic systems, which already tend to be N deficient (Clark et al. 1999; Poudel et al. 2002; Cavigelli et al. 2008). Greater leachate N concentration and denitrification potential within ST may partially explain the reduced N availability. Early season PMN did not differ between the two tillage systems, but we found lower inorganic N availability within ST, likely due to increased N losses. Future research should determine the exact mechanisms responsible for differences in N losses between legume-based FWT and ST. Additionally, more research is needed to determine strategies to increase nitrogen use efficiency within legume-based ST.

**SUMMARY AND CONCLUSION**

Our objective was to determine how strip-tillage affected the mineralization and availability of N, as well as potential for N losses, from a legume-based organically managed system. ST had no effect on PMN in the first half of the sweet corn season, but reduced PMN in the second half of the season when combined with RV. ST increased the concentration of inorganic N within the soil leachate and the potential for N losses via denitrification across the three years of this study. The combined effects of reduced PMN and increased N losses explain why ST had lower inorganic N availability compared to FWT. Tillage within the crop row increased inorganic N compared to the undisturbed BR in only 1 out of 3 years. Additionally, we found no consistent benefit in N availability from the rye-vetch cover crop. Despite ST having lower inorganic N, it only had negative effects on sweet corn in one out of three years, 2013, the year with the lowest hairy vetch biomass. ST increased soil gravimetric moisture in 2012 and 2014, which may have compensated for the lower inorganic N.
Despite lower inorganic N, ST can produce yields equivalent to FWT in years with sufficient vetch biomass. Increased N losses likely exacerbated the lower soil inorganic N within ST. The greater potential for N losses within ST are concerning, not only because N is a limiting resource in organic systems, but also because reactive N lost to the environment results in negative environmental impacts. Future research should examine the mechanisms responsible for increased N losses in between ST, as well as examine strategies to increase nitrogen use efficiency and decrease N losses in legume-based RT systems.
## Table 2.1. Table of Activities and Operations.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Dates of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2011-2012</td>
</tr>
<tr>
<td>Planted cover crops</td>
<td>8/31/2011</td>
</tr>
<tr>
<td>Primary tillage</td>
<td>6/13/2012</td>
</tr>
<tr>
<td>Secondary tillage</td>
<td>6/18/2012</td>
</tr>
<tr>
<td>Diviner tube installed</td>
<td>NA</td>
</tr>
<tr>
<td>Installed PMN-Late Season</td>
<td>7/27/2012</td>
</tr>
</tbody>
</table>
Table 2.2. P values from a three-way ANOVA for inorganic N across the whole CORN and NOCORN subplots (weighted average of WR and BR) in 2012, 2013, and 2014. Fixed effects include tillage (full-width and strip-tillage), cover crop (Rye-vetch and NoRV), and date as a repeated measure.

<table>
<thead>
<tr>
<th>Effect</th>
<th>No Corn</th>
<th>With Corn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2012  2013  2014</td>
<td>2012  2013  2014</td>
</tr>
<tr>
<td>Till (T)</td>
<td>0.088  0.0048  0.016</td>
<td>NS  0.033  0.063</td>
</tr>
<tr>
<td>Cover (C)</td>
<td>NS      NS      NS</td>
<td>NS  0.069  NS</td>
</tr>
<tr>
<td>T*C</td>
<td>NS      NS      NS</td>
<td>NS  NS      NS</td>
</tr>
<tr>
<td>Date</td>
<td>&lt;.0001  &lt;.0001  &lt;.0001</td>
<td>&lt;.0001  &lt;.0001  &lt;.0001</td>
</tr>
<tr>
<td>T*D</td>
<td>NS      0.0004  &lt;.0001</td>
<td>NS  0.013  0.015</td>
</tr>
<tr>
<td>C*D</td>
<td>NS      0.0017  &lt;.0001</td>
<td>NS  NS      0.011</td>
</tr>
<tr>
<td>C<em>T</em>D</td>
<td>NS      0.059   NS</td>
<td>NS  0.0445  NS</td>
</tr>
</tbody>
</table>
Table 2.3. P values from a four-way ANOVA for inorganic N within NOCORN subplots in 2012, 2013, and 2014. Fixed effects include tillage (full-width and strip-tillage), cover crop (Rye-vetch and NoRV), zone (WR and BR), and date as a repeated measure.

<table>
<thead>
<tr>
<th>Effect</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone (Z)</td>
<td>NS</td>
<td>0.0119</td>
<td>NS</td>
</tr>
<tr>
<td>Till (T)*Z</td>
<td>NS</td>
<td>0.028</td>
<td>NS</td>
</tr>
<tr>
<td>Cover (C)*Z</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>C<em>T</em>Z</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Z*Date (D)</td>
<td>NS</td>
<td>NS</td>
<td>0.068</td>
</tr>
<tr>
<td>T<em>Z</em>D</td>
<td>NS</td>
<td>NS</td>
<td>0.0938</td>
</tr>
<tr>
<td>C<em>Z</em>D</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>C<em>T</em>Z*D</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

† For main effects of tillage and cover crop spatial arrangement, and their interactions with date see Table 2.2.
Table 2.4. P values from a three-way ANOVA for gravimetric soil moisture across the whole CORN subplot (weighted average of WR and BR) in 2012, 2013, and 2014. Fixed effects include tillage (full-width and strip-tillage), cover crop (Rye-vetch and NoRV), and date as a repeated measure.

<table>
<thead>
<tr>
<th>Effect</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Till (T)</td>
<td>0.0763</td>
<td>NS</td>
<td>0.0194</td>
</tr>
<tr>
<td>Cover (C)</td>
<td>NS</td>
<td>0.0267</td>
<td>0.0299</td>
</tr>
<tr>
<td>T*C</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Date (D)</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>T*D</td>
<td>0.0014</td>
<td>0.0717</td>
<td>0.0777</td>
</tr>
<tr>
<td>C*D</td>
<td>&lt;.0001</td>
<td>NS</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>T<em>C</em>D</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
Table 2.5. P values from a three-way ANOVA for volumetric soil moisture within CORN subplots at three different depths (0.1 to 0.3 m, 0.4 to 0.7 m, and 0.8 to 0.9 m) in 2012, 2013, and 2014. Fixed effects include tillage (full-width and strip-tillage), cover crop (Rye-vetch and NoRV), and date as a repeated measure.

<table>
<thead>
<tr>
<th>Effect</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1-0.3</td>
<td>0.4-0.7</td>
</tr>
<tr>
<td>Depth (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Till (T)</td>
<td>0.012</td>
<td>NS</td>
</tr>
<tr>
<td>C )</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>C*T</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Date (D)</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>C*D</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>T*D</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>C<em>T</em>D</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
Table 2.6. P values from a two-way ANOVA for sweet corn nonharvested and corn ear biomass, as well as sweet corn N content in 2012, 2013, and 2014. Fixed effects include tillage (full-width and strip-tillage) and cover crop (Rye-vetch and NoRV).

<table>
<thead>
<tr>
<th>Effect</th>
<th>Nonharvested Biomass</th>
<th>Corn Ears</th>
<th>Total Corn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Till (T)</td>
<td>0.091</td>
<td>0.005</td>
<td>NS</td>
</tr>
<tr>
<td>Cover (C)</td>
<td>0.007</td>
<td>0.008</td>
<td>0.032</td>
</tr>
<tr>
<td>T*C</td>
<td>0.045</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effect</th>
<th>Nonharvested Biomass</th>
<th>Corn Ears</th>
<th>Total Corn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Till (T)</td>
<td>NS</td>
<td>0.0036</td>
<td>NS</td>
</tr>
<tr>
<td>Cover (C)</td>
<td>0.0146</td>
<td>0.0222</td>
<td>0.0281</td>
</tr>
<tr>
<td>T*C</td>
<td>0.0168</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
Figure 2.1. Mean (+/− SEM) *in situ* potentially mineralizable N within the top 25 cm of soil from planting to midseason (Early, left) and Midseason to Harvest (Late, right) over 2012, 2013, and 2014 combined.
Figure 2.2. Mean (+/- SEM) inorganic N availability in the top 20 cm of soil across the whole subplot (weighted average of WR and BR), with Corn (top) and without corn (No Corn, bottom) in 2012, 2013, and 2014. Inorganic N comparisons include full-width tillage (FWT) and strip-tillage (ST) combined with either no cover crop (NoRV) or a rye and vetch mixture (Rye-Vetch).
Figure 2.3. Mean (+/- SEM) inorganic N availability in the top 20 cm of soil both within (WR) and between crop rows (BR) in subplots without corn (No Corn) in 2012, 2013, and 2014. Inorganic N comparisons include full-width tillage (FWT) and strip-tillage (ST) combined with either no cover crop (NoRV) or a rye and vetch mixture (Rye-Vetch).
Figure 2.4. Mean (+/- SEM) gravimetric soil moisture in the top 20 cm of soil across the whole subplot (weighted average of IR and BR) with Corn (top) present in 2012, 2013, and 2014. Gravimetric soil moisture comparisons include full-width tillage (FWT) and strip-tillage (ST) combined with either no cover crop (NoRV) or a rye and vetch mixture (Rye-Vetch).
Figure 2.5. Mean (+/− SEM) volumetric soil moisture in subplots with corn (Corn) present in 2013, and 2014. Measurements were taken every 10 cm, and depths were combined according to: 0.1 to 0.3, 0.4 to 0.7, and 0.8 to 0.9 meters. Volumetric soil moisture comparisons include full-width tillage (FWT) and strip-tillage (ST) combined with either no cover crop (NoRV) or a rye and vetch mixture (Rye-Vetch).
Figure 2.6. Mean (+/- SEM) sweet corn biomass (top) and N content (bottom) of both nonharvested biomass and corn ears in 2012, 2013, and 2014. Comparisons of fixed effects include full-width tillage (FWT) and strip-tillage (ST) combined with either no cover crop (NoRV) or a rye and vetch (RV) mixture.
Figure 2.7. Precipitation in Hickory Corners, MI (top) and mean (+/- SEM) inorganic N within the soil leachate (bottom) during the sweet corn growing season in subplots with corn in 2012, 2013, and 2014. Sampled at a depth of 1.2 m. Tillage comparisons include full-width tillage (FWT) and strip-tillage (ST).
Figure 2.8. Mean (± SEM) denitrification potential in both full-width (FWT) and strip-tillage (ST). Data is a compilation of 2013 and 2014, and three time points (Planting, Midseason, and Harvest). Sampled to a depth of 20 cm.
Figure 2.9. Mean (+/- SEM) denitrification potential due to tillage (A and B) and cover crop (C and D) effects within different zones in the cropping system (WR=within corn row, BR=between crop rows). Tillage comparisons include full-width tillage (FWT) and strip-tillage (ST); cover crop comparisons include no cover crop (NoRV) or a rye and vetch (RV) mixture. Sampled to a depth of 20 cm.
LITERATURE CITED


CHAPTER THREE

Strip-intercropping of rye-vetch mixtures affects biomass, C:N ratio and spatial distribution of cover crop residue

ABSTRACT

Altering the spatial arrangement of cover crop mixtures with strip-intercropping is an under-explored strategy that may enhance their performance. We hypothesized that strip-intercropping would increase overall cover crop productivity and improve N use efficiency in legume-based cropping systems by concentrating the low C:N vetch residue within the crop root zone. We conducted a field study in southwest Michigan to examine how strip-intercropping of cereal rye and hairy vetch (RV) mixtures influences: i) total cover crop productivity, and ii) the spatial distribution and C:N ratio of RV residues in the between-row versus within-row zones of subsequent crops. Spatial arrangements included a full-width mixture (MIX) in which rye and vetch were sown together in the same rows; and segregated mixtures involving either 2 rows of rye alternated with 2 rows of vetch (SEG2) or 3 rows of rye alternated with 1 row of vetch (SEG1). Benefits of strip-intercropping of RV for reducing interspecific competition appear to have been offset by the costs of increased intraspecific competition and/or reduced facilitation. Over 5 site-years, strip-intercropping either had no effect or reduced RV biomass or the biomass of component species relative to MIX. However, SEG2 resulted in greater concentration of N-rich vetch tissue and a lower C:N ratio of both above- and below-ground RV biomass in the crop-planting zone. Strip-intercropping of RV is a promising strategy for increasing access of future crops to mineralized N.
INTRODUCTION

Winter cover crops can provide a number of useful ecosystem services to a cropping system, including weed suppression, reduced soil erosion, nutrient cycling, and increased soil organic matter (Wander and Traina, 1996; Wyland et al. 1996; Teasdale and Mohler, 2000; Snapp et al. 2005). Cover crop services can be enhanced by combining species that differ in growth habit and resource capture strategies. For example, mixtures of legume and cereal cover crops may provide several complementary benefits: legumes provide N via biological N fixation, and cereal grasses suppress weeds (Mohler and Teasdale, 1993) scavenge residual nutrients (Wyland et al. 1996), and produce large quantities of biomass.

Grass and legume cover crop mixtures often produce greater biomass than either species in monoculture, and may increase the total N supplied to the cropping system (Holderbaum et al. 1990; Fujita et al. 1992; Karpenstein-Machan and Stuelpnagel, 2000). By reducing soil N availability, grasses can stimulate legumes to increase biological N fixation, thereby increasing the proportion of total N derived from N fixation by the legume (Karpenstein-Machan and Stuelpnagel, 2000; Izaurralde et al. 1992; Jensen, 1996). This can result in lower seed costs for a given level of N fixation, since legume seeds (e.g. hairy vetch) are typically much more expensive than grass seeds (e.g. cereal rye) (Brainard et al. 2012). Fixed N can be transferred from legumes to grasses (Eagelsham et al. 1981; Ta and Faris, 1987; Dakora et al. 2008), which may increase the N content of the grasses when intercropped with legumes (Ta and Faris 1987; Fujita et al. 1990; Sainju et al. 2005).
Hairy vetch and cereal rye are commonly used winter cover crops in northern climates and combining them in mixture can result in a number of synergistic benefits compared to either species in monoculture. For example, despite hairy vetch being a relatively cold-hardy legume, vetch is susceptible to low overwinter survival and poor biomass in years with cold winters (Jannick et al. 1997). Hairy vetch is often less effective at weed suppression compared to cereal grains including rye (Hayden et al. 2012). Cereal rye is quick to establish in cool fall temperatures (Shipley et al. 1992) and acts to insulate hairy vetch from extreme frosts, thereby increasing vetch overwinter survival (Jannick et al. 1997; Brainard et al. 2012). Additionally, cereal rye is effective at suppressing winter annual weeds and acts as a nurse crop for the slow establishing hairy vetch. Cereal rye and hairy vetch also have complementary architectures. Vining legumes, such as vetch, can utilize upright cereal grasses as a climbing scaffold to increase light interception and productivity (Keating and Carberry et al. 1993).

In organically managed systems, winter cover crops such as rye and vetch may serve as the primary source of nitrogen to the subsequent crop (Gaskell and Smith, 2007). However, N availability is often highly variable and insufficient to fully meet crop N demand (Kuo and Sainju, 1998; Zotarelli et al. 2009). Whether a legume-cereal cover crop mixture is able to supply the crop N requirement depends on both the N accumulated within cover crop biomass, as well as the timing of residue decomposition and N mineralization (Crews and Peoples, 2005). The ratio of the legume and grass biomass within the mixture is a major determinant of mixture C:N ratio (Hayden et al. 2014), which is a dominant factor determining the rate and pattern of residue N mineralization (Allisons, 1966). Grasses are often the dominant competitor within
intercrops, and certain growing conditions, such as high soil fertility (Brainard et al. 2011) or late planting dates resulting in colder than average temperatures (Hayden et al. 2015), can enhance grass competitiveness for light and other resources. Overly vigorous grass growth results in decreased legume productivity and N fixation (Wahua and Miller, 1978; Nambiar et al. 1983; Brainard et al. 2011).

Hairy vetch and cereal rye productivity within intercropped mixtures varies tremendously. Several approaches have been proposed to increase rye and vetch productivity and maximize their capacity for weed suppression and N provisioning. For example, utilizing earlier planting dates and later termination dates can increase vetch growth and N accumulation (Teasdale et al. 2004; Cook et al. 2010). However, cash crop rotations do not always accommodate adjustments in cover crop planting and termination. Increasing the proportion of vetch seeds within the mixture seeding rate may increase vetch biomass, but also increases the total seed costs and decreases weed suppression (Hayden et al. 2014). Hayden et al. (2015) found that delayed seeding of rye until the time of vetch emergence resulted in up to 1.0 Mg ha$^{-1}$ greater biomass compared to co-seeding rye and vetch together. But fall is generally a busy time for farmers due to the harvesting of cash crops, and they may not have time to employ two planting dates to establish a winter cover crop. Given these limitations, new strategies are needed to alleviate interspecific competition in grass and legume mixtures, thereby ensuring adequate proportions of legume biomass and enhancing their capacity for provisioning N.

One under-explored strategy that may reduce interspecific competition and enhance the provisioning of N in legume-cereal cover crop mixtures is to alter the
spatial arrangement of component species (Fujita, 1990; Lithourgidis et al. 2011). Strip-intercropping involves separating component species within a mixture into distinct alternate strips with the ultimate aim of delaying the onset of competition (Ofori and Stern, 1987; Midmore, 1993). Strip-intercropping of grasses and legumes may provide the greatest benefit to the less-competitive legume. By reducing the space allocated to the dominant species, the companion species gains access to a greater share of space, light, and other resources. For example, strip-intercropping in double alternate rows increased yields of soybeans when grown in combination with maize or sorghum (Mohta and De, 1980).

Several studies have examined the advantages of strip-intercropping in cash crop mixtures (Li et al. 2001; Gao et al. 2009; Li et al. 2011), but this practice has yet to be applied to grass-legume cover crops. Strip-intercropping of rye and hairy vetch may reduce rye suppression of hairy vetch, especially in years with colder winter temperatures when rye competitiveness over vetch is greatly enhanced. Strip-intercropping of rye and vetch may also enhance N-use efficiency within a subsequent crop, much like banding of N fertilizers in conventional systems (Reinersten et al. 1984; Malhi and Nyborg 1985; Maddux et al., 1991; Nash et al. 2013). Planting the vetch strips directly in-line with the rows of the subsequent crop concentrates N-rich vetch residue where it may be more easily accessed by crop roots, and thus may increase the synchrony between N mineralization and crop N uptake. In the absence of carbon rich rye residue, in-row hairy vetch may increase result in higher N availability within the crop row due its lower C:N ratio compared to rye-vetch mixtures. Planting the high C:N
rye between future crop rows may initially immobilize N that can potentially serve as a reservoir of late-releasing N.

Segregation of rye and vetch in distinct zones may also alleviate other challenges associated with rye-vetch mixtures, especially when used in reduced tillage organic production systems. Previous studies have demonstrated reductions in crop establishment and early growth due to interference from rye residue. Rye residue may inhibit crop establishment through allelopathy (Barnes and Putnam, 1986), N immobilization (Kuo and Sainju 1998) or through interference with planting equipment (Mirsky et al. 2012). By excluding rye from the in-row zone, such suppression can be minimized. Second, in organic reduced-tillage production systems, termination of hairy vetch is challenging, and hairy-vetch re-growth may interfere with crop growth (Mischler et al. 2010). By concentrating vetch in the in-row zone, strip-tillage equipment may be used to effectively terminate vetch while retaining the advantages of reduced tillage in the between row zone.

The primary objectives of this study were to examine how strip-intercropping of rye and hairy vetch affects i) the overall productivity of a rye-vetch mixture, as well as the relative biomass of each component; and ii) the spatial distribution and C:N ratio of rye-vetch residues between the vetch and rye zones (within- and between-rows of the future crop, respectively). A secondary objective was to evaluate the impact of cover crop spatial arrangement on the timing of flowering of vetch. We hypothesized that compared to full-width rye-vetch mixtures, strip-intercropping of cereal rye and hairy vetch would result in i) increased total rye-vetch biomass through alleviation of rye suppression of vetch; ii) a greater proportion of vetch biomass and a lower C:N ratio of
cover crop residues within the vetch zone (VZ); and iii) a greater proportion of rye biomass and a higher C:N ratio of residue within the rye-zone (RZ).

MATERIALS AND METHODS

Site Description and experimental design

Two experiments were conducted between 2011-2014 on organically managed (5 years) Kalamazoo (fine-loamy, mixed, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, mesic Typic Hapludalfs) loams (Crum and Collins, 1995), at the Kellogg Biological Station in Hickory Corners, MI (85° 24’W, 42° 24’ N). The treatments for both Experiments 1 and 2 can be found in Table 3.1. Initially, in 2011-2012 (Year 1), Experiments 1 and 2 were combined within one field, but were separated into two fields in subsequent years: 2012-2013 (Year 2) and 2013-2014 (Year 3). Dates of key field operations and data collection can be found in Table 3.1.

Experiment 1: Cover crop productivity

To determine how spatial arrangements of cereal rye and hairy vetch mixtures influenced productivity, we evaluated mixtures of rye and vetch grown in three different spatial arrangements compared to rye and vetch monocultures (Table 3.2). When considered on a whole plot basis, all bi-culture treatments have the same seeding rate for both rye and vetch, but differ in seed placement according to Figure 3.1. Between-row spacing for both rye and vetch was 19 cm across all the treatments. Spatial arrangements included a full-width mixture (MIX) in which rye and vetch were sown together in the same rows; a segregated mixture (SEG2) in which 2 rows of hairy vetch were alternated with 2 rows of rye; and a second segregated mixture (SEG1) in which 3 rows of rye were alternated with 1 row of vetch. All three spatial arrangements had the
same seed rate on a per plot basis: 62.7 kg ha\(^{-1}\) for rye, and 22.4 kg ha\(^{-1}\) for vetch. The rye monoculture was sown at 125.5 kg ha\(^{-1}\) for rye, and the vetch monoculture was sown at 44.8 kg ha\(^{-1}\).

In Year 1, cover crop treatments were part of a larger trial in which we evaluated effects of cover crops on a subsequent crop under two tillage systems. As such, in Year 1, each cover crop treatment was replicated twice (for each tillage interaction) within each block, for a total of 8 replications. In Years 2 and 3, no subsequent crop or tillage treatments were evaluated, and cover crop treatments were arranged in a randomized complete block design with 4 replications. Plot sizes were 55.5 m\(^2\) (18.2 m X 3.1 m) in Year 1, and 13.5 m\(^2\) (4.5 m X 3.0 m) in Years 2 and 3. A larger plot size was used in Year 1 to accommodate measurements of subsequent crop responses.

Prior to cover crop planting in September, in the experimental area cereal rye was harvested for seed in July in Year 1, snap beans grown from late-June to August in Year 2, and no crop in Year 3. Fields of both Experiment 1 and 2 were flail mowed, chisel plowed, disked, and harrowed.

Both cereal rye and hairy vetch seeds were “Variety Not Stated” and organically certified across all three years. Cereal rye was planted with a grain drill with the drop tubes blocked as appropriate to establish rows for each treatment as described above (Figure 3.1). Hairy vetch was planted with a Jang push-seeder within the designated rows and rates.

**Experiment 2: Spatial distribution and C:N ratio of root and shoot tissue**

The focus of Experiment 2 was to evaluate in more detail the effects of cover crop spatial arrangement on the spatial distribution of cover crop biomass and the C:N
ratio of cover crop tissue. For this experiment, only the effects of two of the cover crop spatial arrangements (MIX vs SEG2) were evaluated, with no SEG1 or monoculture treatments included (Table 3.1). Experiment 2 was part of a larger experiment that included the effects of cover crop spatial arrangement and subsequent tillage (full width tillage versus strip tillage) on N dynamics and yield of subsequent sweet corn crop. The interactive effects of cover crop spatial arrangement and tillage on subsequent soil and crop responses are reported elsewhere (Lowry 2015; Chapters 4 and 5). Because cover crop x tillage treatments were arranged in a randomized complete block design with 4 replications, each cover crop treatment was replicated twice within each block, resulting in a total of 8 replications. In Year 1, Experiment 2 was imbedded in Experiment 1 as described above. Plot sizes were 55.5 m² (18.2 m X 3.1 m), 73.8 m² (12.1 X 6.1 m), and 62.6 m² (13.6 m X 4.6 m) in Years 1, 2, and 3, respectively. Plot sizes were adjusted each year based on availability of organically certified land and size of available equipment.

Crops grown prior to Experiment 2 included cereal rye harvested for grain in July in Year 1, wheat harvested for grain in Year 2, and cereal rye in Year 3. As in Experiment 1, fallow periods were tilled frequently to minimize growth of perennial weeds, and to minimize volunteer rye or wheat from the previous crop.

Data collection

Cover crop aboveground biomass. We obtained cover crop aboveground biomass prior to mowing by clipping shoot tissue at ground level from two 0.25 m² quadrats for each vetch-zone (VZ) and rye-zone (RZ) area in segregated (SEG) treatments, and two random quadrats in mixed (MIX) bicultures. Due to lodging of the cover crops in Year 2
in Experiment 1 it was difficult to distinguish rows so we collected three quadrats for segregated treatments and did not separate by rows. Fresh cover crop biomass was separated into hairy vetch, cereal rye, and weeds, dried at 60°C, and weighed. To determine the effect that spatial arrangement has on rye and vetch biomass across the whole plot, rye and vetch biomass within the vetch- and rye-zones were weighted by the relative area of that zone.

*Root biomass.* In Years 2 and 3 of Experiment 2, we obtained belowground biomass of the cover crop mixture and associated weeds. Within one day of the cover crops being mowed, we excavated 3 cores (5 cm width and 25 cm depth) from the VZ and RZ within SEG2 (3 cores X 2 zones= 6 cores), and at three random locations within the MIX (3 cores). The three cores from each plot and zones were homogenized, weighed, and a subsample was taken for gravimetric moisture. The cores were then stored at 4°C until further processing to extract roots. To extract roots, samples were sieved twice through a 6 mm sieve. Once roots were isolated from soil, they were washed thoroughly, then dried at 60°C. Dried roots were weighed and ground with mortar and pestle within liquid nitrogen, and then analyzed for elemental C and N (see below). No attempt was made to distinguish roots by species.

*Hairy vetch percent flowering.* We calculated percent flowering of hairy vetch at three time-points in Year 2, and two time-points in Year 3 in Experiment 1. We selected 10 random vetch vines and traced stems to the base of the plant to ensure we removed the full vine length. We then removed any branches, and counted the total number of nodes, number of flowering nodes, and number of nodes that had set pods along the primary vine.
Percent flowering = \( \frac{\text{# flowering nodes} + \text{# of nodes with pods}}{\text{total # nodes}} \)

**Hairy vetch height.** Hairy vetch height was measured in Experiment 1 at three time-points in the spring in both Years 2 and 3. We measured the height of rye and vetch at 10 random locations within each plot. For segregated spatial arrangements, at each location we measured the height of vetch within the VZ, vetch that had climbed the rye in the RZ, and rye in the RZ. We then determined the average height of each species across the whole plot by weighting the species height within each zone by the area of that zone.

**Percent lodging.** Visual estimates of percent lodging of rye-vetch mixtures were made prior to cover crop termination in Experiment 2. A percentage between 0 and 100 (to the nearest 5%), was assigned on a whole plot basis: 0% represented rye-vetch across the entire plot standing, and 100% represented rye-vetch across the whole plot lodged on or near the ground. Two researchers independently estimated lodging percentages, and then their estimates were averaged.

**Rye and vetch C:N ratio.** Above-ground tissue samples of hairy vetch and cereal rye from Experiment 2 were analyzed for total C and N at the University of California-Davis Stable Isotope Facility (SIF) using an elemental analyzer (ANCA-GSL, PDZ Europa, Norwich, Cheshire, UK) interfaced to an isotope ratio mass spectrometer (20-20, Sercon, UK).

**Statistical analysis**

Due to high variability between years, as well as differences in experimental procedures by year, years were analyzed separately with one exception: years were pooled for analyzing the effect of cover crop spatial arrangement on the C:N ratio within
rye and vetch zones, due to a lack of significant interaction with year for this response. All data was analyzed using Proc MIXED procedures in SAS with block as a random factor (Version 9.3, SAS Institute, Cary, NC). We evaluated assumptions of normality and homogenous variances, and utilized log or square-root transformations and unequal variance models where appropriate. For Experiments 1, the fixed effect of cover crop spatial arrangement was evaluated for effects on cover crop biomass and hairy vetch height. For Experiment 2, we analyzed the VZ and RZ separately to evaluate the fixed effect of cover crop spatial arrangement on cover crop biomass and distribution, cover crop N content, and above- and belowground C:N ratio. Treatments were separated using Fisher's protected LSD $P < 0.05$. All figures were made using the GGPlot2 package in R (Wickham, 2009).

RESULTS

Growing Degree Days and Precipitation

Cumulative GDD accumulation during cover crop growth in Year 1 was approximately 70 to 100 GDD higher than subsequent years in Experiment 1, and 170 and 360 GDD higher than Year 2 and Year 3, respectively in Experiment 2. The higher GDD accumulation in Year 1 was largely due to approximately 110 to 190 greater GDD accumulation in the fall of 2011 compared to Year 1 and Year 2. Additionally, spring 2012 experienced an extremely warm March with GDD accumulation approximately 20 times greater than in spring of Year 2 and Year 3. Experiment 2 experienced low GDD accumulation throughout both fall and spring in Year 2. For both Experiments 1 and 2, precipitation was greatest in Year 2, especially during the winter and spring. Total precipitation was 680, 870-900, and 630 mm in Year 1, Year 2, and Year 3,
respectively. Higher precipitation in Year 2 was largely due to greater rainfall in April and May, when rye and vetch are in their exponential growth phase. Precipitation was very low in May 2012 (39 mm), which may have inhibited cover crop growth.

**Experiment 1: Cover crop productivity**

*Cover crop aboveground biomass.* Total shoot biomass was significantly affected by cover crop spatial arrangement in 1 of 3 years (Table 3.4). In Year 1 the MIX rye-vetch spatial arrangement had 16% greater total biomass production than both SEG1 and SEG2 segregated arrangements (Figure 3.2), however we found no detectable difference in total rye-vetch biomass in Years 2 and 3 of Experiment 1. In Year 1, total cover crop biomass was approximately 8.2 Mg ha\(^{-1}\) within the MIX spatial arrangement, and 7.1 Mg ha\(^{-1}\) within SEG1 and 2. Total rye-vetch biomass was approximately 8.0 Mg ha\(^{-1}\) in Year 2, and ranged between 7.8 to 10 Mg ha\(^{-1}\) in Year 3. In all three years the cover crop mixtures had greater total biomass than the vetch monoculture. Compared to the rye monoculture, the three mixtures had lower total biomass in Year 2, but higher biomass in Year 3 (Year 1 did not contain a rye monoculture).

Hairy vetch shoot biomass was significantly affected by cover crop spatial arrangement in two out of three years (Table 3.4). The MIX spatial arrangement had approximately 35% greater vetch biomass than SEG1 in 2012, and 45% greater biomass than both SEG1 and SEG2 in Year 3. (Figure 3.2). There were no detectable differences in vetch biomass within the rye-vetch mixtures or monoculture in Year 2. In Year 1, SEG2 had approximately 30% greater vetch biomass than SEG1, but there was no significant difference between the two segregated spatial arrangements in Year 2 or 3. In Years 1 and 3, all biculture treatments had significantly lower vetch biomass than
monocultures. Vetch within MIX produced equal or greater biomass per unit of vetch seed sown then vetch in monoculture in all three years. In other words, vetch in mixture was sown at 50% of the monoculture rate but always produced more than the 50% level of monoculture biomass. On the contrary, SEG2 produced less than 50% of monoculture biomass in 1 out of 3 years, and SEG1 produced less than 50% of monoculture biomass in 2 out of 3 years.

Cereal rye biomass was reduced within SEG2 by 20% compared to MIX and SEG1 respectively within Year 1 (Figure 3.2; Table 3.4). We found no detectable difference in rye biomass between cover crop spatial arrangements in Years 2 and 3. Cereal rye biomass within mixtures was approximately 5.5 Mg ha\(^{-1}\) in SEG1 and MIX, and 4.4 Mg ha\(^{-1}\) in SEG2 within Year 1; and approximately 5.0 Mg ha\(^{-1}\) and 7.6 Mg ha\(^{-1}\) across rye-vetch mixtures in Years 2 and 3, respectively. In Year 2, all bicultures had approximately 50% lower rye biomass than the rye monoculture, however, there was no significant difference between the rye in mixture and monoculture in Year 3 (there was no rye monoculture in Year 1). Rye in mixtures produced more biomass then rye monocultures per unit of rye seed sown in 1 out of 3 years.

**Vetch height.** In both Years 2 and 3, hairy vetch within MIX was taller than both SEG1 and 2, as well as the vetch monoculture (Figure 3.3, \(P=<.0001\)). In Year 2, hairy vetch was also taller in SEG1 compared to the SEG2 arrangement, but there was no detectable difference between SEG1 and SEG2 in Year 3. Within Year 2, hairy vetch height was 74, 63, and 44 cm in the MIX, SEG1, and SEG2, respectively; and within Year 3, hairy vetch height was 85 cm within MIX, and approximately 57 cm in the
segregated spatial arrangements. In both years rye height was measured, but we saw no detectable differences based on rye and vetch spatial arrangement (data not shown).

**Vetch flowering.** We found no detectable difference in vetch flowering time between rye-vetch spatial arrangements in any year of the study (data not shown).

**Experiment 2: Spatial distribution and C:N ratio of root and shoot tissue**

**Cover crop lodging.** In both Years 1 and 3 there was substantial lodging of the rye-vetch cover crops, which likely affected the rye and vetch residue distribution. We found no detectable difference in lodging of rye and vetch between the MIX and SEG2 spatial arrangement in Year 1 when lodging was approximately 65%; while in Year 3 lodging was marginally lower in SEG 2 (37%) compared to MIX (51%) ($P=0.07$). We found no lodging of rye and vetch in Year 2 of the study.

**Shoot biomass spatial distribution.** Segregation of rye and vetch into zones resulted in greater vetch biomass within the VZ of SEG2 compared to the MIX in 2 out of 3 years, Years 1 and 2, but not Year 3 (Table 3.5, Figure 3.4). In Year 2, 74% of the vetch biomass was concentrated within the VZ within SEG2, and this was approximately twice the vetch biomass within an equivalent area of the MIX. Similarly, in Year 1, 70% of vetch biomass within SEG2 was concentrated within the VZ, and this was 30% greater than the MIX. However due to high variability this difference was only marginally significant ($P=0.06$). In Year 3, we detected no difference between the spatial distribution of vetch biomass between MIX and SEG2.

Across all three years we found significantly less rye shoot biomass within the VZ in SEG2 compared to an equivalent area in the MIX (Table 3.5, Figure 3.4). Similarly, we found significantly greater rye biomass within the RZ of SEG2 compared to an
equivalent area in the MIX in 1 of 3 years; in Year 2, rye had 32% more biomass in the RZ compared to the MIX. Within the SEG2 treatment, rye biomass in the VZ represented 35%, 15% and 35% of total rye biomass in Years 1, 2 and 3 respectively (Figure 3.4).

* Shoot N content. We found no significant effect of cover crop spatial arrangement on total N within either the VZ, RZ, or across the whole plot in Years 2 and 3. However, in Year 1, MIX had 16% greater N contained within the RZ than SEG2 (Table 3.5, Figure 3.4). On a whole plot basis, total N was approximately 130, 100, and 160 kg N ha⁻¹ in Years 1, 2, and 3, respectively. Despite having a greater proportion of the N-rich vetch within the VZ, the SEG2 had only 55% of shoot N in Year 1 and Year 2, and 40 % of shoot N concentrated within the VZ in Year 3 due to lower vetch biomass compared to rye.

* C:N ratio of shoot tissue. Table 3.6 shows the C:N ratio of shoot tissue of hairy vetch and cereal rye within both the MIX and SEG2 spatial arrangements over the three years. We did not detect any effects of spatial arrangement on the C:N ratio of rye or vetch shoots, but we did see marginal differences among years. Hairy vetch C:N ratio ranged from 11 to 13.5 throughout the three years of the study. Cereal rye C:N ratio was more variable, and was highest in Year 1 at approximately 55, and lowest in Year 3 at approximately 42.

Across all three years, the C:N ratio of rye and vetch aboveground biomass was lower within the VZ of SEG2 compared to MIX \((P=0.001)\), but the difference between SEG2 and MIX was only marginal when each year was analyzed separately \((0.05>P>0.09)\). In both Years 2 and 3, the shoot C:N ratio within the VZ of SEG2 was below
25, while the C:N in the MIX was approximately 40 and 31 in Year 2 and 3, respectively. However, we found no detectable difference between MIX and SEG2 in the C:N ratio of rye-vetch residue across the whole plot, or shoot C:N ratio within the RZ throughout the three years of this study.

C:N ratio of root tissue. In both Years 2 and 3 we found that strip-intercropping of rye and vetch reduced the C:N ratio of roots within the VZ from approximately 32 in MIX to 24 in SEG2 (Figure 3.5, \( P<0.0001 \)). However, strip-intercropping had no effect on the C:N ratio of roots in the RZ; regardless of spatial arrangement the mean C:N ratio of roots in the RZ ranged from approximately 30 to 35 (we did not sample rye-vetch roots in Year 1). It is likely that winter annual weed roots were also present within root samples. However, because weed biomass was between 4 and 9% of total aboveground biomass, we expect that weed contributions to root biomass were also small.

**DISCUSSION**

Spatial arrangement and cover crop biomass

The hypothesis that strip-intercropping of rye and vetch will increase rye and vetch biomass due to reduced interspecific competition was not supported by the data. On the contrary, we found that strip-intercropping either had no effect or lowered biomass relative to full width mixtures (Table 3.4, Figure 3.2). In the SEG2 spatial arrangement, in which the rye and vetch biculture seeding rate was planted in two alternating rows of rye and vetch, we found lower rye biomass in 3 of 5 site-years, and lower vetch biomass in 1 of 5 site-years compared to MIX. While in the SEG1 in which
we had 1 row of vetch to 3 rows of rye, in 2 out of 3 site-years we found lower vetch biomass than MIX, and lower vetch biomass than SEG2 in 1 out of 3 site-years.

By concentrating individuals of each species into separate zones (VZ and RZ), we likely decreased interspecific competition at the cost of increasing intraspecific competition. Because mixture seed rates were 50% of monocultures, we might expect the mixtures to have 50% of the monoculture biomass if inter- and intraspecific competition was equal. Rye showed little evidence of suppression; rye biomass in mixture across the three spatial arrangements was 46-53% of monoculture biomass in Year 2, and between 91-112% in Year 3. Within MIX we found 50% or greater vetch biomass as compared to the vetch monoculture across all three years, and as high as 85% of monoculture biomass in Year 2, suggesting that there may have been some facilitation from the rye. These results are consistent with Hayden et al. (2014) who found little evidence of interspecific competition between rye and vetch across varying densities within a replacement series design. In contrast, in SEG1 we found evidence of suppression of vetch in Years 1 and 3, and in SEG2 there was evidence of increased competition in Year 3, when SEG2 was 36% of the vetch monoculture.

The reasons for reduced vetch biomass in strip-intercropping compared to MIX are unclear, but may have been the result of either intraspecific competition from the high vetch planting density or from reduced access to light due to a loss of facilitative effects from proximity to rye (e.g. trellis effect). Rye provides structural support for vetch, a vining legume, to climb and increase its light interception. Increasing the distance between rye and vetch with strip-intercropping reduced the overall height of hairy vetch within the mixture (Figure 3.3). This may have been the result of vetch
shoots having to extend a longer distance horizontally to reach a rye plant. The reduction in vetch height in the segregated treatments was likely a contributing factor to the lower vetch biomass in both Years 2 and 3 within Experiment 1, and may have outweighed any potential benefits resulting from reduced competition with rye for soil resources.

**Implications for weed suppression**

For organic reduced-till systems, it has been reported that approximately 8.0 Mg ha\(^{-1}\) of biomass is required to sufficiently suppress weeds throughout the growing season when used as mulch (Teasdale and Mohler, 2000). Previous studies have shown that it is difficult to reach those levels of biomass in northern climates (Brainard et al. 2013; Légère et al. 2013). We had greater success in achieving rye-vetch biomass that was close to 8.0 Mg ha\(^{-1}\) or greater in Experiment 1 because the rye-vetch was harvested and terminated later than in Experiment 2 (see Table 3.1), and had greater GDD accumulation in spring. In Experiment 2 a sweet corn crop followed the cover crops, and thus we followed timing requirements for cover crop planting and termination that were realistic of an operating vegetable farm. Under those conditions the MIX only reached 8.0 Mg ha\(^{-1}\) in Year 1 when we had greater GDD accumulation, while SEG2 never reached 8.0 Mg ha\(^{-1}\) across the whole plot. However, SEG2 had 7400 or greater total biomass within the RZ, which would ultimately be between the rows of the subsequent crop, and therefore, may be effective at weed suppression within that zone.

**Implications for N management**

Within Experiment 2, the MIX and SEG2 spatial arrangements did not differ in total N contained within the rye and vetch shoots across the whole plot in any of the...
three years. Total shoot N content was 130, 100, and 160 kg ha$^{-1}$ in years 2012, 2013, and 2014, respectively. Rye-vetch mixtures have been found to fully meet the N requirements of a subsequent sweet corn crop when they contained greater than 150 kg ha$^{-1}$ (Cline and Silvernail, 2002). Therefore, N contained within both the MIX and SEG2 spatial arrangements may have been insufficient to meet the full N requirements of a subsequent crop in two out of the three years. Nonetheless, in all cases, N contribution from vetch would have reduced fertilizer N requirements.

Perhaps the most important finding of our research is that strip-intercropping has potential to improve N use efficiency in legume-based cropping systems by concentrating the low C:N vetch residue within the crop root zone (VZ, Figure 3.5). We found that segregating cereal rye and vetch into strips lowered the C:N ratio of the rye-vetch mixture both above- and belowground in the VZ. Strip-intercropping resulted in a reduction of C:N ratio from more than 30 to less than 25 in 2 of 3 years. Since C:N ratios of less than 25 typically result in net N mineralization (Allison, 1966), concentrating vetch through strip-intercropping resulted in a zone of mineralization (VZ) and a zone of immobilization (RZ). Subsequent crops planted into the zone of mineralization (VZ) would be expected to efficiently access N in a manner analogous to banding of N fertilizers. Banding of N fertilizers has been shown to increase N use efficiency and increase yields in many cropping systems, including field corn (Maddux et al. 1991), wheat (Reinersten et al. 1984), and barley (Mahli and Nyborg 1985). N banding may also reduce fertilizer costs and minimize N losses to the environment (Maddux et al, 1991; Nash et al. 2012). However, future research is needed to
determine whether similar benefits might be realized through strip-intercropping of rye and vetch.

**Practical limitations of strip-intercropping**

The practical use of strip-intercropping may be hindered by several practical constraints. First, the residue of cover crops sown into specific zones will not remain exclusively in those zones during cover crop growth or following mowing and incorporation into the soil. As expected, vetch grew beyond the VZ into the RZ. In addition, both rye and vetch lodged in late spring in 2 of 3 years in Experiment 2, resulting in movement of rye residue into the VZ, and vetch residue into the RZ. Segregation of the rye and vetch residue into zones would have been greater without such lodging. This can be seen by comparing the extent of residue mixing in Year 2—when no lodging occurred—with Years 1 and 3 (Table 3.5, Figure 3.4). Lodging effects on cover crop distribution depends on the direction of the lodging and the orientation of fallen cover crops within the zones. The spatial distribution of cover crop residues in the subsequent crop will also depend critically on the method used to terminate the cover crop and prepare the soil for planting. For example, mowing will redistribute cover crop shoots, and aggressive tillage methods will redistribute both roots and shoots across zones. Therefore, the practical benefits of strip-intercropping are likely to be greatest when less aggressive methods are utilized to terminate cover crops (e.g. roller-crimping in the direction of strips), and reduced tillage (e.g. no-till or strip-till).

Segregating cereal rye and hairy vetch into strips would likely be more effective at “banding” N availability within the crop row if lodging could be avoided. One way to reduce the potential for lodging would be to terminate the cover crops before vetch
flowering, when vetch is at its peak biomass and more likely to cause lodging of the rye. We inferred that lodging was caused by heavy vetch biomass because we found no relationship between spring precipitation and lodging. Year 2 was the year with the greatest precipitation in the spring (Table 3.3), but had essentially zero lodging. Year 2 was also the year with the lowest vetch and total biomass, which suggests that lodging in Years 1 and 3 resulted from vetch being too heavy for the rye to support. In Experiment 2, our goal was to utilize the rye and vetch cover crops for an organic reduced-till study, so we waited until vetch was between 30% flowering and early pod set before mowing. Terminating vetch after early pod set reduces chance of regrowth during the subsequent crop (Mischler et al. 2010). However, waiting to terminate the rye and vetch until after vetch podset allows vetch to continue accruing biomass, thus increasing the chance of lodging. Therefore, if farmers were to use strip-intercropping of rye and vetch for an organic reduced-till system, they would face a tradeoff between decreasing susceptibility to either lodging or vetch regrowth.

**SUMMARY AND CONCLUSION**

Our objectives were to evaluate the effect of strip-intercropping of cereal rye and hairy vetch on i) cover crop productivity; ii) the distribution of rye-vetch biomass between cropping systems zones; and iii) N content and C:N ratio of the rye-vetch mixture inputs into cropping system zones.

Productivity benefits of segregation for reducing interspecific competition appear to have been outweighed or offset by the costs of increased intraspecific competition and/or reduced facilitation. Rye and vetch biomass was either unaffected (4 of 5 site-years) or reduced (1 of 5 site-years) in segregated spatial arrangements (SEG1 and
SEG2) compared to the full width mixture (MIX). Vetch biomass was either unaffected (4 out of 5 site-years) or reduced (1 out of 5 site-years) in SEG2; and unaffected (1 out of 3 site-years) or reduced (2 out of 5 site-years) in SEG1. Cereal rye biomass was reduced in 2 out of 5 site-years in SEG2, but not in SEG1.

Despite lodging of rye and vetch, segregating rye and vetch into strips of alternating rows of two (SEG2), resulted in a greater concentration of the N rich vetch and lower C:N ratio of aboveground rye-vetch biomass within the VZ in two out of three years. SEG2 also reduced C:N ratio of belowground biomass within the VZ in two out of two years. Therefore, strip-intercropping of cereal rye and hairy vetch is a promising strategy to concentrate N rich vetch residue within the row of future crops, thereby increasing their access to mineralized N. Future research will determine the effect that strip-intercropping of rye and vetch has on the subsequent crop.
Table 3.1. Dates of key field operations and data collection.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
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<tr>
<td></td>
<td>2011-2012</td>
<td>2012-2013</td>
<td>2013-2014</td>
</tr>
<tr>
<td>Experiment 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planted cover crops</td>
<td>8/31/2011</td>
<td>9/6/2012</td>
<td>8/30/2013</td>
</tr>
<tr>
<td>Sampled cover crop biomass</td>
<td>5/30/2012</td>
<td>6/14/2013</td>
<td>6/9/2014</td>
</tr>
<tr>
<td>Experiment 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planted cover crops</td>
<td>8/31/2011</td>
<td>9/10/2012</td>
<td>9/6/2013</td>
</tr>
<tr>
<td>Evaluated cover crop emergence</td>
<td>9/24/2011</td>
<td>9/23/2013, 10/30/2013</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.2. Cereal rye and hairy vetch spatial arrangement treatments for Experiment 1 and Experiment 2.

<table>
<thead>
<tr>
<th>Experiment 1 Treatment Factors</th>
<th>Experiment 2 Treatment Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed biculture</td>
<td>MIX</td>
</tr>
<tr>
<td>Segregated (1 row vetch, 3 rows rye)</td>
<td>SEG1</td>
</tr>
<tr>
<td>Segregated (2 rows vetch, 2 rows rye)</td>
<td>SEG2</td>
</tr>
<tr>
<td>Vetch monoculture</td>
<td>Vetch</td>
</tr>
<tr>
<td>Rye monoculture</td>
<td>Rye</td>
</tr>
<tr>
<td>Mixed biculture</td>
<td>MIX</td>
</tr>
<tr>
<td>Segregated (2 rows vetch, 2 rows rye)</td>
<td>SEG2</td>
</tr>
</tbody>
</table>
Table 3.3. Monthly GDD accumulation during cereal rye and hairy vetch growth for both Experiments 1 and 2 at the Kellogg Biological Station in Hickory Corners, MI.

<table>
<thead>
<tr>
<th></th>
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<td>Exp. 1</td>
<td>Exp. 2</td>
<td>Exp.1 &amp; 2</td>
<td>Exp. 1</td>
<td>Exp. 2</td>
</tr>
<tr>
<td>September</td>
<td>413</td>
<td>329</td>
<td>247</td>
<td>403</td>
<td>295</td>
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<td>214</td>
<td>229</td>
<td>229</td>
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<td>48</td>
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<td>45</td>
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<td>10</td>
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<td>May</td>
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<td>384</td>
<td>335</td>
<td>335</td>
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<td>June</td>
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<td>188</td>
<td>32</td>
<td>206</td>
<td>206</td>
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<td></td>
<td>786</td>
<td>592</td>
<td>509</td>
<td>677</td>
<td>569</td>
<td>257</td>
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</tr>
<tr>
<td></td>
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<td>537</td>
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</tr>
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<td>1323</td>
<td>1085</td>
<td>1382</td>
<td>1274</td>
<td>684</td>
</tr>
</tbody>
</table>

† GDD was calculated using base 4°C
‡ Beginning after planting of cereal rye and hairy vetch, according to the dates in Table 2.
§ Calculated until time of vetch and rye biomass collection and termination.
Table 3.4. Experiment 1. Significance of fixed effect of cover crop spatial arrangement (MIX, SEG1, and SEG2) on vetch, rye, and total biomass.

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
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<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vetch</td>
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<td>*</td>
</tr>
<tr>
<td>Rye</td>
<td>*</td>
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<td>ns</td>
</tr>
<tr>
<td>Total</td>
<td>*</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

¶ Significance at $p \leq 0.1$ level.
* Significance at $p \leq 0.05$ level.
** Significance at $p \leq 0.01$ level.
*** Significance at $p \leq 0.001$ level.
Table 3.5. Experiment 2. Significance of fixed effect of cover crop spatial
arrangement (MIX vs. SEG2) on biomass, C:N, and N content of rye and
vetch in mixtures within the vetch zone (VZ), rye zone (RZ) and across
the whole plot (WP).

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
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<th>2014</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>WP</td>
<td>VZ</td>
<td>RV</td>
<td>WP</td>
<td>VZ</td>
<td>RV</td>
</tr>
<tr>
<td>Biomass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vetch</td>
<td>ns</td>
<td>¶</td>
<td>**</td>
<td>¶</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Rye</td>
<td>*</td>
<td>***</td>
<td>ns</td>
<td>**</td>
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<tr>
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<td>*</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>Vetch</td>
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<td>—</td>
<td>ns</td>
<td>—</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Total</td>
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<td>¶</td>
<td>ns</td>
<td>ns</td>
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<td>N kg ha⁻¹</td>
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<td>Vetch</td>
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<td>ns</td>
<td>ns</td>
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</tr>
<tr>
<td>Rye</td>
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<td>**</td>
<td>ns</td>
<td>¶</td>
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<td>Total</td>
<td>ns</td>
<td>ns</td>
<td>**</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

¶  Significance at $p \leq 0.1$ level.
*  Significance at $p \leq 0.05$ level.
** Significance at $p \leq 0.01$ level.
*** Significance at $p \leq 0.001$ level.

<table>
<thead>
<tr>
<th>Spatial Arrangement</th>
<th>Vetch</th>
<th>Rye</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIX</td>
<td>13.72 (1.75)</td>
<td>55.36 (2.62)</td>
</tr>
<tr>
<td>SEG2</td>
<td>13.06 (0.60)</td>
<td>54.83 (6.57)</td>
</tr>
</tbody>
</table>

*P values*  
ns  ns

<table>
<thead>
<tr>
<th>2013</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MIX</td>
<td>11.70 (0.72)</td>
<td>45.24 (6.86)</td>
</tr>
<tr>
<td>SEG2</td>
<td>12.32 (1.01)</td>
<td>46.54 (3.92)</td>
</tr>
</tbody>
</table>

*P values*  
ns  ns

<table>
<thead>
<tr>
<th>2014</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MIX</td>
<td>10.81 (0.42)</td>
<td>43.58 (4.87)</td>
</tr>
<tr>
<td>SEG2</td>
<td>11.18 (0.67)</td>
<td>39.35 (3.00)</td>
</tr>
</tbody>
</table>

*P values*  
ns  ns
Figure 3.1. Planting arrangement of cereal rye and hairy vetch seeds among the different rye and vetch spatial arrangements in Experiments 1 and 2: 1) the standard Mixed Biculture (MIX), 2) strip-intercropping with 2 rows of rye and 2 rows of vetch (SEG2), and 3) strip-intercropping with 1 row of vetch and 3 rows of rye (SEG1).
Figure 3.2. Experiment 1. Mean (+/- SEM) of hairy vetch, cereal rye, and total aboveground biomass among mixtures with varying spatial arrangements, compared to a rye (dotted line) and vetch (dashed line) monoculture in Year 1 (2011-2012), Year 2 (2012-2013), and Year 3 (2013-2014). Spatial arrangements include the standard MIX biculture, compared to two forms of segregation: SEG1 (3 rows of rye, 1 row of vetch), and SEG2 (2 rows of rye, 2 rows of vetch). We did not have a rye monoculture treatment in Year 1.
Figure 3.3. Experiment 1. Mean (+/- SEM) of hairy vetch height within rye-vetch mixtures with varying spatial arrangements, compared to a vetch monoculture in Year 2 (2012-2013) and Year 3 (2013-2014). Spatial arrangements include the standard Mix biculture, compared to two forms of segregation: SEG1 (3 rows of rye, 1 row of vetch), and SEG2 (2 rows of rye, 2 rows of vetch).
Figure 3.4. Experiment 2. Mean (+/- SEM) hairy vetch and cereal rye aboveground biomass within the vetch zone (VZ) and rye zone (RZ) of a rye-vetch mix biculture (MIX) and segregated (SEG2) into two rows of rye and two rows of vetch in Year 1 (2011-2012), Year 2 (2012-2013), and Year 3 (2013-2014).
Figure 3.5. Experiment 2. Mean (+/- SEM) C:N ratio of cereal rye and hairy vetch mixture aboveground (shoots) and belowground (root) biomass in the mixed (MIX) spatial arrangement and both the vetch-zone (VZ) and rye-zone (RZ) within the segregated (SEG2) spatial arrangement in Year 1 (2011-2012), Year 2 (2012-2013), and Year 3 (2013-2014).
LITERATURE CITED
LITERATURE CITED


CHAPTER FOUR

Rye and vetch spatial arrangement and strip-tillage influence N availability and sweet corn root growth

ABSTRACT

Strip-intercropping of functionally diverse cover crops, such as cereal rye and hairy vetch, is one mechanism by which N dynamics could be altered to enhance crop N use efficiency and alleviate N deficiency in organic systems. We established a field study in southwest Michigan between 2011 and 2014 to examine the effects of rye-vetch cover crop spatial arrangement (full width mixture [MIX] or segregated strips [SEG]) and tillage (strip-tillage [ST] or full width tillage [FWT]) on soil N, sweet corn N uptake, above- and belowground biomass, and root morphology. ST reduced Late season potentially mineralizeable N in the MIX, but not the SEG spatial arrangement. ST had lower soil inorganic N compared to FWT in two out of three years in both the MIX and SEG spatial arrangements. Despite lower N availability, ST increased sweet corn total biomass and N uptake in two out of three years, and increased sweet corn ear weight in one year. ST reduced root biomass both within and between crop rows, and increased root diameter within the untilled between-row (BR). Segregating rye and vetch into strips increased inorganic N and reduced root biomass within the crop row, but had no effect on sweet corn biomass or N content. Strip-tillage and strip-intercropping show promise in adapting reduced-till systems for organic production, but more work is needed to develop new strategies to band organic N within the crop row and increase nitrogen use efficiency.
INTRODUCTION

Legume cover crops are a widely used source of N in organic systems (Bingen et al. 2007), due in part to being relatively inexpensive sources of N (Gaskell and Smith, 2007) and because they provide soil protection and improve soil structure (McVay et al. 1989; Cherr et al. 2006). However, legume-based systems are often N deficient, and exhibit reduced crop yields compared to systems with synthetic fertilizers because of lower overall N availability (Clark et al. 1999; Kirchmann and Bergstöm, 2001; Poudel et al. 2002). Crop N deficiency resulting from a dependence on legumes as the primary N source is especially common in reduced tillage systems (Varco et al. 1993; Dou et al. 1994; Doane et al. 2009). Improving nitrogen use efficiency within legume-based systems is important for increasing crop yields as well as for maintaining ecosystem health and functioning.

Synchrony of legume N release and crop N demand depends on a number of factors, including the quality of legume residue (Kuo et al. 1996; Rannells and Wager, 1996), the timing of legume termination and incorporation (Crews and Peoples, 2005), as well as environmental conditions- such as soil moisture and temperature (Honeycutt et al. 1988; Ruffo and Bollero, 2003). Variation in the rate of legume residue decomposition and timing of N release complicates the predictability of legume N contribution to a succeeding crop. Studies have found that mineralization of N typically peaks anywhere between 3 to 6 weeks after legume incorporation (Gaskell and Smith, 2007). Depending on the length of time and environmental conditions between legume incorporation and planting of the crop, peak N availability may occur significantly earlier than timing of peak crop N demand (Kuo et al. 1997; Rosecrane et al. 2000). On the
other hand, when soil temperature and moisture are inadequate to promote
decomposition and mineralization, organic N may be retained within legume residue,
ultimately leading to crop N deficiency and increased potential for N leaching (Dou et al.
1995; Rannells and Wagger, 1996; Pimentel et al. 2005; Ruffo and Bollero, 2003; Cook
et al. 2010).

Legume based systems are prone to N losses when patterns of N release are
asynchronous with crop N demand or when inorganic N is inaccessible to crop roots
(Robertson, 1997). In organic cropping systems, efforts to improve the synchrony and
spatial coincidence of N supply and demand have been limited. Previous research
efforts have focused on modulating the rate of decomposition and inorganic N release
from legume residues by combining them in mixtures with cereal grasses (Rannels and
Wagger 1996; Lawson et al. 2012; Hayden et al. 2014). Cereal grasses are utilized as
cover crops because of their high capacity for suppressing weeds and returning large
quantities of carbon to the soil. Varying proportions of high carbon cereal residue with
N-rich legume residue leads to alterations in the total C:N ratio, a major determinant of
hairy vetch, a legume, in mixture with cereal rye, and found the rate of N release was
decreased by as much as 15%. It was concluded that this slower release of N was more
likely to be synchronized with timing of crop N demand. However, while mixtures of rye
and vetch may lead to a slower release of N, the total N available to the subsequent
crop is often reduced due to N immobilization by cereal rye (Lawson et al. 2012).

Rather than focus on optimizing the rate of decomposition and N mineralization
of legume cover crops, an alternative strategy to enhance crop nitrogen use efficiency is
to alter the placement of N. In conventional cropping systems, banded applications of N adjacent to the crop row can significantly improve crop N uptake efficiency and yields (Mengel et al. 1982; Maddux et al. 1991), decrease N immobilization (Maddux et al. 1991) and may reduce N losses (Waddell and Weil, 2006; Nash et al. 2012; Haramoto, 2014). Studies examining changes in plant productivity under controlled greenhouse conditions have found that concentrating forms of organic N in close proximity to crop roots leads to an increase in N uptake and plant biomass (Robinson et al. 1994; Hodge et al. 1999). For example, red clover residue increased maize aboveground productivity when aggregated into clumps compared to uniform distribution throughout the soil (Loecke and Robertson, 2009). Plants stimulate root proliferation in regions of the soil with concentrated reserves of nutrients by diverting energy for root growth away from nutrient poor regions (Robinson, 1994). This reduces the energy required by the plant for acquisition of the limiting nutrient and allows more energy to be diverted to aboveground productivity. The ability of a crop to benefit from a spatial advantage to a N rich resource in the soil may be greater with an organic source of N because of its slower, yet continuous release (Hodge, 1999).

Strip-intercropping of functionally diverse cover crops, such as cereal rye and hairy vetch, is one mechanism by which N dynamics could be altered to enhance crop N use efficiency in organic systems. Legume cover crops sown solely in a strip directly in-row with future crop establishment may provide N directly to the crop roots and increase the likelihood of crop uptake of N prior to being lost. High C:N cover crops, such as cereal rye, sown between crop rows may create a zone initially deficient in N that can potentially serve as a reservoir of late-releasing N. The synchrony and spatial
coincidence of N supply and demand may also be enhanced in organic cropping systems through use of strip-tillage (ST). Tillage targeted to the crop row (within-row; WR) can stimulate mineralization of soil organic N directly where the crop needs it (McCarthy et al. 1995), without unnecessarily releasing N between crop rows (BR) where N is not needed until later in the growing season. This could potentially decrease the amount of N inaccessible to crop roots leading to reductions in N losses, as well as increase the proportion of soil inorganic N in the soil taken up the crop.

Our goal was to evaluate whether strip-intercropping of cereal rye and hairy vetch within an organic ST system could increase cover crop N mineralization and availability to the crop, and consequently increase sweet corn biomass and N uptake. We hypothesized that concentration of vetch residue in the WR zone through strip-intercropping would increase both potentially mineralizeable N (PMN) and soil inorganic N in close proximity to sweet corn roots, hence improving N use efficiency. We also expected that these beneficial effects of would be more pronounced within ST than full-width tillage (FWT). A secondary objective was to evaluate the impact of changes in spatial distribution of N pools on sweet corn root allocation. We expected that the magnitude of sweet corn response to strip-intercropping and strip tillage would depend on the plasticity of root response to differences in N spatial dynamics, and hypothesized that under strip-intercropping, sweet corn would allocate a greater proportion of root biomass to the N-rich WR zone.
MATERIALS AND METHODS

Site description and experimental design

The experiment was conducted between 2011-2014 on organically managed (between 5-7 years, depending on field) Kalamazoo (fine-loamy, mixed, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, mesic Typic Hapludalfs) sandy loams (Crum and Collins, 1995), at the Kellogg Biological Station in Hickory Corners, MI (85° 24’W, 42° 24’ N). Treatments were arranged in a split plot, randomized complete block design with four replicates. Main plots consisted of a 2 X 2 factorial of tillage (FWT and ST) and rye and vetch spatial arrangement (Mixed Biculture [MIX] and Segregated into strips [SEG]). The split plot factor was crop (sweet corn [CORN] or no crop [NOCORN]). Zones within the cropping system were also treated as subplots. The zone within the crop row (WR) is the 25 cm zone where the crop is planted (and where tillage occurs within strip-tilled treatments), and the between-row (BR) zone is the 50 cm zone between crop rows and also is untilled in strip-tilled treatments. Subplot area with corn (CORN) was 27.3 (9.1 X 3.0 m), 37.2 (6.1 X 6.1 m), and 41.0 (9.1 X 4.5 m) m² in 2012, 2013, and 2014 respectively. Subplots without corn were 9.0 (3.0 X 3.0 m), 9.0 (3.0 X 3.0 m), and 20.3 (4.5 X 4.5 m) m² in 2012, 2013, and 2014 respectively.

Field activities were performed according to Table 4.1. Both cereal rye and hairy vetch seeds were “Variety Not Stated” and organically certified across all three years. Spatial arrangements included a full-width mixture (MIX) in which rye and vetch were sown together in the same rows; and a segregated mixture (SEG) in which 2 rows of hairy vetch were alternated with 2 rows of rye. Both spatial arrangements had the same seed rate on a per plot basis (62.7 kg ha⁻¹ rye; 22.4 kg ha⁻¹ vetch). In both rye and vetch
spatial arrangements, between-row spacing for rye and vetch rows was 19.1 cm. Cereal rye was planted with a grain drill and every two drop tubes were blocked within SEG to prevent seeding rye in the vetch rows. Hairy vetch was planted with a Jang push-seeder. No N fertilizers were added prior to cover crop establishment or sweet corn planting. Organic forms of P and K were added according to soil tests, and consisted of: 34 kg K ha\(^{-1}\) of NOP certified Potassium Sulfate Plus and Tennessee Brown Phosphate in 2012 and 34 kg K ha\(^{-1}\) of Ks+ in 2013.

Cover crops were flail mowed twice when vetch had reached approximately 50% flowering in mid- to late- May of 2012, 2013, and 2014. Conventional tilled treatments were chisel plowed to a depth of approximately 20 cm, and then rototilled to break up cover crop residue. A Hiniker Model 6000 two-row strip tiller (equipped with notched row-cleaners, cutting-coulter, shank point assembly, berming discs, and rolling basket) was used for WR tillage in ST treatments. To improve soil tilth for planting in ST, a walk behind rototiller was used for WR secondary-tillage. The resulting WR zone was approximately 25 cm wide and 20-25 cm deep. Two weeks after tillage, sweet corn was planted using a high residue planter (Monosem vacuum seeder) at a between-row spacing of 76.2 cm and in-row spacing of 10 cm. Once sweet corn emerged, population density was thinned to an in-row spacing of 16.5 cm. After corn emergence, corn was removed via hoeing for NOCORN subplots. Weeds were controlled through a combination of hand weeding and hoeing once a week for the first 5 weeks, and every other week thereafter. Sweet corn was irrigated during low-rainfall periods in 2012 and 2014, totaling 62.2 and 46.8 mm of irrigated water, respectively throughout the sweet
corn season. In 2013, rainfall was sufficient so we did not provide any additional irrigation.

**Data collection**

*Potentially Mineralizeable N.* In *situ* N mineralization assays were employed to evaluate the potential for N release from cover crop residues within each tillage system (Robertson, et al. 1999). *In situ* or in field mineralization incubations incorporate effects that tillage and cover crop mulch have on soil structure, moisture, and temperature, as well as the subsequent effect these differences have on N mineralization. Incubations were initiated in treatments within the CORN subplots 7 and 35 days after tillage. Five centimeter internal diameter (24 cm depth) PVC pipes were installed in each whole plot (3 cores per zone and tillage combination) and capped until core removal. At installation, we collected two soil samples directly adjacent to installed cores at the start of incubation and extracted for soil inorganic N to determine initial inorganic N (see below for inorganic N). We removed soil cores after 30 to 35 days and measured soil for gravimetric moisture and inorganic N.

Mineralization per day was calculated according to the following equation:

\[
N_{\text{mineralized}} = \frac{(\text{Nitrate}_{\text{final}} + \text{Ammonium}_{\text{final}}) - (\text{Nitrate}_{\text{initial}} + \text{Ammonium}_{\text{initial}})}{T_{\text{days}}}
\]

**Bulk density.** Upon mineralization tube extraction, soil cores were pooled, homogenized, and weighed. Two 10 g subsamples were removed for gravimetric soil moisture to determine soil dry weight (see below). Bulk density was then calculated by dividing soil dry weight by soil volume. If soil was missing from the tube bottom, we measured the length of tube with soil missing to estimate the volume of each soil core for calculation of bulk density.
Soil sampling - Inorganic N and gravimetric soil moisture. Soil samples were collected every 7-14 days (8 sampling times in 2012, 2013, and 9 sampling points in 2014) throughout the growing season in all treatments and subplots in both the WR and BR. At each sampling date, 10-12 cores (2.5 cm diameter X 20 cm deep) were taken for each plot. Soil samples were dried at 38°C and ground. Fifty milliliters of 1M KCl were used to extract soil inorganic N on 10 g of dry soil and samples were analyzed on a QuikChem 8500 Flow Injection Analyzer (Gelderman and Beegle, 1998). Two 10 g subsamples of moist soil were dried at 100°C and reweighed for gravimetric soil moisture. Gravimetric water content (GWC) was calculated according to the following:

\[ GWC = \frac{(g \text{ moist soil} - g \text{ dry soil})}{g \text{ dry soil}} \]

To calculate the soil inorganic N and gravimetric moisture across the whole plot, we used weighted means of the measured values from the WR and BR zones adjusted by their respective areas. For example, for inorganic N (IN) we used:

\[ IN_{\text{whole plot}} = IN_{WR} \times \frac{1}{3} + IN_{BR} \times \frac{2}{3} \]

Where the within-row (WR) zone is the 25 cm zone where the crop is planted (and where tillage occurs within strip-tilled treatments), and the between-row (BR) zone is the 50 cm zone between crop rows and also is untilled in strip-tilled treatments.

Sweet corn aboveground biomass and N content. At harvest, we removed all primary ears from sweet corn plants in a designated harvest area of 9.3, 14, and 22.3 m² in 2012, 2013, and 2014, respectively. Harvest areas were adjusted each year based on available plot size and stand uniformity, which varied each year. Secondary ear weight was grouped with nonharvested biomass and consisted of no more than 5% of nonharvested biomass. To obtain plant dry weight and percent N, we collected the
nonharvested aboveground portion of 5 randomly sampled plants from each plot, and 5 representative corn ears. We removed a 2.5 cm section from corn ears, dried to determine a fresh to dry weight ratio, and multiplied this ratio by total fresh weight to estimate total ear dry weight. Both nonharvested corn biomass and corn ear sections were dried at 60°C and ground through a 1 mm screen. A Kjehldahl digest (Kalra, 1998) was performed on 0.15 g samples of nonharvested corn biomass and corn ears (2 lab replicates per sample) and analyzed for total Kjehldahl nitrogen with a QuikChem 8500 Flow Injection Analyzer.

*Sweet corn belowground biomass.* Three cores (5 cm diameter X 25 cm depth) were excavated from both the WR and BR zones at sweet corn harvest to compare differences in allocation of root biomass between the WR and BR zones. A meter stick was laid adjacent to a sweet corn plant and perpendicular to the sweet corn row, and root cores were excavated 7.5 cm (WR) and 25 cm (BR) from the plant; samples thus represented the mid-point between the edge and center of each zone. The root samples were weighed, and a subsample was taken for gravimetric soil moisture. Samples were sieved twice through a 4 mm sieve and roots were collected, thoroughly washed, and scanned with an EPSON (V700) scanner. We used a WinRHIZO (Régent Instruments Inc. Québec, Canada) image analysis system to analyze root images for root length and average root diameter (ARD). Roots were dried at 60°C for 72 hours and weighed. Root data was used to calculate specific root length (SRL, root length per unit root dry weight (m g⁻¹)) and root length density (RLD, root length per unit of soil volume (cm cm⁻³)).
**Statistical analysis**

All data were analyzed using mixed models ANOVA with PROC MIXED procedures in SAS (Version 9.3, SAS Institute, Cary, NC). Year was initially treated as a fixed factor to determine if fixed effects interacted with year to affect response variables, and if there was no differences data were pooled across years. In all cases, block was nested in year, and block and interactions of block with fixed factors were treated as random effects. The data were checked for assumptions of normality and equal variance, and when necessary, unequal variance models were used selected based on AIC values. To increase normality, we log transformed inorganic N, specific root length, and sweet corn root mass.

The fixed effects of tillage (FWT vs ST), cover crop spatial arrangement (MIX vs SEG), and zone (WR vs BR) were analyzed for potentially mineralizeable N (PMN), inorganic N (IN), and gravimetric moisture responses. For IN and gravimetric moisture, the NOCORN and CORN subplots were analyzed separately. The WR and BR zones were analyzed separately for the fixed effects of tillage and cover crop spatial arrangement on sweet corn root mass and morphology. For soil IN and moisture, data were analyzed using repeated measures mixed models with date included as a repeated factor, and AIC and BIC values were compared to determine the best model fit.

When significant treatment effects were detected, means were separated using Fisher's protected LSD $P < 0.05$. In cases where $P$-values were between 0.05 and 0.10, differences are reported as “marginally significant” with the $P$-value presented.
parenthetically. All figures were made using the GGPGLOT2 package in R (Wickham, 2009).

**RESULTS**

*Potentially mineralizeable N*

PMN was measured from planting to mid-season (Early) and mid-season to harvest (Late) in 2012, 2013, and 2014 (Figure 4.1). For both Early and Late N mineralization potential, there were no interactions of year with either cover crop spatial arrangement or tillage so years were pooled. We found no detectable difference in whole plot Early PMN due to tillage or cover crop spatial arrangement. In Late season PMN, within FWT, the MIX spatial arrangement had 30% greater PMN compared to the SEG arrangement (Till*SA, \( P=0.0155 \)). ST MIX has 28% lower PMN compared to FWT-MIX, but we found no detectable difference between ST and FWT within SEG arrangements.

Within ST, we found a marginal interaction between RV spatial arrangement and zone when measuring Early Season PMN (Figure 4.2). The BR of the MIX spatial arrangement had 38% greater PMN than SEG-BR, but there was no detectable difference within the WR between RV spatial arrangements (SA*Zone, \( P=0.062 \)). SEG-BR had greater PMN than SEG-WR. We found no detectable difference in Late PMN between the zones of ST due to cover crop spatial arrangement.

*Soil Inorganic N*

The effects of tillage on soil inorganic N (IN) in the absence of sweet corn varied with sampling time in 2013 and 2014, but did not vary with cover crop spatial arrangement in any year (Table 4.2, Figure 4.3). Without corn, ST decreased soil IN by
an average of 33% compared to FWT in both 2013 and 2014, and the difference between tillage systems increased throughout the season. We found no detectable difference in IN due to tillage in either NOCORN or CORN subplots in 2012. Results with corn were very similar to those without corn: FWT had a season-average of 24% and 28% greater IN compared to the ST in 2013 and 2014, respectively. The effects of tillage on IN in the presence of sweet corn varied with sampling time in 2013 and 2014, but did not vary with cover crop spatial arrangement (Table 4.2, Figure 4.3). IN within CORN subplots peaked in July, and then decreased throughout the month of August as corn was growing exponentially.

Figure 4.4 shows IN within the WR and BR zones of NOCORN subplots. 2014 was the only year we found an interaction of tillage and zone, which was also affected by sampling date (Table 4.3, Figure 4.4). ST-WR had 20% greater IN compared to the ST-BR had 25% lower IN compared to the FWT-WR/BR, and differences in soil IN tended to increase throughout the sweet corn season.

We found no detectable difference in whole plot IN due to cover crop spatial arrangement across the whole plot in either FWT or ST in any of the three years (Table 4.2, Figure 4.3). However, tillage and spatial arrangement did influence zonal availability of IN in subplots without corn (Table 4.3; Figure 4.4). In 2012, we found a marginal effect (SA*Zone, $P=0.064$) of cover crop spatial arrangement and zone, with SEG-WR having 16% greater inorganic N than SEG-BR and 11% greater than MIX-WR, regardless of tillage. When we analyzed the effect of cover crop spatial arrangement on IN within ST, we found that SEG increased IN within the crop row (WR) by 11% compared to MIX (SA*Zone, $P=0.0016$).
**Bulk density**

Cover crop spatial arrangement had no effect on bulk density in any year, but tillage and zone influenced bulk density in 2013 and 2014 (Table 4.4). In 2013, ST-BR had approximately 10% greater bulk density than ST-WR and either zone within FWT. In 2014, ST-BR had greater bulk density than the ST-WR and FWT-BR, but not FWT-WR.

**Gravimetric soil moisture**

The effect of tillage on gravimetric soil moisture in CORN subplots interacted with sampling date in both 2012 and 2014, but not 2013 (Table 4.5 Figure 4.5). In 2012, ST had 11% greater soil moisture compared to FWT, and this difference was greatest in mid-July. In 2014, ST had 9% greater soil moisture compared to FWT, and the difference was greatest in mid-July and early September. Cover crop spatial arrangement significantly affected gravimetric moisture in 2013, but did not interact with tillage or date. The MIX spatial arrangement increased gravimetric soil moisture by 10% compared to SEG.

**Sweet corn aboveground biomass and N content**

Tillage influenced sweet corn above ground biomass, but we found no detectable differences due to cover crop spatial arrangement, nor interactions between tillage and cover crop spatial arrangement in any of the three years (Table 4.6, Figure 4.6). ST increased total sweet corn biomass by 19% in 2012 and 16% in 2014 compared to FWT. The effect of tillage was marginal in 2013 (P=0.09), in which ST had 10% lower total biomass compared to FWT. ST increased sweet corn nonharvested biomass by 37% and 19% in 2012 and 2014, respectively, compared to FWT. ST
increased sweet corn ear dry weight by 18% in 2014 compared to FWT, but had no detectable effect on corn ear weight in 2012 and 2013. We found no detectable difference in biomass partitioned to corn ears or nonharvested biomass in 2013 and 2014. Corn ear biomass represented 35% of total biomass in both 2013 and 2014. In 2012, we found marginally greater biomass partitioned to the corn ear in FWT+MIX compared to FWT+SEG, and ST (Till*SA, $P=0.082$).

As with corn biomass, the effect of tillage on sweet corn N uptake interacted with year, but not cover crop spatial arrangement. ST increased total sweet corn N uptake by 15 and 17% compared to FWT in 2012 and 2014, respectively, but decreased total sweet corn N uptake by 21% in 2013 (Table 4.6, Figure 4.6). Tillage had no effect on the N partitioned to either nonharvested biomass or sweet corn ears in any year. N partitioned to sweet corn ears was 54, 43, and 33% in 2012, 2013, and 2014, respectively.

We found no detectable difference in sweet corn N uptake in nonharvested biomass, sweet corn ears, or total N uptake in any year. In 2012, we found a marginal increase in the percent of total N partitioned to nonharvested biomass compared to corn ears within the SEG spatial arrangement ($P=0.06$), but there was no detectable difference in 2013 and 2014.

**Sweet corn belowground biomass**

Within the WR (7.5 cm from the sweet corn plant), both tillage and cover crop spatial arrangement affected sweet corn root mass, but there was no interaction between the two main effects, nor did they interact with year (Table 4.7, Figure 4.7.A). SEG reduced sweet corn root mass within the WR by 34% compared to MIX, regardless
of tillage. ST reduced sweet corn root mass in the WR zone by 30% compared to FWT, regardless of spatial arrangement. Between crops rows (at the 25 cm distance) we found a significant interaction between tillage and cover crop spatial arrangement, but no interactions with year. SEG rye and vetch increased root biomass by 43% within the BR of FWT, but had no detectable effect on root biomass in the BR of ST.

Figure 4.7.B. shows the ratio of WR/BR root mass, in which we found a significant interaction between tillage and cover crop spatial arrangement. FWT+MIX had a significantly greater WR/BR root mass compared to FWT+SEG and ST. We found no detectable difference in the WR/BR mass ratio due to cover crop spatial arrangement within ST.

**Sweet corn root morphology**

Within the BR, tillage and cover crop spatial arrangement interacted to affect both sweet corn SRL and ARD, but neither main effect interacted with year (Table 4.7, Figure 4.8). ST reduced SRL within the BR of the MIX, but not the SEG spatial arrangement. SEG increased ARD in the BR of FWT, but not of ST. Within the WR, we found a marginal increase in SRL in SEG spatial arrangements across both tillage systems (SA, $P=0.077$), and a marginal decrease in root diameter but only within ST (Till*SA, $P=0.095$).

RLD was influenced by tillage but not by cover crop spatial arrangement (Table 4.7, Figure 4.8). The effects of tillage on RLD differed by year (Table 4.7). In 2014, ST decreased the RLD in both zones compared to FWT (data not shown). In 2013, RLD was also lower in ST, regardless of zone, but the difference was not substantial enough to be significant.
**DISCUSSION**

*Strip-tillage effects on PMN, soil inorganic N, and sweet corn*

We expected that PMN would be greater within FWT compared to ST. However, we only found a reduction in Late season PMN within the MIX spatial arrangement. This was surprising given that we found lower IN in ST compared to FWT in both cover crop spatial arrangements. Incorporating crop residues into the soil typically enhances decomposition and mineralization. It is possible that the lack of a tillage effect on PMN is due to the recalcitrant rye residue is immobilizing N as it decomposes. Rye immobilization of N is greatest when the C:N ratio is at its highest, typically after anthesis, which also corresponds to the timing of rye and vetch termination in this study. Residues left on the soil surface have slower rate of decomposition, and are thus less likely to tie-up N. The discrepancy between PMN and IN may have resulted from greater N losses through leaching (See Chapter 2; Figures 2.7 and 2.8) or greater N uptake in ST in two out of the three years (Figure 4.6). Our results are consistent with previous studies that have found lower IN availability within legume-based reduced-till systems (Dou et al. 1994; Mulvaney et al. 2010).

It is surprising that despite lower IN in ST compared to FWT, ST only negatively affected corn aboveground biomass and corn ear weight in 2013. This suggests that factors other than N—such as soil moisture—may have affected sweet corn growth in FWT treatments in 2012 and 2014. This hypothesis is consistent with the observation that soil moisture was lower in FWT then ST treatments in 2012 and 2014, but higher in 2013 (Figure 4.5). Soil moisture, rather than soil IN, may have been the primary factor influencing tillage effects on sweet corn root growth and morphology in the WR zone.
The lower root mass and RLD within ST suggests that sweet corn plants allocated less carbon to resource acquisition within the top 0.25 m compared to FWT. Plants generally increase root growth and RLD when nutrients or water are limiting (Bloom et al. 1985; Boot and Mensink, 1990), but when soil resources are sufficient carbon allocation is prioritized to shoots. Thus, the lower root mass and RLD within ST suggests a more efficient uptake of soil resources.

Differences in bulk density between tillage systems may also have strongly influenced corn root growth and morphology, especially in the BR zone. We found lower RLD in both the WR and BR zones of ST, which is consistent with some (Chassot et al. 2001, Qin et al. 2005) but not all (Acharya and Sharma, 1994; Ball-Coehlo et al. 1998) prior studies. Dal Ferro (2014) et al. found that bulk density was negatively correlated with RLD and mass and attributed it to increased mechanical impedance restricting root growth. Within the un-tilled zone (BR) of ST, we found lower SRL and an increase in root diameter within the MIX rye-vetch spatial arrangements. Increased bulk density, such as was found within the BR of ST, can result in roots with a greater average diameter (Barber, 1971; Bathke et al. 1992). Previous studies have suggested that in soils with greater bulk density, roots must be stronger and denser to penetrate the soil (Barber, 1971; Unger and Kaspar, 1994). Increased soil moisture within untilled soils combined with a mulch can alleviate obstructions to root growth by increasing soil aggregate malleability (Unger and Kaspar, 1994). However, within our study it seems that increased soil moisture did not offset the effects of bulk density on root diameter and SRL.
Cover crop spatial arrangement effects on PMN, soil inorganic N, and sweet corn

Differences in IN due to spatial arrangement were smaller than expected, perhaps due in part to movement of cover crop shoot tissue across zones prior to corn planting. Although segregating rye and vetch into strips increased IN, these differences were very small relative to differences due to tillage (Figure 4.4). Cover crop lodging in two out of the three years likely reduced the spatial segregation of N between the WR and BR zones. Additionally, mowing likely contributed to additional lateral movement of rye and vetch between the WR and BR zones. Finally the chisel plowing and rototilling within FWT likely increased the lateral movement of rye and vetch residues. We may have seen greater differences in N availability between the WR and BR zones if we had used a roller crimper to terminate the cover crops and no-till planted the sweet corn. However, we mowed the rye and vetch to facilitate strip-tillage.

Given these relatively small differences in IN, it is not surprising that we found no effect of cover crop spatial arrangement on sweet corn aboveground biomass, ear dry weight, or N uptake in any of the three years. However, we did find SEG-RV effects on sweet corn root biomass and morphology. Segregating rye and vetch into strips reduced corn root biomass in the WR zone by 38%, and decreased root biomass in the BR zone of ST by 43%. This suggests that sweet corn plants within SEG spatial arrangements allocated less carbon for roots within the top 25 cm of soil to support equal shoot growth and sweet corn yields.

Fine roots with a greater surface area and larger length to mass ratio (SRL) are capable of exploiting larger soil volumes, and may be more efficient at absorbing N. SRL may be an indicator of the cost (root mass) to benefit (resource acquisition) ratio of
obtaining soil resources (Eissenstat, 1992; Ostonen et al. 2007). Resource absorption is directly proportional to the length of the roots, so increased SRL indicates higher resource absorption per carbon investment in root growth. Roots with a greater SRL are more efficient at taking up soil resources, which enables energy to be diverted to aboveground productivity. Response of SRL to N fertilization varies considerably among species (Hill et al. 2006; Ryser, 2006); however previous studies have found N fertilization increases SRL of field corn (Anderson, 1988; Bonifas and Lindquist, 2009). This is counterintuitive, because it seems logical that the costs of building new roots, would be minimized when resources are limiting, thereby increasing SRL (Ryser, 2006). It is likely that differences in SRL do not result from any differences in absolute nutrient availability, but rather result from the heterogeneous distributions of resources within SEG-RV. Increased SRL within the WR zone of SEG-RV is likely a response to the WR enrichment with N rich organic residues, and is consistent with numerous studies that have found that SRL and N uptake increases in patches or zones of nutrient enrichment (Drew, 1975; Hodge et al. 1999; Hodge, 2004; Loecke and Robertson, 2009).

We had expected that the greatest difference between the WR and BR zones in root mass and morphology would be in the ST-SEG, the treatment with the greatest zonal differences in soil resources and physical properties. Therefore, it was surprising that the root WR/BR mass ratio was greatest in the most homogenous treatment, FWT-MIX. FWT loosened the soil across the plot to a depth of approximately 20 cm, and likely facilitated root penetration deeper into the soil profile. Compared to no-till, tillage results in a more vertical orientation of root development (Ball-Coelho et al. 1998). It is possible that the lower root growth in FWT-MIX BR is the result of a more vertical
orientation of roots that penetrate more deeply but less laterally within the soil, however we did not sample deeper than 0.25 m so can only speculate about root mass at greater depths. It is not clear why we detected such a large difference in root WR/BR mass ratio between the FWT-MIX and FWT-SEG.

**SUMMARY AND CONCLUSION**

Despite lower soil IN in ST compared to FWT, ST increased sweet corn total biomass and N uptake in two out of three years, and increased sweet corn ear weight in one year. Our results suggest that this may have been the result of increased gravimetric soil moisture, and perhaps more efficient resource uptake by roots in ST. ST reduced carbon allocation to root biomass in both the WR and BR zones, and increased root diameter within the untilled BR.

Segregating rye and vetch into strips increased IN and reduced root biomass within the crop row, but had no effect on sweet corn biomass or N content. These results suggest that sweet corn roots are surprisingly plastic in their response to relatively small differences in the distribution of IN within the soil. Further studies are required to understand the mechanisms responsible for these differences in carbon allocation to roots as well as their implications for crop productivity.

Strip-tillage and strip-intercropping show promise in adapting reduced-till systems for organic production, but more work is needed to develop new strategies to band organic N within the crop row and increase nitrogen use efficiency. Alternative approaches for increasing the effectiveness of strip-intercropping may include roller-crimping, earlier termination of cover crops to reduce rye and vetch susceptibility to lodging, or a “cut and carry” approach to cover crop residues. Additional options for
targeted N placement within organic RT systems including banding of manure, compost, or other organic N amendments (ie. feathermeal, blood meal, etc.) within the crop row.
Table 4.1. Dates of key field activities and data collection.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Dates of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2011-2012</td>
</tr>
<tr>
<td>Planted cover crops</td>
<td>8/31/2011</td>
</tr>
<tr>
<td>Primary tillage</td>
<td>6/13/2012</td>
</tr>
<tr>
<td>Planted sweet corn</td>
<td>6/19/2012</td>
</tr>
<tr>
<td>Installed PMN-Late Season</td>
<td>7/27/2012</td>
</tr>
<tr>
<td>Collected root samples</td>
<td>9/17/2012</td>
</tr>
</tbody>
</table>
Table 4.2. P values from a three-way ANOVA for inorganic N across the whole CORN and NOCORN subplots (weighted average of WR and BR) in 2012, 2013, and 2014. Fixed effects include tillage (full-width and strip-tillage), rye and vetch spatial arrangement (Mixed and Segregated), and date as a repeated measure.

<table>
<thead>
<tr>
<th>Effect</th>
<th>With Corn</th>
<th>Without Corn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2012</td>
<td>2013</td>
</tr>
<tr>
<td>Till (T)</td>
<td>NS</td>
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</tr>
<tr>
<td>Spatial Arrangement (SA)</td>
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<td>NS</td>
</tr>
<tr>
<td>SA*T</td>
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<td>NS</td>
</tr>
<tr>
<td>Date</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>T*D</td>
<td>NS</td>
<td>0.0261</td>
</tr>
<tr>
<td>SA*D</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>SA<em>T</em>D</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
Table 4.3. P values from a four-way ANOVA for inorganic N within NOCORN subplots in 2012, 2013, and 2014. Fixed effects include tillage (full-width and strip-tillage), rye and vetch spatial arrangement (Mixed and Segregated), zone (within- and between-row), and date as a repeated measure.

<table>
<thead>
<tr>
<th>Effect†</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone (Z)</td>
<td>0.0977</td>
<td>0.085</td>
<td>0.0032</td>
</tr>
<tr>
<td>Till (T) * Z</td>
<td>NS</td>
<td>NS</td>
<td>0.0463</td>
</tr>
<tr>
<td>Spatial arrangement (SA) *Z</td>
<td>0.0638</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>SA<em>T</em>Z</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
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<td>NS</td>
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<tr>
<td>T<em>Z</em>D</td>
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<td>NS</td>
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<td>SA<em>Z</em>D</td>
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<td>NS</td>
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<tr>
<td>SA<em>T</em>Z*D</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

† For main effects of tillage and cover crop spatial arrangement, and their interactions with date see Table 4.2.
Table 4.4. Mean (+/- SEM) bulk density in the top 0.25 cm of soil in 2012, 2013, and 2014. Fixed effects include tillage (full-width and strip-tillage) and zone (within- and between-row).

<table>
<thead>
<tr>
<th>Tillage and Zone</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
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<tr>
<td></td>
<td>— g cm$^3$ —</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FWT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BR</td>
<td>1.32</td>
<td>0.04</td>
<td>1.31</td>
</tr>
<tr>
<td>WR</td>
<td>1.31</td>
<td>0.03</td>
<td>1.33</td>
</tr>
<tr>
<td>ST</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BR</td>
<td>1.40</td>
<td>0.04</td>
<td>1.46</td>
</tr>
<tr>
<td>WR</td>
<td>1.38</td>
<td>0.04</td>
<td>1.31</td>
</tr>
</tbody>
</table>

Significance of Fixed Effects

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Till (T)</td>
<td>NS</td>
<td>0.0718</td>
<td>0.0903</td>
</tr>
<tr>
<td>Zone (Z)</td>
<td>NS</td>
<td>0.0018</td>
<td>NS</td>
</tr>
<tr>
<td>T*Z</td>
<td>NS</td>
<td>0.0002</td>
<td>0.0042</td>
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</table>
Table 4.5. P values from a three-way ANOVA for gravimetric soil moisture in CORN subplots. Fixed effects include tillage (full-width and strip-tillage) and rye and vetch spatial arrangement (Mixed and Segregated), and date as a repeated measure.

<table>
<thead>
<tr>
<th>Effect</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Till (T)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Spatial Arrangement (SA)</td>
<td>NS</td>
<td>0.0459</td>
<td>NS</td>
</tr>
<tr>
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<td>NS</td>
</tr>
<tr>
<td>Date</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>T*D</td>
<td>&lt;.0001</td>
<td>NS</td>
<td>0.0001</td>
</tr>
<tr>
<td>SA*D</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>T<em>SA</em>D</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
Table 4.6. P values from a two-way ANOVA for sweet corn nonharvested and ear biomass, as well as N content from 2012, 2013, and 2014. Main effects include tillage (full-width and strip-tillage) and rye and vetch spatial arrangement (Mixed and Segregated).

<table>
<thead>
<tr>
<th>Effect</th>
<th>Nonharvested Biomass</th>
<th>Biomass (Mg ha(^{-1}))</th>
<th>Total Corn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Till (T)</td>
<td>0.0078</td>
<td>NS</td>
<td>0.0621</td>
</tr>
<tr>
<td>Cover (C)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>T*C</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effect</th>
<th>Nonharvested Biomass</th>
<th>Corn Ears</th>
<th>Total Corn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Till (T)</td>
<td>0.0162</td>
<td>0.0144</td>
<td>0.0703</td>
</tr>
<tr>
<td>Cover (C)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>T*C</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effect</th>
<th>Nonharvested Biomass</th>
<th>Corn Ears</th>
<th>Total Corn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2012</td>
<td>2013</td>
<td>2014</td>
</tr>
<tr>
<td>Till (T)</td>
<td>0.0162</td>
<td>0.0144</td>
<td>0.0703</td>
</tr>
<tr>
<td>Cover (C)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>T*C</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
Table 4.7. P values from a three-way ANOVA for root mass, root mass ratio, specific root length (SRL), average root diameter (Diameter), and root length density (RLD) within the within-row (WR-7.5 cm from plant) and between-row (BR-25 cm from plant). Main effects include tillage (full-width and strip-tillage), rye and vetch spatial arrangement (Mixed and Segregated), and year (2013 and 2014).

<table>
<thead>
<tr>
<th>Effect</th>
<th>Root Mass</th>
<th></th>
<th></th>
<th>SRL</th>
<th></th>
<th></th>
<th>Root Morphology</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WR</td>
<td>BR</td>
<td>WR/BR</td>
<td>WR</td>
<td>BR</td>
<td>WR</td>
<td>BR</td>
<td>WR</td>
<td>BR</td>
</tr>
<tr>
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<td>0.043</td>
<td>NS</td>
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<td>NS</td>
<td>0.021</td>
<td>0.0001</td>
<td>0.0019</td>
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<tr>
<td>Spatial Arrangement (SA)</td>
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<td>0.049</td>
<td>0.077</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>T*SA</td>
<td>NS</td>
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<td>0.027</td>
<td>NS</td>
<td>0.025</td>
<td>0.095</td>
<td>0.024</td>
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</tr>
<tr>
<td>Year(Y)</td>
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<td>NS</td>
<td>NS</td>
<td>NS</td>
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</tr>
<tr>
<td>T*Y</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.058</td>
<td>NS</td>
<td>NS</td>
<td>0.001</td>
<td>NS</td>
</tr>
<tr>
<td>SA*Y</td>
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<td>NS</td>
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<td>NS</td>
<td>NS</td>
<td>NS</td>
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<tr>
<td>T<em>SA</em>Y</td>
<td>NS</td>
<td>NS</td>
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<td>NS</td>
<td>NS</td>
<td>NS</td>
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<td>NS</td>
</tr>
</tbody>
</table>
Figure 4.1. Mean (+/− SEM) potentially mineralizeable N (PMN) in early and late season of sweet corn season with 2012, 2013, and 2014 combined. PMN comparisons include tillage (full-width tillage [FWT] and strip-tillage [ST]) and rye and vetch spatial arrangement (Mixed [MIX] and Segregated [SEG]).
Figure 4.2. Mean (+/- SEM) potentially mineralizeable N (PMN) within both the WR and BR zones of strip-tillage combined with either a Mixed (MIX) or segregated (SEG) rye and vetch spatial arrangement. PMN was measured from planting to midseason (Early) and from midseason to harvest (Late).
Figure 4.3. Mean (+/- SEM) inorganic N in the top 20 cm of soil across the whole plot throughout the sweet corn season in 2012, 2013, and 2014 in subplots with and without corn. Inorganic N comparisons include full-width tillage (FWT) and strip-tillage (ST) combined with either a Mixed (MIX) or segregated (SEG) rye and vetch spatial arrangement.
Figure 4.4. Mean (+/- SEM) of inorganic N by zone in the top 20 cm of soil throughout the sweet corn season in 2012, 2013, and 2014 in NOCORN subplots. Inorganic N comparisons include full-width tillage (FWT) and strip-tillage (ST) combined with either a Mixed (MIX) or Segregated (SEG) rye and vetch spatial arrangement.
Figure 4.5. Mean (+/- SEM) gravimetric soil moisture sampled to a depth of 20 cm in the CORN subplots in 2012, 2013, and 2014. Gravimetric soil moisture comparisons include full-width tillage (FWT) and strip-tillage (ST) combined with either a Mixed (MIX) or Segregated (SEG) rye and vetch spatial arrangement.
Figure 4.6. Mean (+/− SEM) sweet corn biomass and N content within nonharvested aboveground biomass and corn ears in 2012, 2013, and 2014. Comparisons of fixed effects include full-width tillage (FWT) and strip-tillage (ST) combined with either a Mixed (MIX) or segregated (SEG) rye and vetch spatial arrangement.
Figure 4.7. A) Mean (+/−SEM) sweet corn root mass in 2013 and 2014 combined. Samples were collected within the WR (7.5 cm) and the BR (25 cm) from the plant. B) The ratio of WR/BR root mass in both the 2013 and 2014 combined. Comparisons of fixed effects include full-width tillage (FWT) and strip-tillage (ST) combined with either a Mixed (MIX) or segregated (SEG) rye and vetch spatial arrangement.
Figure 4.8. Mean (+/SEM) sweet corn average root diameter (Diameter), specific root length (SRL), and root length density (RLD) in 2013 and 2014 combined. Samples were collected within the WR (7.5 cm) and the BR (25 cm) from the plant. Comparisons of fixed effects include full-width tillage (FWT) and strip-tillage (ST) combined with either a Mixed (MIX) or segregated (SEG) rye and vetch spatial arrangement.


and organic tomato systems. Agriculture, Ecosystems & Environment, 73: 257–270.


CHAPTER FIVE

Cover crop spatial arrangement and strip-tillage effects on weed emergence, growth and competition with organic sweet corn

ABSTRACT

Strip-intercropping of functionally diverse cover crop mixtures including cereal rye and hairy vetch (RV) is one mechanism by which N banding can be applied to an organic system to increase crop competitiveness over weeds. We hypothesized that by targeting hairy vetch, a low C:N legume, to the strip directly in-row with future crop establishment, and rye, a high C:N grass, to the strip directly between future crop rows, that N would be preferentially available to the crop at the expense of weeds. We conducted a field study between 2011 to 2013 in southwest Michigan to examine the effects of tillage (strip-tillage [ST] vs full-width tillage [FWT], spatial arrangement of RV (strip-intercropping vs full width mixture) and weed management intensity (low vs high) on 1) soil inorganic N (IN) and moisture; 2) weed emergence and growth; and 3) sweet corn N uptake and yield. Segregating rye and vetch into strips increased IN availability in 1 out of 2 years, but did not affect sweet corn yields or N uptake, nor did it have any detectable benefits for weed suppression. Cover crop biomass was 30 to 40% greater in 2012 compared to 2013, resulting in very different effects of ST on weed and crop growth. In 2012, under low weed management ST increased sweet corn yields by suppressing weed emergence and growth. In contrast, in 2013, ST decreased sweet corn yields under high weed management, and resulted in significantly greater weed biomass compared to FWT. Complete elimination of tillage is likely not feasible for most organic crops in northern climates, but ST in combination with rye-vetch cover crops
can suppress weeds and maintain or improve crop yields in years when cover crop growth is adequate.

**INTRODUCTION**

Effective weed management is one of the greatest challenges faced by organic vegetable producers (Bingen et al. 2007; Lotter, 2003). Transitioning to organic production often increases both the diversity and density of weed seeds (Albrecht, 2005). If not controlled effectively, weeds can lead to significant reductions in crop yields (Cavigelli et al. 2008). Time, labor, and fuel required for weed management is a significant contributor to total costs in organic production (Archer et al. 2007). For example, time spent hand weeding was almost double in organic fresh market tomato production compared to conventional production (Hillger et al. 2006). Similarly, in organic soybean costs for hired labor were roughly ten times greater and on-farm fuel costs almost double those in conventional production (McBride and Greene, 2009). Organic farmers could greatly benefit from farm management strategies that reduce the number of cultivation passes or time spent hand weeding.

Without the option of chemical herbicides, organic farmers typically rely on mechanical cultivation either to bury or uproot weeds through soil inversion or cut weeds at the soil surface (Bond and Grundy, 2001). Frequent and intense soil disturbance can result in oxidation and depletion of soil organic matter, loss of soil structure, increased susceptibility to soil erosion, as well as soil compaction due to recurrent traffic (Lal, 1991). A desire to alleviate the negative effect that tillage has on soil quality has generated interest in adapting reduced tillage strategies to organic systems (Carr et al. 2012, Brainard et al. 2013).
Reduced tillage (RT) practices can provide a number of economic and environmental benefits, including increased soil aggregation and organic matter accumulation (Wander and Bollero, 1999; Franzluebbers 2002; West and Post, 2002) as well as reduced soil erosion, compaction, and fuel use (Phillips et al. 1980; Gebhardt et al. 1985). Reducing tillage and leaving crop residue on the soil surface can increase water infiltration into the soil and reduce runoff of soil and nutrients (Franzlubbers 2002; Triplett and Dick, 2008). Increasing water infiltration may help mitigate the effects of extreme precipitation events, which are predicted to increase due to climate change (Hayhoe et al. 2010).

Cultural strategies that utilize an ecological approach to weed control must be integrated into organic systems for reduced tillage to be a viable option (Bàrberi, 2002; Brainard et al. 2013; Mirsky et al. 2013). Cultural weed management aims to reduce weed density and competition through strategies that reduce the number of viable weed seeds in the soil seedbank, hinder weed seedling establishment, and prevent weed seed production (Anderson, 2005). Two cultural strategies that may reduce weed density and vigor are cover crop mulches and targeted placement of nutrient amendments.

The inclusion of cover crops into a crop rotation and use of cover crop residue as mulch can lead to substantial reductions in weed emergence and competition. Mulches can suppress weeds through a variety of physical, biological, and chemical mechanisms. When used as mulch, rye residue can decrease the number of recruited weed seedlings and delay weed germination (Mohler and Teasdale, 1993) by decreasing soil temperatures and reducing light availability. Additionally, if sufficient
residue is retained on the soil surface, rye mulches can reduce emergence of
germinated seedlings by exhausting seed reserves before penetration of the mulch
layer (Teasdale and Mohler, 2000). The cool and moist environment underneath rye
residue may also provide refuge for insects and pathogens involved in weed seed
predation and decay (Chauhan et al. 2006; Pullaro et al. 2006; Menalled et al. 2007),
which can lead to significant reductions of weed seeds in the soil seedbank.
Allelochemicals released from rye and vetch decomposition have also been shown to
suppress emergence and growth of weeds (Barnes and Putnam, 1986; Creamer et al.
1996; Hill et al. 2006).

An additional strategy of cultural weed management is the manipulation of N
fertilization to favor crop growth over weeds (Di Tomaso, 1995). Many common
agricultural weeds are luxurious consumers of N, and increasing N fertilizer rates can
release weed seeds from dormancy and stimulate both seedling emergence and growth
(Baskin and Baskin, 1998; Sweeney et al. 2008). The high relative growth rate and
nutrient uptake efficiency of many problematic weeds enables them to rapidly exploit
inorganic soil N (Harbur and Owen, 2004; Wortman et al. 2011). Blackshaw et al. (2003)
compared the growth response of 23 species of common agricultural weeds to wheat in
the presence of N fertilizer and found 15 weed species exhibited a greater increase in
shoot biomass compared to wheat. Because weed species are especially responsive to
soil N, reducing N available to stimulate weed emergence and growth is a viable option
for alleviating crop-weed competition.

Targeting fertilizer placement so that nutrient inputs are in close proximity to crop
roots increases the chance for crop N uptake and may reduce weed competition and
increase crop yields (Di Tomaso, 1995). Banding N within the crop row or point injecting liquid forms of N increased wheat yields by as much as 12% (Kirkland and Beckie, 1998) and significantly reduced weed density, biomass, and N uptake of both wild oat \((Avena fatua \text{ L.})\) and green foxtail \((Setaria viridis)\) (Blackshaw et al. 2004). Effective N placement can reduce the energy expended by the crop for nutrient scavenging, allowing for greater resources devoted to aboveground productivity. Hodge et al. (1999) postulates that plants will gain a greater advantage from root proliferation in N rich patches when nutrient availability is continuous, such as from slowly decomposing organic matter, and when interspecific competition for that N is likely. While banding of conventional fertilizers has been shown to enhance crop competitiveness against weeds (Anderson, 2008; Blackshaw et al. 2004), little work has been done to apply the same principle to organic forms of N in agronomic systems.

Strip-intercropping of functionally diverse cover crops, such as cereal rye and hairy vetch, is one mechanism by which N banding can be applied to an organic system to increase crop competitiveness over weeds. Rye-vetch (RV) cover crops are often planted together in full width mixtures (either randomly distributed by broadcasting, or together in drilled rows) in organic production systems. Segregating rye and vetch into strips has the potential for improving weed management by simultaneously targeting N to the crop root zone, and creating a weed suppressive mulch between crop rows. Hairy vetch, a legume, sown in a strip directly in-row with future crop establishment could provide N directly to the crop and reduce N available to competing weeds. Cereal rye planted between crop rows may immobilize N and minimize interference with the crop.
The potential benefits of strip-intercropping of rye-vetch mixtures may be enhanced if combined with strip-tillage. Incorporating hairy vetch residue in-row will result in faster mineralization of vetch residue and greater nutrient availability to the crop, also reducing the potential for cereal rye to suppress crop growth. The cereal rye in the between-row zone will be left on the soil surface to suppress weeds via immobilizing N, reducing light penetration, and decreasing soil temperatures.

The goal of this study was to evaluate the effect of cover crop spatial arrangement, strip-tillage, and weed management intensity on weeds, soil N, and crop biomass and yields within organic sweet corn production. We hypothesized that strip-intercropping of RV would result in greater soil inorganic N within the crop row (WR) and less inorganic N between crop rows (BR). Additionally, we expected that the concentration of inorganic N in the WR zone would increase sweet corn access to N, thereby resulting in greater N uptake and competitiveness against weeds. Finally, we hypothesized that in the BR zone, strip-intercropping combined with strip-tillage would suppress weed emergence and growth due to the combined effects of lower N availability, and cover crop surface mulch. Overall, we anticipated that sweet corn yield loss due to weeds would be reduced with strip intercropping and strip-tillage.

**MATERIALS AND METHODS**

**Site description and experimental design**

The experiment was conducted between 2011-2013 on organically managed (approximately 5-7 years, depending on year) Kalamazoo (fine-loamy, mixed, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, mesic Typic Hapludalfs) loams (Crum and Collins, 1995), at the Kellogg Biological Station in Hickory Corners, MI
(85° 24′W, 42° 24′ N). Treatments were arranged in a split plot, randomized complete block design with four replicates. Main plots consisted of a 2 X 2 factorial of tillage (Full-width tillage [FWT] and Strip-tillage [ST]) and rye and vetch spatial arrangement. Spatial arrangements included a full-width mixture (MIX) in which rye and vetch were sown together in the same rows, and a segregated mixture (SEG) in which 2 rows of hairy vetch were alternated with 2 rows of rye. The split plot factor consisted of two levels of weed management: i) high weed management treatments were intended to be weed free, and were maintained by hoeing and hand-weeding weekly until mid-July and every two weeks thereafter; ii) low weed management treatments were intended to have a relatively high level of weed competition and included broadcasting of supplemental weed seeds at planting, followed by hoeing and hand weeding twice throughout the sweet corn season (see Table 5.1 for weeding dates). In low weed management treatments, we distributed 3.0 g m⁻² (approximately 8500 seeds m⁻²) of stratified C.album seeds in 2012, and 1.8 g m⁻² (approximately 3180 seeds m⁻²) in 2013. Zones within the cropping system were also treated as subplots. The zone within the crop row (WR) is the 25 cm zone where the crop is planted (and where tillage occurs within strip-tilled treatments), and the between-row (BR) zone is the 50 cm zone between crop rows and also is untilled in strip-tilled treatments.

High weed management subplot sizes were 27.3 (9.1 X 3.0 m) and 37.2 m² (6.1 X 6.1 m) in 2012 and 2013, respectively; and low weed management subplots sizes were 18.6 (9.1 X 3.0 m) and 27.9 m² (6.1 X 4.5 m) in 2012 and 2013, respectively. Plot sizes were adjusted each year based on availability of organically certified land and size of available equipment. Larger plots were used for High Weed Management subplots to
accommodate more frequent and intense sampling used for other questions associated with this study.

Field activities were performed according to Table 5.1. Both cereal rye and hairy vetch seeds were “Variety Not Stated” and organically certified across all three years. When considered on a whole plot basis, the cover crop spatial arrangement treatments had the same seeding rate for both cereal rye (62.72 kg ha\(^{-1}\)) and hairy vetch (22.4 kg ha\(^{-1}\)), but differed in seed placement. In both rye and vetch spatial arrangements, between-row spacing for rye and vetch rows was 19.1 cm. Cereal rye was planted with a grain drill and every two drop tubes were blocked within SEG to prevent seeding rye in the vetch rows. Hairy vetch was planted with a Jang push-seeder at the designated rates and rows. No N fertilizers were added prior to cover crop establishment or sweet corn planting. Additional organic forms of P and K were added according to soil tests, and consisted of: 34 kg K and P ha\(^{-1}\) of NOP certified Potassium Sulfate Plus and Tennessee Brown Phosphate in 2012 and 34 kg K ha\(^{-1}\) of Potassium Sulfate Plus in 2013.

Cover crops were flail mowed twice in mid- to late- May. In 2012, vetch had reached approximately 50% flowering, and in 2013 vetch had reached 30% flowering. Conventional tilled treatments were chisel plowed, and then rototilled to break up cover crop residue. A Hiniker Model 6000 two-row strip tiller (equipped with cutting-coulter, shank point assembly, berming discs, and rolling basket) was used for WR tillage in strip-tilled treatments. To improve soil tilth for planting in ST treatments, a walk behind rototiller was used for WR secondary-tillage. The resulting WR zone was approximately 25 cm wide and 25-30 cm deep. Sweet corn was planted using a high residue planter
(Monosem vacuum seeder) at a between-row spacing of 76.2 cm and in-row spacing of 10 cm. Once sweet corn emerged, population density was thinned to an in-row spacing of 16.5 cm. Sweet corn was irrigated during low-rainfall periods in 2012, totaling 62.2 mm of irrigated water throughout the sweet corn season. In 2013, rainfall was sufficient so we did not provide any additional irrigation.

Data collection

Cover crop and winter weed biomass. Dry weights of cover crop and winter annual weed biomass were obtained prior to cover crop termination by clipping shoot tissue at ground level from two 0.25 m² quadrats for each WR and BR area in every plot. Fresh cover crop biomass was separated into hairy vetch, rye, and weeds, dried at 60°C, and weighed.

Soil sampling- Inorganic N and gravimetric soil moisture. Soil samples were collected every 7-14 days (8 sampling times per year), throughout the growing season in all treatments and subplots in both the WR and BR. At each sampling date, 10 to 12 soil cores (5 cm diameter and 20 cm deep) were taken for each plot. Soil samples were dried at 38°C, and ground. A 1M KCl extraction (Gelderman and Beegle, 1998) was performed and samples were analyzed on a QuikChem 8500 Flow Injection Analyzer. 10 g of wet soil was utilized for gravimetric soil moisture, dried at 100°C, and re-weighed. Gravimetric water content (GWC) was calculated according to Equation 5.1 below. In addition, gravimetric water content was evaluated from separate soil samples taken to 5 cm depth during the period when weed germination was monitored (7/5/2012, 7/4/2013).

\[
GWC = \frac{(g \text{ moist soil} - g \text{ dry soil})}{g \text{ dry soil}}
\]
To calculate the soil inorganic N and gravimetric moisture across the whole plot, we used weighted means of the measured values from the WR and BR zones adjusted by their respective areas. For example, for inorganic N (IN) we used:

\[ \text{IN}_{\text{whole plot}} = \text{IN}_{\text{WR}} \times \frac{1}{3} + \text{IN}_{\text{BR}} \times \frac{2}{3} \]

Where the within-row (WR) zone is the 25 cm zone where the crop is planted (and where tillage occurs within strip-tilled treatments), and the between-row (BR) zone is the 50 cm zone between crop rows and also is untilled in strip-tilled treatments.

**Soil temperature.** Soil temperature was measured using waterproof HOBO® Temperature/Light Pendant® Data Logger sensors (Onset Computer Corporation, Bourne, MA) installed to a depth of 5 cm both within the WR and BR of each plot. Temperature sensors were installed at corn planting only in the MIX rye-vetch treatments to compare tillage and zonal differences. We calculated mean daily minimum and maximum temperatures, as well as the temperature amplitude across treatments.

**Weed emergence.** Seeds of common lambsquarters (*Chenopodium album* L) and giant foxtail (*Setaria faberi* Herrm.) were seeded into separate quadrats (0.093 m$^2$) in both the in- and between-row strips of high weed management subplots of each tillage and cover crop mainplot. Four hundred seeds of each species were seeded in 2012 one week after tillage, and 500 seeds of each species were seeded 2 days after tillage in 2013. We collected weed seeds in the fall preceding the year of sowing from an organically managed farm approximately 35 km from the site (2012) or an adjacent field at the research farm (2013). Seeds of both species were separated from chaff using a rub board and seed cleaner, and stratified under moist conditions at 4°C for three months.
Emergence of each species was counted every 3-5 days for approximately the first month of the sweet corn growing season. After each count, weed seedlings were pulled. **Weed biomass.** Weed biomass was collected within the low weed management subplot prior to each timed weeding event (2 times during sweet corn growth), and then again at harvest. Weeds in two 0.25 m² quadrats per WR and BR were collected, dried at 60°C, and weighed. In 2012, we separated weed biomass into *C. album* (which was overseeded) and all other weeds. Due to a large infestation of grasses and clover in 2013, we separated weed biomass into *C. album*, clover, grasses, and all other broadleaf species.

**Sweet corn biomass and yield.** Sweet corn was harvested from 9.3 and 6.5 m² in high and low weed management subplots in 2012, respectively; and from 14 m² in both high and low weed management subplots in 2013. At harvest, total aboveground biomass was collected from five random corn plants per plot. Samples were dried at 60°C, weighed, and ground to pass through a 1 mm screen. To measure corn plant N content, a Kjeldahl digestion (Kalra, 1998) was performed on corn tissue from corn ears and aboveground biomass, and Kjehldahl N analysis was performed using a QuikChem 8500 Flow Injection Analyzer.

**Statistical analysis**

All data were analyzed using mixed models ANOVA with proc MIXED procedures in SAS (Version 9.3, SAS Institute, Cary, NC). Year was initially treated as a fixed factor to determine if fixed effects interacted with year to affect response variables, and if there was no difference year were pooled. In all cases, block was nested in year, and block and interactions of block with fixed factors were treated as random effects.
For cover crop and winter annual weed biomass the fixed effects included cover crop spatial arrangement (MIX and SEG) and year. For cumulative weed biomass and weed emergence, the fixed effects included cover crop spatial arrangement, tillage (FWT vs ST), and zone (WR vs BR). For sweet corn biomass, N uptake, and yield the fixed effects included cover crop spatial arrangement, tillage, and weed management intensity (High vs Low). For soil IN and moisture the fixed effects included tillage, cover crop spatial arrangement, weed management, and zone; and for soil temperature the fixed effects included tillage and zone. For soil IN, moisture, and temperature, date was included as a repeated factor and repeated measures mixed models were performed with Proc MIXED in SAS, and AIC and BIC values were compared to determine the best model fit. When cover crop spatial arrangements were not significant, MIX and SEG were pooled to examine effects of tillage within a rye-vetch cover crop.

When significant treatment effects were detected, means were separated using Fisher's protected LSD \( P < 0.05 \). In cases where P-values were between 0.05 and 0.10, differences are reported as “marginally significant” with the P-value presented parenthetically. All figures were made using the GGPILOT2 package in R (Wickham, 2009).

**RESULTS**

*Precipitation and temperature*

Temperature, growing degree days (GDD) base 10°C accumulation, and precipitation during sweet corn growth in 2012 and 2013 varied widely (Table 5.2). In 2012, total GDD accumulation was 17% higher, and precipitation was 50% lower than in 2013. Average daily temperatures during the month of July in 2012 were 3.4°C higher than
2013. Precipitation during sweet corn growth was 128 mm greater in 2013 than in 2012, but with irrigation this difference was in 2012 reduced to 66 mm. Warm temperatures and low precipitation in 2012 likely resulted in droughty conditions, especially during the month of July.

**Effects of cover crop spatial arrangement on cover crop and weed biomass**

Cover crop spatial arrangement affected total cereal rye and hairy vetch biomass in one out of two years, and affected cereal rye biomass in both years. In Year 1 the MIX rye-vetch spatial arrangement had 16% greater total biomass production than SEG (Chapter 3: Table 3.5 Figure 3.4), but there was no detectable difference in total biomass in 2013. In both 2012 and 2013, SEG had lower cereal rye biomass compared to the MIX. Cereal rye biomass was approximately 5.5 and 4.4 Mg ha$^{-1}$ in MIX and SEG in 2012, and 4.7 and 3.6 Mg ha$^{-1}$ in 2013. We found no detectable difference in hairy vetch biomass across the whole plot, but SEG did increase the vetch biomass within the WR in both years. Hairy vetch biomass was approximately 2.6 Mg ha$^{-1}$ in 2012, and 1.5 Mg ha$^{-1}$ in 2013. More information on cover crop spatial arrangement effects on cover crop biomass and N content can be found in Chapter 3.

Winter annual weed biomass in the no cover crop control was approximately 3.0 and 2.1 Mg ha$^{-1}$ in 2012 and 2013, respectively (Figure 5.1). Dominant species in 2012 included common chickweed (*Stellaria media*) and corn chamomile (*Anthemis arvensis*). Dominant species in 2013 included red clover (*Trifolium pratense*), corn chamomile, and common chickweed. In 2012, we found no detectable difference in winter annual weed biomass due to spatial arrangement in either the WR or BR zones; rye and vetch suppression of winter annual weeds across the whole plot was
approximately 55% regardless of spatial arrangement. In 2013, we found marginally lower winter annual weed biomass within the WR ($P=0.093$) of the SEG compared to the MIX treatment, but no detectable difference BR. Across the whole plot, suppression of winter annual weeds by the rye and vetch cover crops was approximately 84% in MIX and SEG in 2013.

**Effects of cover crop spatial arrangement on soil inorganic N, soil moisture, weeds, and sweet corn**

There was a significant effect of rye and vetch spatial arrangement on soil inorganic N (IN) across the whole plot in 2012, but not in 2013 (Table 5.3, Figure 5.2). Averaged across all sampling dates in 2012, SEG had 8% greater IN compared to MIX in high weed management, and 6% greater under low weed management. When analyzed by zone within ST, SEG had marginally greater IN concentrated within the crop row (WR) in ST under low weed management (Figure 5.3, Cover*Zone*Date, $P=0.07$), at several sampling dates within each year. Compared to the MIX spatial arrangement, SEG had 12% greater IN within the crop row in July of 2012, and 9% greater IN within the crop row in June of 2013.

Spatial arrangement had few detectable effects on soil moisture (Table 5.4; Figure 5.4). In 2013, SEG resulted in 5-9% lower soil moisture compared to MIX, but this effect was only marginally significant ($P=0.06$).

Segregating rye and vetch into strips had no effect on weed emergence or biomass, or sweet corn biomass, N uptake, or yield in either high or low weed management (data not shown).
Effects of tillage and weed management on soil inorganic N, moisture, and temperature

Tillage influenced IN in 2013, but not 2012 (Table 5.3, Figure 5.2). In 2012, tillage interacted with weed management, but did not interact with date. Tillage had no detectable effect on IN under either high or low weed management. However, low weed management reduced season long IN by 13% within FWT, but weed management had no effect on IN within ST. In 2013, tillage interacted with date, but did not interact with weed management. ST reduced IN by 25% compared to FWT at all but the final sampling date, regardless of weed management. IN was lower in 2013 compared to 2012, and in both years IN peaked in early July and then decreased as corn entered the exponential growth phase in mid-July to August. In August of 2012, IN plateaued between 30 to 40 kg N ha$^{-1}$, while in August of 2013 IN plateaued under 20 kg N ha$^{-1}$.

In 2012, ST increased gravimetric soil moisture (20 cm depth) across the whole plot (WR and BR) during sweet corn growth by approximately 15% compared to FWT, with the difference being more pronounced in the later part of the growing season (Table 5.3, Figure 5.4). In contrast, in 2013, FWT had 8% greater soil moisture compared to ST during sweet corn growth.

Gravimetric soil moisture in the top 5 cm of soil during evaluation of weed emergence was influenced by tillage and zone in both 2012 and 2013 (Figure 5.5). In 2012, gravimetric soil moisture in the BR zone of ST+RV was 2-3 times greater than that in all other treatments and zones. In 2013, gravimetric soil moisture was consistently high in all treatments during the period of evaluation of weed emergence.
Figure 5.6 contains the maximum, minimum, and daily temperature amplitude for the one month period during which *C. album* and *S. faberi* emergence counts were collected in both 2012 and 2013. In both years, maximum daily temperature varied more between tillage treatments than minimum daily temperatures (Table 5.5, Figure 5.6). In 2012 and 2013, the effect of tillage on maximum and minimum temperatures varied with sampling date and zone. In both years, we found no detectable difference in the maximum, minimum, and daily temperature amplitude between the WR of FWT and ST. Maximum soil temperature was 14% and 6% lower in the BR of ST compared to FWT-BR in 2012 and 2013, respectively; and 13% and 1% lower than ST-WR in 2012 and 2013, respectively. The daily temperature amplitude (difference between daily maximum and minimum) across the period of emergence was reduced from 8 in FWT-BR to 3.5 in ST-BR in 2012, and from 8 to 5.6 in 2013.

**Effects of tillage on weed emergence and biomass**

The effect of tillage on emergence of *C. album* (Till*Year, \( P=0.0081 \)) and *S. faberi* (Till*Year, \( P=0.0056 \)) varied by year. In 2012, the effect of tillage on emergence of *C. album* and *S. faberi* varied by zone (Table 5.6, Figure 5.7); in particular, emergence of both species was lower in the BR of ST compared to FWT, but we found no detectable effect in the WR zone. In 2013 we found marginally greater *C. album* emergence in ST compared to FWT (\( P=0.08 \)), regardless of zone, but we found no detectable differences in *S. faberi* emergence due to tillage or zone within 2013.

In both years, the effect of tillage on weed biomass varied with zone (Figure 5.8). In 2012, ST reduced weed biomass relative to FWT in the BR zone, but not the WR zone. In contrast, in 2013, ST increased weed biomass relative to FWT in the BR
zone but not in the WR zone. Dominant species included within the other category included *S. faberi* and ladysthumb (*P. persicaria*).

**Effects of tillage on sweet corn biomass, N-uptake, and yield**

Tillage effects on sweet corn biomass and N uptake varied by year and weed management. In 2012, total sweet corn aboveground biomass and N uptake were greater within ST compared to FWT in both high and low weed management (Figure 5.9). ST increased total sweet corn aboveground biomass by 19% under high weed management, and by 71% under low weed management. Low weed management reduced sweet corn N uptake by 47% within FWT, but only 24% in ST (Till*Weed management, *P*=0.045). In 2013, there was no detectable difference in total corn biomass between FWT and ST within either high or low weed management. However, we found greater total N uptake within FWT compared to ST within high weed management (Till*Weed management, *P*=0.03), and no detectable differences between the two tillage systems under low weed management.

In both years, the effect of tillage on sweet corn yields varied with weed management (Figure 5.9). In 2012, ST increased sweet corn yields by 60% compared to FWT under low weed management (Till*Weed Management, *P*=0.026), but had no effect under high weed management. In contrast, in 2013, ST marginally reduced yields by 25% relative to FWT under high weed management (Till*Weed Management, *P*=0.07), but had no effect under low weed management.
DISCUSSION

Rye and vetch spatial arrangement

We hypothesized that segregating rye and vetch into strips would increase sweet corn access to N within ST, thereby resulting in greater N uptake and competitiveness against weeds. However, despite having slightly higher IN concentrated within the crop row in ST-SEG (Figure 5.3), we found no detectable effect of cover crop spatial arrangement on sweet corn or weeds. This may be partially because the increase in N occurred prior to sweet corn exponential growth, especially in 2013. One likely explanation for relatively minor effects of spatial arrangement is that above ground cover crop shoots were not as concentrated in their zones as we expected. While we anticipated some lateral mixing of rye and vetch, lateral growth of vetch, cover crop lodging (in 2012) and flail-mowing resulted in greater movement of shoot tissue across zones than anticipated. Although root tissue was unlikely to have moved laterally, it is thought to represent only about 18-30% of total cover crop tissue for rye-vetch mixtures (Mwaja et al. 1995)

Strip-tillage effects on weeds and sweet corn

Cover crop residues may affect weed germination and emergence by altering light, moisture, nutrients and temperature (Teasdale and Mohler, 1993). Mulch effects on weed emergence depend on the quantity of biomass, environmental conditions, and target weed species. The mulch had more of an effect on maximum daily temperatures compared to minimum, and strongly affected the daily temperature amplitude (difference in max and min). The higher soil moisture, combined with reduced light penetration from the mulch, likely reduced temperature fluctuations in ST-BR in 2012
C. album germination is strongly promoted by daily temperature amplitudes between 10 and 20°C (Henson, 1970; Murdoch et al. 1970), and in 2012 the temperature amplitude in FWT periodically increased above 10°C, however, temperature amplitude was consistently below 5°C within ST-BR. Additionally, the RV mulch created a physical barrier, which likely forced weed seedlings to exhaust seed reserves while penetrating the mulch. Our results are consistent with Teasdale and Mohler (2000) who found that C. album is more sensitive to mulch suppression than S. faberi, and they determined that weed sensitivity to mulch was inversely related to seed size. Seeds of S. faberi are larger than those of C. album, and thus have larger seed reserves which may explain their higher emergence through RV mulch.

In 2013, RV biomass was lower than in 2012, and we found no suppression of either S. faberi or C. album emergence in the BR of ST compared to FWT. On the contrary, ST marginally increased C. album emergence relative to FWT. At low residue levels, mulches can stimulate weed emergence by increasing soil moisture, but we found no evidence of greater soil moisture in ST in the top 5 cm of soil in 2013 (Figure 5.5). Therefore, we are unsure what soil factors could have promoted C. album emergence within ST in 2013.

Tillage effects on weed competition and organic sweet corn varied dramatically between the two years of this study. 2012 was an example of how well a mulch based organic-RT system can function under the right conditions. In 2012, the weed community was dominated by summer annuals, and rye and vetch biomass production was at or near the 8.0 Mg ha⁻¹ level considered necessary for summer annual weed suppression (Teasdale and Mohler, 2000). In 2012, ST decreased weed biomass within
the BR throughout the sweet corn growing season compared to FWT (Figure 5.8), likely
due primarily to suppressive effects of surface mulch on emergence (Figure 5.7).
Additionally, 2012 was a hot and dry year, and despite irrigation, the sweet corn likely
benefited from the increased soil moisture observed under ST (Figure 5.4). While we
detected no difference in soil N between the two tillage systems under either high or low
weed management, low weed management reduced IN in FWT but not within ST.
Therefore, competition for IN and soil moisture between sweet corn and weeds was
likely lower under ST compared to FWT.

In contrast, 2013 was an example of the challenges inherent within organic RT
systems. Rye and vetch biomass was approximately 25% lower in 2013 compared to
2012, and red clover, a perennial, established within the cover crops and was not
terminated with mowing. Despite frequent weeding events in high weed management
treatments, persistent red clover in the untilled BR of ST likely caused some resource
depletion, and may explain the lower gravimetric moisture in ST compared to FWT
(Figure 5.4). The combined effects of lower cover crop biomass, lower IN, and lower
gravimetric moisture within ST in 2013, combined with the presence of a pre-
established perennial weed, help explain the lower yields in ST compared to FWT under
high weed management in 2013 (Figure 5.9).

Interestingly, despite lower soil IN and moisture in ST compared to FWT under
low weed management in 2013, sweet corn yields were equal between the two tillage
systems. The reasons for this are unclear. It is possible that factors other than IN and
moisture (e.g. light, P or K) were the primary limitations to growth in 2013, and that
weed biomass was not well correlated with those limiting factors.
SUMMARY AND CONCLUSION

Although segregating rye and vetch into strips showed promise for increasing inorganic N within the crop row, it did not result in improved sweet corn yields or N uptake. Several adaptations to strip-intercropping might enhance its effectiveness. First, use of a roller crimper (drawn in the same direction as segregated strips) rather than a flail mower, would likely have reduced lateral movement of shoots, resulting in more distinct WR and BR environments. With roller-crimping, greater concentration of N-rich vetch residue in the WR zone, and greater concentration of rye mulch in the BR zone may have enhanced weed suppression, improved N use efficiency, and reduced the potential interference of rye residue with crop establishment. Second, the effectiveness of strip-intercropping might be enhanced through integration of a “cut and carry” systems, in which residue is moved from the BR to the WR zone for suppression of WR weeds, and to facilitate mechanical cultivation within the BR (Rostampour, 2011). Strip-intercropping may work well with a cut and carry system, because the rye roots would not be in the WR to immobilize N and interfere with strip-tillage and planting. But rye aboveground residue could be moved to the WR for weed suppression and soil moisture conservation, as well as to allow mechanical cultivation BR.

Our study suggests that a rye-vetch cover crop in combination with ST can result in similar sweet corn yields to FWT, and effective suppression of weed emergence and growth in years when cover crop growth is abundant (e.g. 2012). However, in years when cover crop growth is weak, or perennial weeds are present, the risk of yield losses due to weeds under ST are substantial due to increased weed pressure (e.g. 2013).
Complete elimination of tillage in organic sweet corn production is risky in northern climates like Michigan. However, our results suggest that ST can be used as part of a rotational tillage strategy in years that are favorable for winter cover crop growth. Strategies to enhance cover crop growth including adjustments in fertilizer rates, planting dates, or planting densities have facilitated successful implementation of no-till or rotational tillage with lower risk of weed competition in field crops (Ryan et al. 2011; Mirsky et al. 2013), and are likely to have similar payoffs in vegetable crops like sweet corn. Segregated plantings of cover crop mixtures may also facilitate weed suppression in reduced tillage systems, but greater attention is needed to identify species combinations, planting patterns, and termination methods to optimize this approach.
Table 5.1. Dates of key field activities and data collection.

<table>
<thead>
<tr>
<th>Activity</th>
<th>2011-2012</th>
<th>2012-2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planted cover crops</td>
<td>8/31/2011</td>
<td>9/10/2012</td>
</tr>
<tr>
<td>Terminated cover crops</td>
<td>6/5/2012</td>
<td>6/4/2013</td>
</tr>
<tr>
<td>Primary tillage</td>
<td>6/13/2012</td>
<td>6/19/2013</td>
</tr>
<tr>
<td>Secondary tillage</td>
<td>6/15-6/18/2012</td>
<td>6/19/2013</td>
</tr>
<tr>
<td>Planted sweet corn</td>
<td>6/19/2012</td>
<td>6/21/2013</td>
</tr>
<tr>
<td>First weeding event</td>
<td>7/16/2012</td>
<td>7/16/2013</td>
</tr>
<tr>
<td>Second weeding event</td>
<td>8/6/2012</td>
<td>8/5/2013</td>
</tr>
<tr>
<td>Harvested sweet corn</td>
<td>9/4/2012</td>
<td>9/4/2013</td>
</tr>
</tbody>
</table>
Table 5.2. Average temperature, GDD, and precipitation during sweet corn growth in 2012 and 2013.

<table>
<thead>
<tr>
<th>Month</th>
<th>Average Temperature (°C)</th>
<th>GDD (base 10°C)</th>
<th>Precipitation (mm)</th>
<th>Precipitation + Irrigation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>22.6</td>
<td>22.5</td>
<td>145.7</td>
<td>128.9</td>
</tr>
<tr>
<td>July</td>
<td>25.1</td>
<td>21.7</td>
<td>461.4</td>
<td>360.1</td>
</tr>
<tr>
<td>August</td>
<td>20.8</td>
<td>20.1</td>
<td>337.2</td>
<td>320.5</td>
</tr>
<tr>
<td>September</td>
<td>21.6</td>
<td>19.6</td>
<td>47.8</td>
<td>39.4</td>
</tr>
</tbody>
</table>

Cumulative                 992.1  849.0  120.4  248.4  182.6  248.41

Average Temperature (°C), GDD (base 10°C), Precipitation (mm), and Precipitation + Irrigation (mm) for sweet corn growth in 2012 and 2013.
Table 5.3. P values from a four-way ANOVA for the effects of tillage (fill-width and strip-tillage), cover crop spatial arrangement (Mixed and Segregated), weed management (High and Low), and date on soil inorganic N across the whole plot (weighted average of WR and BR) during the 2012 and 2013 sweet corn growing season.

<table>
<thead>
<tr>
<th>Effect</th>
<th>2012</th>
<th>2013</th>
<th>P &gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Till (T)</td>
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</tr>
<tr>
<td>Spatial Arrangement (SA)</td>
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<tr>
<td>T*SA</td>
<td>NS</td>
<td>NS</td>
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<tr>
<td>Weed Management (WM)</td>
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<tr>
<td>T*WM</td>
<td>0.044</td>
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</tr>
<tr>
<td>WM*SA</td>
<td>NS</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>T<em>WM</em>SA</td>
<td>NS</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Date (D)</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td></td>
</tr>
<tr>
<td>T*D</td>
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</tr>
<tr>
<td>SA*D</td>
<td>NS</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>T<em>SA</em>D</td>
<td>NS</td>
<td>NS</td>
<td></td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>T<em>WM</em>D</td>
<td>NS</td>
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<tr>
<td>T<em>WM</em>SA*D</td>
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Table 5.4. P values from a four-way ANOVA for the effects of tillage (fill-width and strip-tillage), cover crop spatial arrangement (Mixed and Segregated), weed management (High and Low), and date on gravimetric soil moisture across the whole plot (weighted average WR and BR) during the 2012 and 2013 sweet corn growing season.

<table>
<thead>
<tr>
<th>Effect</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>P &gt;F</td>
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<td>Till (T)</td>
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<td>Spatial Arrangement (SA)</td>
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<tr>
<td>T*SA</td>
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<td>NS</td>
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<tr>
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<td>WM*SA</td>
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Table 5.5. P values for a four way ANOVA for the effects of tillage (fill-width and strip-tillage) zone (within- and between-row), and date on soil temperature from sensors buried 5 cm below the soil surface.

<table>
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<tr>
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<tbody>
<tr>
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<tr>
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<tr>
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<td></td>
</tr>
<tr>
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</tbody>
</table>

Table 5.6. P values for a two-way ANOVA for the fixed effects of tillage (full-width and strip-tillage) and zone (within-and between-row) on percent emergence of sown *Chenopodium album* and *Setaria faberi* seeds in 2012 and 2013.

<table>
<thead>
<tr>
<th>Effect</th>
<th><em>C. album</em></th>
<th></th>
<th><em>S. faberi</em></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2012</td>
<td>2013</td>
<td>2012</td>
<td>2013</td>
</tr>
<tr>
<td>Zone (Z)</td>
<td>0.001</td>
<td>0.0776</td>
<td>&lt;.0001</td>
<td>NS</td>
</tr>
<tr>
<td>Till (T)</td>
<td>NS</td>
<td>0.0806</td>
<td>0.0445</td>
<td>NS</td>
</tr>
<tr>
<td>Z*T</td>
<td>NS</td>
<td>NS</td>
<td>0.0005</td>
<td>NS</td>
</tr>
</tbody>
</table>
Figure 5.1. Mean (+/-) SEM winter annual weed biomass in both Mixed (Mix) and Segregated (SEG) rye and vetch spatial arrangements in 2012 and 2013. Within segregated rye and vetch, vetch was solely planted within the WR, and rye was planted within the BR.
Figure 5.2. Mean (+/- SEM) soil inorganic N within the top 20 cm of soil across the whole plot in both high and low weed management in 2012 and 2013. Inorganic N comparisons include full width tillage (FWT) and strip tillage (ST), with Mixed (MIX) and Segregated (SEG) rye and vetch spatial arrangements.
Figure 5.3. Mean (+/- SEM) soil inorganic N within the top 20 cm of soil in the WR and BR of strip-tilled treatments in low weed management subplots. Soil inorganic N comparisons include mixed (MIX) and segregated (SEG) rye and vetch spatial arrangements.
Figure 5.4. Mean (+/- SEM) gravimetric soil moisture within the top 20 cm of soil across the whole plot in both high and low weed management subplots in 2012 and 2013. Gravimetric soil moisture comparisons include full-width tillage (FWT) and strip-tillage (ST), and mixed (MIX) and segregated (SEG) rye and vetch spatial arrangements.
Figure 5.5. Mean (+/- SEM) gravimetric soil moisture in the top 5 cm of the soil during emergence counts of *C. album* and *S. faberi*. Comparisons include full-width tillage (FWT) and strip-tillage (ST), both within (WR) and between (BR) crop rows.
Figure 5.6. Daily maximum (top) and minimum (middle) soil temperature, as well as the temperature amplitude (maximum-minimum, bottom) measured from hobo sensors buried 5 cm below the soil surface both within (WR) and between crop rows (BR). Comparisons include full-width tillage (FWT) and strip-tillage (ST).
Figure 5.7. Mean (+/- SEM) percent emergence of sown seeds of *C.album* and *S.faberi* in 2012 and 2013. 400 seeds of each species were sown in 2012, and 500 seeds were sown in 2013. Emergence comparisons include full-width tillage (FWT) and strip-tillage (ST) within (WR) and between (BR) crop rows.
Figure 5.8. Mean (+/- SEM) cumulative weed biomass in low weed management subplots in both 2012 and 2013. Weed biomass was summed across weed harvests at two time points during sweet corn growth (before each major weeding event), and then biomass was also collected at sweet corn harvest. Weed biomass comparisons include full-width tillage (FWT) and strip-tillage (ST) within (WR) and between (BR) crop rows.
Figure 5.9. Mean (+/- SEM) sweet corn marketable yield (top), total aboveground biomass (middle), and total aboveground N uptake (bottom). Sweet corn yield is fresh weight of corn ears. Aboveground biomass is the sum of the dry weight of nonharvested biomass and marketable and nonmarketable corn ears. Total aboveground N is the sum of Kjehldahl N contained within nonharvested biomass and corn ears. Comparisons include full-width tillage (FWT) and strip-tillage (ST) in both high and low weed management in 2012 and 2013.
LITERATURE CITED


