

July 2018

Integrating Cover Crop Mixtures and No-Till for Sustainable Sweet Corn Production in the Northeast

Julie S. Fine
University of Massachusetts Amherst

Follow this and additional works at: https://scholarworks.umass.edu/masters_theses_2



Part of the [Agricultural Economics Commons](#), [Agricultural Science Commons](#), [Agronomy and Crop Sciences Commons](#), and the [Weed Science Commons](#)

Recommended Citation

Fine, Julie S., "Integrating Cover Crop Mixtures and No-Till for Sustainable Sweet Corn Production in the Northeast" (2018). *Masters Theses*. 637.
https://scholarworks.umass.edu/masters_theses_2/637

This Open Access Thesis is brought to you for free and open access by the Dissertations and Theses at ScholarWorks@UMass Amherst. It has been accepted for inclusion in Masters Theses by an authorized administrator of ScholarWorks@UMass Amherst. For more information, please contact scholarworks@library.umass.edu.

**INTEGRATING COVER CROP MIXTURES AND NO-TILL FOR
SUSTAINABLE SWEET CORN PRODUCTION IN THE NORTHEAST**

A Thesis Presented

by

JULIE STULTZ FINE

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

May 2018

Plant Biology

© Copyright by Julie S. Fine 2018

All Rights Reserved

**INTEGRATING COVER CROP MIXTURES AND NO-TILL FOR
SUSTAINABLE SWEET CORN PRODUCTION IN THE NORTHEAST**

A Thesis Presented

by

JULIE STULTZ FINE

Approved as to style and content by:

Masoud Hashemi, Chair

Wesley Autio, Member

Prasanta Bhowmik, Member

Li-Jun Ma, Director
Plant Biology Program

DEDICATION

For my parents, Rick and Josie, who always encourage me to grow.

For Jacob, with gratitude for much love and support.

For my daughters, Meira and Nessa, who I hope learned something valuable from watching their mother pursue a challenge and a dream.

“The important thing is not to stop questioning. Curiosity has its own reason for existence. One cannot help but be in awe when he contemplates the mysteries of eternity, of life, of the marvelous structure of reality. It is enough if one tries merely to comprehend a little of this mystery each day.

— Albert Einstein

ACKNOWLEDGEMENTS

I would like to thank my advisor, Masoud Hashemi, for having patience with me, having faith in me, and giving me room to grow. I'm so grateful he was willing to take on a nontraditional graduate student like myself. My colleagues Emily Cole and Samantha Glaze-Corcoran were tremendously supportive resources and helped me solve countless problems in the field, in the lab and on paper. Talia Aronson, my amazing research assistant deserves much credit; without her hard work and attention in the field and the lab it would have taken another five years to complete this research. Thank you to Sarah Weis for keeping our lab running and teaching me the mysterious ways of the Lachat.

I appreciate the hard work of Neal Woodard and Zack Zenk at the UMass Research Farm in S. Deerfield, without whom this research could not happen.

I'm so grateful to my family and friends, including my parents who once donned lab coats to help process soil samples, for their enduring love, encouragement, and support. Megan, Sharon, Leah, Deb, Larry, Emily, Aaron, Dave, Julie, and Dan, thank you!

I want to acknowledge the importance of the Northeast SARE Graduate Student Grant and the Lotta Crabtree Graduate Fellowship for financial support.

ABSTRACT

INTEGRATING NO-TILL AND COVER CROP MIXTURES FOR SUSTAINABLE SWEET CORN PRODUCTION IN THE NORTHEAST

MAY 2018

JULIE STULTZ FINE, B.A., VASSAR COLLEGE

M.S., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Masoud Hashemi

Fall-planted forage radish (*Raphanus sativus* L. *longipinnatus*) cover crops have shown successful weed suppression and recycling of fall-captured nutrients. This research evaluated the nutrient cycling and weed suppressive benefits of forage radish cover crop mixtures to develop an integrated system for no-till sweet corn (*Zea mays* L. var *rugosa*) production that improves crop yield and soil health. Treatments included forage radish (FR), oats (*Avena sativa* L.) and forage radish (OFR), a mixture of peas (*Pisum sativum* subsp *arvense* L.), oats and forage radish (POFR), and no cover crop control (NCC). Subplots were assigned to nitrogen fertilizer treatments to evaluate N sufficiency and timing: 0 kg N ha⁻¹ as the control, 28 kg N ha⁻¹ at side-dress, and 56 kg N ha⁻¹ with application split between planting and side-dress. Results indicated that POFR and OFR provided improved N cycling and sweet corn yield compared with FR and NCC. Early season N from decomposing cover crop residue was sufficient to eliminate the need for N fertilizer at sweet corn planting, thereby reducing input costs and risks of environmental pollution.

TABLE OF CONTENTS

Chapter	Page
ACKNOWLEDGEMENTS	v
ABSTRACT	vi
LIST OF TABLES	ix
LIST OF FIGURES	x
1. USING COVER CROPS AND NO-TILL FOR INCREASED AGRICULTURAL SUSTAINABILITY	1
No-Till Management	3
Cover Crops	4
Radish Cover Crops	5
Mixtures Versus Monocultures	6
Cover Crops in No-Till Production	7
Increasing Sustainability in Sweet Corn	8
Weed Management in Sweet Corn	10
Rationale	10
Objectives	11
References	11
2. CREDITING COVER CROP MIXTURES FOR NO-TILL SWEET CORN YIELD AND QUALITY	17
Hypotheses	22
Objectives	22
Materials & Methods	23
Experimental Site	23
Treatments	24
Statistical Analysis	28
Results and Discussion	29
Aboveground Cover Crop Biomass	29
Total Cover Crop Biomass	32
Cover Crop Carbon and Nitrogen Content	36
Year Effect on Sweet Corn Yield	39
Spring Soil Temperature	40
Influence of Cover Crop on Soil Nitrate for Sweet Corn	42
Soil Biological Activity	48
Sweet Corn Yield	49
Cover Crop Effects on Sweet Corn Yield	50
Influence of Supplemental N Fertilizer on Sweet Corn Yield	52
Post-Harvest N Sufficiency Assessment	56
Nitrogen Use Efficiency	59
Conclusion	61

References	63
3. WEED SUPPRESSION IN WINTER-KILLED RADISH COVER CROP	
MIXTURES.....	71
Forage Radish as a Cover Crop	72
Spring Weed Suppression.....	73
Cover Crop Mixtures	73
Conservation Tillage for Vegetable Production	74
Sweet Corn in No-Till Production.....	75
Weed Management in Sweet Corn	76
Rationale.....	77
Objectives	77
Hypotheses	78
Materials & Methods.....	78
Experimental Site	78
Statistical Analysis	80
Results and Discussion.....	81
Fall Weed and Cover Crop Biomass Production.....	81
Spring Biomass Production	84
Conclusion.....	88
References	89
4. ECONOMIC ANALYSIS OF COVER CROP BENEFITS FOR NO-TILL SWEET	
CORN PRODUCTION	93
Conclusion.....	96
Cover Crop Mixtures for the Future.....	97
Research Implications	99
References	99
BIBLIOGRAPHY	102

LIST OF TABLES

Table	Page
1. Precipitation and Growing Degree Days (GDD) for experimental sites. GDD= $\Sigma (T_{\max}-T_{\min})-T_b$ where T_{\max} and T_{\min} are daily maximum and minimum temperatures, respectively, and T_b is base temperature. For cover crop mixtures T_b was set as 4°C and for sweet corn T_b was 10°C.	23
2. Cover crop seeding rates for 2014 and 2015.	24
3. Field activity at UMass Research Farm, S. Deerfield, MA.	26
4. Cover crop biomass characteristics at experimental site in both years. Years analyzed separately. Treatments with different letters indicate significant differences (Tukey’s HSD $p<0.05$). No letter indicates no significant differences.	33
5. Solvita soil respiration test results for 2015 and 2016.	49
6. Field activity at UMass Crop and Animal Research Farm in S. Deerfield, MA.	79
7. Precipitation and Growing Degree Days (GDD) for experimental sites. GDD= $\Sigma (T_{\max}-T_{\min})-T_b$ where T_{\max} and T_{\min} are daily maximum and minimum temperatures, respectively, and T_b is base temperature. For cover crop mixtures T_b was set as 4°C and for sweet corn T_b was 10°C.	80
8. Aboveground biomass of cover crops, weeds, and respective N content, in November 2014 and 2015. Cover crops planted August 23, 2014 and August 24, 2015. Year data analyzed separately. Treatments with different letters indicate significant differences (Tukey’s HSD $p<0.05$).	82
9. Cover crop treatment seeding rates and seed costs.	93
10. The cover crop impact on overall sweet corn profit. Costs are indicated by parentheses. Costs were subtracted from profits resulting from cover crop treatments.	95

LIST OF FIGURES

Figure	Page
1. Aboveground cover crop biomass measured in November prior to winter-kill.....	30
2. Total cover crop dry matter by species, including FR roots, for 2014 and 2015.	35
3. Nitrogen in total cover crop dry matter, November 2014 and 2015.....	37
4. Soil temperature as affected by cover crop treatment prior to sweet corn planting from April 22 to May 4, 2015 and April 22 to May 8, 2016.....	41
5. Soil nitrate during the 2015 growing season. Plots received no additional N fertilizer. Green arrows indicate when sweet corn was seeded. Red arrows indicate peak N crop demand.	42
6. Soil nitrate during the 2016 growing season. Plots received no additional N fertilizer. Green arrows indicate date of sweet corn planting. Red arrows indicate peak N crop demand.	44
7. Photo of sweet corn plots at V5 growth stage, just prior to	47
8. Pre-sidedress Nitrate Test (PSNT) concentrations of nitrate at V5 stage of sweet corn growth in mid-June 2015 and 2016.....	48
9: Sweet corn yield as affected by cover crop treatment, measured by marketable ears (left) and ear fresh weight (right). Values are averaged over all N treatments over two years. Different letters in columns indicate significant differences (Tukey’s HSD p<0.05).	51
10. Sweet corn yield as affected by supplemental N fertilizer rate. Values are averaged over all cover crop treatments and two years.....	53
11. Proposed interpretations of the at-harvest stalk N test for sweet corn excerpted from Heckman, et al., 2002.....	57
12. Corn stalk nitrate test values for cover crop treatments at each level of N fertilizer treatment in 2015 (left) and 2016 (right).	57
13. Nitrogen Use Efficiency (NUE) of sweet corn following cover crop treatments. $NUE = (\text{fresh weight yield in N-treated cover crop plots} - \text{yield in untreated NCC control plots}) / \text{kg applied N fertilizer}$	60

14. Relationship between cover crop dry matter and weed dry matter by cover crop treatment just prior to winter-kill in November 2014 (left) and November 2015 (right).....	83
15. Spring weed dry matter and weed density in plots following cover crop treatment, prior to herbicide application, April 2016. Treatments with different letters indicate significant differences (Tukey’s HSD $p < 0.05$).	85
16. Relationship between November cover crop biomass and April weed biomass (prior to termination and sweet corn planting).....	86
17. Summer weed dry matter and weed density in plots following cover crop treatment, June 2016. Treatments with different letters indicate significant differences (Tukey’s HSD $p < 0.05$). No significant differences were observed in weed dry matter.	86
18. Average cost to achieve N sufficiency of 145 kg ha^{-1} utilizing cover crop-mediated N residue and sidedressed synthetic N fertilizer.....	94

CHAPTER 1

USING COVER CROPS AND NO-TILL FOR INCREASED AGRICULTURAL SUSTAINABILITY

Soil is a finite resource. The creation of an inch of topsoil requires thousands of years of transformation of parent rock and plant material by forces of wind, rain, and biological activity. The scale of soil creation is beyond human time, and therefore humans cannot afford to lose soil faster than it can develop. The current movement to consider soil health, not only in terms of soil conservation but also in regard to function and sustainability, is crucial for food production on a planet with a growing population and limited arable land. The word ‘sustainable’ refers to something that can be maintained or upheld. A sustainable agricultural production system is economically viable, reduces off-farm inputs, eliminates farm-source pollution, uses minimal chemical pest controls, and promotes healthy soil.

Conserving topsoil has been a concern of American farmers since the Dustbowl of the 1930s, but the concept of “soil health” has been more recently evolving. The Natural Resource Conservation Service, the soil conservation arm of the USDA, defines soil health as “the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans” (USDA-NRCS). Practically speaking, this means a soil that has the capacity to regulate water flow, absorbing and releasing water in response to moisture conditions. This means a soil that is hospitable to life, from bacteria and fungi to invertebrates and small mammals. This means a soil that is a good growing medium for crops, in terms of providing structural support, nutrient release, and water holding capacity.

There is no definitive test for soil health, because there are no absolute values or parameters to measure and the results vary depending on soil type. Instead, soil health assessments focus on physical, chemical and biological qualities of soil. Physical qualities include aggregate stability, available water capacity, and surface and subsurface hardness. Chemical qualities include cation exchange capacity, macro- and micronutrients, and soil pH. Biological qualities include soil carbon, soil protein, soil respiration and soil organic matter (SOM). Many researchers describe SOM as being at the heart of soil health because it influences all three spheres, the biological, chemical and physical. Research has shown that SOM improves crop yield response, soil pH buffering, aggregate stability, erosion resistance, water infiltration, and soil compaction (Balesdent et al., 2000; Brock et al., 2011; Fageria, 2012). Without sufficient SOM it is impossible to have a healthy soil and optimal crop yield.

In most agricultural soils, a healthy range of SOM is 3-6% and there are significant challenges to increasing percentage of SOM without massive expense or loss of productivity (Magdoff and Weil, 2004). The main approaches to building SOM are minimizing loss and increasing inputs of organic matter. SOM loss is prevented by 1) decreasing erosion that washes away SOM particles, 2) decreasing tillage that oxidizes SOM, and 3) reducing crop residue loss, adding organic matter. Unfortunately, SOM and soil health are often at odds with the intensive tillage requirements of many crops (Hoyt, 1986). Tillage is needed to incorporate residue and create a fine seedbed, but destroys soil aggregates and oxidizes SOM.

No-Till Management

Farmers have been transitioning to no-till as an effective way to reduce soil erosion, increase water infiltration, reduce tractor work, and improve soil health. The development of herbicides and specialized planting equipment in the 1950s and 1960s allowed growers to manage their crops without tillage. This revolution of no-till agriculture in the United States has increased use of no-till practices to almost 75% of midwestern corn and soybean growers. The primary no-till crops are corn (*Zea mays*), soybean (*Glycine max*), wheat (*Triticum aestivum*), oats (*Avena sativa*) and cotton (*Gossypium hirsutum*), the majority of which are grown over vast acreage and rely on chemical weed control.

Tillage damages important functions of soil, such as soil aggregates and SOM. Aggregates are held together by biological products and chemical bonds, which are essentially fragmented by tillage implements. By reducing or eliminating tillage, soil aggregates remain intact, which results in reduced soil erosion, increased water infiltration, and improved soil structure and function (Hobbs, 2007; Hoyt, 1986; Lal, 2004; Six et al., 1999).

Major changes occur in soil ecosystems with the elimination of tillage. The soil food web shifts toward fungal dominance and organic matter residue becomes more stratified (Stubbs et al., 2004). In addition, the transition to no-till increases soil mycorrhizal associations and earthworm populations. Weed pressure is reduced because new weed seeds aren't brought to the soil surface. When no-till systems are integrated with cover crops, multiple benefits to the soil and cash crops are significantly enhanced (Kuo et al., 1997; Sainju et al., 2002; Sainju et al., 2005).

Cover Crops

Cover crops are select plant species grown for multiple agronomic benefits: soil protection, compaction reduction, nitrate scavenging, nitrogen fixation, biomass production, weed suppression, or beneficial insect habitat. The term “cover crop” is used generally and can include summer or winter crops grown for various purposes: green manures, catch crops, nitrogen-fixation, and high-residue mulch. Cover crops have proven to be effective at scavenging residual fall nitrate to prevent winter N leaching (Kristensen and Thorup-Kristensen, 2004; Meisinger and Delgado, 2002; Möller and Reents, 2009). Deep rooting catch crops can reduce nitrate losses due to leaching up to 95% when compared with fallow plots (Cooper et al., 2017).

While cover crops are universally recognized as an N sink, their biomass residue can be an N source for subsequent cash crops. In general, the main sources of nitrogen are supplemental fertilizer, soil organic matter, and decomposing plant residue (from cash crop or cover crop). Soil organic matter mineralizes with biological activity at moderate temperatures and sufficient soil moisture. Plant residue, from previous cash crops or from cover crops, decomposes at rates dependent on temperature, moisture, and pH. Cover crops can serve to mediate N, from soil excess to plant sufficiency under the right circumstances and conditions.

The key to maximizing benefits from cover crops is to identify agricultural production goals based on soil requirements, climate, season, and chemical management. Based on these goals, appropriate species can be selected to serve those purposes. Fall-planted forage radish (*Raphanus sativus* L. *longipinnatus*) establishes quickly, suppresses

weeds, and scavenges soil nitrate and other nutrients from deep in the soil profile (Lawley et al., 2012; Weil and Kremen, 2007; Weil et al., 2009).

Use of forage radish as a cover crop has become popular in a wide range of climates, from the Mid-Atlantic to the Midwest. In Massachusetts, vegetable growers have been experimenting with forage radish cover crops as an alternative to high-residue winter rye (*Secale cereale* L.) or hairy vetch (*Vicia villosa* L.). These high residue cover crops can create cold, wet soil conditions that delay planting in spring. Rye residue must be managed and terminated within a narrow timeframe, between flowering and pollination, which can be impossible if soils are highly saturated. Large amounts of decomposing cover crop residue can immobilize nutrients and cause poor synchronization of N mineralization with succeeding crop's demand (Dabney et al., 2001). When cash crops rely on N from cover crop residue, N immobilization reduces cash crop yields (Wells et al., 2013).

Radish Cover Crops

The no-till movement has adopted forage radish cover crops because of minimal residue-management requirements, compaction reduction, soil water conservation, weed suppression and nitrogen cycling. The taproot of radish rapidly grows down to 2.4 m depth, removing nitrogen from deep in the soil profile (Dean and Weil, 2009; Kristensen and Thorup-Kristensen, 2004; Thorup-Kristensen, 2000). Forage radish scavenges more residual soil nitrate and phosphorus, and produces more fall biomass (3,500 kg ha⁻¹) compared to commonly used winter rye (2,680 kg ha⁻¹) (Dean and Weil, 2009).

Forage radish plants winter-kill only when temperatures are sub-freezing for several days (Dean and Weil, 2009; Lounsbury and Weil, 2014). The radish biomass

continues to protect the soil from rain and wind over winter, even after freezing temperature terminates its growth. In spring, forage radish residue, which contains low lignin, decomposes quickly. Where the fleshy roots grew, large ‘pores’ remain that improve water infiltration rates to prevent runoff (Chen and Weil, 2010).

One disadvantage of forage radish is its low carbon to nitrogen ratio (C:N ratio), ranging from 14:1 to 18:1 (Schomberg et al., 2006). This results in fast decomposition and release of nutrients in early spring prior to the growth of the succeeding crop (Trinsoutrot et al., 2000). More specifically, if the nitrogen released by decomposition is not synchronized with the nitrogen demand of the spring planted cash crop, the result contributes to nutrient pollution and financial loss. Mixing forage radish with grass cover crops, which are rich in carbon, is a sound strategy to adjust the C:N ratio of cover crop residue (Dabney et al., 2001).

Mixtures Versus Monocultures

Multi-species cover crop mixtures have the potential to expand the agroecosystem benefits compared to single species cover crops. Under the right conditions, mixtures can increase SOM, improve C:N ratio of residue, diversify soil biology, and reduce weed density. Complementary root structure (both tap-rooted and branching) and complementary plant architecture (both broadleaved and grasses) can provide elasticity that enable mixtures to adjust to stressors such as weed pressure or weather conditions (Kunz et al., 2016).

Polyculture cover crop biomass can out-yield monocultures, with a few exceptions such as winter rye (Finney et al., 2016; Messiga et al., 2016). Grass species in a mixture outperform those in monoculture (Murrell et al., 2017). Legume/grass

bicultures increased dry matter production compared to monocultures, with only slight reductions in N availability compared to legume monocultures (Ranells and Waggoner, 1996). In low-residue cover crops, it is hypothesized that a mixture of species with complementary traits, such as growth habit or phenology, can enhance ecosystem services, including aggregate protection, nutrient uptake, and weed suppression (Finney et al., 2016). Creamer et al. (1997) experimented with winter-hardy cover crop mixtures that would improve C:N ratios, and provide erosion control and weed suppression in no-till vegetable production. They found that mixtures including winter rye, hairy vetch, crimson clover and/or barley met those criteria successfully in Ohio.

Cover Crops in No-Till Production

The integration of no-till and cover crops can be essential for yield increases and soil health benefits. No-till systems do not intrinsically sequester C or increase SOM, which are important for long-term soil health and productivity. In order to add carbon and OM, no-till systems need to be integrated with winter cover crops (Blanco-Canqui et al., 2015; Kuo et al., 1997; Sainju et al., 2002; Snapp et al., 2005). In a no-till corn/soybean system, winter cover crops improved soil physical properties and helped better cycling of N and P (Villamil et al., 2006). Though no-till maintains SOM levels, additional carbon inputs, such as cover crops or manure, are needed to actually increase SOM (Kuo et al., 1997).

There are challenges that come with the transition to no-till. There are two to three years of yield lag following the transition to no-till as soil aggregates and microbial communities adjust (Stubbs et al., 2004). Management of weeds becomes critical in no-till systems because cultivation can no longer be used as a management tool.

Not every crop is suitable for no-till. Corn, soybeans, wheat, and cotton are the major crops that can be successfully grown on a large scale. Some vegetable crops, like squash, cabbage, and tomatoes, have been successfully grown no-till (Hoyt et al., 1994). However, crops that require a fine seedbed (carrots, greens, lettuce) or a furrow for planting (potatoes, sweet potatoes) have not been successfully grown using field-scale no-till techniques.

Sweet corn is a vegetable crop well-adapted to no-till production (Groff, 2006; Mohler, 1991). It is possible that by integrating low-residue forage radish cover crop mixtures with no-till production, farmers could reduce fertilizer and herbicide inputs while maintaining or improving sweet corn yields.

Increasing Sustainability in Sweet Corn

In 2015, sweet corn was planted on 4,730 hectares across New England—about 10% of total vegetable production (USDA-NASS, 2016). In this region sweet corn is commonly grown without supplemental irrigation as long as soil texture is not too sandy (Dicklow and McKeag, 2016). Early sweet corn (*Zea mays* L. *rugosa*) in New England garners a price premium and draws customers to roadside stands, but production comes with challenges of weeds, frequent tillage and high rates of fertilizer applications (Galloway and Weston, 1996).

Sweet corn requires is sensitive to nitrogen stress and requires soil temperatures above 16 °C for successful emergence. Due to these characteristics, it has been difficult to use traditional high-residue cover crops, such as winter rye, in sweet corn production systems. After winter-killed forage radish, the soil surface is relatively residue-free, making it optimal for direct seeding in a no-till system. Large radish root channels

provide excellent water infiltration and warmer soil temperature for early planting (Lounsbury and Weil, 2014).

Like field corn, sweet corn is considered a high nitrogen-demanding crop. The New England Vegetable Management Guide recommends applying 112 to 145 kg ha⁻¹ of nitrogen fertilizer to achieve optimum yields (Dicklow and McKeag, 2016). At planting, 45 kg N ha⁻¹ should be applied in a band (unless soils are very sandy), and the remainder applied at side-dress when corn reaches approximately 25 cm tall.

The seasonal timing of sweet corn fits very well with N recycling from late-summer or fall-planted cover crops. Fall cover crops can capture residual soil N and recycle that to the following crop to potentially reduce the amount of required N fertilizer (Isse et al., 1999). Forage radish cover crops can immobilize 75 to 250 kg N ha⁻¹ (Lounsbury and Weil, 2014), which could potentially meet the nitrogen needs of sweet corn if synchronized with the crop's demand. The nitrogen dynamics of cover crops are complicated and vary depending on soil type, cover crop, and climate. In a Canadian study, oats (*Avena sativa* L.), oilseed radish and a mixture of radish and rye increased sweet corn profitability compared with no cover crop (O'Reilly et al., 2012). However, those cover crops did not increase plant available N compared with no cover crop.

Research suggests that cover crops may improve sweet corn yield, not only by reducing weed pressure, but also by increasing competitiveness against growing weeds (Carrera et al., 2004). (Burgos and Talbert, 1996) found that cover crops of hairy vetch, wheat and rye reduced the emergence and yield of no-till sweet corn. However, the use of cover crops allowed the use half rates of atrazine and metolachlor without reducing yields compared to full rate herbicide.

Weed Management in Sweet Corn

Sweet corn is highly sensitive to weed competition due to its limited root system (Williams, 2008). Research has shown that cover crops can significantly reduce weed emergence in sweet corn production (Galloway and Weston, 1996; Griffin et al., 2000; Peachey et al., 2004). Of ten cover crop treatments over four years, forage radish was the only one that, compared to a weedy fallow, reduced fall weed biomass by 89-97% regardless of dominant fall weed species, from grasses (*Digitaria spp.*) to broadleaf species (*Portulaca oleracea* L. and *Amaranthus retroflexus*) (Hodgdon et al., 2016). Kunz et al. (2016) reported that monoculture forage radish, and a mixture including radish, decreased weed biomass by 60 and 66% respectively. The weed suppressive effect is limited to winter and early spring periods and does not carry through the main growing season (Lawley et al., 2011). However, research on weed emergence dynamics following mixtures of winter-killed cover crops is not well documented. If winter-killed multi-species cover crop mixtures produce enduring residue, it may enhance weed suppression.

Rationale

Most of the published research regarding forage radish has been conducted in the mid-Atlantic region, where it does not always winter kill and where spring cash crops are often planted in early March. There is insufficient research documenting the benefits and limitations of forage radish in colder Northeastern climates. Given the short northern growing season, cover crops must be planted earlier to efficiently scavenge nutrients and quickly establish a leaf canopy to suppress weeds. Additionally, spring decomposition of cover crop residues occurs at lower temperatures beginning in April, compared to

February in the mid-Atlantic region. Reports indicate that a mixture of cover crops rather than a single species can provide better services including weed suppression and natural fertility of soils (Bybee-Finley et al., 2016; Finney et al., 2016; Wendling et al., 2016). Research is needed to measure the effects of forage radish-based cover crop mixtures on soil nutrient cycling, weed growth, and yield response in a Northeastern production system. No-till sweet corn production affords complementary timing to integrate these winter-killed cover crop mixtures.

Objectives

The objective of this research is to develop an integrated system for no-till sweet corn production that utilizes the nutrient cycling and weed suppressive benefits of forage radish cover crop mixtures to benefit sweet corn yields and soil health. Cover crop mixtures should improve carbon additions to contribute to long-term SOM stabilization. Low- to medium-residue cover crop mixtures will not present the management challenges in terms of soil temperature reduction or spring residue management. These cover crop mixtures should scavenge more fall N, thereby recycling inorganic N to the sweet corn cash crop the following spring and summer. Ideally, this would result in fertilizer savings to reduce costs for the farmer and reduce the environmental risk of N leaching.

References

- Balesdent J., Chenu C., Balabane M. (2000) Relationship of soil organic matter dynamics to physical protection and tillage. *Soil & Tillage Research* 53:215-230. DOI: 10.1016/s0167-1987(99)00107-5.
- Blanco-Canqui H., Shaver T.M., Lindquist J.L., Shapiro C.A., Elmore R.W., Francis C.A., Hergert G.W. (2015) Cover crops and ecosystem services: Insights from studies in temperate soils. *Agronomy Journal* 107:2449-2474. DOI: 10.2134/agronj15.0086.

- Brock C., Fließbach A., Oberholzer H.R., Schulz F., Wiesinger K., Reinicke F., Koch W., Pallutt B., Dittman B., Zimmer J., Hulsbergen K.J., Leithold G. (2011) Relation between soil organic matter and yield levels of nonlegume crops in organic and conventional farming systems. *Journal of Plant Nutrition and Soil Science* 174:568-575. DOI: 10.1002/jpln.201000272.
- Burgos N.R., Talbert R.E. (1996) Weed control and sweet corn (*zea mays* var *rugosa*) response in a no-till system with cover crops. *Weed Science* 44:355-361.
- Bybee-Finley K.A., Mirsky S.B., Ryan M.R. (2016) Functional diversity in summer annual grass and legume intercrops in the northeastern United States. *Crop Science* 56:2775-2790. DOI: 10.2135/cropsci2016.01.0046.
- Carrera L.M., Abdul-Baki A.A., Teasdale J.R. (2004) Cover crop management and weed suppression in no-tillage sweet corn production. *HortScience* 39:1262-1266.
- Chen G., Weil R.R. (2010) Penetration of cover crop roots through compacted soils. *Plant and Soil* 331:31-34. DOI: 10.1007/s11104-009-0223-7.
- Cooper R.J., Hama-Aziz Z., Hiscock K.M., Lovett A.A., Dugdale S.J., Sunnenberg G., Noble L., Beamish J., Hovesen P. (2017) Assessing the farm-scale impacts of cover crops and non-inversion tillage regimes on nutrient losses from an arable catchment. *Agriculture Ecosystems & Environment* 237:181-193. DOI: 10.1016/j.agee.2016.12.034.
- Creamer N.G., Bennett M.A., Stinner B.R. (1997) Evaluation of cover crop mixtures for use in vegetable production systems. *HortScience* 32:866-870.
- Dabney S.M., Delgado J.A., Reeves D.W. (2001) Using winter cover crops to improve soil and water quality. *Communications in Soil Science and Plant Analysis* 32:1221-1250. DOI: 10.1081/css-100104110.
- Dean J.E., Weil R.R. (2009) Brassica cover crops for nitrogen retention in the mid-atlantic coastal plain. *J Environ Qual* 38:520-8. DOI: 10.2134/jeq2008.0066.
- Dicklow M.B., McKeag L. (Eds.). (2016) *New England vegetable management guide*, UMass Extension, Amherst, MA.
- Fageria N.K. (2012) Role of soil organic matter in maintaining sustainability of cropping systems. *Communications in Soil Science and Plant Analysis* 43:2063-2113. DOI: 10.1080/00103624.2012.697234.
- Finney D.M., White C.M., Kaye J.P. (2016) Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. *Agronomy Journal* 108:39-52. DOI: 10.2134/agronj15.0182.

- Galloway B.A., Weston L.A. (1996) Influence of cover crop and herbicide treatment on weed control and yield in no-till sweet corn (*zea mays l*) and pumpkin (*cucurbita maxima duch*). *Weed Technology* 10:341-346.
- Griffin T., Liebman M., Jemison J. (2000) Cover crops for sweet corn production in a short-season environment. *Agronomy Journal* 92:144-151.
- Groff S. (2006) A no-till success story. *American Vegetable Grower* 54:24.
- Hobbs P.R. (2007) Conservation agriculture: What is it and why is it important for future sustainable food production? *Journal of Agricultural Science* 145:127-137. DOI: 10.1017/s0021859607006892.
- Hodgdon E.A., Warren N.D., Smith R.G., Sideman R.G. (2016) In-season and carry-over effects of cover crops on productivity and weed suppression. *Agronomy Journal* 108:1624-1635. DOI: 10.2134/agronj2015.0419.
- Hoyt G., Monks D., Monaco T. (1994) Conservation tillage for vegetable production. *Horttechnology* 4:129-135.
- Hoyt G.D. (1986) Conservation tillage for vegetable and tobacco production. *Soil & Tillage Research* 8:341-341. DOI: 10.1016/0167-1987(86)90381-8.
- Isse A., MacKenzie A.F., Stewart K., Cloutier D.C., Smith D.L. (1999) Cover crops and nutrient retention for subsequent sweet corn production. *Agronomy Journal* 91:934-939.
- Kristensen H.L., Thorup-Kristensen K. (2004) Root growth and nitrate uptake of three different catch crops in deep soil layers. *Soil Science Society of America Journal* 68:529-537.
- Kunz C., Sturm D.J., Varnholt D., Walker F., Gerhards R. (2016) Allelopathic effects and weed suppressive ability of cover crops. *Plant Soil and Environment* 62:60-66.
- Kuo S., Sainju U.M., Jellum E.J. (1997) Winter cover crop effects on soil organic carbon and carbohydrate in soil. *Soil Science Society of America Journal* 61:145-152.
- Lal R. (2004) Soil carbon sequestration impacts on global climate change and food security. *Science* 304:1623-1627. DOI: 10.1126/science.1097396.
- Lawley Y.E., Teasdale J.R., Weil R.R. (2012) The mechanism for weed suppression by a forage radish cover crop. *Agronomy Journal* 104:205-214. DOI: 10.2134/agronj2011.0128.
- Lawley Y.E., Weil R.R., Teasdale J.R. (2011) Forage radish cover crop suppresses winter annual weeds in fall and before corn planting. *Agronomy Journal* 103:137-144. DOI: 10.2134/agronj2010.0187.

- Lounsbury N.P., Weil R.R. (2014) No-till seeded spinach after winterkilled cover crops in an organic production system. *Renewable Agriculture and Food Systems* 30:473-485.
- Magdoff F., Weil R.R. (Eds.). (2004) *Soil organic matter in sustainable agriculture*, CRC Press, Boca Raton, FL.
- Meisinger J.J., Delgado J.A. (2002) Principles for managing nitrogen leaching. *Journal of Soil Water Conservation* 57:485-498.
- Messiga A.J., Sharifi M., Munroe S. (2016) Combinations of cover crop mixtures and bio-waste composts enhance biomass production and nutrients accumulation: A greenhouse study. *Renewable Agriculture and Food Systems* 31:507-515. DOI: 10.1017/s1742170515000423.
- Mohler C.L. (1991) Effects of tillage and mulch on weed biomass and sweet corn yield. *Weed Technology* 5:545-552.
- Möller K., Reents H.-J. (2009) Effects of various cover crops after peas on nitrate leaching and nitrogen supply to succeeding winter wheat or potato crops. *Journal of Plant Nutrition and Soil Science* 172:277-287. DOI: 10.1002/jpln.200700336.
- Murrell E.G., Schipanski M.E., Finney D.M., Hunter M.C., Burgess M., LaChance J.C., Baraibar B., White C.M., Mortensen D.A., Kaye J.P. (2017) Achieving diverse cover crop mixtures: Effects of planting date and seeding rate. *Agronomy Journal* 109:259-271. DOI: 10.2134/agronj2016.03.0174.
- O'Reilly K.A., Lauzon J.D., Vyn R.J., Van Eerd L.L. (2012) Nitrogen cycling, profit margins and sweet corn yield under fall cover crop systems. *Canadian Journal of Soil Science* 92:353-365. DOI: 10.4141/cjss2011-065.
- Peachey R.E., William R.D., Mallory-Smith C. (2004) Effect of no-till or conventional planting and cover crops residues on weed emergence in vegetable row crop. *Weed Technology* 18:1023-1030. DOI: 10.1614/wt-03-205r.
- Ranells N.N., Waggoner M.G. (1996) Nitrogen release from grass and legume cover crop monocultures and bicultures. *Agronomy Journal* 88:777-882. DOI: 10.2134/agronj1996.00021962008800050015x.
- Sainju U.M., Singh B.P., Whitehead W.F. (2002) Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. *Soil and Tillage Research* 63:167-179.
- Sainju U.M., Whitehead W.F., Singh B.P. (2005) Biculture legume-cereal cover crops for enhanced biomass yield and carbon and nitrogen. *Agronomy Journal* 97:1403-1412. DOI: 10.2134/agronj2004.0274.

- Schomberg H.H., Endale D.M., Calegari A., Peixoto R., Miyazawa M., Cabrera M.L. (2006) Influence of cover crops on potential nitrogen availability to succeeding crops in a southern piedmont soil. *Biology and Fertility of Soils* 42:299-307. DOI: 10.1007/s00374-005-0027-8.
- Six J., Elliott E.T., Paustian K. (1999) Aggregate and soil organic matter dynamics under conventional and no-tillage systems. *Soil Science Society of America Journal* 63:1350-1358.
- Snapp S.S., Swinton S.M., Labarta R., Mutch D., Black J.R., Leep R., Nyiraneza J., O'Neil K. (2005) Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agronomy Journal* 97:322-332.
- Stubbs T.L., Kennedy A.C., Schillinger W.F. (2004) Soil ecosystem changes during the transition to no-till cropping. *Journal of Crop Improvement* 11:105-135. DOI: 10.1300/J411v11n01_06.
- Thorup-Kristensen K. (2000) Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-n content, and how can this be measured? *Plant and Soil* 230:185-195.
- Trinsoutrot I., Recous S., Bentz B., Line`res M., Che`neby D., Nicolardot B. (2000) Biochemical quality of crop residues and carbon and nitrogen mineralization kinetics under nonlimiting nitrogen conditions. *Soil Sci. Soc. Am. J.* 64:918-926. . DOI: doi:10.2136/sssaj2000.643918x.
- USDA-NASS. (2016) New england fruits and vegetables, in: G. R. Keough (Ed.), *New England Agricultural Statistics 2015*, USDA National Agricultural Statistics Service, Concord, NH.
- United States Department of Agriculture, Natural Resource Conservation Service. Soil health. October 26, 2017. <https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/>.
- Villamil M.B., Bollero G.A., Darmody R.G., Simmons F.W., Bullock D.G. (2006) No-till corn/soybean systems including winter cover crops: Effects on soil properties. *Soil Science Society of America Journal* 70:1936-1944. DOI: 10.2136/sssaj2005.0350.
- Weil R., Kremen A. (2007) Thinking across and beyond disciplines to make cover crops pay. *Journal of the Science of Food and Agriculture* 87:551-557. DOI: 10.1002/jsfa.2742.
- Maryland Cooperative Extension. Forage radish: New multi-purpose cover crop for the mid-atlantic. Fact sheet 824. March 13. [https://enst.umd.edu/sites/enst.umd.edu/files/docs/FactSheet824 Weil et al 2009.pdf](https://enst.umd.edu/sites/enst.umd.edu/files/docs/FactSheet824%20Weil%20et%20al%202009.pdf).

- Wells M.S., Reberg-Horton S.C., Smith A.N., Grossman J.M. (2013) The reduction of plant-available nitrogen by cover crop mulches and subsequent effects on soybean performance and weed interference. *Agronomy Journal* 105:539-545. DOI: 10.2134/agronj2012.0396.
- Wendling M., Buchi L., Amosse C., Sinaj S., Walter A., Charles R. (2016) Influence of root and leaf traits on the uptake of nutrients in cover crops. *Plant and Soil* 409:419-434. DOI: 10.1007/s11104-016-2974-2.
- Williams M.M. (2008) Sweet corn growth and yield response to planting dates of the north central united states. *HortScience* 43.

CHAPTER 2

CREDITING COVER CROP MIXTURES FOR NO-TILL SWEET CORN YIELD AND QUALITY

Nitrogen (N) is usually a critically limiting nutrient in crop production and can be difficult to efficiently manage in soil. Applied N fertilizer is prone to leaching, which contributes to environmental pollution and economic loss (Meisinger and Delgado, 2002; Weinert et al., 2002). Improved management practices focusing on enhancement of soil biological activity result in natural soil fertility, reduced N fertilizer loss, and thus increase N use efficiency. Integrating cover crops into a system along with reduced tillage and improved synchronization of N inputs with crops' demands are among effective methods to improve N management (Blanco-Canqui et al., 2015; Meisinger and Delgado, 2002; Snapp et al., 2005).

Farmers increasingly transition to no-till production as an effective way to reduce soil erosion, increase water infiltration, improve nutrient management, decrease tractor labor, and boost soil health (Drinkwater et al., 2000; Six et al., 1999; Triplett and Dick, 2008). Tillage can harm some of the most important soil functions, in particular soil aggregates and soil organic matter (SOM) (Reeves, 1997). Research indicates that no-till practices decrease soil erosion, increase water infiltration, improve soil structure and function, and stabilize soil aggregates (Hobbs, 2007; Hoyt, 1986; Lal, 2004; Six et al., 1999). In addition, major changes occur in soil ecosystems with the elimination of tillage. The soil food web shifts toward fungal dominance (Stubbs et al., 2004) and SOM builds slowly over time as a result of increased microbial biomass and reduced OM oxidation (Kallenbach et al., 2016; Six et al., 2004). A major limitation of no-till systems

is that they do not inherently sequester C or increase SOM, which are important for long-term soil health and productivity. In order to add carbon and OM, no-till systems need to be integrated with winter cover crops (Blanco-Canqui et al., 2015; Kuo et al., 1997a; Sainju et al., 2002; Sainju et al., 2005).

Winter cover crops are planted in early fall and are either winter-killed by cold temperatures or are winter hardy, resuming growth in spring. These cover crops can effectively serve multiple functions to improve N cycling while protecting soil from erosion, reducing compaction, supporting soil biological activity, and suppressing weeds (Blanco-Canqui et al., 2015; Gabriel et al., 2016; Kuo et al., 1997b). Cool season cover crops are crucial in regions with short growing seasons, such as the Northeast, to protect soil health and sustainability.

In soils with high concentrations of N, non-legume cover crops can provide effective nitrate scavenging following a cash crop (Dabney et al., 2001; Hashemi et al., 2013; Kristensen and Thorup-Kristensen, 2004a; O'Reilly et al., 2012). If soil is low in residual N, legume cover crops can actively fix atmospheric N and immobilize it in the plant tissue (Drinkwater et al., 1998; Gabriel et al., 2016; Sainju et al., 2005).

In vegetable production systems, fall-planted cover crops can scavenge on average 40 to 200 Kg N ha⁻¹ with the higher range following high residual N crops, such as potatoes (Dabney et al., 2001; Dabney, 2010; Hashemi et al., 2013; Jahanzad et al., 2017; Wendling et al., 2016). Cover crop capacity for nitrate scavenging is related to root depth but not density (Kristensen and Thorup-Kristensen, 2004a; Thorup-Kristensen, 2000; Thorup-Kristensen, 2001) as well as the initial N status of the soil and the date of planting. In short-season regions like the Northeast, it can be challenging to get winter

cover crops planted in time for sufficient growth. If planted in late August through September, cover crops are likely to take up 17 to 78 kg N ha⁻¹ (Dabney et al., 2001; Hashemi et al., 2013; Murrell et al., 2017). When the cover crop is winter-killed or otherwise terminated, plant biomass decomposes and organic N is recycled to the subsequent crop through mineralization (Cabrera et al., 2005; Jahanzad et al., 2016).

Winter rye (*Secale cereal* L.) is the most common cover crop in the Northeast used for fall nitrate scavenging and soil protection. It establishes well even quite late in the fall, is winter-hardy, and resumes growth in spring to produce high rates of biomass. However, large amounts of cover crop residue on the soil surface in spring can cause adverse cropping conditions by insulating the soil surface, trapping soil moisture, and interfering with seed placement (Teasdale et al., 2008). Especially in areas with a short growing season excess soil moisture and cool soil temperatures delay planting (Teasdale and Mohler, 1993; Wells et al., 2013), which may compromise crop yield and reduce revenue.

In several studies, forage radish (FR) (*Raphanus sativus* L. *longipinnatus*) showed greater capacity for N uptake and immobilization compared with commonly used cover crop species (Hodgdon et al., 2016; Kristensen and Thorup-Kristensen, 2004a). The no-till movement has adopted forage radish cover crops because of minimal residue-management requirements, effective compaction reduction, soil water conservation, weed suppression and nitrogen cycling (Lawley et al., 2011). The fleshy root and penetrating taproot of radish grows to 2.4 m deep and removes nitrogen and other nutrients from deep in the soil profile (Dean and Weil, 2009; Kristensen, 2004; Thorup-Kristensen, 2000). Forage radish scavenges more residual soil nitrate and phosphorus, and produces more

fall biomass than commonly used winter rye (Chen and Weil, 2010; Chen and Weil, 2011; Dean and Weil, 2009). It winter-kills at temperatures just below freezing and a light residue remains on the soil surface in spring, resulting in no need for spring residue management (Lounsbury and Weil, 2014).

Vegetable growers often select winter-killed species, such as oats or peas, to avoid potential issues with delayed planting and massive spring residue management. Low-residue cover crop mixtures, including forage radish, may avoid creating such adverse conditions (Lawley et al., 2011; Lounsbury and Weil, 2014; Teasdale and Mohler, 1993).

Multi-species cover crop mixtures have the potential to expand the agroecosystem benefits of cover crops. Mixtures can, under the right conditions, increase SOM, improve C:N ratio of residue, diversify soil biology, improve weed suppression. Polyculture cover crop biomass can out-yield monocultures, with a few exceptions like winter rye (Finney et al., 2016; Messiga et al., 2016). In terms of biomass production, grass species in a mixture outperform those in monoculture (Murrell et al., 2017). The combination of legume and non-legume cover crop species may reduce potential N leaching and adjust the timing of N-mineralization relative to crop uptake (Tonitto et al., 2006). Complementary root structure and plant architecture can help mixtures adjust to weather conditions and nutrient availability (Berendsen et al., 2012; Finney et al., 2016; Gardner and Sarrantonio, 2012).

In low-residue cover crops it is hypothesized that a mixture of species with complementary traits (eg. growth habit or phenology) can enhance ecosystem services, such as aggregate protection, nutrient uptake, and weed suppression (Finney et al., 2016).

Creamer et al. (1997) experimented with numerous species for cover crop mixtures in order to improve C:N ratios and weed suppression in no-till vegetable production.

Sweet corn is well-suited to no-till production (Galloway and Weston, 1996). The seasonal timing of sweet corn growth and development fits well with N recycling from winter-killed low residue cover crops (Isse et al., 1999). It has been documented that cover crops can improve sweet corn growth, not only by reducing weed pressure, but also through improving soil function and nutrient cycling (Burgos and Talbert, 1996; Carrera et al., 2004; Cline and Silvernail, 2002; Griffin et al., 2000; Lawson et al., 2012; O'Reilly et al., 2011). However, the effect of cover crops on sweet corn yield has been inconsistent in the literature (Carrera et al., 2004; Isse et al., 1999). In part this is due to the variations in cover crop type, planting date, and the soil history at the experimental site.

Both the amount of N and the timing of availability are important for successful sustainable corn production. The New England Vegetable Management Guide recommends an application of 45 kg N ha⁻¹ (40 lbs N ac⁻¹) at planting, plus 67 to 100 kg N ha⁻¹ (60 to 90 lbs N ac⁻¹) as sidedress, for sweet corn depending on results of a pre-sidedress nitrate test (PSNT) (Dicklow and McKeag, 2016). When cover crop mineralization is a significant N source, it's difficult to quantify how much and when the cover crop N is available to the succeeding cash crop because it is influenced by temperature, moisture, soil contact, and carbon-to-nitrogen ratio (C:N) of the crop residue.

Hypotheses

We hypothesized that:

- 1) Cover crop mixtures will produce more biomass dry matter than FR monoculture or weedy control;
- 2) Winter-killed cover crop mixtures will not reduce spring soil temperature and thereby will not prevent timely spring planting;
- 3) Cover crop mixtures will improve synchrony between N release and corn uptake;
- 4) Sweet corn yield will be higher following cover crop mixtures.

Objectives

The objective of this research was to develop an integrated system for no-till sweet corn production that can efficiently utilize the nutrient cycling and weed suppressive benefits of forage radish cover crop mixtures. CC mixtures should improve carbon additions to contribute to long-term SOM stabilization. Low- to medium-residue CC mixtures will not present the management challenges in terms of soil temperature reduction or spring residue management. These CC mixtures should scavenge more fall N, thereby recycling inorganic N to the sweet corn cash crop the following spring and summer. Ideally, this would result in increased yields, fertilizer savings, and reduced production costs for the farmer, in addition to the reduced risk from nitrate leaching to the environment.

Materials & Methods

Experimental Site

Two field experiments were conducted at the University of Massachusetts Amherst Crop, Animal, Research and Education Farm in South Deerfield, MA (lat. 42°47'N, long. 72°58'W). Soils at the research farm are characterized as coarse-silty, mixed, superactive, nonacid, mesic Typic Udifluvents (Hadley series). Mean annual precipitation at this site ranges from 940-1300mm (37-51 inches). The mean annual temperature is 3-10.5 °C (37-51° F). The selected research site had previously been un-tilled for 3 years and planted with buckwheat the summer prior.

Table 1: Precipitation and Growing Degree Days (GDD) for experimental sites. $GDD = \sum (T_{max} - T_{min}) - T_b$ where T_{max} and T_{min} are daily maximum and minimum temperatures, respectively, and T_b is base temperature. For cover crop mixtures T_b was set as 4°C and for sweet corn T_b was 10°C.

Cover Crops	Precipitation (mm)			Growing Degree Days	
	2014	2015	20 yr avg	2014	(GDD ₄₀) 2015
Aug	103	95	90	875	975
Sep	29	167	106	682	805
Oct	126	58	107	416	310
Nov	77	47	77	71	183
Dec	96	104	84	11	76
<i>Total</i>	<i>431</i>	<i>470</i>	<i>464</i>	<i>2055</i>	<i>2348</i>
No Crop/ Winter	2015	2016	20 yr avg	2015	2016
Jan	80	42	67	0	3
Feb	24	106	67	0	30
Mar	40	68	89	3	130
Apr	50	40	77	186	215
<i>Total</i>	<i>194</i>	<i>256</i>	<i>300</i>	<i>189</i>	<i>378</i>
Sweet Corn	2015	2016	20 yr avg	2015	(GDD ₅₀) 2016
May	35	57	84	418	270
Jun	189	27	112	451	499
Jul	121	43	90	659	706
<i>Total</i>	<i>345</i>	<i>127</i>	<i>286</i>	<i>1527</i>	<i>1475</i>

Treatments

Treatments consisted of three cover crops including forage radish (FR) (*Raphanus sativus* L. *longipinnatus*), a mixture of oats (*Avena sativa* L.) and forage radish (OFR), a mixture of peas (*Pisum sativum subsp arvense* L.), oats, and forage radish (POFR), and a control treatment of local weeds (NCC) (Table 2).

Table 2: Cover crop seeding rates for 2014 and 2015.

Cover crop treatment	Seeding rate (kg ha ⁻¹)
Forage radish (FR)	7.8 kg ha ⁻¹
Oats & forage radish (OFR)	56.0 kg ha ⁻¹ & 3.4 kg ha ⁻¹ , respectively
Peas, oats, and forage radish (POFR)	50.4 kg ha ⁻¹ , 33.6 kg ha ⁻¹ , & 2.2 kg ha ⁻¹ , respectively

Selection of cover crops was based on following justifications:

- 1- Forage radish has become popular in recent years, planted either as monoculture or mixture, for nitrate scavenging and weed suppression.
- 2- Oats are the most common grass cover crop used by vegetable growers in New England. Oats produce high biomass, are winter killed, and can adjust the C:N ratio in a mixed cover crop.
- 3- Peas were included for the ecological benefits of legumes, including increasing soil microbial population thus increased soil organic matter, fixation of atmospheric N, and low soil C:N ratio.
- 4- All species in these cover crop mixes are winter-killed in New England's weather condition, therefore simplifies spring residue management.

The experimental design was a randomized complete block, with split-plots, replicated four times. Main plots consisted of four cover crop treatments described above. Sub-plots were assigned to in-season N fertilizer application rates to sweet corn.

Cover crop treatments in October 2016. From left to right: FR (forage radish); OFR (oats and forage radish); POFR (peas, oats and forage radish); and NCC (no cover crop) control.



Cover crops were planted August 23, 2014 and August 24, 2015 (Table 3) using a plot cone seeder (Vogel, 1978). Seeding rates are indicated in Table 2. Plots were 8.5 m by 9 m in order to accommodate 9 rows of sweet corn with sufficient buffer area. Control plots (NCC), were not seeded and existing natural weed population was allowed to establish and grow until they winter-killed.

Cover crop biomass was measured just prior to winter-kill, approximately late November (Table 3). Plants were cut at the soil line and then separated by cover crop species or weeds. The fleshy tuber of forage radish was also sampled as it contributes significantly to total biomass and is dissimilar to root biomass of peas and oats. Harvested cover crops were dried separately at 40°C in a forced-air oven until they reached a constant mass. Control plots were also sampled for weed biomass. Cover crop

residues were analyzed at the UMass Soil and Plant Nutrient Testing Laboratory for measurement of carbon (C) and nitrogen (N) content.

Table 3. Field activity at UMass Research Farm, S. Deerfield, MA.

Field Activity	Site Year 1 2014-15	Site Year 2 2015-16
Cover crop planting	August 23	August 24
Cover crop biomass sampling (just prior to winter-kill)	Nov 10	Nov 24
Soil temperature measurements	April 15-May 7	April 25-May 12
Sweet corn planting	May 7	May 12
Herbicide application to sweet corn plots	May 8	May 9
Sampling for PSNT and corn tissue N%	June 14	June 13
Supplemental N fertilizer application to sweet corn	June 18	June 15
Soil nitrate sampling	April 27 May 18 June 18 August 3	April 18 May 13 June 14 August 4
Sweet corn harvest	July 30 and August 1	July 28 and August 3

In April, as soils began to warm, soil temperature was monitored using Fisher Scientific Traceable Hi-Accuracy Digital thermometer at the same time each day for several weeks until the average soil temperature approached 16 °C. Prior to corn planting, plots were sprayed with a tank mix of burn down herbicide and pre-emergence herbicide. Rates were as follows: glyphosate (N-phosphonomethyl glycine) at 864 g a.i.

ha⁻¹ and Lumax (S-metolachlor, 321 g a.i. L⁻¹; Atrazine 32 g a.i. L⁻¹; and Mesotrione g a.i. L⁻¹) at 5.8 L ha⁻¹. At soil temperature of 16 °C, sweet corn (*Zea mays L. rugosa* var. ‘Trinity’) was no-till planted at an estimated population of 64,000 seeds per hectare.

Three nitrogen fertility treatments were used to examine the synchrony between nutrient release from decomposing cover crop and the uptake by sweet corn. Nitrogen treatments consisted of application of 0 kg N ha⁻¹ as the control, 28 kg N ha⁻¹ at sidedress, and 56 kg N ha⁻¹ split equally between planting and sidedress (approximately 25 cm tall). Urea fertilizer (46% N) was hand applied. We selected lower rates of fertilizer application than recommended for sweet corn (an average of 130 kg N ha⁻¹) in order to assess the N contribution of cover crop residue to sweet corn.

Soil samples were taken at 3 depths (0-20 cm, 20-40 cm, and 40-60 cm) every four weeks from April through August. Three soil cores were taken at each depth from each plot, and then bulked. Samples were air-dried for 2 to 3 days. Nitrate and phosphorus were extracted using Modified Morgan solution and analyzed by colorimetric determination using flow injection analysis (QuickChem 8000, Lachat Instruments).

When corn plants were approximately 30 cm tall, two different soil samples were taken for measuring Pre-Sidedress Nitrate Test (PSNT) and soil respiration. For PSNT measurement, three soil cores per plot were taken at 0-30 cm depth and air dried before extraction with calcium chloride solution for colorimetric determination of nitrate (Heckman et al., 1995). Soil respiration, as an indicator of microbial activity, was measured following the Solvita testing protocol: basal respiration and CO₂ burst (Woods End Laboratory, Woods End, ME).

When sweet corn plants reached V5 stage, tissue was sampled to determine N concentration. Eight sweet corn plants were cut at the base and dried in a forced-air oven at 40 °C until a constant weight was reached. Tissue was ground and analyzed for C and N at the UMass Soil and Plant Nutrient Testing Laboratory.

At maturity, sweet corn was hand harvested. Sweet corn yield, number of marketable ears and ear fresh weight, were assessed in samples harvested from six linear meters (4.5 m²) per subplot. Three ears were randomly selected to measure ear length and percent tip-fill as criteria for sweet corn quality.

At harvest, the corn stalk nitrate test (CSNT) was performed to evaluate end of season nitrogen sufficiency test. Three stalks from harvested plants in each subplot were randomly chosen. A 20 cm segment of stalk was cut starting 15 cm above ground level. Stalks were dried in a forced-air oven at 40 °C for a week. Corn stalks were ground and extracted with 2% acetic acid solution for colorimetric determination of nitrate (Fox et al., 1989).

Statistical Analysis

Data were analyzed using the general linear model (GLM) procedure of SAS 9.4 (SAS Institute, Cary, NC) with cover crop and N fertilizer as fixed effects and replicate as random effect. Tukey's HSD was used for means comparisons of cover crop effects. Linear regression analysis was used for yield data means comparisons of N fertilizer.

Results and Discussion

Aboveground Cover Crop Biomass

Cover crops were established successfully both years. However, dry matter produced in the two years of study was statistically different. Analysis of aboveground cover crop biomass indicated a significant difference in treatment by year interaction; therefore, data from each year was analyzed and presented separately.

In 2014, aboveground biomass was 11% greater than in 2015, averaged over all cover crop treatments. Weather conditions in both years may have significantly affected biomass production. In September and October 2014, precipitation and rainfall were ideal for plant growth, with sufficient rain and moderate GDD (Table 1). In September 2015, greater than average rainfall may have had a negative impact on biomass production. During this time cover crops were establishing and saturated soil conditions can inhibit root growth. While seasonal GDD in the fall of 2014 was similar to the norm for the location, calculated GDD for 2015 was approximately 20% higher than the norm for the experimental site.

At winter-kill in 2014, OFR out-yielded FR monoculture by roughly 2.5 Mg ha⁻¹ (Figure 1). Although biomass produced by POFR and OFR were not statistically different, OFR produced 23% more dry matter than POFR. When grown as monoculture, FR produced a moderate amount of aboveground dry matter which was 47% lower than OFR but still produced 67% more than NCC. However, in 2015 there were no significant differences between POFR, OFR and FR dry matter production, which ranged from 3.3 Mg ha⁻¹ (FR) to 4.0 Mg ha⁻¹ (POFR).

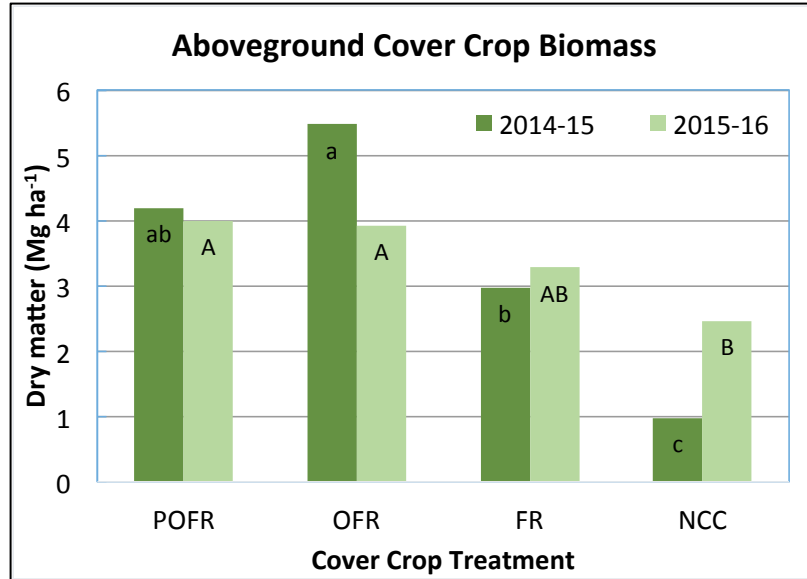


Figure 1. Aboveground cover crop biomass measured in November prior to winter-kill.

POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

Aboveground dry matter produced by FR in current study is on the lower end of the published range, partly because of fewer accumulated GDD prior to winter-kill and partly due to low starting residual soil N. Lounsbury and Weil (2014) reported a range of 3.2 to 5.5 Mg ha⁻¹ over 4 site years, while Wendling et al. (2016) reported an average of 6.3 Mg ha⁻¹. The experimental site in current study had been left fallow prior to planting with low soil N and received a minimal application of 28 kg N ha⁻¹ at the planting time. Under more similar low residual N conditions to this experiment, Murrell et al. (2017) reported 2 Mg ha⁻¹ aboveground FR dry matter averaged over three years.

In regard to OFR, Lounsbury and Weil (2014) reported a range from 4.6 to 6.0 Mg ha⁻¹ dry matter, which is comparable to the results obtained in this experiment. However, information about aboveground biomass of a pea, oat, and radish mixture (POFR) is limited. In general legumes are less productive compared with non-legumes, so the inclusion of a legume in a mixture may reduce total dry matter production.

However, beyond productive biomass, mixed legume-grass cover crops are known for improvement of soil carbon deposition and soil biology, which improves crop yield. Therefore the ecological benefits of cover crops may not necessarily derive from higher biomass production.

As expected, NCC accumulated lower biomass than actual cover crop treatments, despite that those are characterized as “low residue” cover crops. Overall, weed biomass in this study ranged from 1.0 to 2.5 Mg ha⁻¹, which was average to slightly lower than weedy control plots in other published reports. For example, Lounsbury and Weil (2014) reported 1.7 to 3.7 Mg ha⁻¹ weed dry matter. Similarly, Grimmer and Masiunas (2004) reported 1.7 Mg ha⁻¹ weed dry matter.

Cover crop mixtures did not yield more aboveground dry matter than sole FR, which is in agreement with (Finney et al., 2016), Murrell et al. (2017), and Wortman et al. (2012). These experiments each concluded that selected mixtures did not yield more biomass than high-yielding monocultures of the same cover crops. This research indicates that cover crop mixture likely do not consistently produce more biomass than monocultures. However, the advantage of mixed cover crops may relate to other ecosystem services, such as improved soil biological activity and/or synchronous nutrient availability to the subsequent crop (Finney et al., 2017a; Finney et al., 2017b; White et al., 2017).

Moreover, comparison between mixed versus monoculture cover crop biomass must take into account the phenology of the cover crop. For example, winter rye biomass, which has been allowed to grow to maturity from September through June, should not be compared with a cover crop that grew for only 90 days before winter-kill.

Many published results about cover crop mixtures include cereal rye, which is winter-hardy and highly competitive with other cover crop species. Cereal rye dominance has been observed by Murrell et al. (2017) and Poffenbarger et al. (2015), such that cereal rye constitutes a disproportionate percentage of biomass in spring compared with original fall establishment.

We could not find a documented report that compares the biomass of winter-killed cover crops in mixtures versus monocultures. An earlier experiment at the same research site reported field pea cover crop produced 3.1 Mg ha⁻¹ dry matter (Jahanzad et al., 2017). Stivers-Young (1998) reported that monocultures of oats and oilseed radish (same genus and species as FR) each produced 3.9 Mg ha⁻¹ dry matter in the short Northeast fall cover crop season.

Certain ecosystem services from cover crops specifically N immobilization and weed suppression are positively correlated with total biomass production. However, most reports have focused on the aboveground cover crop biomass. Exclusive consideration of aboveground biomass neglects to reflect the influence of the cover crop roots on soil biology and nutrients recycling in the soil. Some ecological services may not be solely derived from aboveground residue but from total biomass, including root biomass. This is particularly important in the case of forage radish, which often produces a fleshy tuber that stores water and nutrients and creates soil pores.

Total Cover Crop Biomass

Root biomass provides considerable ecological benefits, particularly in a no-till system, in terms of providing substrate for microbial decomposition and earthworm consumption, which contribute substantially to natural soil fertility and nutrient cycling

(Austin et al., 2017; Malpassi et al., 2000). Puget and Drinkwater (2001) found that nearly half of root-derived cover crop C remained in soils after one growing season, as opposed to only 13% of shoot-derived C.

In the current study, total cover crop biomass consisted of aboveground biomass plus the fleshy forage radish roots. Taproots and lateral roots were not harvested and are not included in calculation of total cover crop biomass. When total cover crop biomass was considered, differences amongst cover crop treatments were minimized and not statistically significant. All cover crops produced significantly more biomass than NCC, the weedy control (Table 4).

Table 4. Cover crop biomass characteristics at experimental site in both years. Years analyzed separately. Treatments with different letters indicate significant differences (Tukey’s HSD $p < 0.05$). No letter indicates no significant differences.

		Total dry matter (Mg ha ⁻¹)	N (g kg ⁻¹)	N in total dry matter (kg ha ⁻¹)	C:N ratio
2014-15	POFR	5.39 a	23	106 a	18:1
	OFR	6.45 a	20	113 a	21:1
	FR	5.33 a	20	90 ab	21:1
	NCC	0.98 b	23	23 b	18:1
2015-16	POFR	4.81 A	19 B	90 AB	22:1 AB
	OFR	4.81 A	16 B	79 AB	25:1 A
	FR	5.14 A	20 AB	104 A	20:1 BC
	NCC	2.46 B	24 A	57 B	17:1 C

POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

In 2014 OFR produced the highest total dry matter (6.45 Mg ha⁻¹), which was 16% and 17% more than POFR and FR, respectively. However, in 2015, FR out-yielded POFR and OFR by approximately 6%. FR yield in the current study was in agreement

with earlier published research (5.7 Mg ha⁻¹) at the same experimental site (Jahanzad et al., 2017). Published ranges for FR total dry matter are 2.4 to 9.4 Mg ha⁻¹ (Lawley et al., 2012; Lawley et al., 2011; Lounsbury and Weil, 2014). This wide range is likely due to differences in planting date, GDD before winter-kill, and initial soil nutrient status.

A two-year study in Vermont on cover crop mixtures for short-season growth revealed that a POFR mixture planted September 15 yielded 1.0 Mg ha⁻¹ dry matter on unfertilized plots and 1.4 Mg ha⁻¹ on plots which had received manure in fall (Carter et al., 2015). This low dry matter yield could be partly due to 35 days less growth compared to our study. In contrast, an OFR mixture in Maryland produced 7.2 Mg ha⁻¹ dry matter (averaged over four site years) under high soil fertility conditions (Lounsbury, 2013). Low soil residual N will limit biomass production and consequently potential cover crop nitrate scavenging.

In the current study, limited N availability in the soil during cover crop growing period may have reduced dry matter production both years, especially in 2015 when higher precipitation during cover crops establishment may have leached soil N (Table 1). As a result, total FR biomass was in mid-range and was more similar to a no-till study conducted on a sandy soil in Maryland, where FR cover crop produced 2.4 to 5.1 Mg ha⁻¹ dry matter (White and Weil, 2011).

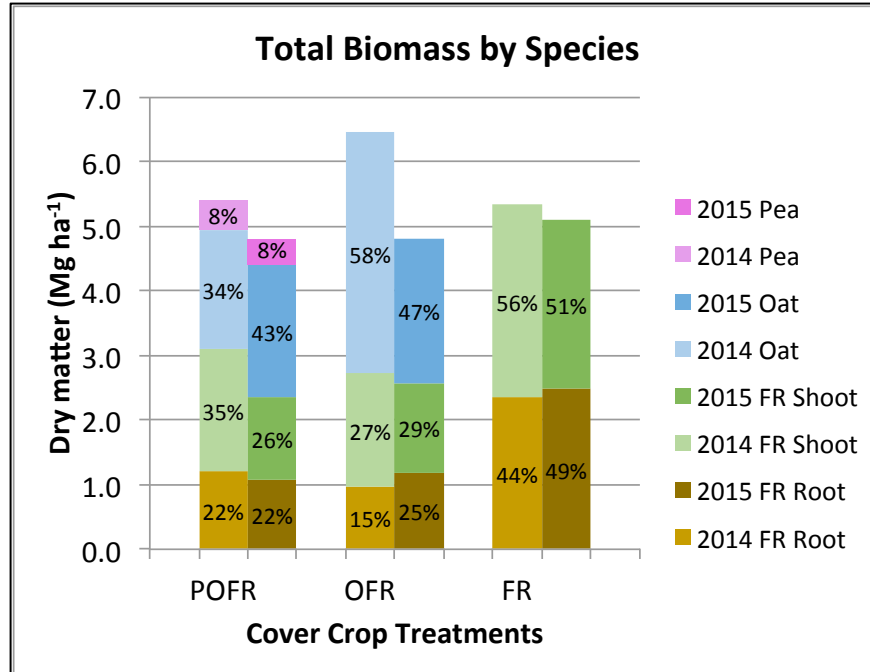


Figure 2. Total cover crop dry matter by species, including FR roots, for 2014 and 2015.

POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish

Species composition of cover crop mixtures depends on seeding date and plant response to soil and environmental conditions. In general, plants store 80-90% of total N in leaves, and 10-20% in roots (Wendling et al., 2016). When a cover crop species like forage radish produces a significant amount of root biomass, both the proportion of species in the mixture and the proportion of root to shoot could potentially play a significant role in N sequestering. We observed that the percentage of total biomass comprised of peas was only 8% in both years. Considering that peas were 58% of the total seed weight of the mix at the planting, the results clearly shows that the selection of peas in a mix cover crop recipe should be carefully determined for an economic sound species selection. The contribution of peas to the total nitrogen accumulation of mix cover crop was not significant as was expected. In the POFR mixture, the oat fraction

ranged from 34% to 43% of the total. In the OFR mixture, the oat fraction ranged from 58% to 47% of the total biomass, indicating some dominance over the FR growth. The proportion of FR leaves to FR roots was higher across all treatments in 2014, under ideal growing conditions with low soil N status, when plants had to actively scavenge N from the soil.

These agree with the findings of Murrell et al. (2017) that both forage radish and Austrian winter peas underperformed in mixtures that included winter-hardy species. The same study concluded that oats, and grasses in general, yielded more than expected in mixtures, if given sufficient time to grow in fall (planted in late August). Because treatments in our study did not include oat or pea monocultures, we are not able to evaluate the performance of species in the mixtures versus monocultures. However, POFR and OFR mixtures had more aboveground biomass than FR, which might be an advantage for nutrient cycling. Leaves generally contain and immobilize more N than roots. The characteristics of cover crop mixture residue require further investigation.

Cover Crop Carbon and Nitrogen Content

In systems where a cash crop is primarily dependent on N mineralization of cover crops residue, the principal factors of N availability are the total N concentration and C:N ratio of the plant materials (Kuo and Sainju, 1998; Ranells and Waggen, 1996).

The more total biomass N is immobilized over the winter in plant tissue, the more N is potentially released through decomposition in spring and summer. POFR had the highest N concentration in both years, compared with other cover crop treatments (Table 4). Specifically, in 2014 POFR accumulated 13% higher N compared with OFR and FR. In 2015 the N concentration in POFR was similar to FR, but still 15% higher than OFR.

The higher total biomass N concentration of the POFR mixture is not surprising since peas as a legume cover crop is capable of fixing atmospheric N. Interestingly, the NCC accumulated more N per kg dry weight than the averaged cover crop treatments. This finding confirms other reports that weeds are more effective nutrient scavengers than crops, especially in low residual N conditions (Qasem, 1992).

Using fall biomass dry matter and nitrogen concentration, we estimated the total N yield of cover crop treatments prior to winter-kill (Table 4). In fall 2014, OFR biomass accumulated 113 kg N ha⁻¹, which was 6% more than POFR and 21% more than FR. This was primarily a result of high biomass yield of OFR that season. In 2015, N yield was highest in FR residue as a consequence of having both the highest N% and the highest dry matter yield. FR residue produced 14% and 24% more N yield than POFR and OFR, respectively.

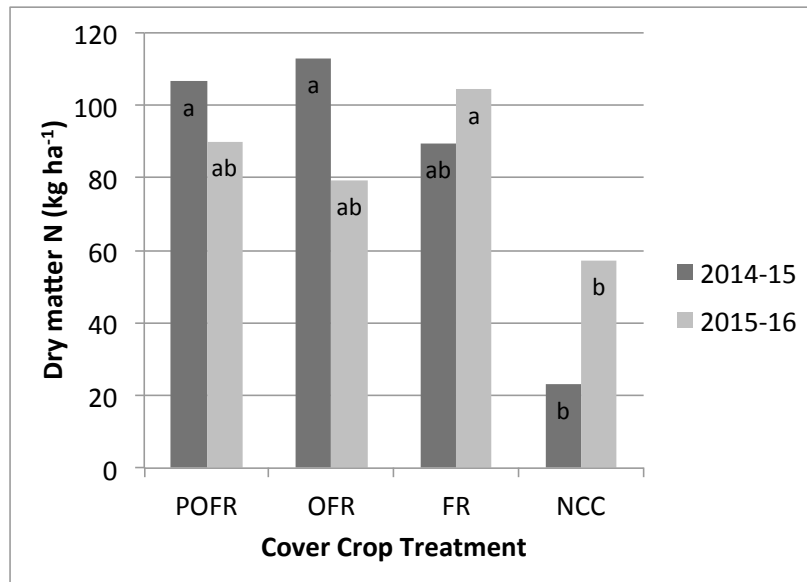


Figure 3. Nitrogen in total cover crop dry matter, November 2014 and 2015. POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

In theory, even if all the cover crop N were recycled to the following sweet corn without loss, it still would not meet the N sufficiency threshold of 112 to 145 kg N ha⁻¹ of sweet corn as recommended by New England Vegetable Management Guide (Dicklow and McKeag, 2016). Winter-killed cover crop residue loses N as a result of residue displacement (wind or erosion), and N leaching during early spring decomposition or fractionation. Stivers-Young (1998) found that over-winter losses of biomass and N were greater in brassicas than in oats. It is estimated that 24 to 54% of the N in winter-killed cover crop tissue can be lost prior to being absorbed by the cash crop (Malpassi et al., 2000). Therefore, not only the quantity of contributory N, but also the timing of N availability to the succeeding crop plays an essential role in optimizing cover crop N recycling.

The rate of residue decomposition is regulated primarily by its C:N ratio and environmental conditions (Tonitto et al., 2006; White et al., 2017). Ideally, residues should have a C:N ratio less than 24:1 for in-season N mineralization into plant available form. Higher C:N ratio residues decompose slowly, due to limited N availability and/or complexity of C such as lignin content, and can lead to immobilization of N in the soil profile. Residues with a low C:N ratio decompose more quickly, sometimes prematurely, before the cash crop can remove it from the soil, which intensifies the N loss and environmental risk of pollution.

In 2014, the C:N ratio of fall OFR and FR residues were 21:1 which was higher than both POFR and NCC however the difference was not statistically different (Table 4). In 2015 there were significant differences between C:N ratios of the cover crops residues which ranged from 25:1 (OFR) to 17:1 (NCC). The average C:N ratio for OFR was still

precisely in the range for timely mineralization of N by microbial decomposition without a risk of early spring nitrate leaching (Constantin et al., 2011). As we hypothesized, mixing oats with FR adjusted the C:N ratio and increased it slightly thus preventing premature spring N release. The more favorable C:N ratio of the OFR mixture compared with FR or NCC indicates the potential of better synchrony between cover crop mixture N mineralization and N uptake by subsequent sweet corn.

Year Effect on Sweet Corn Yield

In western Massachusetts, farmers traditionally direct seed the first succession of sweet corn the first week of May. Timely planting is essential to ensure early harvest and consequent price premium. Critical periods of growth for sweet corn are during rapid vegetative growth (mid-June) when N is in high demand, and during ear filling stage (mid-July) when adequate soil moisture is critical to maximize yield. Precipitation and GDD differed greatly between the 2015 and 2016 growing seasons (Table 1). May 2015 was dry and hot and the experimental site received 58% less precipitation than the norm, while GDD was 80% higher than average (Table 1). However, sweet corn uses C₄ carbon fixation pathway, and therefore is able to use water efficiently and optimize growth under high temperature conditions. In June 2015, precipitation was 40% higher than normal while GDD was average, which supported healthy vegetative growth of corn plants. During July 2015, the site received 25% more rainfall than average with average GDD, creating ideal conditions for sweet corn ear development.

New England experienced a severe drought during the summer of 2016. The GDD were normal over the course of the summer, but the seasonal precipitation was 60% less than the norm for experimental site. In particular, during June the site received only

27 mm of precipitation, 80% less than normal. Since irrigation is not a common regional practice for growing sweet corn, the severe and prolonged drought period had a profound negative impact on growth of sweet corn plants during tasseling and ear set. In July 2016 the site received less than half the usual precipitation, which likely reduced sweet corn ear size and yield. Although it was not measured in this experiment, weed competition may also have been a factor. Teasdale and Cavigelli (2010) found that in years with below-average rainfall, sweet corn was more limited by weed competition than by nitrogen availability.

Spring Soil Temperature

Many growers are concerned that high residue cover crops will delay early spring corn planting in a climate that has a short growing season. Large amounts of biomass on the soil surface can insulate cold soils, retain excess moisture, and lower soil temperatures. In New England, soil temperature begins warming in early May of an average year. Any delay in planting sweet corn can significantly reduce the prime market price that farmers receive for an early crop. Successful sweet corn germination depends on a minimum soil temperature of 16°C. While negative impacts of high-residue cover crops on soil temperature are well known (Dabney et al., 2001), we hypothesized that the low residue cover crops used in this experiment would have minimal impact on early spring soil temperatures, and thus not delay planting.

Overall, cover crop mixtures did not significantly affect spring soil temperatures prior to sweet corn planting (Figure 4). Although the difference among cover crop treatment was significant around April 27 in both years, but by the sweet corn planting date differences were less than 1 °C. As Figure 4 indicates, soil temperature gradually

increased from 8 degrees C to around 14 degrees C and then decreased to about 9 degrees as a result of cold weather. Soil temperature increased again by the first of May.

We did not find a significant impact of cover crop on early soil temperatures. The cover crop treatments neither increased precocity nor delayed timely seeding. We anticipated that the FR treatment would allow for earlier corn planting compared with NCC, due to improved moisture drainage by large root channels, but that was not the case.

As observed by other researchers, cover crop residue on the soil surface moderates the amplitude of soil temperature changes (Dabney et al., 2001; Teasdale and Mohler, 1993). Moderate to low residue on the soil surface, as in this study, may not interfere with moisture evaporation and/or light interception, so soil warming can proceed normally.

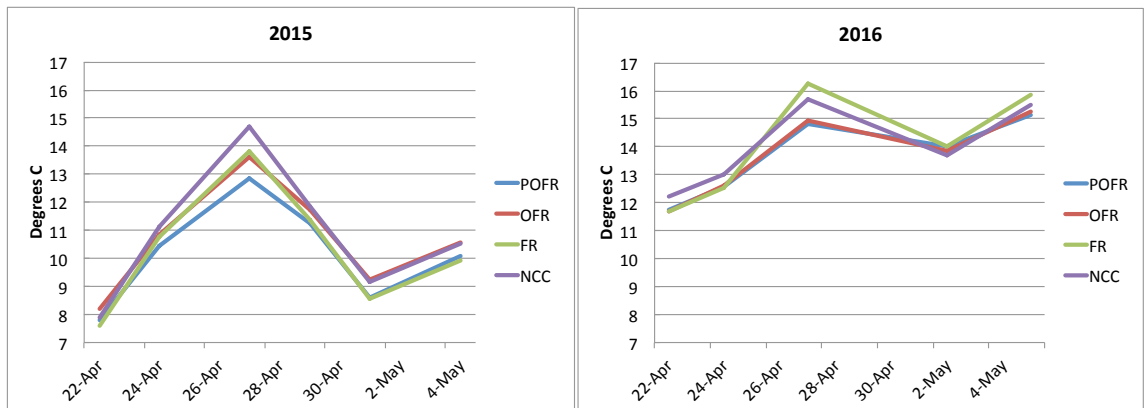


Figure 4. Soil temperature as affected by cover crop treatment prior to sweet corn planting from April 22 to May 4, 2015 and April 22 to May 8, 2016. *POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control*

Influence of Cover Crop on Soil Nitrate for Sweet Corn

Soil nitrate was sampled in April, May, June and the end of July to provide periodic information of plant available N released from cover crop residue. levels can fluctuate widely depending on rainfall, soil temperature, and topography. To reduce variability sampling was done not within 3 days of rainfall. Due to expected environmental variations, trends for soil nitrate and 2016. Overall, soil nitrate was higher in 2015 (Figure 5) than 2016 (Figure 6), which is explained by higher the total cover crop biomass N and higher background N in 2015 (

Figure 3).

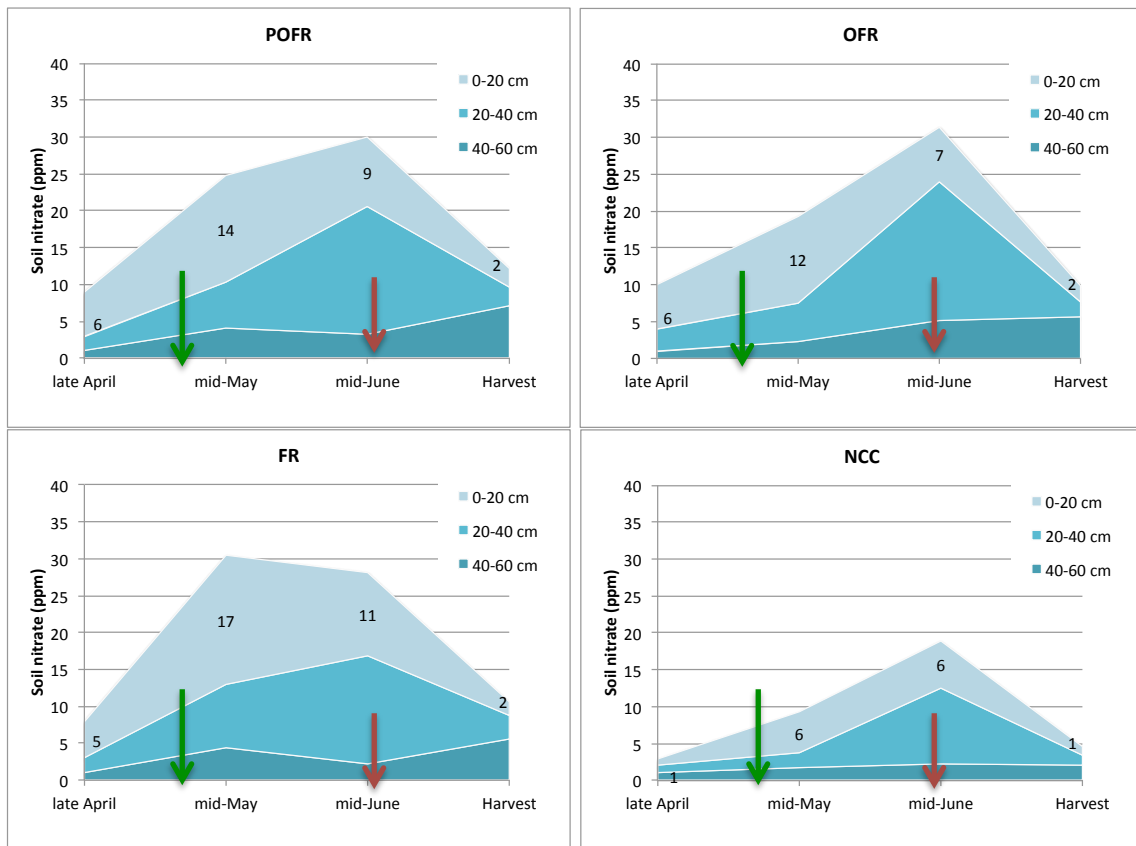


Figure 5. Soil nitrate during the 2015 growing season. Plots received no additional N fertilizer. Green arrows indicate when sweet corn was seeded. Red arrows indicate peak N crop demand.
POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

In April 2015, all cover crop treatments had similar amounts of soil nitrate at each sampling depth: 6 ppm at 0-20 cm, 2 ppm at 20-40 cm, and 1 ppm at 40-60 cm. Soil in NCC treatment had 1 ppm nitrate at all depths. At this date, the soils were just beginning to warm up and residue decomposition was initiating. Slightly higher nitrate in cover crop plots was likely leached from dead residues.

At the mid-May sampling date sweet corn had just germinated, so the primary root was in the top 8 cm of the soil. FR treatments had concentrations of 17 ppm soil nitrate in 0-20 cm, approximately 3 times that of NCC (Figure 5), whereas POFR and OFR had approximately 2 times greater nitrate than no cover crop plots. Higher nitrate concentration in FR plots cannot be explained by the C:N ratio. The ratio of FR biomass averaged 21:1, which should result in slower decomposition and N release than NCC (17:1). Other factors such as biochemical composition, physical fractionation, or higher microbial activity may be initiating the earlier N release from FR residue.

In mid-June 2015, when sweet corn N demand is at its peak, the highest nitrate concentrations in all cover crop plots were higher than the weedy control plots, NCC. At this growth stage (V5-7), sweet corn rooting depth is largely concentrated within 0-20 cm with branching roots extending into the 20-40 cm range (Kristensen and Thorup-Kristensen, 2004b). Cover crop plots had around 35% more nitrate in the 0-40 cm zone than the NCC plots, while no significant differences were detected between the cover crop treatments.

The effective root zone of mature sweet corn, the top 50% of the rooting area, is concentrated at 0-60 cm so plants would have been absorbing available nitrate from all sampled depths. At crop harvest, all cover crop plots had 50% (OFR) to 60% (POFR)

more nitrate in the root zone than NCC. No differences were seen between cover crop treatments.

In 2016, different soil nitrate trends were observed (Figure 6). In April 2016, sampled soil nitrate was low overall, and cover crop treatments all had similar nitrate concentrations at all sampled depths. Cover crop plots averaged 55-63% more nitrate than NCC (control), which likely resulted from more total N originating in cover crop residue than the NCC residue (Table 4).

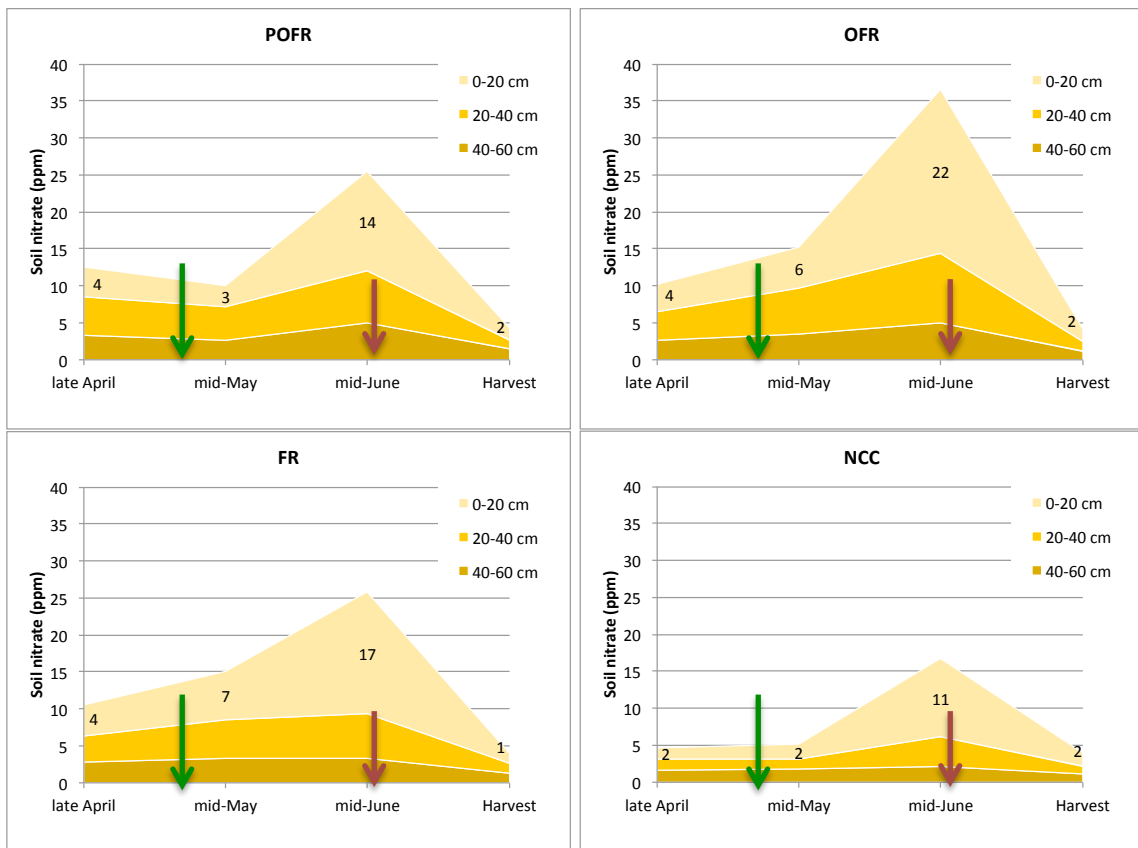


Figure 6. Soil nitrate during the 2016 growing season. Plots received no additional N fertilizer. Green arrows indicate date of sweet corn planting. Red arrows indicate peak N crop demand.
POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

In mid-May 2016, soil nitrate concentrations were low and varied from 2 to 7 ppm, because the soil just began to warm and cover crop residue just started to decompose. At all depths, nitrate concentrations were around 50% greater in cover crop treatments compared with NCC. At this date, sweet corn had just germinated and the primary root was less than 8 cm deep. At this growth stage, plants are initiating root system development but not yet taking up high concentrations of nutrients.

In mid-June, at peak sweet corn N demand, OFR had a significantly higher concentration of soil nitrate at 0-20 cm than all other treatments. At that growth stage, sweet corn roots are concentrated in the top 40 cm. Soil in OFR plots contained around 35%, 28% and 118% more nitrate in the 0-40 cm zone than POFR, FR, and NCC plots respectively.

At harvest in late July all treatments showed very low nitrate concentrations, ranging from 1 to 2 ppm at each sampling depth. Generally low nitrate concentrations at this date reflect high crop demand, which was intensified by drought conditions. Limited water likely slowed residue decomposition and N mineralization resulting in low levels of mineralized N at this time point.

Periodic nitrate sampling can provide perspective on plant-available N at critical stages in crop growth. In 2015, overall FR had higher concentrations of soil nitrate at rooting depth from mid-May to mid-June for better synchronization with sweet corn N demand. In 2016, overall OFR and FR had more synchronized trends of N availability and demand. These differences can't be explained by any single factor, such as C:N ratio or total N concentration in cover crop residue. The complexity of soil systems, from biological activity to the influence of mulch residue, can obscure the relationships among

many variables. However, from the soil nitrate data it was concluded that FR and OFR do a slightly better job of stabilizing nitrate for peak sweet corn demand than POFR and NCC. These results contradict the findings of (O'Reilly et al., 2012), which found similar cover crops in Ontario, Canada, did not increase plant available N during the sweet corn season compared with NCC. Those experimental sites soils were loamy sand, which may have influenced soil nitrate dynamics.

In general, soil nitrate status is not a good predictor of vegetable yield (Christiansen et al., 2006). However, the Pre-Sidedress Nitrate Test (PSNT) has been used extensively to efficiently predict crop yield response to supplemental N fertilizer (Heckman et al., 1995). PSNT measures in-season nitrate concentrations at 0-30 cm when soil temperature is warm enough for maximum mineralization rate. If soil nitrate concentration is lower than 25 ppm, it is likely that sweet corn yield will respond to additional sidedressed N fertilizer. The PSNT test is more accurate for soils with relatively high OM when moisture is adequate. Using this test, growers have a tool to help decide whether sidedressed N is cost-effective and environmentally responsible.



Figure 7. Photo of sweet corn plots at V5 growth stage, just prior to sidedress N application, in June 2016.

In both years, PSNT nitrate concentrations were lower than the 25 ppm N threshold for all treatments (Figure 8). Supplemental sidedress N fertilizer therefore was required. The POFR and FR treatments had slightly higher concentrations of soil nitrate at the 0-30 cm sampling depth when sweet corn usually has the highest demand for nitrogen, but not enough to disregard the need for sidedressed N fertilizer. In this study, the combined mineralization from cover crop residue and pre-existing soil organic matter was not sufficient to meet the N demand of sweet corn for the entire growing season (Figure 8).

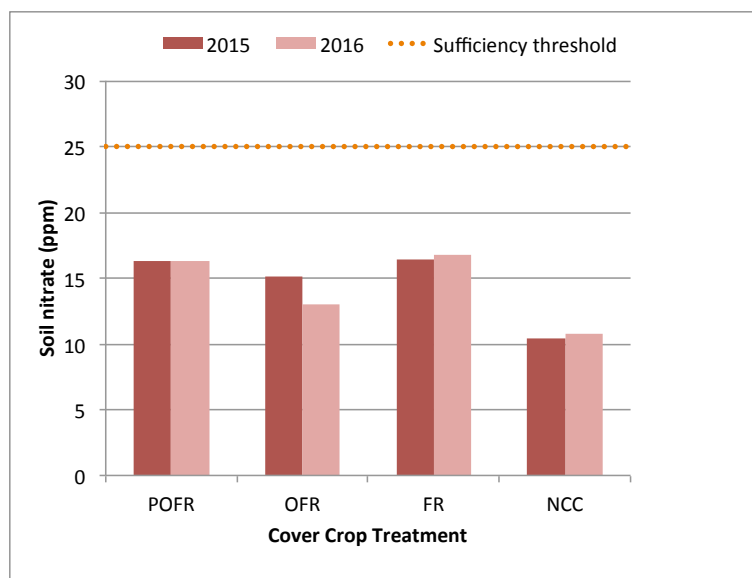


Figure 8. Pre-sidedress Nitrate Test (PSNT) concentrations of nitrate at V5 stage of sweet corn growth in mid-June 2015 and 2016.

POFR=pea, oat and forage radish, OFR=oat and forage radish; FR=forage radish, NCC=no cover crop control

Soil Biological Activity

Natural soil fertility relies on biological activity in the soil to mineralize plant residues and soil organic matter. Soil biological activity was assessed using two Solvita tests, basal respiration and CO₂ burst (Woods End Laboratories). Basal respiration utilizes fresh field soil with natural moisture to measure biological respiration, including microbes, plant roots and arthropods. The CO₂ burst test measures CO₂ release by microbial respiration as an indicator of microbial biomass and directly tied to potential carbon and nitrogen mineralization in fertile soils.

Solvita test results were highly variable and provided no conclusive results (Table 5). Multiple replicates of samples showed dramatic variation. Laboratory methods supplied by the manufacturer were amended during the course of this experiment. Consequently, the data was not considered reliable and therefore will not be discussed.

Table 5. Solvita soil respiration test results for 2015 and 2016.

		Basal respiration (ppm CO₂)	Solvita Interpretation of biological activity	CO₂ burst (ppm CO₂)	Solvita Interpretation of N mineralization potential
2015	POFR	21	Ideal	37	Moderate
	OFR	21	Ideal	9	Low
	FR	26	Med/high	18	Moderate/Low
	NCC	26	Med/high	8	Low
2016	POFR	53	Med/high	89	Moderate
	OFR	51	Med/high	87	Moderate
	FR	46	Med/high	70	Moderate
	NCC	60	Med/high	89	Moderate

POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

Sweet Corn Yield

Sweet corn yield was measured both as the number of marketable ears ha⁻¹ (Fig. 8A) and as ear fresh weight ha⁻¹ (Fig. 8B). Average yield in both years exceeded the regional average of 35,500 ears per hectare, except in the NCC plots in 2016 (Figure 9). Fresh weight yield exceeded the national average of 13,000 kg ha⁻¹ and was nearly twice than the Massachusetts average of 7,400 kg ha⁻¹ (USDA-NASS, 2016). Sweet corn yields were higher in 2015 than in 2016 as a result of severe drought period during the 2016 growing season, however the difference was not statistically different by year. Yield data from the two years was analyzed as additional replicates. Sweet corn plant population was used as a covariate. Cover crop treatment differences were tested using Tukey's HSD; supplemental N fertilizer treatment effects were tested using a linear regression analysis.

Cover Crop Effects on Sweet Corn Yield

Marketable ears ha^{-1} was significantly affected by cover crop treatments compared to the NCC control (Figure 9A). Sweet corn planted after the POFR treatment increased yield by 20% compared with NCC. OFR and FR treatments improved sweet corn yields 15% compared to NCC plots, but the difference was not statistically significant. The 5% difference between POFR and OFR/FR cover crop treatments is on average 1,700 ears ha^{-1} , equivalent to \$700 ha^{-1} revenue for growers, which would justify the greater seed cost of POFR cover crop (see Chapter 4).

Sweet corn ear fresh weight ha^{-1} was also significantly affected by cover crop treatments (Figure 9B). All three cover crop treatments improved sweet corn yield compared with the NCC control, POFR by 22%, OFR by 18% and FR by 16%. The results indicate that cover crops improve not only the number of ears per hectare, but also produce heavier ears, which improves sweet corn quality.

Sweet corn quality, evaluated by tip fill percentage and ear length, was not affected by cover crop treatment or supplemental N fertilizer in either year (data not shown).

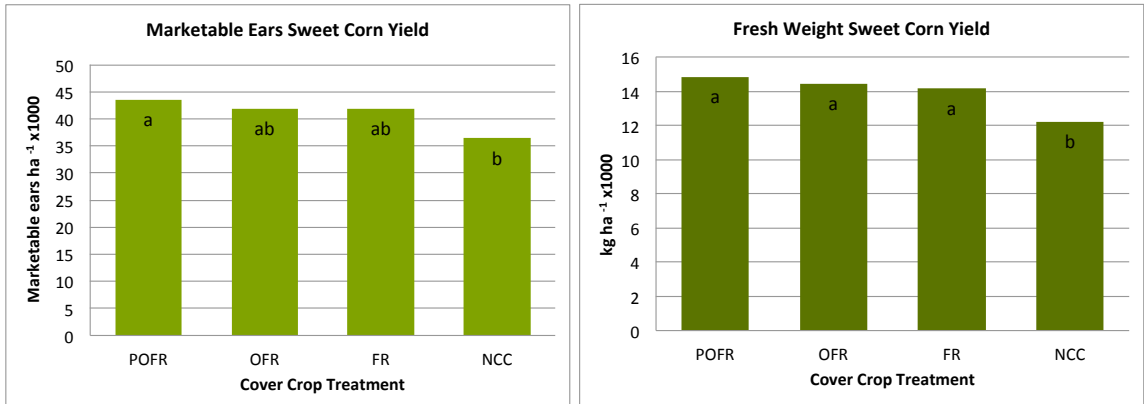


Figure 9: Sweet corn yield as affected by cover crop treatment, measured by marketable ears (left) and ear fresh weight (right). Values are averaged over all N treatments over two years. Different letters in columns indicate significant differences (Tukey’s HSD $p < 0.05$).

POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

The positive influence of cover crops on sweet corn yield was anticipated. We hypothesized that in a no-till, low fertility production system, cover crops could provide more N cycling, improve soil physical characteristics, and potentially enhance soil biological activity compared to the NCC control. However, we did not observe consistent yield differences between cover crop treatments correlating with the highest N yielding cover crop treatments (Figure 3). While some studies have found that cover crops improve sweet corn yield (Cline and Silvernail, 2002; Kabir and Koide, 2002; O'Reilly et al., 2012), others have found a negligible effect depending on soil type and cover crop selection (Isse et al., 1999; Lawson et al., 2012). Most of the published studies examined winter rye, hairy vetch or a mixture of rye and vetch, which are known as high residue cover crops, and require successful termination and specific management for a subsequent no-till sweet corn crop. Isse et al. (1999); Lawley (2010) concluded that grain N uptake was better indicator of cover crop N contributions, as opposed to yield

response, and that 40 to 60 kg N ha⁻¹ from cover crops was sufficient for optimal sweet corn yield.

Influence of Supplemental N Fertilizer on Sweet Corn Yield

The current recommended rate of nitrogen for sweet corn is 112 to 145 kg ha⁻¹ with 45 kg N ha⁻¹ of the total applied at planting (unless soils are very sandy), and the remainder applied as sidedress when corn plants reach approximately 25 cm tall (Dicklow and McKeag, 2016). This recommendation assumes that there is no nitrogen being mineralized from cover crop residue or other organic sources extant in soil.

Each initial cover crop plot was divided into three randomized subplots for supplemental N fertilizer treatment. Subplots received either 0 supplemental N fertilizer (control), 28 kg N ha⁻¹ applied at sidedress, or a split application of 28 kg N ha⁻¹ at planting plus 28 kg N ha⁻¹ at sidedress (subsequently referred to as 28+28 kg N). These low rates of supplemental N were selected to test whether cover crop mediated N would be sufficient for optimal yields, without conflating the effect of higher rates of commercial fertilizer. The split application treatment was designed to test the timing of N application, with the hypothesis that cover crop residue might provide sufficient N for early stages of growth thus reducing N fertilizer application at the planting when nitrate leaching risk is high.

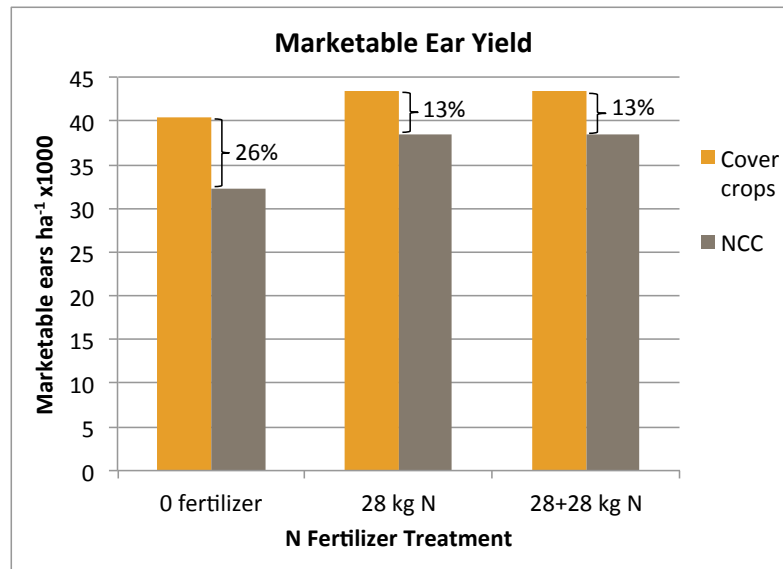


Figure 10. Sweet corn yield as affected by supplemental N fertilizer rate. Values are averaged over all cover crop treatments and two years. POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

The supplemental N fertilizer rate significantly affected the number of marketable ears ha⁻¹ (Figure 10). The application of 28 kg N ha⁻¹ as sidedress fertilizer increased sweet corn yield by 13% compared to control plots. Application of an additional 28 kg N ha⁻¹ at planting plus 28 kg N ha⁻¹ as sidedress did not increase sweet corn yield over plots that received only 28 kg N ha⁻¹ at sidedress. This result is unexpected in a low fertility system such as the experimental site, where application of more N fertilizer should result in a yield response.

Ear fresh weight ha⁻¹ was not significantly affected by N fertilizer treatment, though a similar trend was observed whereby the sidedress fertilizer treatment, 28 kg N ha⁻¹, increased ear fresh weight yield by 13% compared with control plots. The 28+28 kg N ha⁻¹ treatment increased fresh weight yield by 19% compared to the control.

The results obtained in this study confirmed that the timing of N availability is critical for optimum sweet corn yield. While cover crop residue is expected to provide

only a minor portion of the total N requirement, mineralized N is available in May and early June when corn plants are establishing. For the first 4 to 6 weeks of relatively slower sweet corn growth, cover crop residue can provide required start-up N ‘fertilizer’. As N demand peaks in June (or at V5 to V7 growth stage), supplemental side-dressed N is necessary to achieve optimal yield. Sweet corn yield would likely have responded with a higher rate of side-dress N, as indicated by corn stalk nitrate test (CSNT) results discussed in the following section (Figure 12). However, the ideal rate of side-dressed N is not well-defined by the results obtained in this study; further investigation is required to explore the optimum rate.

The additional 28 kg N ha⁻¹ fertilizer applied at planting in the split application treatment did not benefit sweet corn yield. These results indicate that the application of N fertilizer at planting may be unnecessary following these cover crops. Eliminating N fertilizer at planting could reduce inputs by 45 kg N ha⁻¹ of fertilizer while minimizing nitrate leaching and consequent environmental pollution.

There was no significant interaction between cover crop treatment and N fertilizer treatment for either marketable ears ha⁻¹ or fresh weight ha⁻¹.

This research is further evidence that cover crops can improve no-till sweet corn production, especially in low N soils. By all measures, and in both years, cover crops improved sweet corn yield compared to the control. This could be attributed to the ecological benefits of cover crops, such as nutrient cycling and soil physical protection. Biological effects of cover crops could also be a contributing factor. Kabir and Koide (2002) found that oats, rye, and a mixture of oats and rye, increased sweet corn P status and mycorrhizal colonization in sweet corn. In the same experiment, a mixture of oats

and rye resulted in the highest sweet corn yield compared with single-species oats or rye (Kabir and Koide, 2002).

We expected to see significant yield differences as a result of cover crop treatments, but that was not the case at this experimental site. This may be related to the low soil OM and residual N and erratic rainfall at the site. In related research, sweet corn ear yield and growth rates were higher compared to NCC under low supplemental N conditions, but showed inferior performance compared to NCC systems when supplemented with 200 kg N ha⁻¹ (Zotarelli et al., 2009). More specific research on winter-killed cover crop mixtures for vegetable production will help identify contrasting benefits of different types of mixtures.

Supplemental N fertilizer results in this study were interesting and supported our hypothesis that the use of these cover crops can improve N use in no-till sweet corn production. Synthetic fertilizer treatment, in the form of dissolved urea, may have affected nutrient cycling and sweet corn yield. Plots that received supplemental N fertilizer at planting plus side-dress yielded less than those that received N fertilizer only at side-dress. It may be that the urea fertilizer at corn planting disturbed microbial communities in the root zone of plants, which had an effect on overall corn yield. Research shows that synthetic nitrogen reduces particular microbial populations that are beneficial to soil health (Khan et al., 2007; Mulvaney et al., 2009). In a system dependent on decomposition for nutrient cycling, there may be negative consequences if synthetic N fertilizer application in early spring retards microbial growth and reduces the rate of N release.

While we did not see consistent differences in sweet corn response to N fertilizer following cover crop mixtures, Griffin et al. (2000) found that following a rye cover crop, sweet corn responded to supplemental N fertilizer while no yield response was detected following either alfalfa or a mixture of hairy vetch and winter rye. The inclusion of legumes and high residue cover crops likely plays a major role in subsequent crop response to N fertilizer. Our results support the reduction or elimination of start-up N fertilizer following these winter-killed cover crops, assuming that sidedress N fertilizer will be applied appropriately.

Post-Harvest N Sufficiency Assessment

The cost of nitrogen fertilizer is an important consideration in most vegetable production systems. While PSNT can be used in-season to determine if sidedress N is required for optimal yield, growers can use the corn stalk nitrate test (CSNT) as a post facto method to evaluate if N fertilizer has been applied adequately or in excess. Information can be used in subsequent years to adjust N application rates.

Nitrogen concentrations are measured in the corn stalk at 15 cm to 35 cm aboveground. According to Heckman et al. (2002), sweet corn CSNT values are larger than those in grain or silage corn because of the physiological stage of the ears at earlier fresh ear harvest compared to senescing corn plants at grain or 50% milk line in silage harvest. A range of 11.0 to 14.0 g kg⁻¹ NO₃-N was reported to be optimal (Figure 11), indicating that sweet corn yield was not limited by nitrogen, nor was excess N applied and wasted. Values above 21.0 g kg⁻¹ NO₃-N indicate that surplus N accumulated in the corn stalks without contributing to improved yield and thus should be considered wasted.

Values below 6.0 g kg⁻¹ indicate that sweet corn was likely under fertilized and could have yielded more with supplemental N applied.

Total Kjeldahl N	NO ₃ -N	Interpretation
----- g·kg ⁻¹ -----		
<11.0	<6.0	N-deficient, underfertilized
11.0 to 16.5	6.0 to 11.0	Marginal, may be underfertilized
16.5 to 21.0	11.0 to 14.0	Optimal range, N sufficient
>21.0	>14.0	Excessive, overfertilized

Figure 11. Proposed interpretations of the at-harvest stalk N test for sweet corn excerpted from Heckman, et al., 2002.

CSNT value ranges were different from 2015 to 2016, although the trends were identical (Figure 12). In both years, all values were below 2.8 g kg⁻¹ indicating severely N deficient sweet corn plants. Overall, corn stalk nitrate in 2016 was much higher than in 2015. This seemingly contradicts with lower overall sweet corn yield in 2016. This incongruity is due to the serious drought in the summer of 2016 that severely restricted plant growth and translocation of nutrients in corn plants.

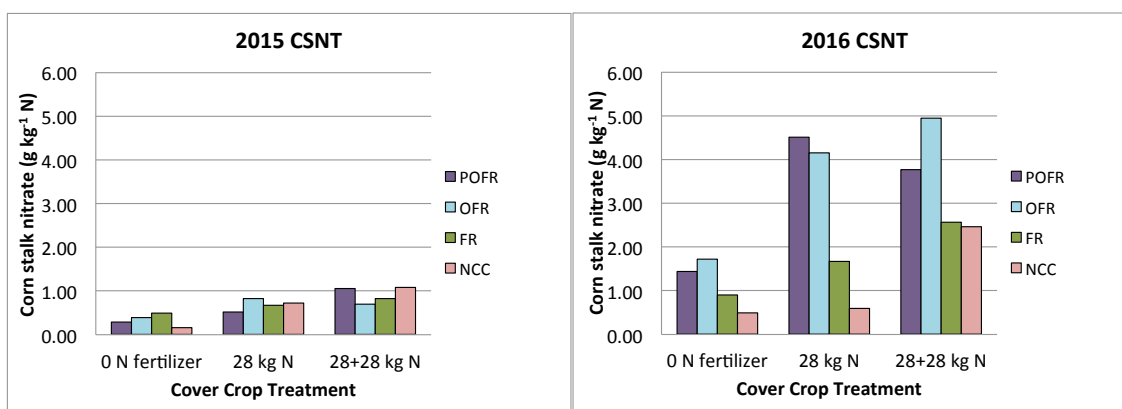


Figure 12. Corn stalk nitrate test values for cover crop treatments at each level of N fertilizer treatment in 2015 (left) and 2016 (right).

POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

Corn stalks in plots following POFR and OFR cover crops contained 2-3 times as much N compared to FR or NCC. In 2015, following the 0 N fertilizer treatment, corn stalks harvested from FR plots contained over 3 times more nitrate than those from NCC plots. Similarly, OFR plot corn stalks contained almost 3 times more, and POFR stalks contained 2 times more nitrate than NCC. More accumulation of N in corn stalks after cover crops illustrates the contribution of cover crop mediated N. Corn stalks that were treated with sidedress N fertilizer at 28 kg N ha^{-1} , we see a small increase in corn stalk nitrate, but no significant differences among cover crop treatments. With a split application of $28+28 \text{ kg N ha}^{-1}$ at planting and sidedress, POFR and NCC plots produced corn stalks with the highest nitrate concentrations, with 1.1 g kg^{-1} nitrate.

In 2016, overall the POFR and OFR treatments had higher CSNT values. At the level of 0 N fertilizer, corn stalks following OFR had 3.5 times more nitrate than those in NCC. Corn stalks from POFR plots had 3 times, and FR had 2 times, more nitrate than the control. With only sidedress N fertilizer, 28 kg N ha^{-1} , OFR and POFR had approximately 7 times more nitrate than NCC. With a split application of $28+28 \text{ kg N ha}^{-1}$ at planting and sidedress, POFR and OFR plots produced corn stalks with the highest nitrate concentrations, from 2.5 to 5 g kg^{-1} nitrate.

These trends indicate that the POFR and OFR cover crop treatments provided sweet corn with more cover crop mediated N than FR. The highest level of supplemental fertilizer increased CSNT somewhat, but not enough to approach the standard range of N sufficiency. It is possible that this standard isn't universally accurate, since overall sweet corn yields were above the regional average.

Nitrogen Use Efficiency

Nitrogen Use Efficiency (NUE) is calculated by comparing the yield of fertilized plots with unfertilized control plots and contrasting that with the amount of fertilizer applied (Figure 13). A higher NUE value indicates that the crop is more effectively recovering N, which prevents economic loss and environmental pollution (Fageria and Baligar, 2005). Teasdale et al. (2008) computed NUE with the following equation:

$$NUE = (\text{fresh weight yield in N-treated cover crop-treated plots} - \text{yield in untreated NCC control plots}) / \text{kg applied N fertilizer}$$

Sweet corn treated with supplemental sidedressed N fertilizer at 28 kg ha⁻¹ had the highest overall NUE (Figure 13). Plots that received a split application of 28+28 kg N ha⁻¹ at planting and sidedress had a lower NUE for POFR and OFR cover crop treatments. The results clearly indicate no positive yield response from the additional N fertilizer at planting. Sweet corn that received 28 kg ha⁻¹ in plots that received the OFR treatment had the highest NUE, 221% more than FR at the same N fertilizer treatment level. Compared to FR, POFR had 111% higher NUE than FR. Sweet corn that received a split application of 28+28 kg N ha⁻¹ at planting and sidedress had a 13% and 28% higher NUE for POFR and OFR treatments respectively, compared to FR. It must be noted that the NUE equation used for comparing treatments did not take into account the N contribution from cover crop residues. However, the N contribution in the fall cover crop biomass was nearly the same in all cover crop treatments (Table 4).

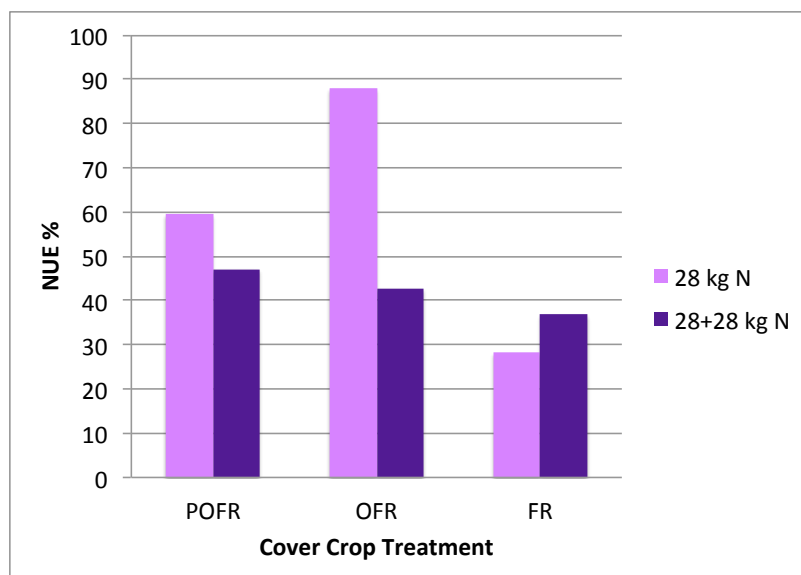


Figure 13. Nitrogen Use Efficiency (NUE) of sweet corn following cover crop treatments. $NUE = (\text{fresh weight yield in N-treated cover crop plots} - \text{yield in untreated NCC control plots}) / \text{kg applied N fertilizer}$.

POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish.

These results are similar to the CSNT data and deserve discussion. There are several explanations of how the mixed-species cover crop treatments improved the NUE of sweet corn plants, and these likely also affected CSNT and yield results.

One explanation could be there is a yield response to the timing of N release from cover crop residue, and that mineralization of OFR, and to a lesser extent POFR, residues are more synchronous with sweet corn N demand. Research in Massachusetts by Jahanzad et al. (2016) showed that aboveground cover crop residue decomposes slower than buried residue, therefore more slowly releasing N. This may also explain differences in the timing of nitrate concentrations. Cover crop treatments OFR and POFR have proportionally more aboveground biomass that decomposes at a slower rate as compared to radish treatment with higher amounts of root biomass below ground.

Another possible explanation is that OFR and POFR residues retain more N in dry matter after winter-kill over the course of winter and spring resulting in more total N delivered to the sweet corn plants (Stivers-Young, 1998). Physical size and shape of cover crop residue affects decomposition rates, potentially affecting subsequent availability to plants (Kruidhof et al., 2009). Furthermore, the cover crops possibly enhanced some soil physical properties, such as aggregation or gravimetric water that could have influenced subsequent sweet corn growth. Further experimentation will have to be conducted to determine the influence of these cover crops on NUE in sweet corn.

Conclusion

Winter-killed cover crops selected for this experiment improved sweet corn production compared with NCC. Overall, cover crops established well and provided nitrate scavenging and soil cover. Originally, we hypothesized that cover crop mixtures would produce more dry matter than FR monoculture or NCC. While this was not the case for total biomass, the trend of mixtures out yielding the FR monoculture held true for aboveground biomass. In spring, surface residue protected the soil without suppressing temperature. This result is likely predicated on early cover crop planting, by September 1, in order to achieve sufficient fall growth.

Sweet corn yields that followed cover crop treatments significantly increased compared with the control. Averaged over the two years, POFR and OFR treatments improved yields slightly more than FR. CSNT concentrations and NUE calculations indicated higher N availability to sweet corn from POFR and OFR compared to FR and NCC. Overall the sweet corn plants were under fertilized but yields still exceeded the regional averages.

All sweet corn benefitted from a small application of side-dressed supplemental fertilizer (28 kg N ha⁻¹). We observed successful N supply by cover crops early in the season, as indicated by data that the low rates of sidedress fertilizer achieved yields comparable to the split application of 28+28 kg N ha⁻¹. By utilizing cover crop mediated N, the need for N fertilizer at sweet corn planting could be eliminated. This would significantly reduce fertilizer costs and potential spring nitrate leaching compared with recommended rates (45 kg N ha⁻¹). Supplemental and timely N fertilizer at sidedress is critical in this system. Sidedress N can be calculated based on cover biomass N, PSNT results, and baseline soil nutrient status.

While this experiment examined many aspects of integrating winter-killed cover crops in no-till sweet corn production, it generated additional questions. Only one sweet corn variety was used in this trial, and the literature indicates that varietal selections can play a large role in N use (Heckman et al., 2002; Williams et al., 2009). Would other varieties exhibit different responses? Also, data should have been collected to calculate nitrogen fertilizer recovery rate and the concentration of N in sweet corn grain; subsequent research should include this data. Additional insight might be generated by trialing these treatments on a site with a longer no-till history (greater than 4 years), and/or higher SOM.

In a long-term no-till study, Constantin et al. (2010) found that catch crop frequency was positively correlated with reductions in nitrate leaching and increases in soil C and N sequestration. By integrating these cover crop mixtures as catch crops it is possible to increase sustainability in Northeast sweet corn production as related to N use and soil conservation. Although there were not major significant differences amongst the

three cover crop treatments, there may be practical and economic differences for agricultural producers beyond the criteria of yield. Results and discussion of weed suppression by cover crop treatments is in Chapter 3. Chapter 4 will discuss the economic differences between cover crop treatment planting costs and N management costs.

References

- Austin E.E., Wickings K., McDaniel M.D., Robertson G.P., Grandy A.S. (2017) Cover crop root contributions to soil carbon in a no-till corn bioenergy cropping system. *GCB Bioenergy* 9:1252-1263. DOI: 10.1111/gcbb.12428.
- Berendsen R.L., Pieterse C.M., Bakker P.A. (2012) The rhizosphere microbiome and plant health. *Trends Plant Sci* 17:478-86. DOI: 10.1016/j.tplants.2012.04.001.
- Blanco-Canqui H., Shaver T.M., Lindquist J.L., Shapiro C.A., Elmore R.W., Francis C.A., Hergert G.W. (2015) Cover crops and ecosystem services: Insights from studies in temperate soils. *Agronomy Journal* 107:2449-2474. DOI: 10.2134/agronj15.0086.
- Burgos N.R., Talbert R.E. (1996) Weed control and sweet corn (*zea mays* var *rugosa*) response in a no-till system with cover crops. *Weed Science* 44:355-361.
- Cabrera M.L., Kissel D.E., Vigil M.F. (2005) Nitrogen mineralization from organic residues: Research opportunities. *Journal of Environmental Quality* 34:75-79.
- Carrera L.M., Abdul-Baki A.A., Teasdale J.R. (2004) Cover crop management and weed suppression in no-tillage sweet corn production. *HortScience* 39:1262-1266.
- University of Vermont Extension Champlain Valley Crop, Soil & Pasture Team Cover crop diversity in no-till systems. March 10, 2018.
<https://www.uvm.edu/sites/default/files/Cover-Crop-Diversity-in-No-Till-Systems-Final-Report.pdf>.
- Chen G., Weil R.R. (2010) Penetration of cover crop roots through compacted soils. *Plant and Soil* 331:31-34. DOI: 10.1007/s11104-009-0223-7.
- Chen G., Weil R.R. (2011) Root growth and yield of maize as affected by soil compaction and cover crops. *Soil and Tillage Research* 117:17-27. DOI: 10.1016/j.still.2011.08.001.

- Christiansen J.S., Thorup-Kristensen K., Kristensen H.L. (2006) Root development of beetroot, sweet corn and celeriac, and soil n content after incorporation of green manure. *Journal of Horticultural Science & Biotechnology* 81:831-838.
- Cline G.R., Silvernail A.F. (2002) Effects of cover crops, nitrogen, and tillage on sweet corn. *Horttechnology* 12:118-125.
- Constantin J., Beaudoin N., Laurent F., Cohan J.-P., Duyme F., Mary B. (2011) Cumulative effects of catch crops on nitrogen uptake, leaching and net mineralization. *Plant and Soil* 341:137-154. DOI: 10.1007/s11104-010-0630-9.
- Constantin J., Mary B., Laurent F., Aubrion G., Fontaine A., Kerveillant P., Beaudoin N. (2010) Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. *Agriculture Ecosystems & Environment* 135:268-278. DOI: 10.1016/j.agee.2009.10.005.
- Creamer N.G., Bennett M.A., Stinner B.R. (1997) Evaluation of cover crop mixtures for use in vegetable production systems. *HortScience* 32:866-870.
- Dabney S.M., Delgado J.A., Reeves D.W. (2001) Using winter cover crops to improve soil and water quality. *Communications in Soil Science and Plant Analysis* 32:1221-1250. DOI: 10.1081/css-100104110.
- Dabney S.M., Delgado, J. A., Meisinger, J. J., Schomberg, H. H., Liebigh, M. A., Kaspar, T., ... & Reeves, W. (2010) Using cover crops and cropping systems for nitrogen management, *Advances in nitrogen management for water quality*. pp. 231-282.
- Dean J.E., Weil R.R. (2009) Brassica cover crops for nitrogen retention in the mid-atlantic coastal plain. *J Environ Qual* 38:520-8. DOI: 10.2134/jeq2008.0066.
- Dicklow M.B., McKeag L. (Eds.). (2016) *New england vegetable management guide*, UMass Extension, Amherst, MA.
- Drinkwater L.E., Janke R.R., Rossoni-Longnecker L. (2000) Effects of tillage intensity on nitrogen dynamics and productivity in legume-based grain systems. *Plant and Soil* 227:99-113. DOI: 10.1023/a:1026569715168.
- Drinkwater L.E., Wagoner P., Sarrantonio M. (1998) Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature* 396:262-265. DOI: 10.1038/24376.
- Fageria N.K., Baligar V.C. (2005) Enhancing nitrogen use efficiency in crop plants, in: D. L. Sparks (Ed.), *Advances in agronomy*, vol 88, Elsevier Academic Press Inc, San Diego. pp. 97-185.
- Finney D.M., Buyer J.S., Kaye J.P. (2017a) Living cover crops have immediate impacts on soil microbial community structure and function. *Journal of Soil and Water Conservation* 72:361-373. DOI: 10.2489/jswc.72.4.361.

- Finney D.M., Murrell E.G., White C.M., Baraibar B., Barbercheck M.E., Bradley B.A., Cornelisse S., Hunter M.C., Kaye J.P., Mortensen D.A., Mullen C.A., Schipanski M.E. (2017b) Ecosystem services and disservices are bundled in simple and diverse cover cropping systems. *Agricultural & Environmental Letters* 2. DOI: 10.2134/acl2017.09.0033.
- Finney D.M., White C.M., Kaye J.P. (2016) Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. *Agronomy Journal* 108:39-52. DOI: 10.2134/agronj15.0182.
- Fox R.H., Roth G.W., Iversen K.V., Piekielek W.P. (1989) Soil and tissue nitrate tests compared for predicting soil-nitrogen availability to corn. *Agronomy Journal* 81:971-974.
- Gabriel J.L., Alonso-Ayuso M., Garcia-Gonzalez I., Hontoria C., Quemada M. (2016) Nitrogen use efficiency and fertiliser fate in a long-term experiment with winter cover crops. *European Journal of Agronomy* 79:14-22. DOI: 10.1016/j.eja.2016.04.015.
- Galloway B.A., Weston L.A. (1996) Influence of cover crop and herbicide treatment on weed control and yield in no-till sweet corn (*zea mays* l) and pumpkin (*cucurbita maxima* Duch). *Weed Technology* 10:341-346.
- Gardner M., Sarrantonio M. (2012) Cover crop root composition and density in a long-term vegetable cropping system trial. *Journal of Sustainable Agriculture* 36:719-737. DOI: 10.1080/10440046.2012.672548.
- Griffin T., Liebman M., Jemison J. (2000) Cover crops for sweet corn production in a short-season environment. *Agronomy Journal* 92:144-151.
- Grimmer O., Masiunas J. (2004) Evaluation of winter-killed cover crops preceding snap pea. *HortTechnology* 14:349-355.
- Hashemi M., Farsad A., Sadeghpour A., Weis S.A., Herbert S.J. (2013) Cover-crop seeding-date influence on fall nitrogen recovery. *Journal of Plant Nutrition and Soil Science* 176:69-75. DOI: 10.1002/jpln.201200062.
- Heckman J., Hlubik W., Probst D., Paterson J. (1995) Pre-sidedress soil nitrate test for sweet corn. *HortScience* 30:1033-1036.
- Heckman J.R., Samulis R., Nitzsche P. (2002) Sweet corn crop nitrogen status evaluation by stalk testing. *HortScience* 37:783-786.
- Hobbs P.R. (2007) Conservation agriculture: What is it and why is it important for future sustainable food production? *Journal of Agricultural Science* 145:127-137. DOI: 10.1017/s0021859607006892.

- Hodgdon E.A., Warren N.D., Smith R.G., Sideman R.G. (2016) In-season and carry-over effects of cover crops on productivity and weed suppression. *Agronomy Journal* 108:1624-1635. DOI: 10.2134/agronj2015.0419.
- Hoyt G.D. (1986) Conservation tillage for vegetable and tobacco production. *Soil & Tillage Research* 8:341-341. DOI: 10.1016/0167-1987(86)90381-8.
- Isse A., MacKenzie A.F., Stewart K., Cloutier D.C., Smith D.L. (1999) Cover crops and nutrient retention for subsequent sweet corn production. *Agronomy Journal* 91:934-939.
- Jahanzad E., Barker A.V., Hashemi M., Eaton T., Sadeghpour A., Weis S.A. (2016) Nitrogen release dynamics and decomposition of buried and surface cover crop residues. *Agronomy Journal* 108:1735-1741. DOI: 10.2134/agronj2016.01.0001.
- Jahanzad E., Barker A.V., Hashemi M., Sadeghpour A., Eaton T. (2017) Forage radish and winter pea cover crops outperformed rye in a potato cropping system. *Agronomy Journal* 109:646-653. DOI: 10.2134/agronj2016.06.0342.
- Kabir Z., Koide R.T. (2002) Effect of autumn and winter mycorrhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in pennsylvania, USA. *Plant and Soil* 238:205-215. DOI: 10.1023/a:1014408723664.
- Kallenbach C.M., Frey S.D., Grandy A.S. (2016) Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls 7:13630. DOI: 10.1038/ncomms13630.
- Khan S.A., Mulvaney R.L., Ellsworth T.R., Boast C.W. (2007) The myth of nitrogen fertilization for soil carbon sequestration. *Journal of Environmental Quality* 36:1821-1832. DOI: 10.2134/jeq2007.0099.
- Kristensen H.L., and K. Thorup-Kristensen. (2004) Root growth and nitrate uptake of three different catch crops in deep soil layers. *Soil Sci. Soc. Am. J.* 68:529-537. DOI: doi:10.2136/sssaj2004.5290.
- Kristensen H.L., Thorup-Kristensen K. (2004a) Root growth and nitrate uptake of three different catch crops in deep soil layers. *Soil Science Society of America Journal* 68:529-537.
- Kristensen H.L., Thorup-Kristensen K. (2004b) Uptake of ¹⁵N labeled nitrate by root systems of sweet corn, carrot and white cabbage from 0.2-2.5 meters depth. *Plant and Soil* 265:93-100.
- Kruidhof H.M., Bastiaans L., Kropff M.J. (2009) Cover crop residue management for optimizing weed control. *Plant and Soil* 318:169-184. DOI: 10.1007/s11104-008-9827-6.

- Kuo S., Sainju U.M. (1998) Nitrogen mineralization and availability of mixed leguminous and non-leguminous cover crop residues in soil. *Biology and Fertility of Soils* 26:346-353. DOI: 10.1007/s003740050387.
- Kuo S., Sainju U.M., Jellum E.J. (1997a) Winter cover crop effects on soil organic carbon and carbohydrate in soil. *Soil Science Society of America Journal* 61:145-152.
- Kuo S., Sainju U.M., Jellum E.J. (1997b) Winter cover cropping influence on nitrogen in soil. *Soil Science Society of America Journal* 61:1392-1399.
- Lal R. (2004) Soil carbon sequestration impacts on global climate change and food security. *Science* 304:1623-1627. DOI: 10.1126/science.1097396.
- Lawley Y.E. (2010) Weed suppression by forage radish winter cover crops, Department of Environmental Science and Technology, University of Maryland, College Park, MD.
- Lawley Y.E., Teasdale J.R., Weil R.R. (2012) The mechanism for weed suppression by a forage radish cover crop. *Agronomy Journal* 104:205-214. DOI: 10.2134/agronj2011.0128.
- Lawley Y.E., Weil R.R., Teasdale J.R. (2011) Forage radish cover crop suppresses winter annual weeds in fall and before corn planting. *Agronomy Journal* 103:137-144. DOI: 10.2134/agronj2010.0187.
- Lawson A., Fortuna A.M., Cogger C., Bary A., Stubbs T. (2012) Nitrogen contribution of rye-hairy vetch cover crop mixtures to organically grown sweet corn. *Renewable Agriculture and Food Systems* 28:59-69. DOI: 10.1017/s1742170512000014.
- Lounsbury N.P. (2013) Spring seedbed characteristics after winterkilled cover crops, Department of Science and Technology, University of Maryland, College Park, MA.
- Lounsbury N.P., Weil R.R. (2014) No-till seeded spinach after winterkilled cover crops in an organic production system. *Renewable Agriculture and Food Systems* 30:473-485.
- Malpassi R.N., Kaspar T.C., Parkin T.B., Cambardella C.A., Nubel N.A. (2000) Oat and rye root decomposition effects on nitrogen mineralization. *Soil Science Society of America Journal* 64:208-215.
- Meisinger J.J., Delgado J.A. (2002) Principles for managing nitrogen leaching. *Journal of Soil Water Conservation* 57:485-498.
- Messiga A.J., Sharifi M., Munroe S. (2016) Combinations of cover crop mixtures and bio-waste composts enhance biomass production and nutrients accumulation: A

- greenhouse study. *Renewable Agriculture and Food Systems* 31:507-515. DOI: 10.1017/s1742170515000423.
- Mulvaney R.L., Khan S.A., Ellsworth T.R. (2009) Synthetic nitrogen fertilizers deplete soil nitrogen: A global dilemma for sustainable cereal production. *Journal of Environmental Quality* 38:2295-2314. DOI: 10.2134/jeq2008.0527.
- Murrell E.G., Schipanski M.E., Finney D.M., Hunter M.C., Burgess M., LaChance J.C., Baraibar B., White C.M., Mortensen D.A., Kaye J.P. (2017) Achieving diverse cover crop mixtures: Effects of planting date and seeding rate. *Agronomy Journal* 109:259-271. DOI: 10.2134/agronj2016.03.0174.
- O'Reilly K.A., Lauzon J.D., Vyn R.J., Van Eerd L.L. (2012) Nitrogen cycling, profit margins and sweet corn yield under fall cover crop systems. *Canadian Journal of Soil Science* 92:353-365. DOI: 10.4141/cjss2011-065.
- O'Reilly K.A., Robinson D.E., Vyn R.J., Van Eerd L.L. (2011) Weed populations, sweet corn yield, and economics following fall cover crops. *Weed Technology* 25:374-384. DOI: 10.1614/wt-d-10-00051.1.
- Poffenbarger H.J., Mirsky S.B., Weil R.R., Maul J.E., Kramer M., Spargo J.T., Cavigelli M.A. (2015) Biomass and nitrogen content of hairy vetch–cereal rye cover crop mixtures as influenced by species proportions. *Agronomy Journal* 107:2069. DOI: 10.2134/agronj14.0462.
- Puget P., Drinkwater L.E. (2001) Short-term dynamics of root- and shoot-derived carbon from a leguminous green manure. *Soil Science Society of America Journal* 65:771-779.
- Qasem J.R. (1992) Nutrient accumulation by weeds and their associated vegetable crops. *Journal of Horticultural Science* 67:189-195. DOI: 10.1080/00221589.1992.11516236.
- Ranells N.N., Waggoner M.G. (1996) Nitrogen release from grass and legume cover crop monocultures and bicultures. *Agronomy Journal* 88:777-882. DOI: 10.2134/agronj1996.00021962008800050015x.
- Reeves D.W. (1997) The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil & Tillage Research* 43:131-167. DOI: 10.1016/s0167-1987(97)00038-x.
- Sainju U.M., Singh B.P., Whitehead W.F. (2002) Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. *Soil and Tillage Research* 63:167-179.
- Sainju U.M., Whitehead W.F., Singh B.P. (2005) Biculture legume-cereal cover crops for enhanced biomass yield and carbon and nitrogen. *Agronomy Journal* 97:1403-1412. DOI: 10.2134/agronj2004.0274.

- Six J., Bossuyt H., Degryze S., Denef K. (2004) A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil & Tillage Research* 79:7-31. DOI: 10.1016/j.still.2004.03.008.
- Six J., Elliott E.T., Paustian K. (1999) Aggregate and soil organic matter dynamics under conventional and no-tillage systems. *Soil Science Society of America Journal* 63:1350-1358.
- Snapp S.S., Swinton S.M., Labarta R., Mutch D., Black J.R., Leep R., Nyiraneza J., O'Neil K. (2005) Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agronomy Journal* 97:322-332.
- Stivers-Young L. (1998) Growth, nitrogen accumulation, and weed suppression by fall cover crops following early harvest of vegetables. *HortScience* 33:60-63.
- Stubbs T.L., Kennedy A.C., Schillinger W.F. (2004) Soil ecosystem changes during the transition to no-till cropping. *Journal of Crop Improvement* 11:105-135. DOI: 10.1300/J411v11n01_06.
- Teasdale J.R., Abdul-Baki A.A., Park Y.B. (2008) Sweet corn production and efficiency of nitrogen use in high cover crop residue. *Agronomy for Sustainable Development* 28:559-565. DOI: 10.1051/agro:2008029.
- Teasdale J.R., Cavigelli M.A. (2010) Subplots facilitate assessment of corn yield losses from weed competition in a long-term systems experiment. *Agronomy for Sustainable Development* 30:445-453. DOI: 10.1051/agro/2009048.
- Teasdale J.R., Mohler C.L. (1993) Light transmittance, soil temperature, and soil moisture under mulch of hairy vetch and rye. *Agronomy Journal* 85:673-680.
- Thorup-Kristensen K. (2000) Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-n content, and how can this be measured? *Plant and Soil* 230:185-195.
- Thorup-Kristensen K. (2001) Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-n content, and how can this be measured? *Plant and Soil* 230:185-195. DOI: 10.1023/A:1010306425468.
- Tonitto C., David M.B., Drinkwater L.E. (2006) Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and n dynamics. *Agriculture*.
- Triplett G.B., Dick W.A. (2008) No-tillage crop production: A revolution in agriculture! *Agronomy Journal* 100:S153-S165. DOI: 10.2134/agronj2007.0005c.
- USDA-NASS. (2016) New England fruits and vegetables, in: G. R. Keough (Ed.), *New England Agricultural Statistics 2015*, USDA National Agricultural Statistics Service, Concord, NH.

- Vogel K.P. (1978) A simple method of converting rangeland drill to experimental plot seeders. *Journal of Range Management* 31:235-237.
- Weinert T.L., Pan W.L., Moneymaker M.R., Santo G.S., Stevens R.G. (2002) Nitrogen recycling by nonleguminous winter cover crops to reduce leaching in potato rotations. *Agronomy Journal* 94:365-372.
- Wells M.S., Reberg-Horton S.C., Smith A.N., Grossman J.M. (2013) The reduction of plant-available nitrogen by cover crop mulches and subsequent effects on soybean performance and weed interference. *Agronomy Journal* 105:539-545. DOI: 10.2134/agronj2012.0396.
- Wendling M., Buchi L., Amosse C., Sinaj S., Walter A., Charles R. (2016) Influence of root and leaf traits on the uptake of nutrients in cover crops. *Plant and Soil* 409:419-434. DOI: 10.1007/s11104-016-2974-2.
- White C.M., DuPont S.T., Hautau M., Hartman D., Finney D.M., Bradley B., LaChance J.C., Kaye J.P. (2017) Managing the trade off between nitrogen supply and retention with cover crop mixtures. *Agriculture Ecosystems & Environment* 237:121-133. DOI: 10.1016/j.agee.2016.12.016.
- White C.M., Weil R.R. (2011) Forage radish cover crops increase soil test phosphorus surrounding radish taproot holes. *Soil Science Society of America Journal* 75:121-130. DOI: 10.2136/sssaj2010.0095.
- Williams M.M., Davis A.S., Rabaey T.L., Boerboom C.M. (2009) Linkages among agronomic, environmental and weed management characteristics in north american sweet corn. *Field Crops Research* 113:161-169. DOI: 10.1016/j.fcr.2009.05.005.
- Wortman S.E., Francis C.A., Bernards M.L., Drijber R.A., Lindquist J.L. (2012) Optimizing cover crop benefits with diverse mixtures and an alternative termination method. *Agronomy Journal* 104:1425-1435. DOI: 10.2134/agronj2012.0185.
- Zotarelli L., Avila L., Scholberg J.M.S., Alves B.J.R. (2009) Benefits of vetch and rye cover crops to sweet corn under no-tillage. *Agronomy Journal* 101:252-260. DOI: 10.2134/agronj2008.0033x.

CHAPTER 3

WEED SUPPRESSION IN WINTER-KILLED RADISH COVER CROP

MIXTURES

Cover crops are used globally to build healthy soil and suppress weeds in a wide variety of cropping systems. Cover crops are select plant species grown for multiple agronomic benefits: soil protection, compaction reduction, nitrate scavenging, nitrogen fixation, soil organic matter, weed management, and beneficial insect habitat (Sarrantonio and Gallandt, 2003). The term “cover crop” is used generally and can include summer or winter crops grown with varying goals: green manures, nitrogen catch crops, weed suppression, nitrogen-fixation, and mulch. In fact, the challenge of weed control is one of the primary reasons that farmers choose to adopt cover cropping, especially in conservation tillage systems (CTIC, 2017).

There are several potential mechanisms of weed suppression. Cover crop residue, when left on the soil surface, contributes to a mulch effect that alters light transmission and soil temperature (Teasdale and Mohler, 1993). Light transmission stimulates phytochrome in seeds, which plays a role in the germination of most weed species (Teasdale, 1996). Therefore crop biomass is a primary factor influencing the weed suppressive effects of cover crops. Kruidhof et al. (2008) found that, in fall, fodder radish (*Raphanus sativus*) was most weed-suppressive and had the fastest rate to reach 50% of maximum light interception compared to lucerne (*Medicago sativa* L.), lupine (*Lupinus angustifolius* L.), winter rye (*Secale cereale*), and oilseed rape (*Brassica napus*). In grasses, aggressive establishment and early growth predict their effectiveness for weed suppression (Baraibar et al., 2018; Dorn et al., 2015). Legumes establish slowly in the

fall and consistently are least effective at controlling fall weeds compared to other cover crop types (Fisk et al., 2001).

A second mechanism of weed control by cover crops is allelopathy—the effect of plants via chemical compounds on other plants (Bhowmik and Inderjit, 2003; Jabran et al., 2015; Kunz et al., 2016). The decomposition of some cover crop residues generates phytotoxins that can selectively affect weed germination (Weston, 2005). Radishes (*Raphanus sativus* L.), winter rye, and oats (*Avena sativa* L.) are counted among cover crops potentially having allelopathic effects (Haramoto and Gallandt, 2004).

Forage Radish as a Cover Crop

While maximizing cover crop biomass is the primary goal for weed suppression, there are some potential associated risks. High biomass cover crop residue left on the soil surface can create cold, wet spring soil conditions that delay planting in spring (Dabney et al., 2001). Additionally, large amounts of biomass, especially with a high C:N ratio, can depress crop yield (Finney et al., 2016; Teasdale et al., 2008). A moderate level of biomass, between 450 and 800 g m⁻², may be sufficient for effective weed suppression (Buchanan et al., 2016; Teasdale and Mohler, 1993).

Use of forage radish (*Raphanus sativus* L. var *longipinnatus*) as a fall cover crop has become popular in a wide range of climates, from the mid-Atlantic to the Midwest, because radishes establish quickly in fall, suppresses weeds, and scavenge soil nitrate and other nutrients from deep in the soil profile (Lawley et al., 2012b; Weil and Kremen, 2007; Weil et al., 2009). The principal mechanism of spring weed suppression following a forage radish cover crop is considered to be fall light interception and not allelopathy (Lawley et al., 2012a). Forage radish reduced fall weed biomass by 89-97% compared to

a weedy fallow across a wide range of weed species (Hodgdon et al., 2016; Kruidhof et al., 2008; Lounsbury and Weil, 2014). Kunz et al. (2016) reported that fall-planted monoculture radish, and a mixture of radish/oats/vetch/berseem clover, decreased unspecified weed species biomass by 62 and 68% respectively. In the Netherlands, fodder radish (*Raphanus sativus* L.) reduced fall weed biomass by 65-95% (Kruidhof et al., 2008).

Spring Weed Suppression

Forage radish cover crops must be planted early enough in the fall to establish quickly and develop a leaf canopy in order to provide effective spring weed suppression. Lawley et al. (2011) observed that, in Maryland, forage radish planted prior to September 1 reduced the growth of annual weeds through the following April.

In Massachusetts, some vegetable growers have been experimenting with winter-killed cover crops as an alternative to high-residue winter rye (*Secale cereale* L.) or hairy vetch (*Vicia villosa* L.). This includes oat, peas, forage radish, and most clover species. In low-residue cover crops it is hypothesized that a mixture of species with complementary traits (eg. growth habit or phenology) can enhance ecosystem services, such as aggregate protection, nutrient uptake, and weed suppression (Finney et al., 2016).

Cover Crop Mixtures

Recent research has shown a relationship between multi-species cover crop mixtures and increased weed suppression (Bybee-Finley et al., 2016; Finney et al., 2016; Wendling et al., 2016). Creamer et al. (1997) found that a winter-hardy cover crop mixture including rye, barley, crimson clover and hairy vetch improved C:N ratios and reduced weed growth in no-till vegetable production.

Baraibar et al. (2018) found that low seeding rates of aggressive grasses reduced weeds in several cover crop mixtures. In that study, mixtures and grass-monocultures (oats and rye) decreased weed growth more than brassicas (forage radish and canola) or legumes (pea and red clover). This is part of the rationale to include grasses along with brassicas in cover crop mixtures. It has been suggested that the inclusion of an aggressive, early-establishing cover crop species in a mixture is more important than the average ability for weed suppression across all included species (Baraibar et al., 2018; Smith et al., 2014).

The duration of spring weed suppression is a concern if herbicide applications are reduced. Lawley et al. (2011) observed that while forage radish cover crops reduced weed biomass to near zero in early spring, this effect did not persist through the main cropping season. In that experiment, forage radish was used in place of a preplant burn down herbicide. As long as a post-emergence herbicide was applied, corn yield was not reduced by the omission of pre-plant herbicide, despite weed presence at planting.

Conservation Tillage for Vegetable Production

Tillage can have a major effect on spring weed emergence. Spring tillage mixes the soil and exposes dormant weed seeds to daylight and stimulates their germination. Additionally, tillage creates a fine seedbed for weeds to establish. Reducing tillage intensity is recommended for many reasons, such as erosion reduction, reducing the loss of soil organic matter, labor and fuel savings, and weed control.

No-till planting can reduce spring weed emergence by eliminating soil disturbance that brings up new seeds. No-till practices reduce the emergence of summer annuals (Swanton et al., 1999), except in cases where tillage exposes seeds to effects of

herbicide (Mohler, 1991). Peachey et al. (2004) found that no-till planting sweet corn and snap beans significantly reduced the emergence of hairy nightshade (*Solanum sarrachoides*) and powell amaranth (*Amaranthus powellii*).

Particular vegetable crops are well-suited to no-till production. Large-seeded vegetable crops, like squash and sweet corn, have been successfully grown no-till, as well as transplanted vegetable like cabbage, broccoli and tomatoes (Hoyt et al., 1994). Management of weeds becomes critical in no-till systems because tillage cannot be used as a backup management tool.

Sweet Corn in No-Till Production

Sweet corn (*Zea mays* L. *rugosa*) has been successfully grown using no-till production (Galloway and Weston, 1996). It has been documented that cover crops can improve sweet corn growth, not only by reducing weed competition, but also through improving soil function and nutrient cycling (Burgos and Talbert, 1996; Carrera et al., 2004; Cline and Silvernail, 2002; Griffin et al., 2000; Lawson et al., 2012; O'Reilly et al., 2011).

Sweet corn is a popular fresh vegetable crop in the Northeast. In 2015, sweet corn was planted on 11,590 acres across New England, which is about 10% of total vegetable production (USDA-NASS, 2016). In this region sweet corn is commonly grown without supplemental irrigation as long as soil texture is not excessively sandy (Dicklow and McKeag, 2016). Early sweet corn in New England garners a price premium and draws customers, but production involves the challenges of weed management and high rates of fertilizer applications (Galloway and Weston, 1996).

Weed Management in Sweet Corn

Sweet corn is highly sensitive to weed competition due to limited root system (Williams, 2008). The critical period of weed control (CPWC) is the period of time when a crop must be weed-free; beyond this point late-season weeds will not negatively impact the crop. In sweet corn this ranges from 182 to 632 GDD (Tursun et al., 2016). Practically, this equates to managing weeds while sweet corn is at V1 through V12 stages in order to prevent yield losses greater than 5%.

Research has shown that cover crops can significantly reduce weed emergence in sweet corn production (Galloway and Weston, 1996; Griffin et al., 2000; Peachey et al., 2004). Carrera et al. (2004) found that that cover crops improved sweet corn yield, not only by reducing weed pressure, but also by increasing competitiveness against growing weeds. (Burgos and Talbert, 1996) found that cover crops of hairy vetch, wheat and rye reduced the emergence and yield of no-till sweet corn. However, the use of cover crops allowed the use of half rates of atrazine and metolachlor (1.1 + 1.1 kg ai ha⁻¹) without reducing sweet corn yields compared to full rate herbicide.

There are concerns about relying on cover crops for weed control, including species-specific weed responses. The nitrate flush from residue decomposition can increase germination rates of responsive weed species, such as common lambsquarters (*Chenopodium album*) (Vincent and Roberts, 1977). Several studies have found that while forage radish cover crops reduce weed biomass in fall and early spring, suppression does not endure long enough in the cash crop growing season (Burgos and Talbert, 1996; Lawley et al., 2011; O'Reilly et al., 2011).

Employing cover crops for weed suppression can be successful depending on the amount of biomass generated, cash crop, weed seed bank, and field conditions. Additionally, cover crops contribute toward general ecosystem services and healthy soil. The weed suppressive effects of certain cover crops under particular circumstances may allow for reduced rates or frequency of herbicide application (Burgos and Talbert, 1996).

Rationale

Cover crop mixture research results can include highly variable and divergent factors such as cover crop species, climate, cash crop, soil type, and growth season. Most of the published research regarding forage radish has been conducted in the mid-Atlantic region, where it does not always winter kill and where spring cash crops are often planted in early March. The growing season is colder and shorter in the Northeast. Research is needed to document the fall and spring weed suppression of forage radish, and multi-species mixtures including radish, in the Northeast region. Oats and forage radish were selected for weed suppression and peas were included in a mixture for N-fixing and biomass adjustment.

Objectives

The objective of this research was to identify evaluate low residue winter-killed cover crop mixtures for no-till sweet corn production in the Northeast. Treatments included forage radish (FR) (*Raphanus sativus* L. *longipinnatus*), a mixture of oats (*Avena sativa* L.) and forage radish (OFR), a mixture of peas (*Pisum sativum* subsp *arvense* L.), oats, and forage radish (POFR), and a control treatment of local weeds (NCC). This experiment will assess sweet corn production without pre-emergence herbicide following cover crop treatments.

Hypotheses

We hypothesized that cover crop mixtures will reduce weed biomass and population density compared with FR monoculture or NCC in both fall and spring.

Materials & Methods

Experimental Site

Two field experiments were conducted at the University of Massachusetts Amherst Crop, Animal, Research and Education Farm in South Deerfield, MA (lat. 42°47'N, long. 72°58'W). Soils at the research farm are characterized as coarse-silty, mixed, superactive, nonacid, mesic Typic Udifluvents (Hadley series). Mean annual precipitation at this site ranges from 940-1300mm (37-51 inches). The mean annual temperature is 3-10.5 °C (37-51°F). The selected research site had previously been untilled for 3 years and planted with buckwheat the summer prior.

Cover crop treatments included forage radish, a mixture of oats and forage radish (OFR), a mixture of peas, oats, and forage radish (POFR), and a no cover crop control (NCC). Following the application of glyphosate to terminate summer weeds, cover crops were planted the last week of August in 2014 and 2015 with a plot cone seeder (Vogel, 1978) (Table 6). Plots were 8.5 m by 9 m in order to accommodate succeeding 9 rows of sweet corn with sufficient buffer area. Seeding rates were: forage radish (7.8 kg ha⁻¹), oats and forage radish (56.0 kg ha⁻¹ and 3.4 kg ha⁻¹, respectively), and peas, oats, and forage radish (50.4 kg ha⁻¹, 33.6 kg ha⁻¹, and 2.2 kg ha⁻¹, respectively). Control plots of no cover crop (NCC) were not planted and the natural weed population was allowed to

grow until winter-killed. In fall, prior to cover crop winter-kill, weed biomass was measured at the same time as cover crop biomass. Plants were cut at the soil line and then separated by cover crop species or weeds. Weed biomass was dried in a forced-air oven at 60 °C until it reached constant mass for weighing.

Table 6. Field activity at UMass Crop and Animal Research Farm in S. Deerfield, MA.

Field Activity	Site Year 1	Site Year 2
Cover crop planting	August 23, 2014	August 24, 2015
Cover crop biomass sampling (just prior to winter-kill)	November 10, 2014	November 20, 2015
Weed biomass sampling	November 10, 2014 April 26, 2015 n/a n/a	November 20, 2015 April 29, 2016 June 20, 2016 August 3, 2016
Sweet corn planting	n/a *Plots accidentally terminated in April	May 12, 2016
Glyphosate application to sweet corn plots	n/a	May 9, 2016
Sweet corn harvest	No yield data	No yield data

In April, prior to herbicide application and sweet corn planting, three weed biomass samples were taken from each plot in 0.078 m² quadrats. Number of plants and species were recorded.

On May 9, 2016, just prior to corn planting, glyphosate at 864 g a.i. ha⁻¹ was applied to all plots. On May 12, 2016, when soil temperature averaged 16 °C, sweet corn (var. ‘Trinity’) was no-till planted at an estimated population of 64,000 seeds ha⁻¹. No

preemergence herbicide was applied to these plots in order to determine late-season weeds following cover crop treatments. Weed biomass samples were taken again June 20, 2016 using the same method, when corn was approximately 25 cm in height.

Statistical Analysis

Data were analyzed using the general linear model (GLM) procedure of SAS 9.4 (SAS Institute, Cary, NC) with cover crop as fixed effect and replicate as random effect. Tukey's HSD was used for means comparisons of cover crop effects.

Table 7: Precipitation and Growing Degree Days (GDD) for experimental sites. $GDD = \sum (T_{max} - T_{min}) - T_b$ where T_{max} and T_{min} are daily maximum and minimum temperatures, respectively, and T_b is base temperature. For cover crop mixtures T_b was set as 4°C and for sweet corn T_b was 10°C.

	Precipitation (mm)			Growing Degree Days	
Cover Crops	2014	2015	20 yr avg	(GDD ₄₀)	
	2014	2015		2014	2015
Aug	103	95	90	875	975
Sep	29	167	106	682	805
Oct	126	58	107	416	310
Nov	77	47	77	71	183
Dec	96	104	84	11	76
<i>Total</i>	<i>431</i>	<i>470</i>	<i>464</i>	<i>2055</i>	<i>2348</i>
No Crop/ Winter	2015	2016	20 yr avg	2015	2016
Jan	80	42	67	0	3
Feb	24	106	67	0	30
Mar	40	68	89	3	130
Apr	50	40	77	186	215
<i>Total</i>	<i>194</i>	<i>256</i>	<i>300</i>	<i>189</i>	<i>378</i>
Sweet Corn	2015	2016	20 yr avg	(GDD ₅₀)	
	2015	2016		2015	2016
May	35	57	84	418	270
Jun	189	27	112	451	499
Jul	121	43	90	659	706
<i>Total</i>	<i>345</i>	<i>127</i>	<i>286</i>	<i>1527</i>	<i>1475</i>

Results and Discussion

Fall Weed and Cover Crop Biomass Production

Cover crop treatments established successfully in both years. Weed biomass was significantly different in 2014 compared to 2015, so year data was analyzed separately (Table 8). This is likely a result of different field history: the second site year was planted in an area previously planted to perennial switchgrass.

In 2014, aboveground cover crop biomass was 11% greater than in 2015, averaged over all cover crop treatments. Weather conditions in both years may have significantly affected biomass production. In September and October 2014, precipitation and rainfall were ideal for plant growth, with sufficient rain and moderate GDD (Table 7). In September 2015, greater than average rainfall and cloudy weather may have had a negative impact on biomass production. During this time cover crops were establishing and saturated soil conditions could have inhibited root growth. While seasonal GDD in the fall of 2014 was similar to the norm for the location, calculated GDD for 2015 was approximately 20% higher than the norm for the experimental site.

Measured prior to winter-kill in November 2014, cover crop treatments averaged 421 g m⁻² while the weedy control plots (NCC) produced 98 g m⁻² (Table 3). All cover crop treatments caused a significant reduction in weed biomass compared to the control (NCC) varying from 95% (POFR) to 94% (OFR) to 99% (FR) (Table 8). The most frequent species were common lambsquarters (*Chenopodium album* L.)[CHEAL], and horseweed (*Conyza canadensis* L.)[ERICA].

In November 2015 the weed biomass was higher than 2014; however, cover crop treatments provided similar weed suppression (Table 8).

Table 8. Aboveground biomass of cover crops, weeds, and respective N content, in November 2014 and 2015. Cover crops planted August 23, 2014 and August 24, 2015. Year data analyzed separately. Treatments with different letters indicate significant differences (Tukey's HSD $p < 0.05$). No letter indicates no significant differences.

		Cover crop aboveground biomass (g m^{-2})	Weed biomass (g m^{-2})	N in total dry matter (kg ha^{-1})
November	POFR	419 ab	5 a	102 a
2014	OFR	547 a	6 a	108 a
	FR	297 b	1 a	58 ab
	NCC	--	98 b	23 b
November	POFR	400	8 a	75
2015	OFR	392	8 a	65
	FR	328	10 a	67
	NCC	--	246 b	57

POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

In November 2015, cover crop biomass averaged 373 g m^{-2} and NCC produced 246 g m^{-2} . Compared to the control, POFR and OFR reduced weed biomass by 97%, while FR reduced it by 96%. These findings are in agreement with Holmes et al. (2017) that FR, while sometimes less productive than other cover crops, can effectively suppress weeds in both monoculture and mixture. Weed biomass in weedy control plots can vary widely by experimental site and year, from 10 to 360 g m^{-2} (Lawley et al., 2011).

In this study, the relationship between fall cover crop biomass and weed biomass was different for each treatment and by year (Figure 14). Overall, as cover crop biomass increased, weed biomass increased slightly, except for FR treatments where similar amounts of cover crop biomass resulted in variable weed biomass. These results disagree with findings that cover crop biomass and weed biomass are inversely related (Buchanan

et al., 2016; Dorn et al., 2015). The assumption that weed suppression is related to high cover crop biomass production is likely based on comparisons of high residue winter rye or vetch biomass with other species, or on studies of small-statured weed species.

Numerous publications support that this correlation is not universal (Baraibar et al., 2018; Galloway and Weston, 1996).

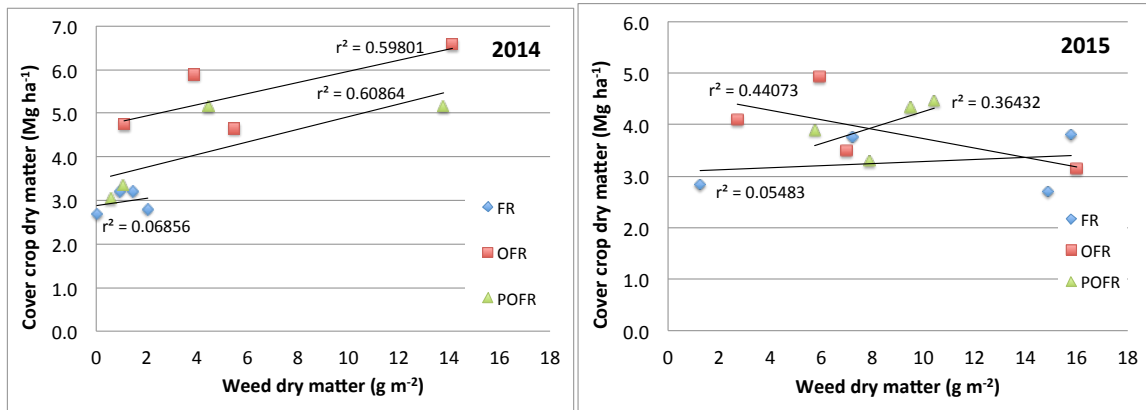


Figure 14. Relationship between cover crop dry matter and weed dry matter by cover crop treatment just prior to winter-kill in November 2014 (left) and November 2015 (right).

POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish

Fall weed suppression is correlated with early light interception, especially in the case of tall statured weeds like common lambsquarters (Kruidhof et al., 2008). Holmes et al. (2017) found that species, like mustard or forage radish, with less biomass can successfully suppress weed growth as long as they are densely sown, and establish quickly and evenly. A very thorough experiment by Lawley et al. (2012a) identified canopy competition as the mechanism for weed suppression in a fall forage radish cover crop. Allelopathy by some Brassica species has been attributed to glucosinolate hydrolysis products (Haramoto and Gallandt, 2004). However, this is not the mechanism

of fall season weed suppression because radish tissue must be lysed for catalysis of glucosinolate hydrolysis in soil, and FR biomass is intact until winter-kill.

Spring Biomass Production

All fall weeds (primarily common lambsquarters and horseweed) and cover crop plants were winter-killed. In spring, new annual weed seeds germinated as soil temperatures increased and species were identified when biomass was sampled. In year one of the weed experiment, weed biomass data was collected in November 2014 but the plots were accidentally terminated in April 2015 by misplaced herbicide application. Therefore, in-season weed biomass data was only collected for one year (Figure 15).

In April 2016, spring weed communities were dominated by yellow hawkweed (*Hieracium pratense* Taush)[HIECA], white campion (*Silene alba* (Mill.))[MELAL], and corn speedwell (*Veronica arvensis*)[VERAR]. At this point in early spring, the weed suppressive effect of cover crop treatments was significant. The weedy control (NCC) had already produced substantial weed biomass at this early date, averaging 199 g m^{-2} (Figure 15). Compared to NCC, the FR and OFR treatment reduced weed biomass by 95% and 92% respectively. Weeds biomass in POFR plots was reduced by 88%. The weed density was lowest in OFR plots, averaging 11 plants m^{-2} . Weed density in plots following POFR and FR was 13 plants m^{-2} , 50% less than NCC with 26 weeds m^{-2} . The results confirm the ability of low-residue fall-planted cover crops to reduce early spring weed biomass and density compared to a weedy fallow. However, contrary to our hypothesis, mixtures did not reduce weed biomass compared to FR monoculture. Weed suppression by cover crops was not enough to eliminate the need for herbicide application prior to sweet corn planting.

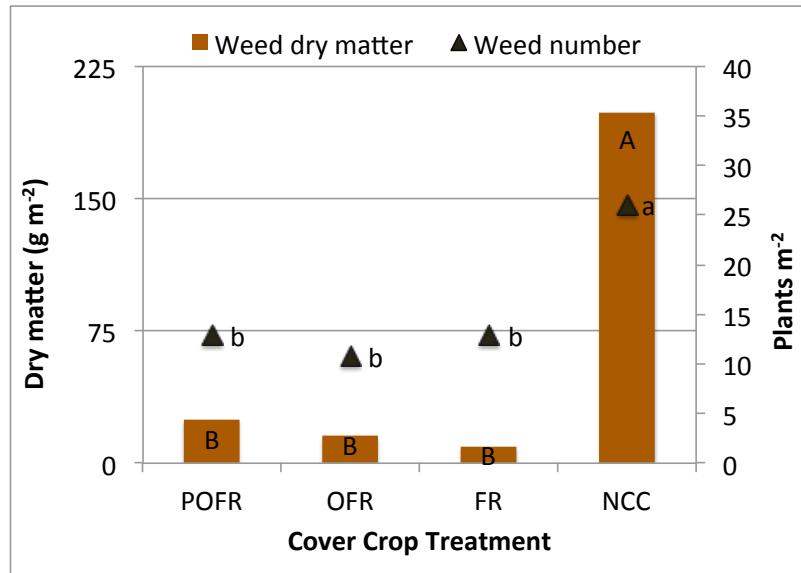


Figure 15. Spring weed dry matter and weed density in plots following cover crop treatment, prior to herbicide application, April 2016. Treatments with different letters indicate significant differences (Tukey's HSD $p < 0.05$). POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

The relationship between November cover crop biomass and April weed biomass showed significant differences between treatments (Figure 16). More biomass production in November from OFR and FR treatments resulted in lower weed biomass the following April, prior to sweet corn planting. There was no relationship ($r^2 < 0.05$) between November biomass of POFR and NCC treatments and the subsequent spring weed biomass.

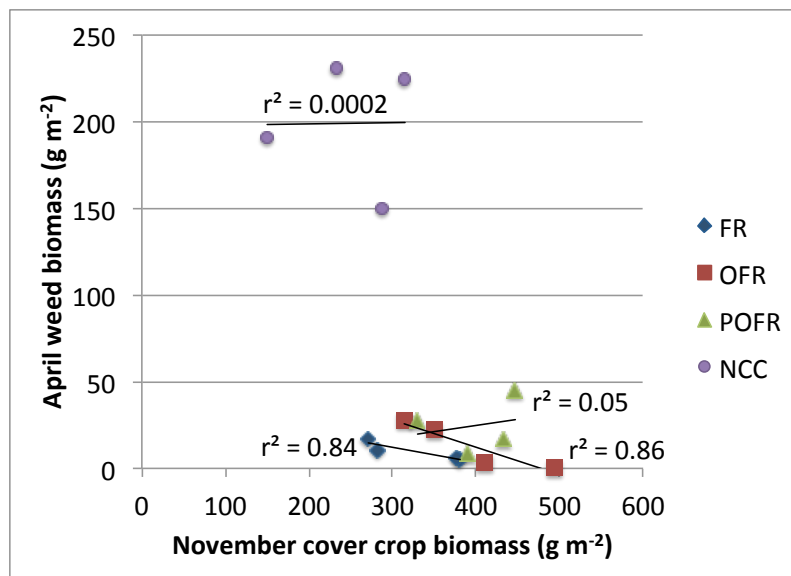


Figure 16. Relationship between November cover crop biomass and April weed biomass (prior to termination and sweet corn planting).

POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

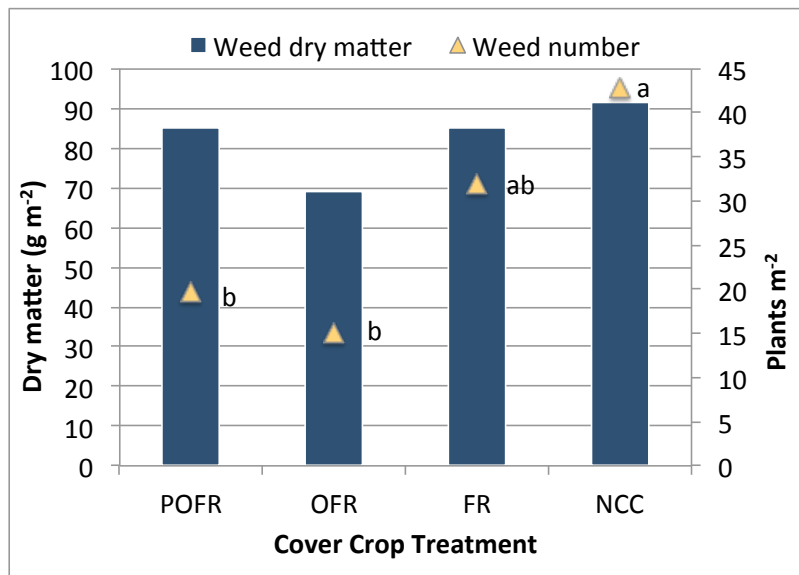


Figure 17. Summer weed dry matter and weed density in plots following cover crop treatment, June 2016. Treatments with different letters indicate significant differences (Tukey's HSD $p < 0.05$). No significant differences were observed in weed dry matter.

POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

In June 2016, at 5 weeks after planting, sweet corn plants had reached an average of 25 cm tall. Growing degree-day accumulations indicated that the critical weed free period extended through mid-June. Up to this point, weed competition with sweet corn plants will significantly reduce sweet corn yield. Most frequent weed species were common lambsquarters, Shepherd's-purse (*Capsella bursa-pastoris* L.)[CAPBP], and various grass species (unidentified).

While there were no statistically significant differences in June weed biomass as an effect of cover crop treatment, weed biomass ranged from 7% to 25% less than NCC (Figure 17). The lowest weed biomass by dry weight was in OFR plots (69 g m⁻²), which was 25% less than NCC. These values are similar to those observed in Galloway and Weston (1996). Physical structure of cover crop residue may play a role in weed growth and may result in suppression. Residue that decomposes slower or has large pieces, like oats, provides more interference with weed growth (Teasdale and Mohler, 1993).

In June, OFR and POFR cover crop treatments had significantly fewer weed plants m⁻², 65% and 53%, respectively, less than NCC (Figure 17). The FR treatment 25% had fewer weeds than NCC, though the difference was not statistically different. Weed species populations were analyzed for effects of cover crop treatment. The only significant difference between weed species populations was in the number of grass plants m⁻². FR had significantly more grasses, an average of 7 plants compared with 1 plant in the NCC plots. With 2 and 4 plants m⁻² respectively, OFR and POFR had an intermediate number of grass weeds.

Cover crop effects on weeds can be contradictory, due to numerous influential factors such as field history, cover crop species, planting date, weed seed bank and crop

management. In a reduced tillage system in the Midwest, crimson clover (*Trifolium incarnatum* L.), barley (*Hordeum vulgare* L.) and a clover/barley mixture reduced spring weed density by 50% but did not influence weed species diversity, or weed biomass cover during the main cropping season (Buchanan et al., 2016). The mixture of cover crop species did not suppress weeds more than the single species cover crops.

By August all plots were totally overtaken by weeds and did not yield any sweet corn (data not shown). Weed biomass averaged 510 g m⁻² with no significant difference between cover crop treatments. These cover crops alone do not provide weed suppression during the sweet corn growing season in no-till production (Gieske et al., 2016; Lawley et al., 2011).

Conclusion

When planted in fall with enough time to establish, cover crops suppressed fall weeds. In this study, all cover crop treatments effectively suppressed fall weeds compared with NCC in November 2014 and 2015. However, weed suppression did carry over to the growing season for sweet corn. While the cover crop treatments were not a substitute for a residual herbicide during the growing season, they did show some weed biomass and density reduction in April and June.

The reduction of fall weed biomass by these cover crops is valuable in agricultural systems. Weed management is costly and increased weed germination or growth leads to extra management costs or yield reductions. Cover crops have economic and environmental benefits beyond weed suppression in terms of preventing nitrate leaching and soil erosion during the fall and winter months. Sweet corn yields were

significantly improved compared with no cover crop treatment (Chapter 2, Figures 9 and 10). The inclusion of low-residue winter-killed cover crops mixtures increases overall sustainability in no-till sweet corn production in the Northeast. Further research should be done to assess whether preemergence herbicide rate reduction might be possible under some field conditions and with sufficient cover crop surface residue.

References

- Baraibar B., Hunter M.C., Schipanski M.E., Hamilton A., Mortensen D.A. (2018) Weed suppression in cover crop monocultures and mixtures. *Weed Science* 66:121-133. DOI: 10.1017/wsc.2017.59.
- Bhowmik P.C., Inderjit. (2003) Challenges and opportunities in implementing allelopathy for natural weed management. *Crop protection* 22:661-671.
- Buchanan A.L., Kolb L.N., Hooks C.R. (2016) Can winter cover crops influence weed density and diversity in a reduced tillage vegetable system? *Crop protection* 90:9-16.
- Burgos N.R., Talbert R.E. (1996) Weed control and sweet corn (*zea mays* var *rugosa*) response in a no-till system with cover crops. *Weed Science* 44:355-361.
- Bybee-Finley K.A., Mirsky S.B., Ryan M.R. (2016) Functional diversity in summer annual grass and legume intercrops in the northeastern united states. *Crop Science* 56:2775-2790. DOI: 10.2135/cropsci2016.01.0046.
- Carrera L.M., Abdul-Baki A.A., Teasdale J.R. (2004) Cover crop management and weed suppression in no-tillage sweet corn production. *HortScience* 39:1262-1266.
- Cline G.R., Silvernail A.F. (2002) Effects of cover crops, nitrogen, and tillage on sweet corn. *Horttechnology* 12:118-125.
- Creamer N.G., Bennett M.A., Stinner B.R. (1997) Evaluation of cover crop mixtures for use in vegetable production systems. *HortScience* 32:866-870.
- CTIC. (2017) Report of the 2016-17 national cover crop survey, Joint publication of the Conservation Technology Information Center, the North Central Region Sustainable Agriculture Research and Education Program, and the American Seed Trade Association, West Lafayette, IN.

- Dabney S.M., Delgado J.A., Reeves D.W. (2001) Using winter cover crops to improve soil and water quality. *Communications in Soil Science and Plant Analysis* 32:1221-1250. DOI: 10.1081/css-100104110.
- Dicklow M.B., McKeag L. (Eds.). (2016) *New England vegetable management guide*, UMass Extension, Amherst, MA.
- Dorn B., Jossi W., Van der Heijden M.G.A. (2015) Weed suppression by cover crops: Comparative on-farm experiments under integrated and organic conservation tillage. *Weed Research* 55:586-597. DOI: 10.1111/wre.12175.
- Finney D.M., White C.M., Kaye J.P. (2016) Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. *Agronomy Journal* 108:39-52. DOI: 10.2134/agronj15.0182.
- Fisk J.W., Hesterman O.B., Shrestha A., Kells J.J., Harwood R.R., Squire J.M., Sheaffer C.C. (2001) Weed suppression by annual legume cover crops in no-tillage corn. *Agronomy Journal* 93:319-325. DOI: 10.2134/agronj2001.932319x.
- Galloway B.A., Weston L.A. (1996) Influence of cover crop and herbicide treatment on weed control and yield in no-till sweet corn (*zea mays l*) and pumpkin (*cucurbita maxima duch*). *Weed Technology* 10:341-346.
- Gieske M.F., Wyse D.L., Durgan B.R. (2016) Spring- and fall-seeded radish cover-crop effects on weed management in corn. *Weed Technology* 30:559-572. DOI: 10.1614/wt-d-15-00023.1.
- Griffin T., Liebman M., Jemison J. (2000) Cover crops for sweet corn production in a short-season environment. *Agronomy Journal* 92:144-151.
- Haramoto E.R., Gallandt E.R. (2004) Brassica cover cropping for weed management: A review. *Renewable Agriculture and Food Systems* 19:187-198. DOI: 10.1079/rafs200490.
- Hodgdon E.A., Warren N.D., Smith R.G., Sideman R.G. (2016) In-season and carry-over effects of cover crops on productivity and weed suppression. *Agronomy Journal* 108:1624-1635. DOI: 10.2134/agronj2015.0419.
- Holmes A.A., Thompson A.A., Wortman S.E. (2017) Species-specific contributions to productivity and weed suppression in cover crop mixtures. *Agronomy Journal* 109:2808-2819. DOI: 10.2134/agronj2017.06.0309.
- Hoyt G., Monks D., Monaco T. (1994) Conservation tillage for vegetable production. *Horttechnology* 4:129-135.
- Jabran K., Mahajan G., Sardana V., Chauhan B.S. (2015) Allelopathy for weed control in agricultural systems. *Crop protection* 72:57-65. DOI: 10.1016/j.cropro.2015.03.004.

- Kruidhof H.M., Bastiaans L., Kropff M.J. (2008) Ecological weed management by cover cropping: Effects on weed growth in autumn and weed establishment in spring. *Weed Research*. DOI: 10.1111/j.1365-3180.2008.00665.x.
- Kunz C., Sturm D.J., Varnholt D., Walker F., Gerhards R. (2016) Allelopathic effects and weed suppressive ability of cover crops. *Plant Soil and Environment* 62:60-66.
- Lawley Y.E., Teasdale J.R., Weil R.R. (2012a) The mechanism for weed suppression by a forage radish cover crop. *Agronomy Journal* 104:205-214. DOI: 10.2134/agronj2011.0128.
- Lawley Y.E., Teasdale J.R., Weil R.R. (2012b) The mechanism for weed suppression by a forage radish cover crop. *Agronomy Journal* 104:205. DOI: 10.2134/agronj2011.0128.
- Lawley Y.E., Weil R.R., Teasdale J.R. (2011) Forage radish cover crop suppresses winter annual weeds in fall and before corn planting. *Agronomy Journal* 103:137-144. DOI: 10.2134/agronj2010.0187.
- Lawson A., Fortuna A.M., Cogger C., Bary A., Stubbs T. (2012) Nitrogen contribution of rye-hairy vetch cover crop mixtures to organically grown sweet corn. *Renewable Agriculture and Food Systems* 28:59-69. DOI: 10.1017/s1742170512000014.
- Lounsbury N.P., Weil R.R. (2014) No-till seeded spinach after winterkilled cover crops in an organic production system. *Renewable Agriculture and Food Systems* 30:473-485.
- Mohler C.L. (1991) Effects of tillage and mulch on weed biomass and sweet corn yield. *Weed Technology* 5:545-552.
- O'Reilly K.A., Robinson D.E., Vyn R.J., Van Eerd L.L. (2011) Weed populations, sweet corn yield, and economics following fall cover crops. *Weed Technology* 25:374-384. DOI: 10.1614/wt-d-10-00051.1.
- Peachey R.E., William R.D., Mallory-Smith C. (2004) Effect of no-till or conventional planting and cover crops residues on weed emergence in vegetable row crop. *Weed Technology* 18:1023-1030. DOI: 10.1614/wt-03-205r.
- Sarrantonio M., Gallandt E. (2003) The role of cover crops in north american cropping systems. *Journal of Crop Production* 8:53-74.
- Smith R.G., Atwood L.W., Warren N.D. (2014) Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services. *Plos One* 9:8. DOI: 10.1371/journal.pone.0097351.
- Swanton C.J., Shrestha A., Roy R.C., Ball-Coelho B.R., Knezevic S.Z. (1999) Effect of tillage systems, n, and cover crop on the composition of weed flora. *Weed Science* 47:454-461.

- Teasdale J.R. (1996) Contribution of cover crops to weed management in sustainable agricultural systems. *Journal of Production Agriculture*.
- Teasdale J.R., Abdul-Baki A.A., Park Y.B. (2008) Sweet corn production and efficiency of nitrogen use in high cover crop residue. *Agronomy for Sustainable Development* 28:559-565. DOI: 10.1051/agro:2008029.
- Teasdale J.R., Mohler C.L. (1993) Light transmittance, soil temperature, and soil moisture under mulch of hairy vetch and rye. *Agronomy Journal* 85:673-680.
- Tursun N., Datta A., Sakinmaz M.S., Kantarci Z., Knezevic S.Z., Chauhan B.S. (2016) The critical period for weed control in three corn (zea mays l.) types. *Crop protection* 90:59-65. DOI: 10.1016/j.cropro.2016.08.019.
- USDA-NASS. (2016) New england fruits and vegetables, in: G. R. Keough (Ed.), *New England Agricultural Statistics 2015*, USDA National Agricultural Statistics Service, Concord, NH.
- Vincent E.M., Roberts E.H. (1977) Interaction of light, nitrate and alternating temperature in promoting germination of dormant seeds of common weed species. *Seed Science and Technology* 5:659-670.
- Vogel K.P. (1978) A simple method of converting rangeland drill to experimental plot seeders. *Journal of Range Management* 31:235-237.
- Weil R., Kremen A. (2007) Thinking across and beyond disciplines to make cover crops pay. *Journal of the Science of Food and Agriculture* 87:551-557. DOI: 10.1002/jsfa.2742.
- Maryland Cooperative Extension. Forage radish: New multi-purpose cover crop for the mid-atlantic. Fact sheet 824. March 13.
[https://enst.umd.edu/sites/enst.umd.edu/files/_docs/FactSheet824 Weil et al 2009.pdf](https://enst.umd.edu/sites/enst.umd.edu/files/_docs/FactSheet824%20Weil%20et%20al%202009.pdf).
- Wendling M., Buchi L., Amosse C., Sinaj S., Walter A., Charles R. (2016) Influence of root and leaf traits on the uptake of nutrients in cover crops. *Plant and Soil* 409:419-434. DOI: 10.1007/s11104-016-2974-2.
- Weston L.A. (2005) History and current trends in the use of allelopathy for weed management. *Horttechnology* 15:529-534.
- Williams M.M. (2008) Sweet corn growth and yield response to planting dates of the north central united states. *HortScience* 43.

CHAPTER 4

ECONOMIC ANALYSIS OF COVER CROP BENEFITS FOR NO-TILL SWEET CORN PRODUCTION

The scientific literature provides extensive evidence that cover crops can improve crop yields and soil health. Despite that, adoption of cover cropping practices has been limited. Only 2.3% of farm acres in the Midwest region of the U.S. are cover cropped (Roesch-McNally et al., 2017). The reasons behind this are complicated, and include a lack of structural support, lack of locally relevant trials, and cultural and historical norms. In order to invest in planting cover crops, growers need proof of successfully implementation in their region. It is also important to quantify the benefits of cover crops in a way that enables producers to calculate the cost opportunities and long-term benefits. Roth et al. (2018) calculated the benefits from cover crops on improved subsurface drainage N loading, soil erosion, and residue N mineralization, and they recovered only 61% of the costs, on average, of implementing a rye and forage radish cover crop in strip-tilled corn.

In this current study, cover crop costs are slightly lower both because it's a no-till system without tillage costs, and because it's a winter-killed cover crop without termination costs. The cost of cover crop seed ranged from \$52 to \$131 ha⁻¹ for FR and POFR, respectively (Table 9).

Table 9. Cover crop treatment seeding rates and seed costs.

Cover crop treatment	Seeding rate (kg ha ⁻¹)	Seed cost (\$ ha ⁻¹)
FR: forage radish	7.8 kg ha ⁻¹	\$52
OFR: oats and forage radish	50.4 kg ha ⁻¹ and 3.4 kg ha ⁻¹ , respectively	\$68

POFR: peas, oats, and forage radish	50.4 kg ha ⁻¹ , 33.6 kg ha ⁻¹ , and 2.2 kg ha ⁻¹ , respectively	\$131
-------------------------------------	--	-------

We used results presented in Chapter 2 to calculate a simple estimate of the cost to reach sweet corn nitrogen sufficiency using these cover crop treatments with supplemental N fertilizer at sidedress. Using the concentration of nitrogen in fall cover crop residue (Table 4), we calculated the potentially mineralizable nitrogen from cover crop residue, which over two years averaged 97 kg N ha⁻¹. It is estimated cover crop tissue loses 30% to 50% of original N as a result of winter-kill and early spring decomposition (Malpassi et al., 2000). We assumed that 50% of cover crop N is lost over winter, therefore almost 50 kg N ha⁻¹ remained available to sweet corn for the growing season. Cover crop mediated N was valued at \$0.91 kg, the same as the urea fertilizer used for supplemental N. The cost of nitrogen fertilizer varies greatly depending on the source and bulk rates, but for this research we assumed \$0.91 kg⁻¹ for bulk urea N.

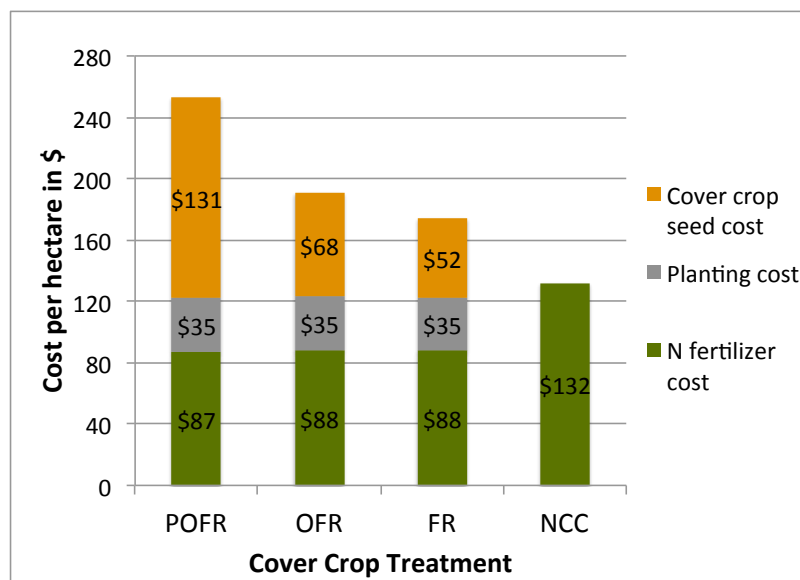


Figure 18. Average cost to achieve N sufficiency of 145 kg ha⁻¹ utilizing cover crop-mediated N residue and sidedressed synthetic N fertilizer.

POFR=pea, oat and forage radish, OFR=oat and forage radish, FR=forage radish, NCC=no cover crop control

In order to reach the N sufficiency rate of 145 kg N ha⁻¹, POFR cover crop and fertilizer costs are approximately \$250 ha⁻¹, and OFR and FR costs are less at \$190 and \$175, respectively (Figure 18). For NCC, though there are no seed or planting costs, the full rate of fertilizer must be applied to reach N sufficiency, which costs approximately \$132 ha⁻¹.

Though there is no cost to a winter fallow of weeds (NCC), subsequent sweet corn yields are significantly lower compared to yield following these cover crop treatments. In Figure 14, the costs alone overemphasize the expense of the cover crop treatments without including gains in yield and N cycling. To obtain a more accurate valuation of the cover crop we included the yield benefit and cover crop mediated N cycled by cover crops, then subtracted the seed cost and cost of fertilizer to meet sufficiency (Table 10).

Table 10. The cover crop impact on overall sweet corn profit. Costs are indicated by parentheses. Costs were subtracted from profits resulting from cover crop treatments.

	———Cover crop treatment———			
	NCC	POFR	OFR	FR
Profit gains ha ⁻¹ compared to NCC	-	\$1,971	\$1,926	\$1,434
Cost of cover crop seed	-	\$(131)	\$(68)	\$(52)
Cost of cover crop planting	-	\$(35)	\$(35)	\$(35)
Cost of supplemental N fertilizer	\$(132)	\$(87)	\$(88)	\$(88)
Cover crop impact on overall gains	\$(132)	\$1,718	\$1,735	\$1,259

*POFR=pea, oat and forage radish, OFR=oat and forage radish,
FR=forage radish, NCC=no cover crop control*

The best value for cover crop mediated N was provided by OFR and POFR, a possible increase of over \$1,100 ha⁻¹. Additionally, these cover crops provide other benefits not taken into account, such as carbon contributions and weed biomass suppression.

Cost is an important factor in selecting cover crops for any production system. While these calculations are not comprehensive in terms of production costs, they do explicate the costs and benefits that vary among treatments. Based on this research, the value of POFR and OFR cover crop mixtures exceed NCC and FR in terms of value and nitrogen cycling. The results of this research point to potential differences between cover crop selections in terms of both cost to farmers and environmental benefits.

Conclusion

Our results indicate that cover crop treatments improved no-till sweet corn yield and sustainability compared to no cover crop. Aboveground biomass in November was highest in POFR and OFR, and as a result more N was recycled via decomposition to the following sweet corn crop. As hypothesized, cover crop mixtures produced more aboveground biomass than FR or NCC. Winter-killed cover crop species must be planted with sufficient time for fall establishment, usually by September 1 in the Northeast.

Cover crop treatments did not reduce spring soil temperature, which fortunately negates a potential concern in no-till production and in short-season climates. Following POFR and OFR treatments, soil nitrate availability was better synchronized with sweet corn N demand compared to FR or LW as indicated by CSNT and NUE results. Sweet

corn yield was greater in POFR and OFR plots compared to FR and NCC, averaged over two years. The highest yielding treatment was OFR with 28 kg N ha⁻¹ at sidedress.

Pre-sidedress nitrate tests from all plots were below 21 ppm, indicating that sweet corn yield would respond to supplemental N fertilizer. Plots that received 28 kg N ha⁻¹ fertilizer at side-dress yielded as much as those that received 56 kg N ha⁻¹ with split application. This result indicates that cover crop mediated N during sweet corn establishment was sufficient without added N fertilizer at planting.

Weed suppression in the fall cover crop was successful and similar among cover crop treatments. Early spring weed biomass and density were reduced following cover crop mixtures, but during the sweet corn growing season residual herbicide was needed to assure sufficient weed suppression.

Analysis of the costs and yield benefits of these cover crop treatments in no-till sweet corn show that despite higher seed costs, POFR and OFR have the potential to increase revenue by \$1,200 ha⁻¹ as a result of yield increases.

Cover Crop Mixtures for the Future

POFR and OFR out-performed FR and NCC in terms of value, dry matter production, nitrogen cycling and weed suppression. While this experiment examined many aspects of integrating certain winter-killed cover crops in no-till sweet corn production, it generates additional questions. Weather plays an important role in cover crop establishment and non-irrigated crop production. In years of excess rainfall, crops are more N-limited, and in years of drought crop yield is more limited by weed competition than by N (Teasdale and Cavigelli, 2010). Long-term studies of cover crop mixtures should examine the effect of weather conditions on cover crop mixture; weather

has complicated effects of biomass production, species dominance and subsequent effects on cash crops.

Only one sweet corn variety was used in this trial, and the literature indicates that varietal selections can play a large role in N use (Heckman et al., 2002; Williams et al., 2009). Stivers-Young (1998) found that over-winter losses of biomass and N were greater in brassicas than in oats. Future studies should measure the spring residue biomass of winter-killed cover crops to more accurately assess winter N and biomass losses. It would also be useful to test a range of sidedress N fertilizer rates to determine the yield response with sufficient N.

This experiment was conducted on a new field each year at the research site. Yearly use of cover crop may reveal even larger benefits. In a long-term study, Constantin et al. (2010) found that main crop responded positively to cover crop frequency.

Currently there is a surge of research exploring the use of multi-species cover crop mixtures (Finney and Kaye, 2017; Finney et al., 2017; Finney et al., 2016; Melkonian et al., 2017; Murrell et al., 2017; Wendling et al., 2017; White et al., 2017; Wortman et al., 2012). Most of these experiments focus on high residue cover crops for commodity crops like field corn and soybeans, but there is much to be learned from the emerging research. In terms of designing a cover crop mixture, it is important to select species with matching rates of growth, in order to avoid competition (Bybee-Finley et al., 2016). Also, species selected for mixtures should be individually weed-suppressive and thrive under conditions of plant competition, as identified by pLER values of those species when grown within mixtures (Holmes et al., 2017; Smith et al., 2014).

Research Implications

Results of this study indicate that mixtures POFR and OFR can most efficiently cycle nutrients, suppress weeds, benefit sweet corn yield, and protect soil for sustainable no-till sweet corn production in the Northeast. The knowledge gained from these experiments can have a major impact in several ways. First, it demonstrates the feasibility of an integrated full-season production system for no-till sweet corn using winter-killed cover crops. A system with no spring residue management requirements and planting delay might be appealing to growers who are considering cover crop adoption. Second, this research indicates the feasibility of reducing nitrogen fertilizer applications at sweet corn planting, which will reduce nitrate leaching into groundwater. This is a concern for regulatory agencies as well as farmers who lose money when they lose N. Third, reduced fertilizer requirements also save input costs for farmers. No-till sweet corn production utilizing these types of winter cover crops could enhance sustainability over 4,800 hectares of production in the Northeast.

References

- Bybee-Finley K.A., Mirsky S.B., Ryan M.R. (2016) Functional diversity in summer annual grass and legume intercrops in the northeastern United States. *Crop Science* 56:2775-2790. DOI: 10.2135/cropsci2016.01.0046.
- Constantin J., Mary B., Laurent F., Aubrion G., Fontaine A., Kerveillant P., Beaudoin N. (2010) Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. *Agriculture Ecosystems & Environment* 135:268-278. DOI: 10.1016/j.agee.2009.10.005.
- Finney D.M., Kaye J.P. (2017) Functional diversity in cover crop polycultures increases multifunctionality of an agricultural system. *Journal of Applied Ecology* 54:509-517. DOI: 10.1111/1365-2664.12765.
- Finney D.M., Murrell E.G., White C.M., Baraibar B., Barbercheck M.E., Bradley B.A., Cornelisse S., Hunter M.C., Kaye J.P., Mortensen D.A., Mullen C.A., Schipanski M.E. (2017) Ecosystem services and disservices are bundled in simple and

- diverse cover cropping systems. *Agricultural & Environmental Letters* 2. DOI: 10.2134/aer2017.09.0033.
- Finney D.M., White C.M., Kaye J.P. (2016) Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. *Agronomy Journal* 108:39-52. DOI: 10.2134/agronj15.0182.
- Heckman J.R., Samulis R., Nitzsche P. (2002) Sweet corn crop nitrogen status evaluation by stalk testing. *HortScience* 37:783-786.
- Holmes A.A., Thompson A.A., Wortman S.E. (2017) Species-specific contributions to productivity and weed suppression in cover crop mixtures. *Agronomy Journal* 109:2808-2819. DOI: 10.2134/agronj2017.06.0309.
- Malpassi R.N., Kaspar T.C., Parkin T.B., Cambardella C.A., Nubel N.A. (2000) Oat and rye root decomposition effects on nitrogen mineralization. *Soil Science Society of America Journal* 64:208-215.
- Melkonian J., Poffenbarger H.J., Mirsky S.B., Ryan M.R., Moebius-Clune B.N. (2017) Estimating nitrogen mineralization from cover crop mixtures using the precision nitrogen management model. *Agronomy Journal* 109:1944-1959. DOI: 10.2134/agronj2016.06.0330.
- Murrell E.G., Schipanski M.E., Finney D.M., Hunter M.C., Burgess M., LaChance J.C., Baraibar B., White C.M., Mortensen D.A., Kaye J.P. (2017) Achieving diverse cover crop mixtures: Effects of planting date and seeding rate. *Agronomy Journal* 109:259-271. DOI: 10.2134/agronj2016.03.0174.
- Roesch-McNally G.E., Basche A.D., Arbuckle J.G., Tyndall J.C., Miguez F.E., Bowman T., Clay R. (2017) The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. *Natural Resource Ecology and Management Publications* 266.
- Roth R.T., Ruffatti M.D., O'Rourke P.D., Armstrong S.D. (2018) A cost analysis approach to valuing cover crop environmental and nitrogen cycling benefits: A central illinois on farm case study. *Agricultural Systems* 159:69-77. DOI: 10.1016/j.agsy.2017.10.007.
- Smith R.G., Atwood L.W., Warren N.D. (2014) Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services. *Plos One* 9:8. DOI: 10.1371/journal.pone.0097351.
- Stivers-Young L. (1998) Growth, nitrogen accumulation, and weed suppression by fall cover crops following early harvest of vegetables. *HortScience* 33:60-63.
- Teasdale J.R., Cavigelli M.A. (2010) Subplots facilitate assessment of corn yield losses from weed competition in a long-term systems experiment. *Agronomy for Sustainable Development* 30:445-453. DOI: 10.1051/agro/2009048.

- Wendling M., Buchi L., Amosse C., Jeangros B., Walter A., Charles R. (2017) Specific interactions leading to transgressive overyielding in cover crop mixtures. *Agriculture Ecosystems & Environment* 241:88-99. DOI: 10.1016/j.agee.2017.03.003.
- White C.M., DuPont S.T., Hautau M., Hartman D., Finney D.M., Bradley B., LaChance J.C., Kaye J.P. (2017) Managing the trade off between nitrogen supply and retention with cover crop mixtures. *Agriculture Ecosystems & Environment* 237:121-133. DOI: 10.1016/j.agee.2016.12.016.
- Williams M.M., Davis A.S., Rabaey T.L., Boerboom C.M. (2009) Linkages among agronomic, environmental and weed management characteristics in north american sweet corn. *Field Crops Research* 113:161-169. DOI: 10.1016/j.fcr.2009.05.005.
- Wortman S.E., Francis C.A., Bernards M.L., Drijber R.A., Lindquist J.L. (2012) Optimizing cover crop benefits with diverse mixtures and an alternative termination method. *Agronomy Journal* 104:1425-1435. DOI: 10.2134/agronj2012.0185.

BIBLIOGRAPHY

- Austin E.E., Wickings K., McDaniel M.D., Robertson G.P., Grandy A.S. (2017) Cover crop root contributions to soil carbon in a no-till corn bioenergy cropping system. *GCB Bioenergy* 9:1252-1263. DOI: 10.1111/gcbb.12428.
- Balesdent J., Chenu C., Balabane M. (2000) Relationship of soil organic matter dynamics to physical protection and tillage. *Soil & Tillage Research* 53:215-230. DOI: 10.1016/s0167-1987(99)00107-5.
- Baraibar B., Hunter M.C., Schipanski M.E., Hamilton A., Mortensen D.A. (2018) Weed suppression in cover crop monocultures and mixtures. *Weed Science* 66:121-133. DOI: 10.1017/wsc.2017.59.
- Berendsen R.L., Pieterse C.M., Bakker P.A. (2012) The rhizosphere microbiome and plant health. *Trends Plant Sci* 17:478-86. DOI: 10.1016/j.tplants.2012.04.001.
- Bhowmik P.C., Inderjit. (2003) Challenges and opportunities in implementing allelopathy for natural weed management. *Crop protection* 22:661-671.
- Blanco-Canqui H., Shaver T.M., Lindquist J.L., Shapiro C.A., Elmore R.W., Francis C.A., Hergert G.W. (2015) Cover crops and ecosystem services: Insights from studies in temperate soils. *Agronomy Journal* 107:2449-2474. DOI: 10.2134/agronj15.0086.
- Brock C., Fliessbach A., Oberholzer H.R., Schulz F., Wiesinger K., Reinicke F., Koch W., Pallutt B., Dittman B., Zimmer J., Hulsbergen K.J., Leithold G. (2011) Relation between soil organic matter and yield levels of nonlegume crops in organic and conventional farming systems. *Journal of Plant Nutrition and Soil Science* 174:568-575. DOI: 10.1002/jpln.201000272.
- Buchanan A.L., Kolb L.N., Hooks C.R. (2016) Can winter cover crops influence weed density and diversity in a reduced tillage vegetable system? *Crop protection* 90:9-16.
- Burgos N.R., Talbert R.E. (1996) Weed control and sweet corn (*zea mays* var *rugosa*) response in a no-till system with cover crops. *Weed Science* 44:355-361.
- Bybee-Finley K.A., Mirsky S.B., Ryan M.R. (2016) Functional diversity in summer annual grass and legume intercrops in the northeastern united states. *Crop Science* 56:2775-2790. DOI: 10.2135/cropsci2016.01.0046.
- Cabrera M.L., Kissel D.E., Vigil M.F. (2005) Nitrogen mineralization from organic residues: Research opportunities. *Journal of Environmental Quality* 34:75-79.
- Carrera L.M., Abdul-Baki A.A., Teasdale J.R. (2004) Cover crop management and weed suppression in no-tillage sweet corn production. *HortScience* 39:1262-1266.

- University of Vermont Extension Champlain Valley Crop, Soil & Pasture Team Cover crop diversity in no-till systems. March 10, 2018.
<https://www.uvm.edu/sites/default/files/Cover-Crop-Diversity-in-No-Till-Systems-Final-Report.pdf>.
- Chen G., Weil R.R. (2010) Penetration of cover crop roots through compacted soils. *Plant and Soil* 331:31-34. DOI: 10.1007/s11104-009-0223-7.
- Chen G., Weil R.R. (2011) Root growth and yield of maize as affected by soil compaction and cover crops. *Soil and Tillage Research* 117:17-27. DOI: 10.1016/j.still.2011.08.001.
- Christiansen J.S., Thorup-Kristensen K., Kristensen H.L. (2006) Root development of beetroot, sweet corn and celeriac, and soil n content after incorporation of green manure. *Journal of Horticultural Science & Biotechnology* 81:831-838.
- Cline G.R., Silvernail A.F. (2002) Effects of cover crops, nitrogen, and tillage on sweet corn. *Horttechnology* 12:118-125.
- Constantin J., Beaudoin N., Laurent F., Cohan J.-P., Duyme F., Mary B. (2011) Cumulative effects of catch crops on nitrogen uptake, leaching and net mineralization. *Plant and Soil* 341:137-154. DOI: 10.1007/s11104-010-0630-9.
- Constantin J., Mary B., Laurent F., Aubrion G., Fontaine A., Kerveillant P., Beaudoin N. (2010) Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. *Agriculture Ecosystems & Environment* 135:268-278. DOI: 10.1016/j.agee.2009.10.005.
- Cooper R.J., Hama-Aziz Z., Hiscock K.M., Lovett A.A., Dugdale S.J., Sunnenberg G., Noble L., Beamish J., Hovesen P. (2017) Assessing the farm-scale impacts of cover crops and non-inversion tillage regimes on nutrient losses from an arable catchment. *Agriculture Ecosystems & Environment* 237:181-193. DOI: 10.1016/j.agee.2016.12.034.
- Creamer N.G., Bennett M.A., Stinner B.R. (1997) Evaluation of cover crop mixtures for use in vegetable production systems. *HortScience* 32:866-870.
- CTIC. (2017) Report of the 2016-17 national cover crop survey, Joint publication of the Conservation Technology Information Center, the North Central Region Sustainable Agriculture Research and Education Program, and the American Seed Trade Association, West Lafayette, IN.
- Dabney S.M., Delgado, J. A., Meisinger, J. J., Schomberg, H. H., Liebig, M. A., Kaspar, T., ... & Reeves, W. (2010) Using cover crops and cropping systems for nitrogen management, *Advances in nitrogen management for water quality*. pp. 231-282.

- Dabney S.M., Delgado J.A., Reeves D.W. (2001) Using winter cover crops to improve soil and water quality. *Communications in Soil Science and Plant Analysis* 32:1221-1250. DOI: 10.1081/css-100104110.
- Dean J.E., Weil R.R. (2009) Brassica cover crops for nitrogen retention in the mid-atlantic coastal plain. *J Environ Qual* 38:520-8. DOI: 10.2134/jeq2008.0066.
- Dicklow M.B., McKeag L. (Eds.). (2016) *New england vegetable management guide*, UMass Extension, Amherst, MA.
- Dorn B., Jossi W., Van der Heijden M.G.A. (2015) Weed suppression by cover crops: Comparative on-farm experiments under integrated and organic conservation tillage. *Weed Research* 55:586-597. DOI: 10.1111/wre.12175.
- Drinkwater L.E., Janke R.R., Rossoni-Longnecker L. (2000) Effects of tillage intensity on nitrogen dynamics and productivity in legume-based grain systems. *Plant and Soil* 227:99-113. DOI: 10.1023/a:1026569715168.
- Drinkwater L.E., Wagoner P., Sarrantonio M. (1998) Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature* 396:262-265. DOI: 10.1038/24376.
- Fageria N.K. (2012) Role of soil organic matter in maintaining sustainability of cropping systems. *Communications in Soil Science and Plant Analysis* 43:2063-2113. DOI: 10.1080/00103624.2012.697234.
- Fageria N.K., Baligar V.C. (2005) Enhancing nitrogen use efficiency in crop plants, in: D. L. Sparks (Ed.), *Advances in agronomy*, vol 88, Elsevier Academic Press Inc, San Diego. pp. 97-185.
- Finney D.M., Buyer J.S., Kaye J.P. (2017) Living cover crops have immediate impacts on soil microbial community structure and function. *Journal of Soil and Water Conservation* 72:361-373. DOI: 10.2489/jswc.72.4.361.
- Finney D.M., Kaye J.P. (2017) Functional diversity in cover crop polycultures increases multifunctionality of an agricultural system. *Journal of Applied Ecology* 54:509-517. DOI: 10.1111/1365-2664.12765.
- Finney D.M., Murrell E.G., White C.M., Baraibar B., Barbercheck M.E., Bradley B.A., Cornelisse S., Hunter M.C., Kaye J.P., Mortensen D.A., Mullen C.A., Schipanski M.E. (2017) Ecosystem services and disservices are bundled in simple and diverse cover cropping systems. *Agricultural & Environmental Letters* 2. DOI: 10.2134/acl2017.09.0033.
- Finney D.M., White C.M., Kaye J.P. (2016) Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. *Agronomy Journal* 108:39-52. DOI: 10.2134/agronj15.0182.

- Fisk J.W., Hesterman O.B., Shrestha A., Kells J.J., Harwood R.R., Squire J.M., Sheaffer C.C. (2001) Weed suppression by annual legume cover crops in no-tillage corn. *Agronomy Journal* 93:319-325. DOI: 10.2134/agronj2001.932319x.
- Fox R.H., Roth G.W., Iversen K.V., Piekielek W.P. (1989) Soil and tissue nitrate tests compared for predicting soil-nitrogen availability to corn. *Agronomy Journal* 81:971-974.
- Gabriel J.L., Alonso-Ayuso M., Garcia-Gonzalez I., Hontoria C., Quemada M. (2016) Nitrogen use efficiency and fertiliser fate in a long-term experiment with winter cover crops. *European Journal of Agronomy* 79:14-22. DOI: 10.1016/j.eja.2016.04.015.
- Galloway B.A., Weston L.A. (1996) Influence of cover crop and herbicide treatment on weed control and yield in no-till sweet corn (*zea mays* l) and pumpkin (*cucurbita maxima* duch). *Weed Technology* 10:341-346.
- Gardner M., Sarrantonio M. (2012) Cover crop root composition and density in a long-term vegetable cropping system trial. *Journal of Sustainable Agriculture* 36:719-737. DOI: 10.1080/10440046.2012.672548.
- Gieske M.F., Wyse D.L., Durgan B.R. (2016) Spring- and fall-seeded radish cover-crop effects on weed management in corn. *Weed Technology* 30:559-572. DOI: 10.1614/wt-d-15-00023.1.
- Griffin T., Liebman M., Jemison J. (2000) Cover crops for sweet corn production in a short-season environment. *Agronomy Journal* 92:144-151.
- Grimmer O., Masiunas J. (2004) Evaluation of winter-killed cover crops preceding snap pea. *Horttechnology* 14:349-355.
- Groff S. (2006) A no-till success story. *American Vegetable Grower* 54:24.
- Haramoto E.R., Gallandt E.R. (2004) Brassica cover cropping for weed management: A review. *Renewable Agriculture and Food Systems* 19:187-198. DOI: 10.1079/rafs200490.
- Hashemi M., Farsad A., Sadeghpour A., Weis S.A., Herbert S.J. (2013) Cover-crop seeding-date influence on fall nitrogen recovery. *Journal of Plant Nutrition and Soil Science* 176:69-75. DOI: 10.1002/jpln.201200062.
- Heckman J., Hlubik W., Probst D., Paterson J. (1995) Pre-sidedress soil nitrate test for sweet corn. *HortScience* 30:1033-1036.
- Heckman J.R., Samulis R., Nitzsche P. (2002) Sweet corn crop nitrogen status evaluation by stalk testing. *HortScience* 37:783-786.

- Hobbs P.R. (2007) Conservation agriculture: What is it and why is it important for future sustainable food production? *Journal of Agricultural Science* 145:127-137. DOI: 10.1017/s0021859607006892.
- Hodgdon E.A., Warren N.D., Smith R.G., Sideman R.G. (2016) In-season and carry-over effects of cover crops on productivity and weed suppression. *Agronomy Journal* 108:1624-1635. DOI: 10.2134/agronj2015.0419.
- Holmes A.A., Thompson A.A., Wortman S.E. (2017) Species-specific contributions to productivity and weed suppression in cover crop mixtures. *Agronomy Journal* 109:2808-2819. DOI: 10.2134/agronj2017.06.0309.
- Hoyt G., Monks D., Monaco T. (1994) Conservation tillage for vegetable production. *Horttechnology* 4:129-135.
- Hoyt G.D. (1986) Conservation tillage for vegetable and tobacco production. *Soil & Tillage Research* 8:341-341. DOI: 10.1016/0167-1987(86)90381-8.
- Isse A., MacKenzie A.F., Stewart K., Cloutier D.C., Smith D.L. (1999) Cover crops and nutrient retention for subsequent sweet corn production. *Agronomy Journal* 91:934-939.
- Jabran K., Mahajan G., Sardana V., Chauhan B.S. (2015) Allelopathy for weed control in agricultural systems. *Crop protection* 72:57-65. DOI: 10.1016/j.cropro.2015.03.004.
- Jahanzad E., Barker A.V., Hashemi M., Eaton T., Sadeghpour A., Weis S.A. (2016) Nitrogen release dynamics and decomposition of buried and surface cover crop residues. *Agronomy Journal* 108:1735-1741. DOI: 10.2134/agronj2016.01.0001.
- Jahanzad E., Barker A.V., Hashemi M., Sadeghpour A., Eaton T. (2017) Forage radish and winter pea cover crops outperformed rye in a potato cropping system. *Agronomy Journal* 109:646-653. DOI: 10.2134/agronj2016.06.0342.
- Kabir Z., Koide R.T. (2002) Effect of autumn and winter mycorrhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in pennsylvania, USA. *Plant and Soil* 238:205-215. DOI: 10.1023/a:1014408723664.
- Kallenbach C.M., Frey S.D., Grandy A.S. (2016) Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls 7:13630. DOI: 10.1038/ncomms13630.
- Khan S.A., Mulvaney R.L., Ellsworth T.R., Boast C.W. (2007) The myth of nitrogen fertilization for soil carbon sequestration. *Journal of Environmental Quality* 36:1821-1832. DOI: 10.2134/jeq2007.0099.
- Kristensen H.L., Thorup-Kristensen K. (2004) Root growth and nitrate uptake of three different catch crops in deep soil layers. *Soil Science Society of America Journal* 68:529-537.

- Kristensen H.L., Thorup-Kristensen K. (2004) Uptake of ¹⁵N labeled nitrate by root systems of sweet corn, carrot and white cabbage from 0.2-2.5 meters depth. *Plant and Soil* 265:93-100.
- Kruidhof H.M., Bastiaans L., Kropff M.J. (2008) Ecological weed management by cover cropping: Effects on weed growth in autumn and weed establishment in spring. *Weed Research*. DOI: 10.1111/j.1365-3180.2008.00665.x.
- Kruidhof H.M., Bastiaans L., Kropff M.J. (2009) Cover crop residue management for optimizing weed control. *Plant and Soil* 318:169-184. DOI: 10.1007/s11104-008-9827-6.
- Kunz C., Sturm D.J., Varnholt D., Walker F., Gerhards R. (2016) Allelopathic effects and weed suppressive ability of cover crops. *Plant Soil and Environment* 62:60-66.
- Kuo S., Sainju U.M. (1998) Nitrogen mineralization and availability of mixed leguminous and non-leguminous cover crop residues in soil. *Biology and Fertility of Soils* 26:346-353. DOI: 10.1007/s003740050387.
- Kuo S., Sainju U.M., Jellum E.J. (1997) Winter cover cropping influence on nitrogen in soil. *Soil Science Society of America Journal* 61:1392-1399.
- Kuo S., Sainju U.M., Jellum E.J. (1997) Winter cover crop effects on soil organic carbon and carbohydrate in soil. *Soil Science Society of America Journal* 61:145-152.
- Lal R. (2004) Soil carbon sequestration impacts on global climate change and food security. *Science* 304:1623-1627. DOI: 10.1126/science.1097396.
- Lawley Y.E. (2010) Weed suppression by forage radish winter cover crops, Department of Environmental Science and Technology, University of Maryland, College Park, MD.
- Lawley Y.E., Teasdale J.R., Weil R.R. (2012) The mechanism for weed suppression by a forage radish cover crop. *Agronomy Journal* 104:205-214. DOI: 10.2134/agronj2011.0128.
- Lawley Y.E., Weil R.R., Teasdale J.R. (2011) Forage radish cover crop suppresses winter annual weeds in fall and before corn planting. *Agronomy Journal* 103:137-144. DOI: 10.2134/agronj2010.0187.
- Lawson A., Fortuna A.M., Cogger C., Bary A., Stubbs T. (2012) Nitrogen contribution of rye-hairy vetch cover crop mixtures to organically grown sweet corn. *Renewable Agriculture and Food Systems* 28:59-69. DOI: 10.1017/s1742170512000014.
- Lounsbury N.P. (2013) Spring seedbed characteristics after winterkilled cover crops, Department of Science and Technology, University of Maryland, College Park, MA.

- Lounsbury N.P., Weil R.R. (2014) No-till seeded spinach after winterkilled cover crops in an organic production system. *Renewable Agriculture and Food Systems* 30:473-485.
- Magdoff F., Weil R.R. (Eds.). (2004) *Soil organic matter in sustainable agriculture*, CRC Press, Boca Raton, FL.
- Malpassi R.N., Kaspar T.C., Parkin T.B., Cambardella C.A., Nubel N.A. (2000) Oat and rye root decomposition effects on nitrogen mineralization. *Soil Science Society of America Journal* 64:208-215.
- Meisinger J.J., Delgado J.A. (2002) Principles for managing nitrogen leaching. *Journal of Soil Water Conservation* 57:485-498.
- Melkonian J., Poffenbarger H.J., Mirsky S.B., Ryan M.R., Moebius-Clune B.N. (2017) Estimating nitrogen mineralization from cover crop mixtures using the precision nitrogen management model. *Agronomy Journal* 109:1944-1959. DOI: 10.2134/agronj2016.06.0330.
- Messiga A.J., Sharifi M., Munroe S. (2016) Combinations of cover crop mixtures and bio-waste composts enhance biomass production and nutrients accumulation: A greenhouse study. *Renewable Agriculture and Food Systems* 31:507-515. DOI: 10.1017/s1742170515000423.
- Mohler C.L. (1991) Effects of tillage and mulch on weed biomass and sweet corn yield. *Weed Technology* 5:545-552.
- Möller K., Reents H.-J. (2009) Effects of various cover crops after peas on nitrate leaching and nitrogen supply to succeeding winter wheat or potato crops. *Journal of Plant Nutrition and Soil Science* 172:277-287. DOI: 10.1002/jpln.200700336.
- Mulvaney R.L., Khan S.A., Ellsworth T.R. (2009) Synthetic nitrogen fertilizers deplete soil nitrogen: A global dilemma for sustainable cereal production. *Journal of Environmental Quality* 38:2295-2314. DOI: 10.2134/jeq2008.0527.
- Murrell E.G., Schipanski M.E., Finney D.M., Hunter M.C., Burgess M., LaChance J.C., Baraibar B., White C.M., Mortensen D.A., Kaye J.P. (2017) Achieving diverse cover crop mixtures: Effects of planting date and seeding rate. *Agronomy Journal* 109:259-271. DOI: 10.2134/agronj2016.03.0174.
- O'Reilly K.A., Lauzon J.D., Vyn R.J., Van Eerd L.L. (2012) Nitrogen cycling, profit margins and sweet corn yield under fall cover crop systems. *Canadian Journal of Soil Science* 92:353-365. DOI: 10.4141/cjss2011-065.
- O'Reilly K.A., Robinson D.E., Vyn R.J., Van Eerd L.L. (2011) Weed populations, sweet corn yield, and economics following fall cover crops. *Weed Technology* 25:374-384. DOI: 10.1614/wt-d-10-00051.1.

- Peachey R.E., William R.D., Mallory-Smith C. (2004) Effect of no-till or conventional planting and cover crops residues on weed emergence in vegetable row crop. *Weed Technology* 18:1023-1030. DOI: 10.1614/wt-03-205r.
- Poffenbarger H.J., Mirsky S.B., Weil R.R., Maul J.E., Kramer M., Spargo J.T., Cavigelli M.A. (2015) Biomass and nitrogen content of hairy vetch–cereal rye cover crop mixtures as influenced by species proportions. *Agronomy Journal* 107:2069. DOI: 10.2134/agronj14.0462.
- Puget P., Drinkwater L.E. (2001) Short-term dynamics of root- and shoot-derived carbon from a leguminous green manure. *Soil Science Society of America Journal* 65:771-779.
- Qasem J.R. (1992) Nutrient accumulation by weeds and their associated vegetable crops. *Journal of Horticultural Science* 67:189-195. DOI: 10.1080/00221589.1992.11516236.
- Ranells N.N., Waggoner M.G. (1996) Nitrogen release from grass and legume cover crop monocultures and bicultures. *Agronomy Journal* 88:777-882. DOI: 10.2134/agronj1996.00021962008800050015x.
- Reeves D.W. (1997) The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil & Tillage Research* 43:131-167. DOI: 10.1016/s0167-1987(97)00038-x.
- Roesch-McNally G.E., Basche A.D., Arbuckle J.G., Tyndall J.C., Miguez F.E., Bowman T., Clay R. (2017) The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. *Natural Resource Ecology and Management Publications* 266.
- Roth R.T., Ruffatti M.D., O'Rourke P.D., Armstrong S.D. (2018) A cost analysis approach to valuing cover crop environmental and nitrogen cycling benefits: A central illinois on farm case study. *Agricultural Systems* 159:69-77. DOI: 10.1016/j.agry.2017.10.007.
- Sainju U.M., Singh B.P., Whitehead W.F. (2002) Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in georgia, USA. *Soil and Tillage Research* 63:167-179.
- Sainju U.M., Whitehead W.F., Singh B.P. (2005) Biculture legume-cereal cover crops for enhanced biomass yield and carbon and nitrogen. *Agronomy Journal* 97:1403-1412. DOI: 10.2134/agronj2004.0274.
- Sarrantonio M., Gallandt E. (2003) The role of cover crops in north american cropping systems. *Journal of Crop Production* 8:53-74.

- Schomberg H.H., Endale D.M., Calegari A., Peixoto R., Miyazawa M., Cabrera M.L. (2006) Influence of cover crops on potential nitrogen availability to succeeding crops in a southern piedmont soil. *Biology and Fertility of Soils* 42:299-307. DOI: 10.1007/s00374-005-0027-8.
- Six J., Bossuyt H., Degryze S., Deneff K. (2004) A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil & Tillage Research* 79:7-31. DOI: 10.1016/j.still.2004.03.008.
- Six J., Elliott E.T., Paustian K. (1999) Aggregate and soil organic matter dynamics under conventional and no-tillage systems. *Soil Science Society of America Journal* 63:1350-1358.
- Smith R.G., Atwood L.W., Warren N.D. (2014) Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services. *Plos One* 9:8. DOI: 10.1371/journal.pone.0097351.
- Snapp S.S., Swinton S.M., Labarta R., Mutch D., Black J.R., Leep R., Nyiraneza J., O'Neil K. (2005) Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agronomy Journal* 97:322-332.
- Stivers-Young L. (1998) Growth, nitrogen accumulation, and weed suppression by fall cover crops following early harvest of vegetables. *HortScience* 33:60-63.
- Stubbs T.L., Kennedy A.C., Schillinger W.F. (2004) Soil ecosystem changes during the transition to no-till cropping. *Journal of Crop Improvement* 11:105-135. DOI: 10.1300/J411v11n01_06.
- Swanton C.J., Shrestha A., Roy R.C., Ball-Coelho B.R., Knezevic S.Z. (1999) Effect of tillage systems, n, and cover crop on the composition of weed flora. *Weed Science* 47:454-461.
- Teasdale J.R. (1996) Contribution of cover crops to weed management in sustainable agricultural systems. *Journal of Production Agriculture*.
- Teasdale J.R., Abdul-Baki A.A., Park Y.B. (2008) Sweet corn production and efficiency of nitrogen use in high cover crop residue. *Agronomy for Sustainable Development* 28:559-565. DOI: 10.1051/agro:2008029.
- Teasdale J.R., Cavigelli M.A. (2010) Subplots facilitate assessment of corn yield losses from weed competition in a long-term systems experiment. *Agronomy for Sustainable Development* 30:445-453. DOI: 10.1051/agro/2009048.
- Teasdale J.R., Mohler C.L. (1993) Light transmittance, soil temperature, and soil moisture under mulch of hairy vetch and rye. *Agronomy Journal* 85:673-680.

- Thorup-Kristensen K. (2000) Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-n content, and how can this be measured? *Plant and Soil* 230:185-195.
- Thorup-Kristensen K. (2001) Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-n content, and how can this be measured? *Plant and Soil* 230:185-195. DOI: 10.1023/A:1010306425468.
- Tonitto C., David M.B., Drinkwater L.E. (2006) Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and n dynamics. *Agriculture*.
- Trinsoutrot I., Recous S., Bentz B., Line`res M., Che`neby D., Nicolardot B. (2000) Biochemical quality of crop residues and carbon and nitrogen mineralization kinetics under nonlimiting nitrogen conditions. *Soil Sci. Soc. Am. J.* 64:918-926. . DOI: doi:10.2136/sssaj2000.643918x.
- Triplett G.B., Dick W.A. (2008) No-tillage crop production: A revolution in agriculture! *Agronomy Journal* 100:S153-S165. DOI: 10.2134/agronj2007.0005c.
- Tursun N., Datta A., Sakinmaz M.S., Kantarci Z., Knezevic S.Z., Chauhan B.S. (2016) The critical period for weed control in three corn (*zea mays* l.) types. *Crop protection* 90:59-65. DOI: 10.1016/j.cropro.2016.08.019.
- USDA-NASS. (2016) New england fruits and vegetables, in: G. R. Keough (Ed.), *New England Agricultural Statistics 2015*, USDA National Agricultural Statistics Service, Concord, NH.
- United States Department of Agriculture, Natural Resource Conservation Service. Soil health. October 26, 2017. <https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/>.
- Villamil M.B., Bollero G.A., Darmody R.G., Simmons F.W., Bullock D.G. (2006) No-till corn/soybean systems including winter cover crops: Effects on soil properties. *Soil Science Society of America Journal* 70:1936-1944. DOI: 10.2136/sssaj2005.0350.
- Vincent E.M., Roberts E.H. (1977) Interaction of light, nitrate and alternating temperature in promoting germination of dormant seeds of common weed species. *Seed Science and Technology* 5:659-670.
- Vogel K.P. (1978) A simple method of converting rangeland drill to experimental plot seeders. *Journal of Range Management* 31:235-237.
- Weil R., Kremen A. (2007) Thinking across and beyond disciplines to make cover crops pay. *Journal of the Science of Food and Agriculture* 87:551-557. DOI: 10.1002/jsfa.2742.

- Maryland Cooperative Extension. Forage radish: New multi-purpose cover crop for the mid-atlantic. Fact sheet 824. March 13.
https://enst.umd.edu/sites/enst.umd.edu/files/_docs/FactSheet824%20Weil%20et%20al%202009.pdf.
- Weinert T.L., Pan W.L., Moneymaker M.R., Santo G.S., Stevens R.G. (2002) Nitrogen recycling by nonleguminous winter cover crops to reduce leaching in potato rotations. *Agronomy Journal* 94:365-372.
- Wells M.S., Reberg-Horton S.C., Smith A.N., Grossman J.M. (2013) The reduction of plant-available nitrogen by cover crop mulches and subsequent effects on soybean performance and weed interference. *Agronomy Journal* 105:539-545. DOI: 10.2134/agronj2012.0396.
- Wendling M., Buchi L., Amosse C., Jeangros B., Walter A., Charles R. (2017) Specific interactions leading to transgressive overyielding in cover crop mixtures. *Agriculture Ecosystems & Environment* 241:88-99. DOI: 10.1016/j.agee.2017.03.003.
- Wendling M., Buchi L., Amosse C., Sinaj S., Walter A., Charles R. (2016) Influence of root and leaf traits on the uptake of nutrients in cover crops. *Plant and Soil* 409:419-434. DOI: 10.1007/s11104-016-2974-2.
- Weston L.A. (2005) History and current trends in the use of allelopathy for weed management. *Horttechnology* 15:529-534.
- White C.M., DuPont S.T., Hautau M., Hartman D., Finney D.M., Bradley B., LaChance J.C., Kaye J.P. (2017) Managing the trade off between nitrogen supply and retention with cover crop mixtures. *Agriculture Ecosystems & Environment* 237:121-133. DOI: 10.1016/j.agee.2016.12.016.
- White C.M., Weil R.R. (2011) Forage radish cover crops increase soil test phosphorus surrounding radish taproot holes. *Soil Science Society of America Journal* 75:121-130. DOI: 10.2136/sssaj2010.0095.
- Williams M.M. (2008) Sweet corn growth and yield response to planting dates of the north central united states. *HortScience* 43.
- Williams M.M., Davis A.S., Rabaey T.L., Boerboom C.M. (2009) Linkages among agronomic, environmental and weed management characteristics in north american sweet corn. *Field Crops Research* 113:161-169. DOI: 10.1016/j.fcr.2009.05.005.
- Wortman S.E., Francis C.A., Bernards M.L., Drijber R.A., Lindquist J.L. (2012) Optimizing cover crop benefits with diverse mixtures and an alternative termination method. *Agronomy Journal* 104:1425-1435. DOI: 10.2134/agronj2012.0185.

Zotarelli L., Avila L., Scholberg J.M.S., Alves B.J.R. (2009) Benefits of vetch and rye cover crops to sweet corn under no-tillage. *Agronomy Journal* 101:252-260. DOI: 10.2134/agronj2008.0033x.