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**Rye cover crop biomass, nutrient composition and crop management practices to enhance corn yield**

by

**Swetabh Patel**

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Soil Science

Program of Study Committee:
John E. Sawyer, Major Professor
Antonio P. Mallarino
Kenneth J. Moore

Iowa State University

Ames, Iowa

2016

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# DEDICATION

I dedicate this thesis to my father Shivdas Singh and my mother Suman Singh. Without their unconditional support, encouragement and love for agriculture this aspiration may never have been fulfilled. A special appreciation for my undergraduate mentor Dr. Amitava Rakshit, whose continuous words of motivation kept reminding me the significance of my contribution to science and earning an advanced degree.

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# CHAPTER 1. GENERAL INTRODUCTION

With the intensification of modern agriculture, overall crop production has increased greatly. However, that increase has come at a price of reduced inherent soil fertility and loss of agricultural biodiversity. Some of the most challenging problems facing crop production systems today are climate change, loss of nutrients (especially N and P) from fields as a result of leaching and runoff, and loss of fertile topsoil with wind and water erosion. Annually, approximately $1 billion worth of crop production is lost in Iowa as a result of soil erosion. Also, N and P escaping from production fields are contaminating surface waters with effects on Iowa drinking water $NO_3$ levels and N and P related effects on hypoxia in the Gulf of Mexico.

In the USA, Iowa has the greatest number of cropland acres annually planted to corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. Optimizing fertilizer nutrient use and reducing loss of N and P from corn and soybean fields is an ongoing issue in Iowa. Following grain crop harvest, the soil is left without any vegetation for rest of the fall and throughout the winter until planting of crops in the spring. The spring period, before planting and during early crop growth, is the most critical period for potential loss of soil and nutrients from fields, especially $NO_3$-N.

Winter cover crops, along with benefits such as erosion control, have the potential to take up residual inorganic-N remaining in the soil after corn or soybean grain crop harvest. Winer cereal rye (*Secale cereal* L.) is one of the most widely adopted cover crops in the Midwest USA due to its ease of establishment, ability to survive severe winter conditions, and ability to effectively scavenge residual inorganic-N with its extensive fibrous root system. These properties result in significant reduction of $NO_3$

leaving fields through tile drainage. Several studies have looked at winter cereal rye above ground biomass production, nutrient uptake, and potential impact on soil and nutrient dynamics. However, questions remain about the relative productivity of cereal rye cover crop plant components: such as how much root biomass is produced, what is the composition of rye roots in terms of C and N storage, and what would be the effect of root biomass decomposition on soil dynamics and nutrient availability. Currently, there is a lack of sufficient information available to fully answer these questions when cereal rye is used as a cover crop between the common corn and soybean grain crops.

Farmers, being the biggest stakeholders, have begun to realize their role in effectively reducing $NO_3$ loss from fields and related soil and water quality conservation. Adoption and integration of cover crops by farmers is increasing, but the rate of adoption is low. Incentives for integrating cover crops into grain crop production systems comes from immediate water quality benefits, and potential for long–term soil quality benefits. However, no grain crop yield enhancement, and especially a reduction in crop yield resulting from rye cover crop use would further discourage adaptation of rye as a cover crop. Previous studies have shown a neutral to positive effect of rye cover crops on soybean yield, but studies have linked a neutral to negative effect of rye cover crops on corn yield. Such yield reduction discourages use in the most vulnerable situation, low crop residue level from soybean harvest to the next crop, which in Iowa is typically corn.

This thesis includes two projects with overall objectives to understand the role of the winter cereal rye cover crop system in regard to biomass production, N cycling, and effects on corn and soybean production. Most importantly, an overall objective was to study potential agronomic practices that can help improve corn grain yield in a rye cover crop system. The first project studied rye root and shoot biomass production, C and N uptake, and plant component allocation at the time of rye termination in the spring. The second project evaluated the effect of a rye cover crop on corn growth and yield, as well as corn response to tillage system and starter N fertilizer. The first project was a one–year study conducted at an ongoing research site with no-till corn in rotation with soybean and winter rye cover seeded after both crops. The second project was a two year study conducted at four locations in major Iowa landform areas.

Results of these studies are helping to better understand improved integration of rye cover crops in grain crop systems for soil and water quality efforts, and its effect on the common corn and soybean production in relation to system resilience and productivity. The results of this research will help promote rye cover crop adoption and integration into grain cropping systems in Iowa and the Midwest USA. Corn yield decrease due to cover crops is not acceptable to farmers, and agronomic practices must be identified that have potential to alleviate any yield reduction, and more importantly improve grain crop yields.

## THESIS ORGANIZATION

This thesis contains 4 chapters. The first chapter is a brief description of the thesis research. Chapters 2 and 3 are manuscripts describing the efforts and outcomes of the individual studies, with the intention of being published in scientific journals such as Agronomy Journal. The titles of the manuscripts are “Root and Shoot Biomass and Nutrient Composition in a Winter Rye Cover Crop” and “Enhancing Corn Yield When

Grown in a Winter Rye Cover Crop System". Chapter 4 provides a summary of general conclusions for the research conducted in this thesis.

# CHAPTER 2. ROOT AND SHOOT BIOMASS AND NUTRIENT COMPOSITION IN A WINTER RYE COVER CROP

A paper to be submitted to Agronomy Journal

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## Abstract

Winter cereal rye (*Secale cereal* L.), a commonly used cover crop in corn (*Zea mays* L.) systems has potential to scavenge soil $NO_3$–N through a fibrous root system. The objective of this study was to quantify root and shoot biomass, C, and N partitioning in rye cover crop at the time of termination in spring. This was a one–year study conducted at a site with a no-till corn–soybean [*Glycine max* (L.) Merr.] rotation, rye drilled following grain crop harvest, and three N rates applied to corn (0, 135, and 225 kg N $ha^{-1}$). Rye root biomass to 60-cm depth following corn and 30-cm depth following soybean was estimated using ingrowth tubes installed in the fall after rye seeding and removed at the time of rye termination in the spring. For rye following corn and soybean, 48 and 62 %, respectively, of the total root biomass was present in the top 15-cm depth. Overall, the shoot biomass, C, and N was significantly greater than for roots, with approximately two times more shoot than root material and only 33–36 % of total plant C and 17–18 % of total plant N in the root biomass. The C:N ratio of root biomass was consistently high (47–52), and at least double the shoot (16–23). With high C, low N, and

high C:N ratio of the rye roots, inorganic-N from soil or degrading shoot biomass could be immobilized with root degradation and reduce potential N recycling.

## Introduction

With advent of N fertilizer production in the first half of 20th century, there has been an extensive use of N in crop production to meet the rapid increase in demand for food with increasing population. High input mono-cropping systems, with either continuous corn or corn in rotation with soybean, are common in the north-central region of the USA. Nitrogen is the most widely used fertilizer nutrient as it is a highly important and most frequently needed input required by corn. For a typical N rate recommendation, about 35 % of the total inorganic fertilizer N applied is recovered in the aboveground biomass of corn plant (Cassman et al., 2002), and the rest is either immobilized in the soil organic pool or lost from the soil system through denitrification and leaching. Widespread leaching of $NO_3$ from agricultural land to groundwater and river systems is a major environmental concern, with as high as 58 kg $NO_3$–N ha$^{-1}$ yr$^{-1}$ lost to drainage water from fields with typical N rates applied to corn (Sawyer and Randall, 2008).

Cover crops are primarily integrated in the annual cropping system at times of the year when crops are not actively growing. Generally seeded in fall before grain crop maturity or after crop harvest, cover crops protect the soil surface from wind and water erosion by providing a cover (Dittmer, 1937; Frankenberger and Abdelmagid, 1985; Smith et al., 1987; Kaspar et al., 2001; Dabney et al., 2001), scavenge residual $NO_3$ (Sainju et al., 1998; Iowa State University, 2014) and therefore lessen $NO_3$ loss from the soil system through drainage water (Meisinger et al., 1990; Kaspar et al., 2007). Cover crops have been reported to reduce $NO_3$–N load in drainage water by 13 to 94 % (Kaspar et al., 2008) and recycle up to 132 kg N $ha^{-1}$ (Dabney et al., 2001) when early planted. Through improved soil physical and chemical conditions, root growth, organic matter addition, and water infiltration (Kuo et al., 1997) cover crops can reduce runoff P loss up to 54–94 % (Kaspar et al., 2008).

Legume crops often were used as a green manure N source before the availability of inexpensive N fertilizers, and due to many environmental benefits cover crops have gained an increased interest in recent years (Iowa State University, 2014). The overall role of cover crops in recycling nutrients and adding organic matter to soil mainly depends on climate, soil characteristics, and growth stage at which the cover crop is terminated or incorporated in to the soil (Meisinger et al., 1991; Shennan, 1992; Kuo et al., 1996; Arun et al., 2015). As cereal plants grow, they continuously produce new roots while the old roots die and decompose (Troughton, 1981), therefore, accumulation and retention of biomass and nutrients between root and shoot can be different at different growth stages and soil conditions (Kuo et al., 1996). A 50 % decrease in rye root N concentration leading to an increased C:N ratio as rye plant growth progresses was reported by Gardner and Sarrantonio (2012). Differences in the chemical composition of cover crop species at different growth stages would determine the rate and the nature of decomposition (Quemada and Cabrera, 1995) as growth and functionality of soil microbial biomass responsible for decomposition depends on the availability of C and N pools (Reinertsen et al., 1984). In the process of plant biomass decomposition, N is needed to balance added C (Kuo et al., 1997), therefore, cover crop residues with a higher

C:N ratio will lead to temporary N immobilization (Pink et al., 1945; Stevenson and Cole, 1999) and slowed release of N available for the following crop.

Just as the aboveground biomass of cover crops is important for protecting the soil surface, the belowground root biomass is also important and plays a significant role in improving the physical and biological characteristics of soil (Schutter and Dick, 2002). Belowground biomass of cover crops can comprise 20–30 % of the total plant biomass (Fransen et al., 1998; Rasse et al., 1999; Puget and Drinkwater, 2001; Williams et al., 2006). In a study conducted by Chen and Weil (2010), roots (0–6 cm depth) of rapeseed (*Brassica napus* cv. Essex) and cereal rye were reported to be 18 and 25 % of the total plant biomass, respectively. Roots remain in the ground after cover crop termination and like shoots, undergo degradation and decomposition transforming C and N in the soil (Arun et al., 2015).

Efforts have been made to estimate root growth and distribution in various cereals, forest trees, and cover crops using different techniques (Bland and Dugas, 1988; Sainju et al., 1998; Makkonen and Helmisaari, 1999; Russell et al., 2004; Ontl et al., 2013). Gardner and Sarrantonio (2012) emphasized that the contribution of cover crop roots to soil dynamics is poorly understood since there is little information available on its quantitative distribution. Roots of cover crops penetrate into soil, and after decomposition a network of root channels are left behind which can facilitate growth of the subsequent crop roots (Williams and Weil, 2004).

Winter cereal rye, a commonly used cover crop in corn–soybean rotations, is one of the most winter hardy cover crops. Cereal rye has intense rooting near the soil surface (Bodner et al., 2010), and therefore living and decaying rye roots, and degradation byproducts, can significantly contribute to soil nutrient dynamics (Kavdir and Smucker, 2005). Greater aboveground biomass production and higher root density per unit soil area makes rye a more efficient N scavenger (Sainju et. al., 1998) compared to leguminous crops like hairy vetch (*Vicia villosa* Roth) or crimson clover (*Trifolium incarnatum* L.) (McCracken et al., 1994; Meisinger et al., 1991).

In order to better understand cover crop performance and N cycling, there is a need to understand root-shoot quantitative characteristics and effects on soil, water, and nutrient dynamics (Gardner and Sarrantonio, 2012). Quantification of cover crop physical and chemical growth parameters is necessary in order to optimize use and management in complex cropping systems. A detailed species description of cover crop physical and chemical characteristics is still lacking, including limited information on the quantitative distribution of biomass components and the relationship of root and shoot in terms of C and N accumulation. Establishing a shoot:root ratio could also be helpful in estimating root biomass when only the shoot biomass is known (Amanullah, 2014). In addition, there is a need to better understand potential net N supply to grain crops from a rye cover crop as some studies have shown no change in corn N fertilization rate when grown following a rye cover crop (Pantoja et al., 2015).

Studies have been conducted on quantification of rye root biomass and surface area in greenhouse growth (Dittmer, 1937; Rosene, 1955), but there is limited information on rye cover crop root systems and nutrient accumulation at termination in the field. Because winter rye as a cover crop is of current high interest in the Midwest USA for use in reducing $NO_3$–N loss to surface waters, and N recycling to annual grain crops, information is needed about the relation of the root system in regard to total plant biomass, C, and N. The objectives of this study were to quantify the root and shoot biomass and partitioning of C and N in a winter cereal rye cover crop at termination in the spring before corn and soybean planting.

## Materials and Methods

### Site Description

The study was conducted from the fall 2014 to spring 2015 at an ongoing cover crop research site situated at the Iowa State University Agricultural Engineering and Agronomy Research farm near Boone, IA (42°00’34”N; 93°46’50”W). Soils included two Mollisols; Clarion loam (fine-loamy, mixed, superactive, mesic typic hapludolls) and Nicollet clay loam (fine-loamy, mixed, superactive, mesic aquic hapludolls). The site had a winter cereal rye cover crop treatment, six N rates applied sidedress to corn, no-till, and corn–soybean rotation history beginning fall 2008 (details presented in Pantoja et al., 2015). Each crop was present each year, in separate field areas. Soil tests for P, K, and pH were maintained in the optimum test category with fertilizer and lime applied as directed by soil tests and crop removal (Mallarino et al., 2013). Monthly precipitation and mean air temperature for the study site were calculated from data collected daily from a nearby weather station and reported by Iowa Environment Mesonet Network (Arritt and Herzmann, 2015).

### Experimental Design and Treatments

Both the corn and soybean phases were used for the study, along with three of the six N fertilizer rates (0, 135 and 225 kg N $ha^{-1}$ applied to corn only). For rye seeding following soybean, there were four replications and for rye following corn only three replications due to water damage in the 2014 corn crop within one replication. The experimental design was a randomized complete block, with rye cover crop the main plot and N rate the subplot. For this study, there is no differential main plot as only rye treatments were used. Individual plot size was eight crop rows (0.76 m row spacing) in width and 15 m in length. Winter cereal rye ('Wheeler') was no-till drilled following soybean (30 Sept. 2014) and corn (22 Oct. 2014) harvest at 63 kg $ha^{-1}$ seeding rate, and in 0.19 m row spacing. Rye was terminated 29 Apr., 2015 following soybean and 8 May, 2015 following corn with application of 1–2 kg a.i. $ha^{-1}$ of glyphosate [N(phosphonomethyl)glycine]. Rye termination was planned for approximately 2 wk before corn planting and 1 wk before soybean planting.

**Rye Root Sampling**

Rye root growth was determined using a root ingrowth core technique (Steingrobe et al., 2000; Russel et al., 2004; Ontl et al., 2013). Potential bias can occur with the ingrowth core method due to the absence of old root channels within the ingrowth tubes (Nambiar and Sands, 1992). However, the ingrowth tube method allows direct estimation of root production and, therefore, is useful to make comparisons across treatments when potential bias is uniform within the study (Messier and Puttonen, 1993). Two ingrowth tubes were installed per plot to help with within-plot rye stand and growth spatial variation. The ingrowth tube depths were 0–60 cm following corn and 0–30 cm following soybean). The tubes were placed between rye rows shortly after seeding.

The ingrowth tubes were polypropylene tubing, 5.6 cm inside diameter, with 0.56 x 0.33 cm mesh openings (Industrial Netting, Minneapolis, MN). The tube bottoms were covered to hold soil in place by sewing a polypropylene screen across the tube end having 0.30 x 0.44 cm mesh. For installation of the ingrowth tubes, soil cores were collected with a hand-operated soil corer that had the same diameter as the outside dimension of the ingrowth tubes. The soil removed was saved, sieved cleaned of any stones, roots and organic debris, placed back into respective tubes, and compacted approximately to the original bulk density using a wooden dowel. For ingrowth tubes in rye following corn, soil from 0–30 cm and 30–60 cm depths was processed separately. The ingrowth tubes were installed into the respective cored holes from where soil was collected. At the time of soil removal and tube installation the soil was considerably wet, especially in the plots of rye following soybean. Therefore, only the 0–30 cm depth could be used following soybean.

Ingrowth tubes were removed at the time of rye termination and stored at 4°C for no more than 7 d before processing to separate root biomass from soil (Ontl et al., 2013). Any root material outside of the tube was removed flush to the tube and the ingrowth tubes were cut into 15-cm increments. The resulting sections of soil were placed inside a 250 μm mesh tube with both ends closed and washed in a modified root elutriator for 3–4 hours (Smucker et al., 1982). All materials remaining inside the elutriator tube were removed and rye roots sorted from sand and organic debris by floating in deionized water and hand picking with forceps under a magnifying lens. Separation of larger and coarser roots was easier compared to small fine rootlets. It was important, however, to recover as much root as possible for analysis and to represent root biomass. Separation of rye roots was possible due to their distinct morphology, color, and resilience. Roots were dried in a pre-weighed aluminum foil envelop at 65°C for 48 hr (Valverde-Barrantes et al., 2007) and then weighed.

**Rye Shoot Sampling**

In order to compare the allocation of biomass and partitioning of C and N between above and belowground rye at the time of termination, aboveground rye biomass was determined by collecting rye shoots within a 0.3-m distance of the ingrowth tube along the rye row on each side of the tube, including shoots from the two rye rows corresponding to the diameter of the ingrowth tube. The equivalent area sampled was adjusted for the rye row spacing, totaling 0.255 $m^2$. It was assumed that this shoot biomass would relate to the root biomass within the ingrowth tube. Shoot biomass collected was dried at 65°C for 48 hr.

**Rye Biomass Analysis**

Dried root and shoot biomass were ground in a ball mill and Udy mill (passed through 2-mm mesh), respectively. All biomass samples were analyzed for total C and N by high temperature combustion analysis using a vario MICRO cube (Elementar Americas Inc., Mt. Laurel, NJ). Rye root dry biomass was up-scaled for each respective depth by converting the amount per tube diameter to an ha basis and the shoot dry biomass was up-scaled using the area sampled. The C and N amounts for root biomass were calculated by multiplying the biomass per depth in the ingrowth tube times the respective concentration. For the shoot, C and N amounts were calculated by multiplying the biomass times the respective concentration. Total C and N amount for root biomass per ha basis was calculated by adding the amounts per increment depth. The C:N ratio of root and shoot biomass were determined from the amount per area.

**Soil Sampling and Analysis**

Composites of three cores, 0–30 cm depth, were collected within close proximity around the ingrowth tube locations at the time of tube installation and removal. Soil samples were dried in a forced air oven at 25°C for 48 hr and ground to pass a 2-mm sieve. Soil was extracted with a 2*M* KCl solution (1:5 soil to solution ratio) and shaking for 1 hr. Soil extracts were filtered through pre-leached Whatman No. 1 filter paper and kept frozen until analysis. The $NO_3$–N concentrations were determine by the microplate colorimetric method using Griess-Ilosvay reagent with Vanadium (III) chloride as reducing agent (Hood-Nowotny et al., 2010).

**Statistical Analysis**

The mean of the two root ingrowth core locations per plot were used for analysis. Rye biomass and partitioning of C and N between rye components (shoot and root) were analyzed using PROC GLIMMIX analysis of variance (SAS Institute, 2015). Nitrogen rate was considered a fixed effect and replication random. Comparison between fall and spring soil $NO_3$–N used sample time as a split-plot. Treatment effects were considered significant at $P \leq 0.05$, with mean separation using the LINES option of the LSMEANS statement. Within each ingrowth tube, the rye root parameters (biomass, C and N concentrations, and C:N ratio) could be correlated by depth. Therefore, different potential analysis models for repeated measure were tested to analyze the effect of rooting depth. No significant correlation between depths was found with the different repeated measure models, therefore, depth was treated as a split-plot. Because corn and soybean were in different areas, and rye seeding and termination dates were different following each crop, rye shoot and root parameters cannot be compared directly between previous crops.

## Results and Discussion

### Weather

Grain crop harvest timing and yield can affect residual soil $NO_3$–N, rye seeding date, and germination/establishment. Similarly, temperature and precipitation conditions in the fall and spring can also affect soil $NO_3$–N level, and rye nutrient uptake, growth, and termination date relative to grain crop planting. Figure 1(a) has the mean monthly air temperature compared to the 30-yr mean (normal). The air temperatures during the time of rye seeding in late September and late October in 2014 (following soybean and corn, respectively) were similar to the 30-yr mean. In the second wk of November 2014, soil temperatures reached freezing and remained for several days, which stopped rye growth. Temperatures through the winter were below freezing and thus prevented rye growth during the wintertime. Spring 2015 temperatures were near normal. Precipitation (Fig. 1b) was above normal in the late summer and early fall 2014, with 2014 annual precipitation 11.5 cm above the 30-yr mean, which resulted in high soil moisture at the end of the season, low soil profile $NO_3$– N (Table 1), and difficulty with some ingrowth tube installations. After rye seeding, precipitation was below normal in November, about normal in December, below normal in the wintertime, and slightly below normal in April. Overall, moisture was adequate for spring rye growth.

### Soil Nitrate-N

Research has shown that in an unfertilized soil the limitation of plant available N results in more root biomass allocation as compared to shoot as roots have to extensively explore a larger soil volume (Bonifas et al., 2005; Liebman et al., 2013). In our study, despite a high N application rate to corn, fertilizer rate had only an inconsistent effect on post-harvest soil $NO_3$–N concentrations, with overall low concentrations in the top 30-cm of soil at the time of ingrowth tube installation following corn (Table 1). Soil $NO_3$–N concentration in the 0 and 225 kg N $ha^{-1}$ rates were similar, and greater than the 135 kg N $ha^{-1}$ rate. The soil $NO_3$–N concentrations were also low in the spring at time of ingrowth tube removal (Table 1). The low concentrations are a reflection of high grain crop yields (data not shown) and high rainfall at the site during the summer and early fall (Fig. 1) during the preceding grain crop. Although the rye cover crop decreased soil $NO_3$–N concentrations compared to no cover crop (data not shown), the concentrations increased slightly from fall to spring. Following soybean, soil $NO_3$–N concentrations were also low, although higher than following corn, and the same from fall to spring despite the rye growth (Table 1).

**Root Distribution and Composition**

Estimates of root biomass production using different techniques may vary depending upon specific assumptions and sampling error (Fahey et al., 1999; Hendricks et al., 2006). The ingrowth core method is an in-situ approach of root estimation and often considered a conservative approach compared to other methods such as minirhizotrons (Milchunas et al., 2009). Altered soil conditions inside the ingrowth tube may increase or decrease growth of roots, but an experiment conducted by Steingrobe et al. (2000) showed that only a large difference in soil bulk density and N content between the ingrowth tube and bulk soil outside the tube would cause differential root growth. The distribution and characterization of rye roots with depth can provide an indication of the cover crop potential to contribute to soil structure and stabilization in the upper soil layer, and ability to accumulate N from the soil profile.

Rye roots were present to the 60-cm depth (Tables 2 and 3), with some coarse as well as fine roots visible extending below the bottom of the ingrowth tubes at 30 and 60-cm. However, more roots were within the upper 30-cm than below 30-cm following corn (Table 2). Rye cover crop roots present to 50-cm and winter wheat (*Triticum aestivum* L.) root distribution to more than 1 m was reported by Sainju et al. (1998) and Derera et al. (1969), respectively. Bodner et al. (2010) found a sharp decrease in rye, hairy vetch (*Vicia villosa* L. cv. Beta) and mustard (*Sinapis alba* L. cv. Caralla) cover crop root biomass with depth, which suggests the majority of roots would be within the depth we measured, however, roots would be present below the depths sampled in our study. We did not have ingrowth tube depths below 30-cm following soybean. Therefore, overall the total rye root amounts presented following both grain crops will be less than the actual total.

The distribution of root biomass (mean across all N rates applied to corn) decreased with depth following both grain crops, with the amount of root biomass present in the top 0–15 cm depth comprising 48 and 62 % of the total root biomass measured following corn and soybean, respectively (Tables 2 and 3). For rye following corn, the root biomass in the top 30-cm was 72 % of the total in the 60-cm depth. These results are similar to the findings of Bodner et al. (2010) where they reported a high density of rye cover crop roots in the top 10-cm soil. Similar result, with about 40 % of total root biomass of winter wheat present in top 15-cm soil, was reported by Jimenez et al. (2002).

With rye following soybean, total root biomass dry matter was 674 kg ha$^{-1}$ (0–30 cm depth) whereas following corn (0–60 cm depth) it was less at 518 kg ha$^{-1}$ (Tables 2 and 3). This difference in root biomass between rye following corn and soybean is likely due to the difference in seeding date and time available for fall growth and establishment; despite the longer time for growth in the spring before termination and the deeper root measurement following corn. The N rate applied to corn and its interaction with rooting depth did not have any significant effect on root biomass production (Tables 2 and 3). This lack of residual N rate effect follows from the low soil $NO_3$–N present in the fall and spring, as well as the extended length of time after N application and two grain crops (a corn and a soybean crop) after N application with the rye following soybean.

The rye root C concentration did not change with soil depth or prior N application rate, and averaged 425 g C $kg^{-1}$ across both following corn and soybean (Tables 4–8). The average root N concentration was 9.19 g N $kg^{-1}$ across following corn and soybean (Tables 7 and 8). There were no differences in rye root N concentration with depth or prior N rate for rye following soybean. However, the root N concentration varied with depth with rye following corn (Table 5), although the differences were inconsistent; lowest at 30–45 cm and not different at other depths. The difference with the one depth might be due to different residual N, but cannot be fully explained. There was no difference in root N concentration due to prior N application with rye following corn.

The rye root C:N ratio did not change with soil depth or prior N rate for rye following soybean, and for rye following corn was not influenced by the prior N rate except at the 45–60 cm depth that had a C:N ratio lower than at the 30–45 cm depth (Tables 9 and 10). That depth difference was due to the root C concentration being lowest and N concentration highest at 45–60 cm depth compared to other depths. The C:N ratio averaged 48 following soybean and 53 following corn. The conceptual model of biomass C:N ratio effect on potential net N immobilization and mineralization is illustrated in

Tisdale et al. (1993). With high C:N ratio material, there is a period of net immobilization of N followed by an equalization period, and then net mineralization. The length and extent of immobilization is affected by various factors like climate, quality of plant residue, and soil conditions; with low C:N ratio material degrading faster and more rapidly supplying plant available N (Green and Blackmer, 1995; Kavdir and Smucker, 2005). The rye root C:N ratio was high enough for potential N immobilization during the initial phase of root degradation following rye termination, and thus could reduce plant available N early in a subsequent grain crop growth period.

**Root-Shoot Partitioning**

The rye shoot C and N concentrations were not affected by N rate (Tables 7 and 8). The rye shoot C concentrations were similar following corn and soybean, the shoot N concentrations greater following soybean, and the shoot C concentrations greater than root C concentrations following soybean but the same following corn. The shoot N concentrations were considerably greater than the root concentrations in both rye following corn and soybean.

The rye biomass, C, and N amounts were greater in the shoot than root with both rye following corn and soybean (Tables 11 and 12). There were no differences among the prior N rates applied to corn. The differences in N amount between the shoot and root were large, 20 and 29 kg N $ha^{-1}$ in the shoot biomass (following corn and soybean, respectively), and only 4 and 6 kg N $ha^{-1}$ for the respective root biomass.

The rye root fraction comprised 32–34 % of the total plant biomass, which is slightly higher than the 20–24 % found in a greenhouse experiment conducted by Amanullah (2014). Differences between conditions in the field and greenhouse could easily explain such differences; such as weather extremes and limited N supply in the field. Even with a small fraction of total plant biomass as roots, the total surface area of the rye roots could be as high as 22 times the aboveground shoot transpirational area (Dittmer, 1937). Of the rye plant total C, 33 % was in the roots following corn and 36 % following soybean. But for plant total N, only 18 % was in the roots following corn and 17 % following soybean; a corresponding 82 and 83 % of the total N in aboveground rye biomass. Greater allocation of total N uptake to shoot biomass would be needed to support rapid growth of aboveground biomass in the spring and demand for N processes such as photosynthetic activity.

Following corn and soybean, rye shoot:root ratios for biomass and C were similar and between 1.9–2.3, but were considerably narrower than for the shoot:root N ratio which was 5.0 (Table 13). As found with the root biomass, the shoot biomass C:N ratio was same for all prior N rates applied to corn (Table 14). The C:N ratio of the root biomass was 2.3 to 2.9 times greater than the shoot, indicating a different potential for the rye shoot and root biomass degradation and net N release.

Unlike a similar C:N ratio in shoot and root biomass found in legumes like crimson clover and hairy vetch (Jani et al., 2015), the C:N ratio of the rye shoot and root biomass was quite different in our study where the shoot had a much lower C:N ratio and more total N. For rye, overall potential biomass degradation and N mineralization would be slower than legumes (Doran and Smith, 1991), with higher N immobilization potential with root biomass degradation. The C:N ratio was more than double in the root biomass (47 to 52 C:N ratio) compared to the shoot (16 to 23 C:N ratio) (Table 14). This high C:N ratio with rye, and a comparatively lower ratio in leguminous cover crops, has been noted in several studies (Touchton et al., 1982; Frye et al., 1985; Doran and Smith, 1991; Hoyt and Mikkelsen, 1991; Kavdir and Smucker, 2005). As compared to leguminous cover crops that do not over-winter, a decrease in N concentration and a corresponding increase in root C:N ratio possibly suggests a biological response that helps rye survive cold winter temperatures and protection from winter freeze-thaw cycles (Gardner and Sarrantonio, 2012).

Roots tend to decompose faster compared to plant residue on the soil surface due to increased soil and microbial contact (Kavdir and Smucker, 2005). However, the high rye root C:N ratio would have a negative effect on potential N mineralization or recycling of plant-available N due to use of soil derived N for microbial degradation of rye root biomass that is well above the 20 to 25:1 C:N ratio where initial N immobilization occurs (Tisdale et al., 1993; Paul and Clark, 1996; Stevenson and Cole, 1999). Immobilization of N with rye root degradation would detract the cover crop from recycling scavenged plant available N to a subsequent grain crop.

## Conclusions

Rye cover crop roots were present within the 60-cm depth measured, with approximately 50–60 % of root biomass present in the top 15-cm. Rye root and shoot biomass, C, and N were not influenced by prior N rate applied to corn, with rye following corn or soybean. Rye shoot biomass was twice the root biomass, with root C and N concentrations similar across soil depths. The rye root and shoot C concentrations were similar, but the N concentration was half or less in the root than shoot biomass. The differences in concentration and biomass resulted in considerable differences in root and shoot total N; 4–6 kg N $ha^{-1}$ in root versus 20–29 kg N $ha^{-1}$ in shoot biomass.

The C:N ratio in root material was much higher compared to shoots (47–52 for roots and 16–23 for shoots) which could result in N immobilization during root degradation. Although rye roots comprised approximately 35 % of rye plant C, there was only approximately 20 % of plant N in roots. Therefore, the largest fraction of total N uptake and C assimilation by the rye cover crop was contained in the aboveground biomass.

Since N taken up by the rye was mainly partitioned to the shoots, rye aboveground biomass could provide a measure of the main N amount for the estimation of rye cover crop N uptake and amount potentially available for recycling. With the high C:N ratio of the root biomass, and neutral C:N ratio (in regard to mineralization-immobilization) of shoot biomass, inorganic-N from the soil or degrading shoot biomass could be immobilized during root degradation and thus reduce the potential for recycling plant-available N to an annual grain crop. These results help explain the lack of rye cover crop effects on corn optimal N fertilization rate in recent Iowa field studies.

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Table 1. Soil $NO_3$–N concentration (0–30 cm depth) at the location of the ingrowth tubes at installation in fall and removal in spring.

| | Following corn | | Following soybean | |
|---|---|---|---|---|
| N rate† | Fall | Spring | Fall | Spring |
| kg ha$^{-1}$ | ------------------------- mg kg$^{-1}$ | ---------------------------- | | |
| 0 | 1.9a | 2.6a | 5.3 | 4.9 |
| 135 | 0.6b | 1.8a | 1.8 | 3.2 |
| 225 | 1.8a | 2.2a | 4.2 | 4.9 |
| Mean | 1.4B‡ | 2.2A | 3.8 | 4.3 |

† Rate applied to corn.
‡ Mean within a crop with different upper and lower case letters significantly different ($P \leq 0.05$).

Table 2. Rye root biomass dry matter by depth in the ingrowth tubes, following corn.

| | Depth (cm) | | | |
|---|---|---|---|---|
| N rate† | 0–15 | 15–30 | 30–45 | 45–60 |
| kg ha$^{-1}$ | -------------------- kg ha$^{-1}$ | ------------------- | | |
| 0 | 261 | 130 | 69 | 85 |
| 135 | 244 | 136 | 87 | 53 |
| 225 | 242 | 109 | 73 | 67 |
| Mean | 249a‡ | 125b | 76c | 68c |

† Rate applied to corn.
‡ Only depth main effect was significant, with different letters indicating significant difference ($P \leq 0.\ 05$).

Table 3. Rye root biomass dry matter by depth in the ingrowth tubes, following soybean.

| | Depth (cm) | |
|---|---|---|
| N rate† | 0–15 | 15–30 |
| kg ha$^{-1}$ | ----------- kg ha$^{-1}$------------ | |
| 0 | 461 | 234 |
| 135 | 440 | 273 |
| 225 | 349 | 264 |
| Mean | 417a‡ | 257b |

† Rate applied to corn.
‡ Only depth main effect was significant, with different letters indicating significant difference ($P \leq 0.05$).

Table 4. Rye root C concentration by depth in the ingrowth tubes, following corn.

| | Depth (cm) | | | |
|---|---|---|---|---|
| N rate† | 0–15 | 15–30 | 30–45 | 45–60 |
| kg ha$^{-1}$ | ------------------- g C kg$^{-1}$--------------------- | | | |
| 0 | 428 | 438 | 418 | 388 |
| 135 | 435 | 418 | 418 | 396 |
| 225 | 437 | 396 | 393 | 415 |
| Mean | 433 | 417 | 410 | 400 |

† Rate applied to corn.
No treatment effect significant ($P \leq 0.\ 05$).

Table 5. Rye root N concentration by depth in the ingrowth tubes, following corn.

| | Depth (cm) | | | |
|---|---|---|---|---|
| N rate† | 0–15 | 15–30 | 30–45 | 45–60 |
| kg ha$^{-1}$ | ------------------------- g N kg$^{-1}$ ------------------------- | | | |
| 0 | 8.87 | 8.94 | 7.26 | 9.67 |
| 135 | 8.43 | 7.63 | 6.86 | 9.46 |
| 225 | 9.35 | 8.42 | 7.30 | 10.64 |
| Mean | 8.88ab‡ | 8.33ab | 7.14b | 9.93a |

† Rate applied to corn.
‡ Only depth main effect was significant, with different letters indicating significant difference ($P \leq 0.05$).

Table 6. Rye root C and N concentration by depth in the ingrowth tubes, following soybean.

| | Depth (cm) | | Depth (cm) | |
|---|---|---|---|---|
| N rate† | 0–15 | 15–30 | 0–15 | 15–30 |
| kg ha$^{-1}$ | ----- g C kg$^{-1}$ ----- | | ----- g N kg$^{-1}$ ----- | |
| 0 | 425 | 425 | 8.64 | 8.11 |
| 135 | 447 | 440 | 8.96 | 9.52 |
| 225 | 424 | 455 | 10.56 | 10.25 |
| Mean | 432 | 440 | 9.38 | 9.29 |

† Rate applied to corn.
No treatment effect significant ($P \leq 0.05$).

Table 7. Rye C and N concentrations for shoot and root, following corn. Root component is for the entire ingrowth depth measured.

| N rate† | Shoot | Root | Shoot | Root |
|---|---|---|---|---|
| kg ha$^{-1}$ | ----- g C kg$^{-1}$ ----- | | ------- g N kg$^{-1}$ ------- | |
| 0 | 405 | 420 | 18.01 | 8.68 |
| 135 | 403 | 417 | 18.66 | 8.09 |
| 225 | 405 | 410 | 18.11 | 8.93 |
| Mean | 404 | 416 | 18.26a‡ | 8.57b |

† Rate applied to corn.
‡ Only main component effect was significant, with different letters indicating significant difference ($P \leq 0.05$).

Table 8. Rye C and N concentration for shoot and root, following soybean. Root component is for the entire ingrowth depth measured.

| N rate† | Shoot | Root | Shoot | Root |
|---|---|---|---|---|
| kg ha$^{-1}$ | ----- g C kg$^{-1}$ ----- | | ------ g N kg$^{-1}$ ------ | |
| 0 | 397 | 425 | 22.76 | 9.11 |
| 135 | 401 | 443 | 22.72 | 9.24 |
| 225 | 406 | 439 | 25.29 | 11.14 |
| Mean | 401b‡ | 436a | 23.58a | 9.82b |

† Rate applied to corn.
‡ Only main component effect was significant, with different letters indicating significant difference ($P \leq 0.05$).

Table 9. Rye root C:N ratio by depth in the ingrowth tube, following corn.

| N rate† | Depth (cm) 0–15 | 15–30 | 30–45 | 45–60 |
|---|---|---|---|---|
| kg ha$^{-1}$ | | | | |
| 0 | 49 | 64 | 59 | 42 |
| 135 | 52 | 56 | 70 | 46 |
| 225 | 47 | 47 | 56 | 42 |
| Mean | 49ab‡ | 56ab | 62a | 43b |

† Rate applied to corn.
‡ Only main depth effect was significant, with different letters indicating significant difference ($P \leq 0.05$).

Table 10. Rye root C:N ratio by depth in the ingrowth tubes, following soybean.

| N rate† | Depth (cm) 0–15 | 15–30 |
|---|---|---|
| kg ha$^{-1}$ | | |
| 0 | 50 | 53 |
| 135 | 51 | 48 |
| 225 | 41 | 45 |
| Mean | 47 | 49 |

† Rate applied to corn.
No treatment effect significant ($P \leq 0.05$).

Table 11. Rye plant components, following corn. Root component is for the entire ingrowth depth measured.

| | Biomass DM† | | C | | N | |
|---|---|---|---|---|---|---|
| N rate‡ | Shoot | Root§ | Shoot | Root | Shoot | Root |
| kg ha$^{-1}$ | ------------------------------- | | kg ha$^{-1}$ | | ------------------------------- | |
| 0 | 983 | 544 | 397 | 229 | 16.8 | 4.4 |
| 135 | 1154 | 519 | 465 | 219 | 21.1 | 4.1 |
| 225 | 1166 | 491 | 475 | 206 | 20.9 | 4.5 |
| Mean | 1101a¶ | 518b | 446a | 218b | 19.6a | 4.3b |

† DM, dry matter.
‡ Rate applied to corn.
§ Total for the entire root ingrowth depth measured.
¶ Only main effect of plant component significantly different, with different letters indicating significant difference ($P \leq 0.05$).

Table 12. Rye plant components, following soybean. Root component is for the entire ingrowth depth measured.

| | Biomass DM† | | C | | N | |
|---|---|---|---|---|---|---|
| N rate‡ | Shoot | Root§ | Shoot | Root | Shoot | Root |
| kg ha$^{-1}$ | ------------------------------- | | kg ha$^{-1}$ | | ------------------------------- | |
| 0 | 1202 | 648 | 480 | 277 | 26.9 | 5.6 |
| 135 | 1267 | 713 | 509 | 318 | 28.6 | 6.3 |
| 225 | 1211 | 565 | 494 | 250 | 30.1 | 6.1 |
| Mean | 1227a¶ | 642b | 494a | 282b | 28.6a | 6.0b |

† DM, dry matter.
‡ Rate applied to corn.
§ Total for the entire root ingrowth depth measured.
¶ Only main effect of plant component significantly different, with different letters indicating significant difference ($P \leq 0.05$).

Table 13. Rye plant shoot:root ratio for biomass dry matter, C, and N content. Root component is for the entire ingrowth depth measured.

| | Following corn | | | Following soybean | | |
|---|---|---|---|---|---|---|
| N rate† | Biomass | C | N | Biomass | C | N |
| kg ha$^{-1}$ | | | | | | |
| 0 | 2.1 | 2.0 | 4.6 | 1.8 | 1.7 | 4.7 |
| 135 | 2.3 | 2.2 | 5.3 | 1.8 | 1.6 | 4.5 |
| 225 | 2.5 | 2.4 | 5.0 | 2.5 | 2.4 | 5.9 |
| Mean | 2.3 | 2.2 | 5.0 | 2.0 | 1.9 | 5.0 |

† Rate applied to corn.
No statistical difference due to N rate ($P \leq 0.05$).

Table 14. Rye plant components C:N ratio. Root component is for the entire ingrowth depth measured.

| | Following corn | | Following soybean | |
|---|---|---|---|---|
| N rate† | Shoot | Root | Shoot | Root |
| kg ha$^{-1}$ | | | | |
| 0 | 23 | 53 | 16 | 50 |
| 135 | 22 | 56 | 18 | 49 |
| 225 | 23 | 48 | 15 | 41 |
| Mean | 23b | 52a‡ | 16b | 47a |

† Rate applied to corn.
‡ Only main effect of plant component significantly different, with different letters within crop indicating significant difference ($P \leq 0.05$).

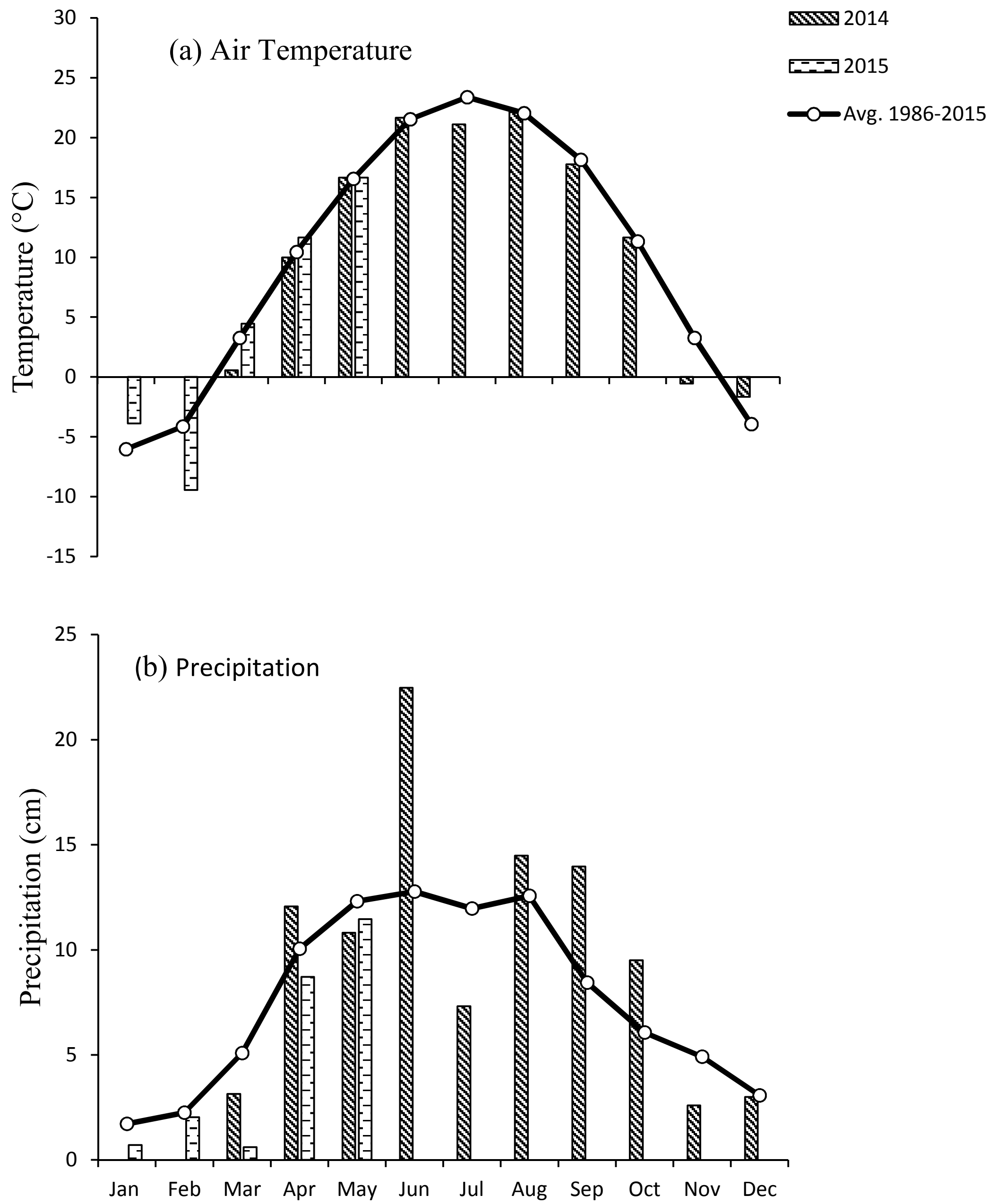


Fig. 1. Monthly mean air temperature (a) and total monthly precipitation (b) for each study year and the 30-yr mean (data from Arritt and Herzmann, 2015).

# CHAPTER 3. ENHANCING CORN YIELD WHEN GROWN IN A WINTER RYE COVER CROP SYSTEM

A paper to be submitted to Agronomy Journal

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## Abstract

Cereal rye (*Secale cereal* L.) cover crops (RCC) have good potential to take up residual $NO_3$ between grain crops and reduce loss to surface waters. However, studies in Iowa have shown a 5–6% corn (*Zea mays* L.) yield reduction when grown following a RCC. The objective of this research was to study agronomic practices that have potential to improve corn yield in a RCC system. This study was conducted at four sites in 2013 through 2015 with corn grown in rotation with soybean [*Glycine max.* (L.) Merr.]. Treatments included cereal rye aerially broadcast into soybean before leaf drop and no RCC, tillage or no-till, and starter N fertilizer (34 kg N ha$^{-1}$) or no starter. The aerial RCC sowing, especially with dry fall conditions the first year and planned RCC termination in the spring at 15–20 cm height, resulted in non-uniform RCC stand and low biomass and N uptake at termination (154–335 kg ha$^{-1}$ and 6–14 kg N ha$^{-1}$). Across site-years, V6 corn plant height and V10 sensing indexes were greater with the tilled system and starter N. Overall, corn yield was slightly reduced with the RCC (2.4%), however, tillage (3.3%) and the high N starter (1.6%) consistently increased yield. Soybean yield was not

influenced by the aerial seeded RCC or the prior year treatments for corn. While the RCC generally resulted in lower corn yield, starter N and tillage did help offset that reduction and would be expected to help improve corn production in a RCC system.

**Abbreviations:** RCC, rye cover crop; NDVI, normalized difference vegetation index; NDRE, normalized difference red edge index.

## Introduction

Water quality related to N is an ongoing concern in Iowa, including meeting the USPEA $NO_3$–N drinking water standard of 10 mg N $L^{-1}$, proposed surface water quality nutrient criteria, and meeting N reduction export goals to the Gulf of Mexico (USEPA, 2007; USEPA, 2008; Iowa State University, 2014). Nitrate-N escaping fields along with drainage water is a major environmental concern related to agriculture crop production systems, and according to the Iowa Nutrient Reduction Strategy nonpoint sources account for 92% of the total N and 80% of the total P entering Iowa streams annually (Iowa State University, 2014). Per the Gulf of Mexico Watershed Nutrient Task Force, N and P delivery to the Gulf needs to be reduced by 45 % (USEPA, 2008), with the Iowa Nutrient Reduction Strategy science assessment identifying a 41% $NO_3$–N and 29% P reduction goal from non-point sources in Iowa needed to meet the Gulf Hypoxia task force stated recommendations.

Long-term N rate trials conducted in Iowa show that application of N fertilizer to corn can increase yield by 40 to 70% compared to an unfertilized field (Sawyer, 2015). However, fertilizer N use efficiency in corn is often only around 35% (Cassman et al., 2002). Nitrogen not taken up by the crop is either lost through various mechanisms like volatilization and leaching (Nielsen, 2006), or is immobilized in the soil organic matter pool. Even in soybean-corn rotations, approximately the same amount of sub-surface drainage N losses occur from the corn and soybean phases (Castellano et al., 2012). Previous study has shown that N released from mineralization of soil organic matter has a major contribution in post-harvest N leaching (Macdonald et al. 1989), therefore, even with less than optimum N rate application, there can be a significant amount of N loss from the soil system (Dinnes et al., 2002). Split N application with application closer to crop uptake requirement, along with in-field management practices like cover crops, can help reduce N loss and improve N use efficiency (Fox et al., 1986; Cassman et al. 2002). Fertilizer management practices such as use of starter fertilizer at planting can improve early season corn growth, reduce grain moisture at harvest, and increase grain yield (Mascagni and Boquet, 1998; Bermudez and Mallarino, 2002; Vetsch and Randall, 2002), which could improve crop N use.

Using a cover crop to scavenge residual soil inorganic-N is a viable solution as an in-field management practice to reduce $NO_3$–N loss to water systems (Sainju et al., 1998). Cover crop adoption will require management practices that are easy to implement and have good potential to minimize non-point source pollution of surface water systems. Benefits from cover crops are not limited to reduction in $NO_3$–N losses as they can reduce soil erosion (Smith et al., 1987; Kaspar et al., 2001; Dabney et al., 2001), improve soil organic matter and nutrient cycling (Oades, 1984; Lu et al. 2000; Sainju et al., 2002; SARE, 2007), reduce compaction (Dexter, 1991; Williams and Weil, 2004), and reduce weed pressure (Teasdale and Daughtry, 1991; Teasdale and Mohler, 2000; Dhima et al., 2006; Teasdale et al., 2007).

Continuous cover crop use over a long period of time can help improve soil quality and provide residual sources of plant available N to grain crops (Doran and Smith, 1991). Cover crops also have potential to enhance or stabilize yield (Snapp et al., 2005) by adding organic matter to the soil and improve the soil organic C content which is a key element for improved soil structure and increased water holding capacity (Hoorman, 2009). Living roots help maintain the soil fauna (Hoorman, 2009) and after cover crop termination root channels provide pathways for grain crop roots, a phenomenon referred as biodrilling (Cresswell and Kirkegaard, 1995). However, effects of cover crops on soil properties takes time and will not appear in initial years of use (Acuna and Villamil, 2014). Integration of cover crops into the grain crop systems can reduce the transition period required for conversion of a conventionally tilled field in to no-till, and may alleviate the 5–10% yield decrease experienced in the initial years of transition (Hoorman et al. 2009).

Adoption of cover crops is promoted by cost share programs like Environmental Quality Incentives Program (EQIP) and Conservation Stewardship Program (CSP) (USDA-NRCS, 2013). However, even with well-established environmental and soil quality benefits, adoption of cover crops has been limited due to the uncertainties in the effects of using a cover crop on subsequent grain crop growth and yield (Westgate et al., 2005; Li et al., 2013); often associated with soil moisture depletion (Munawar et al., 1990) or allelopathy effects (Raimbault et al., 1990; Kessavalou and Walters., 1997).

The soybean-corn rotation is the most popular cropping system in Midwest USA because of the yield and economic benefits compared to continuous corn (Olson and Sander, 1982; Walters and Shapiro, 1988; Peterson and Varvel, 1989; Franzluebbers, 1994). However, soil erosion is an enhanced concern due to low crop residue following the soybean phase (Laflen and Moldenhauer, 1979; Miller et al., 1988). Therefore, having a successful cover crop following soybean can help protect the soil surface from rainfall impact, provide rooting to improve soil structure and hold soil in place, and accumulate residual inorganic-N.

Winter cereal rye is a well-known and most widely adopted cover crop in the Midwest USA due to its relative ease of establishment, ability to over winter, large potential biomass production, and easy termination with herbicides (Moschler et al., 1967; Duiker and Curran, 2004). Benefits of a RCC are well-known and optimizing environmental benefits requires optimal RCC growth and biomass production. However, RCC benefits need to be achieved without reducing grain crop yields, such as might occur as a consequence of delayed planting as a means to allow time for large RCC growth (Roth and Beegle, 2003). Release of phytochemicals (allelopathy) from degrading RCC mulch may suppress weed establishment and growth (Putnam and DeFrank, 1983), but at the same time allelopathic effects to some grain crops have also been found to sometimes decrease subsequent crop yield, such as in cotton (Li et al., 2013) and corn (Pantoja et al*.,* 2015). Importantly, a RCC can also affect subsequent grain crop growth by depleting soil moisture (Raimbault et al., 1991) and immobilizing soil N (Karlen and Doran, 1991).

The potential RCC benefits are highly dependent on soil and weather conditions, agronomic management practices, and the specific subsequent grain crop. The science assessment in the Iowa Nutrient Reduction Strategy (Iowa State University, 2014) identified a corn yield reduction of 6% when grown following a RCC, a similar decrease found in a multiple location and year study in Iowa by Pantoja et al. (2015). Since rye is most often used as a cover crop in Iowa, and much less frequently for forage or rye grain production, the incentive for farmers to include a RCC in their production systems should come from the long-term cover crop soil and environmental benefits, while not negatively impacting grain crop yields. Yield improvement would be an additional and important economic incentive for RCC use. Therefore, the objective of this research was to study agronomic production practices that have potential to improve corn yield within a RCC system.

## Materials and Methods

### Site Descriptions

A two-year field study (2014–2015) was initiated in the fall 2013 at four Iowa State University research and demonstration farms. Soils at all sites had loam or silty clay loam texture (Table 1). The soil was moderately to somewhat poorly drained at the southeast site near Crawfordsville (41°12’13”N; 91°29’42”W); well-drained soil at the southwest site near Lewis (41°18’47”N; 95°10’47”W); poorly to somewhat poorly-drained soil at the northeast site near Nashua (42°55’54”N; 92°34’36”W); and well to moderately well-drained soil at the northwest site near Sutherland (42°55’47”N; 95°31’52”W). Before the start of this study, three sites since fall 2008 (Crawfordsville, Lewis, and Nashua) and one site since fall 2009 (Sutherland) had a no-till corn-soybean rotation with a RCC treatment planted following corn and soybean. Therefore, the sites for this study had a multi-year history of a corn-soybean rotation, RCC and no RCC, and no-till management.

Monthly mean temperature, total precipitation and the historic weather data across the study sites were calculated with data collected from automated weather stations located at or near each study site and reported by the Iowa Environmental Mesonet Network (Arritt and Herzmann, 2015).

Soil test levels were maintained by P, K, and lime application as determined by soil testing. Sites at the beginning of this study had pH, P, and K soil tests (Table 1) within optimum or above levels for the corn-soybean rotation in Iowa (Mallarino et al., 2013).

**Experimental Design and Treatment Implementation**

The experimental design at each site was a randomized complete block, with a split-split plot treatment arrangement with four replications. Three treatments were arranged in factorial combination, RCC and no RCC the main plot, no-till and tillage the split-plot, and no starter or starter N for corn the split-split-plot. The RCC was maintained in the same plots as the prior treatment history in order to maintain RCC continuity. Individual plot size was 15.2 m in length and eight rows wide at Crawfordsville, Lewis, and Sutherland; and 18.3 m in length and six row wide at Nashua. Corn and soybean were planted in 0.76 m row spacing at all sites. Both crops were present each year.

Winter cereal rye (Wheeler) was aerially inter-seeded by hand across standing soybean at 94 kg ha$^{-1}$ (2013) and 126 kg ha$^{-1}$ (2014) prior to leaf drop in early-to-mid

September. The intent by sowing rye seed into the standing soybean crop rather than following harvest was to provide more time for fall RCC growth and establishment (Bich et al. 2014). No RCC was planted following corn. In late April or early May, the RCC was terminated with application of 2–3 kg a.i. $ha^{-1}$ glyphosate [N-(phosphonomethyl)glycine] herbicide in both tillage systems, with the intent to terminate the RCC at 15–20 cm of growth and as soil conditions allowed field access for herbicide application. Following glyphosate application, spring preplant tillage in the tilled plots was delayed at least 24 hr if daytime temperatures were above 16 ºC, or at least 72 hr if daytime high temperatures were cooler than 13 ºC and nighttime low temperatures were between -1 and 4 ºC.

Tillage for corn was spring disking, with field cultivation if needed, for seedbed preparation. Tillage was completed after glyphosate application. Tillage for soybean was fall chisel plow corn stalks, with spring disking and field cultivation as needed for seedbed preparation.

The intent was to plant corn at least 2 wk after RCC termination in an attempt to lessen allelopathic effects of degrading RCC biomass on germinating corn and seedlings. Across years, corn was planted between 1 May and 22 May, and soybean between 1 May and 2 June. As per the USDA report for Iowa, 80% of corn was planted between 10 April and 15 May and 80 % of soybean between 28 April and 1 June in 2014 and 2015 (USDA, 2015). Commonly adapted corn hybrids and soybean varieties were used for each location, and commonly used herbicides were applied as needed for weed control.

The starter N fertilizer was urea (46% N) at 34 kg N $ha^{-1}$ placed 5-cm to the side and 5-cm below the seed during corn planting. The main N was sidedress applied 12–36 days after corn planting as urea-ammonium nitrate solution (UAN, 28 or 32% N) injected to every other inter-row (1.52 m), for an equalized total of 168 kg N $ha^{-1}$. The total N rate was at the upper end of the rate range suggested by the Corn N Rate Calculator (Sawyer et al., 2006) for a soybean-corn rotation.

**Rye Cover Crop Measurements**

Rye plant height and aboveground biomass samples were collected each spring the same day or the day before RCC termination. Samples were collected from each replicate by tillage system and starter fertilizer treatment. Rye height (from soil surface to extended leaf tip) was measured from six random locations within each plot and then the mean of the six measurements recorded. Aboveground RCC biomass sampling was performed by placing a 0.093 $m^2$ frame at six random locations within each plot, cutting the above ground biomass at the soil surface, and compositing the biomass into one sample. The RCC biomass was dried in an oven at 60°C, weighed to determine dry matter, and then adjusted for the total area sampled to estimate RCC biomass production per area. Dried samples were ground in an Udy® Mill (UDY Corporation, Fort Collins, CO) to pass through 2-mm sieve and analyzed for total C and N by dry combustion (LECO CHN-2000 analyzer, LECO Corp., St. Joseph, MI) (Nelson and Sommers, 1982). Total RCC aboveground C and N was calculated by multiplying the respective concentration by the aboveground biomass dry matter.

**Grain Crop Plant Measurements**

The effect of RCC, tillage system, and starter fertilizer on corn early vegetative growth was determined by measuring plant height and stand count at approximately the V6 growth stage (Abendroth et al., 2011) (range from V5–V7), with corn growth stage tracked by punching holes on the outer margin of the topmost leaf with a visible collar. For the corn stand count and height measurement, a 12.2 m length of row was marked in the middle two rows of each plot. All plants within the marked sections were counted and then the average number of plants from the two rows used to calculate plant population, with adjustment for row spacing. Pre-harvest corn population was also determined using the same marked section in the middle two rows. The mean corn plant height was determined by measuring the height (from soil surface to extended leaf tip) of 10 randomly selected plants from within the two marked row sections (Warrington and Norton, 1991).

Corn establishment and early growth was evaluated at mid-vegetative growth by canopy sensing at the V10 stage (range from V9–V11). Canopy sensing measurements were collected with a handheld RapidSCAN CS–45 active canopy sensor (Holland Scientific, Lincoln, NE). The RapidSCAN CS–45 integrates a modulated polychromatic light source and three silicon photodetector channels that measure reflected light at 670, 730, and 780 nm wavelengths. The sensor was oriented in the nadir position at least 0.5 m directly above the crop row. Four middle rows were scanned per plot, with the mean reflectance determined from the measured values per plot. Normalized difference red edge index (NDRE) and normalized difference vegetative index (NDVI) were calculated from the reflected wavelengths: $NDRE = (R_{NIR} - R_{RED\ EDGE}) / (R_{NIR} + R_{RED\ EDGE})$ and $NDVI = (R_{NIR} - R_{VIS}) / (R_{NIR} + R_{VIS})$ (Gitelson et al., 1996; Thompson et al., 2015), where $R_{NIR}$= near-infrared reflectance (780 nm); $R_{RED\ EDGE}$= red edge reflectance (730 nm) and $R_{VIS}$ = visible reflectance (670 nm).

Corn grain yield was determined by harvesting the middle 4 rows and reported at 155 g $kg^{-1}$ moisture, and soybean grain yield determined by harvesting the middle 4 or 6 rows and reported at 130 g $kg^{-1}$ moisture. Across years, corn and soybean was harvested between 9–26 October and 30 September–19 October, respectively.

**Soil Sampling and Analysis**

Soil samples (0–0.6 m depth in 0.3-m increments) were collected in the spring 2014 at time of RCC termination, fall 2014 after soybean harvest, and spring 2015 at time of RCC termination from each replicate (RCC and no RCC plots within each tillage system treatment and combined across starter treatments) to determine profile soil $NO_3$–N. Samples were not collected in the fall 2013 for this study due to a different sampling protocol finishing the prior treatment history. Soil $NO_3$–N samples were a composite of six random cores collected using 0.02 m diameter soil probe. Due to early soil freezing in the fall 2104, profile samples at Crawfordsville could not be collected until spring (23 Mar., 2015) before RCC regrowth began.

Soil samples were dried in a forced air oven at 25ºC for 48 hr before grinding to pass a 2-mm sieve. Soil $NO_3$–N was determined by 2 *M* KCl extraction and microplate colorimetric method using Griess-Ilosvay reagent with Vanadium (III) chloride as reducing agent (Hood-Nowotny et al., 2010). Soil $NO_3$–N was converted to a mass basis using a constant bulk density of 1.3 g $cm^{-3}$, a common bulk density for Iowa soils (Al-Kaisi et al., 2005), and summed across soil depths sampled.

**Statistical Analysis**

There was a tillage error at Crawfordsville in fall 2013 and corn planting error at Sutherland in spring 2014, therefore, corn and RCC data from these two sites for 2014 are not included in the analysis and reported results. Corn and soybean phases were analyzed separately. Analysis of variance (ANOVA) of treatment effects was performed across site-years using PROC GLIMMIX (SAS Institute, 2015) for a randomized complete block design. For RCC biomass, C, and N, the analysis was for tillage system; for soil $NO_3$–N the analysis was a split-plot of RCC and tillage system; and for corn plant height, population, NDRE, NDVI, and yield, the analysis was a split-split-plot of RCC, tillage system, and starter N; and for soybean yield the analysis was a split-split plot. Treatment effects and their interactions were considered fixed; with site, year, and their interactions considered random. Treatment means were compared using the LINES option of LSMEANS, with differences considered significant at $P \leq 0.10$.

## Results and Discussion

### Weather

Weather conditions such as temperature and precipitation in the early spring can influence RCC growth, N uptake, termination date, and grain crop planting date. Fig. 1a has the across site-years mean monthly air temperature compared to the 30-yr mean (normal). Early spring (March and April) in 2014 was slightly cooler with mean monthly temperature 2°C below normal, whereas 2015 early spring temperature similar to normal. For the same 2 mo period, there was 1 and 3 cm less precipitation than normal in year 2014 and 2015 respectively (Fig. 1b). However, April air temperature and precipitation were near normal each year. Springtime conditions can also influence corn seedling establishment and early growth, and interaction with RCC residue. In 2014 and 2015 May air temperatures were near normal, however precipitation was below normal.

Late spring and summer weather conditions can influence RCC biomass degradation, grain crop growth, and potential for residual soil $NO_3$–N. Late spring (May and June) air temperature in 2013 was near normal (1°C cooler), but May precipitation was high with 13-cm more precipitation compared to normal. For the same period in 2014 and 2015, mean air temperatures were near normal, with high June precipitation in 2014 (13 cm above normal). During the July–September part of the grain crop growing season, mean air temperatures were near normal, with 2013 being comparatively dry and receiving only 14-cm precipitation compared to the normal 30-cm, 2014 precipitation similar to normal, and 2015 receiving 5-cm more precipitation than normal.

Late summer and fall weather after RCC sowing is crucial for seedling establishment and influences fall growth and N uptake, especially with aerial broadcast sowing. Temperatures in late September to November, as compared to normal, were 1°C and 2°C cooler in 2013 and 2014, respectively. In 2013, precipitation was well below normal for July through September, which resulted in dry surface soil and poor RCC establishment and subsequent low fall growth. In 2014, there was more than normal precipitation from August through October, which resulted in improved seed germination and RCC establishment compared to 2013.

**Rye Cover Crop Biomass and Nutrient Uptake**

Visually, the RCC stand was not uniform (patchy) each year as a result of the hand broadcasting (simulated aerial sowing) onto the soil surface, especially with the fall 2013 dry conditions. The non-uniform and sparse RCC stand would reduce effectiveness as a cover crop. Poor establishment and growth of cover crop mixtures broadcasted in standing corn was reported by Bich et al. (2014) in a multi-year and multi-location study conducted in South Dakota. With our project goal of RCC termination at 15–20 cm height, and with the poor stand, the amount of RCC biomass and N uptake measured was low each spring. The RCC control timing (RCC height) was intended to minimize any delay in corn planting, and avoid RCC effects on corn plants, both of which can result in reduced corn growth and yield loss (Duiker and Curran, 2005; Lauer et al., 1999). In the spring 2014 (first year of the study), there would be no effect of tillage system on the RCC as the tilled system had not yet been implemented for the corn crop or soybean crop. Therefore, the following RCC measurements are means across all site-year RCC plots in the spring 2014; 16-cm height, 154 kg dry matter $ha^{-1}$ aboveground biomass, 57 kg C $ha^{-1}$, and 6 kg N $ha^{-1}$.

In the spring 2015, tillage system had a positive effect on RCC growth and uptake parameters compared to no-till (Table 2), with the mean RCC height at 19-cm. In a study conducted in Nebraska by Kessavalou and Walters (1997), where a RCC was drilled, the growth and total dry biomass production was greater in a no-till system as compared to a tilled system. However, in our study, the RCC aboveground biomass dry matter production (Table 2) overall was small, and less with no-till compared to the tilled system. The improved RCC growth with the tilled system could potentially be an effect of seedling germination and stand establishment in the fall due to better seed-soil contact where there was less surface residue than in the long-term no-till. Or, surface soil physical conditions were better in the tilled system that promoted early RCC growth. In the study conducted by Pantoja et al (2016) on the same research sites, drilled rye following soybean was reported to produce 990 kg $ha^{-1}$ dry biomass and accumulated 27 kg N $ha^{-1}$ at the time of rye termination in spring, more than twice as much measured in our study. Another study by Johnson et al. (1998) showed that an early (mid–August) seeded RCC into soybean accumulated up to 1870 kg $ha^{-1}$ shoot dry matter in the spring.

The RCC growth difference between tillage systems carried through to the other measured parameters; where aboveground C and N were greater with tillage than no-till (Table 2). Of most interest is the amount of N uptake by the RCC, which was low (≤ 14 kg $ha^{-1}$) in our study due to the small biomass and early RCC termination when the height was small. A similar amount of N uptake at spring terminated RCC following soybean has been reported in other studies (Qi et al., 2011). The RCC biomass C:N ratio in our study was low (11:1), which indicates there should be rapid mineralization of N, although the amount would be low. In a study by Pantoja et al (2016) with RCC following soybean, the RCC had a low C:N ratio (14:1) and recycled 22 kg N $ha^{-1}$ (80%) by 105 d after termination.

**Soil Nitrate**

Soil profile $NO_3$–N was not determined in the fall 2013. In the spring 2014, there would not be an effect of tillage system on soil $NO_3$–N at the time of RCC termination as the tilled system had not yet been implemented for the corn crop. Therefore, the following spring 2014 soil profile $NO_3$–N measurements (0.6 m depth) are means across tillage systems; 34 kg N $ha^{-1}$ with the RCC and 58 kg N $ha^{-1}$ without the RCC. As there was no N applied to soybean, any $NO_3$–N would be residual in the soil and differences in profile $NO_3$–N in the fall and spring with the RCC would be due to scavenging and uptake by the RCC (Meisinger et al., 1991; Shipley et al., 1992).

Since the RCC was inter-seeded into the standing soybean crop, and soil $NO_3$–N was determined after the 2014 soybean harvest, there was a period of late summer-early fall RCC growth that could influence fall profile $NO_3$–N. Despite the low overall RCC biomass, the fall 2014 soil $NO_3$–N was reduced by 10 kg $NO_3$–N $ha^{-1}$ (Table 3) (0.6 m depth, mean across tillage systems). There was no effect of tillage system or interaction of tillage system and RCC.

In 2015 at the time of RCC termination, as found in the fall 2014, the amount of $NO_3$–N was decreased with the RCC; by 32 kg N $ha^{-1}$ (Table 4). This indicates an accumulated effect of the RCC N uptake from sowing to spring termination. The decrease in $NO_3$–N with the RCC was more than the amount of N in the aboveground RCC vegetation (Table 2). It is unknown why the decrease in soil $NO_3$–N due to the RCC was more than the RCC N uptake, but based on RCC root measurements in another study the N difference would not be fully accounted for by N in rye roots. Perhaps it could be the legacy effect of long term cover cropping history where more N is immobilized in the cover crop plots. In the study by Pantoja et al. (2015), they reported a 15 kg N $ha^{-1}$ change between RCC and no RCC in the spring at the time of rye termination. Overall, the decrease in soil $NO_3$–N indicates the positive effect of a RCC on taking up residual $NO_3$–N and thus potentially reducing the amount exiting fields with water drainage.

**Corn Early Growth and Canopy Sensing**

The RCC, starter fertilizer, and their interaction with tillage system did not affect corn plant population at either the V6 stage or at pre-harvest (Tables 5 and 6). There was a lower plant population with the tilled system compared to no-till across the RCC and starter fertilizer treatments, although the difference was only 2700–2800 plants $ha^{-1}$. The corn planters used in the study were equipped with row cleaners to remove RCC residue from the row at the time of planting and likely helped with seed soil contact, especially in the no-till. In addition, the attachments to apply the starter N, and the urea-N rate used as the starter fertilizer, did not influence corn population.

Corn early season growth (plant height at V6 and canopy sensing at V10 growth stages) was not affected by the RCC, and there were no interactive effects of tillage system, RCC, and starter on V6 plant height and V10 canopy sensing (Tables 7-9). The starter N and tilled system had a positive effect on V6 plant height as well as NDRE and NDVI indexes at the V10 growth stage. Active canopy sensors can reflect overall plant growth and N stress conditions (Barker and Sawyer, 2010). The starter N did result in increased small plant height, which carried over to the V10 canopy sensing. Since the main N application was sidedress applied, it is likely the high starter N rate helped with N supply in the early corn growth. The positive starter effect was consistent across tillage systems and the RCC. This corn growth response to starter N with the RCC is important as that can help offset effects of an RCC on early corn growth.

The corn plant height and canopy sensing (NDVI only) was greater with the tilled system than no-till, indicating a positive effect of soil disturbance and surface residue on early season corn growth compared to no-till (Tables 7-9). The effect of soil tillage was consistent whether there was or was not a RCC; which indicates that tillage and starter N can help offset effects of an RCC on early corn growth. The NDVI for tillage system by starter interaction was significant, where no-till without starter N had the lowest NDVI; again indicating the starter N effect on increased corn plant growth in the no-till system. This interaction was not significant with the NDRE index.

The no-till soil system, in the presence of residue and mulch cover, typically has a lower soil temperature (Gupta et al., 1983; Bristow, 1988; Unger, 1988) which could decrease the rate of N mineralization from soil organic matter (Bonan and Van Cleve, 1992). This effect could be enhanced by RCC residue after termination. Therefore, the high rate of starter N fertilizer would have supplied N needed for initial corn growth, especially in no-till with the main N sidedress applied and with a longer time after planting to sidedressing. We did not observe any aboveground insect feeding at any site in either year that might have affected early season growth. A net immobilization of N at the end of 20 days of rye root incubation was reported by Gardner and Sarrantonio (2012), while a net release of N from the decomposition of oat and rye roots over a period of 112 days was reported in an incubation study by Malpassi et al. (2000). A study by Pantoja et al. (2016) reported that only 25 % of N present in an RCC biomass was released by 21d after termination. This suggest that the use of starter N at planting would help offset N stress on corn growth due to the presence of decomposing RCC biomass and associated effects on plant-N availability.

**Corn Grain Yield**

Corn grain yield across site-years was significantly affected by all treatment main effects, but there was no interaction between RCC, tillage system and starter (Table 10). The two agronomic practices employed as potential methods to enhance corn yield in a RCC system, tillage and starter N, resulted in consistent yield increases compared to no-till and no starter. The highest corn yield occurred with the tilled system plus starter N, with or without the RCC. The positive effect of starter N and tillage on corn early season growth (plant height and canopy sensing at V10 growth stages) translated into increased grain yield. However, yield was still lower with the RCC system.

Research has shown that corn yield response to starter fertilizer varies, and is most often related to response when soil nutrient supply is deficient. Vetsch and Randall (2002) found that application of a N-P-K starter fertilizer increased corn yield (0.5 Mg $ha^{-1}$) in different tillage systems. Also, starter fertilizer can enhance vegetative growth and early maturity (Usherwood, 1991), and reduce grain moisture at harvest (Mengel et al., 1988). The effect of starter fertilizer on corn early growth is common (Mallarino et al., 1999), but often has an inconsistent effect on yield (Wolkowski, 2000; Bermudez and Mallarino, 2004). Various studies have shown a positive effect of starter N on corn yield as compared to no starter (Ritchie et al., 1995; Scharf, 1999; Niehues et al., 2004; Roth et al., 2006). In our study, across site-years corn yield was increased by 1.6 % with the use of the 34 kg N $ha^{-1}$ starter application and was consistently higher across tillage and RCC treatments. Corn yield increase up to 6–7 % (0.9 Mg $ha^{-1}$) was recorded at two of the six site-years, perhaps an enhanced effect of later sidedress N application (36 d after planting). Enhanced corn vegetative growth and grain yield with the starter N when grown following the RCC could be due to enhanced available N supply and thus overcoming reduced soil inorganic N with the RCC N uptake (Table 4), competition for available N with decomposition of RCC root and shoot biomass, and no fertilizer N application until sidedressing where starter N was not applied.

In a 4-yr study conducted by Vetsch and Randall (2002) in Minnesota, there was no significant difference between various tillage systems on corn grain yield following soybean. In a long term study conducted at multiple locations in Iowa, corn yield varied between tilled and no-till systems, especially in the northern region of the state (Al-Kaisi et al., 2015). However, in our study corn yield was consistently greater (mean 3.3%) with the tilled system compared to no-till. Tilled soils warm up more rapidly in the springtime as compared to no-till (Licht and Al-Kaisi, 2005), which can result in more favorable soil conditions and more rapid N mineralization. Tillage can reduce the allelopathic effect of a RCC by evenly mixing small pockets of concentrated phytochemicals released by patches of degrading RCC biomass (Lynch et al. 1980; Barnes and Putnam, 1986). However, because there was no interaction between tillage system and RCC, the presence of the RCC did not exacerbate the no-till effect on corn yield. In our study, there was only a 3.3% lower no-till yield compared to the tilled system. Despite lower corn yields in a no-till system, no-till can be economically competitive due to differences in production costs (Al-Kaisi et al., 2015).

The presence of the RCC resulted in reduced corn yield, mean effect across tillage and starter, however, the yield difference was small at 0.3 Mg $ha^{-1}$. A reduction in corn yield when corn was planted immediately after RCC termination or after a gap of several days has been reported in several studies (Johnson et al., 1998; Kaspar et al., 2007; Pantoja et al, 2015). In our study, regardless of the minimum waiting period of 14 d between RCC termination and corn planting, there was a small yield reduction of 2.4% when corn followed the RCC. This effect on corn yield with the RCC could be attributed to several factors, including an alleopathic effect of rye (Shilling et al., 1986; Raimbault et al., 1990; Kessavalou and Walters; 1997) or reduced soil moisture (Raimbault et al., 1991). In addition, immobilization of inorganic N is possible (Karlen and Doran, 1991), however, the starter N application in this study was not able to fully overcome effects of the RCC. Lower corn yield with RCC could also be explained by the presence of rye crowns near the soil surface, where corn seed planted in to the crowns could lessen germination and plant stand. However, with or without tillage there was no RCC effect on corn plant population. More years of research would be helpful in order to better understand the effect of starter fertilizer, tillage, and the relationship to time interval between RCC termination, corn planting, and sidedress N timing on corn growth and yield.

**Soybean Grain Yield**

Soybean grain yield was not affected by starter N applied at planting to the previous-year corn, the presence of rye aerially inter-seeded into the soybean for the next corn crop, or residual effects of the RCC system (Table 11). Research has shown an inconsistent effect of a RCC on soybean yield, sometimes an increase (Williams and Weil, 2004) or decrease (Williams et al., 2000; Davis, 2010), but typically no effect (Reddy, 2001; Ruffo et al., 2004; Acuna and Villamil, 2014; Pantoja et al., 2015). Since there was no RCC seeded before the soybean crop (following corn), any season-long RCC effect on soybean yield would be a residual effect of the overall rye cover cropping system or response to the inter-seeded rye; and there was none. Tilled and no-till systems were used for the soybean production, and there was no yield difference between the tillage systems (Table 11). This finding is consistent with the results of long term study in Iowa by Al-Kaisi et al. (2016).

## Conclusions

The winter cereal RCC was able to be established by aerial inter-sowing into standing soybean. However, the RCC was sparse and non-uniform; and in the first fall had quite poor establishment due to dry surface soil conditions and lack of precipitation.

These effects reduce effectiveness as a cover crop. Since our project goal was for an early RCC termination at 15 to 20-cm height, and in conjunction with the non-uniform RCC stand, the amount of RCC biomass and N uptake was correspondingly small. However, the RCC did reduce soil profile $NO_3$–N in the fall post-soybean harvest and in the spring at time of RCC termination. The amount of RCC biomass was greater in the tilled system, potentially an effect of stand establishment due to better seed-soil contact and germination following the aerial sowing or soil physical conditions that improved rye growth. Corn population was not affected by the RCC. Despite the small amount of RCC biomass at termination, and waiting 2 wk to plant corn, there was a 2.4% lower corn grain yield with the RCC compared to no RCC. The tilled system had higher yield than no-till (mean 3.3%), and in both tillage systems with the RCC, corn early growth and yield was consistently (mean 1.6%) improved with the 5-cm by 5-cm placed high N rate starter. The starter N response, as studied here with the main N applied sidedress, indicates that starter N would be a management practice that can help offset negative corn yield effects of a RCC.

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Table 1. Site information and initial soil test values (0–6 inch) for each study site.

| Site | Soil series | Soil classification | pH | STP† | STK† |
|---|---|---|---|---|---|
| | | | | ------- mg kg$^{-1}$ ------ | |
| Crawfordsville | Mahaska silty clay loam | fine, smectitic, mesic Aquertic Argiudolls | 6.3 | 30 (H) ‡ | 194 (O) |
| | Nira silty clay loam | fine-silty, mixed, superactive, mesic Aquic Argiudolls | | | |
| Lewis | Marshal silty clay loam | fine-silty, mixed, superactive, mesic Typic Hapludolls | 6.5 | 22 (H) | 238 (H) |
| Nashua | Floyd loam | fine-loamy, mixed, superactive, mesic Aquic Pachic Hapludolls | 6.2 | 22 (H) | 169 (O) |
| | Clyde silty clay loam | fine-loamy, mixed, superactive, mesic Typic Endoaquolls | | | |
| Sutherland | Galva silty clay loam | Fine-silty, mixed, superactive, mesic Typic Hapludolls | 6.7 | 35 (VH) | 252 (VH) |
| | Sac silty clay loam | Fine-silty, mixed, superactive, mesic Oxyaquic Hapludolls | | | |
| | Primghar silty clay loam | Fine-silty, mixed, superactive, mesic Aquic Hapludolls | | | |

† STP, soil test P and STK, soil test K.
‡ Soil test interpretation category for O, optimum; H, high; VH, very high (Mallarino et al., 2013).

Table 2. Effect of tillage system on rye cover crop height, aboveground biomass dry matter, and nutrient uptake at the time of termination in spring 2015, across sites.

| Tillage | Height | Biomass | N | C |
|---|---|---|---|---|
| | cm | -------------- kg ha$^{-1}$ ------------- | | |
| Till | 19.5a† | 364a | 14.0a | 155a |
| No-Till | 18.5b | 306b | 11.3b | 130b |

† Different letters in a column indicate significant difference between tillage systems ($P \leq 0.10$).

Table 3. Effect of rye cover crop (RCC) and tillage system on fall 2014 post-soybean harvest profile soil $NO_3$–N (0.6 m depth), across sites.

| Tillage | Cover crop | | Mean |
|---|---|---|---|
| | RCC | No RCC | |
| | ------------------ kg ha$^{-1}$ ------------------ | | |
| Till | 11.5 | 23.7 | 17.6 |
| No-till | 11.9 | 19.4 | 15.6 |
| Mean | 11.7b† | 21.5a | |

† Only main effect of RCC was significant, with different letters indicating significant difference ($P \leq 0.10$).

Table 4. Effect of rye cover crop (RCC) and tillage system on spring 2015 profile soil $NO_3$–N (0.6 m depth) at the time of RCC termination, across sites.

| Tillage | Cover crop | | Mean |
|---|---|---|---|
| | RCC | No RCC | |
| | ------------------ kg ha$^{-1}$ --------------- | | |
| Till | 17 | 49 | 33 |
| No-till | 15 | 46 | 30 |
| Mean | 16b† | 47a | |

†Only main effect of RCC was significant, with different letters indicating significant difference ($P \leq 0.10$).

Table 5. Effect of rye cover crop (RCC), tillage system, and starter N on corn V6 stage plant population, across site-years.

| Starter | RCC | | | No RCC | | | Tillage mean | | Starter |
|---|---|---|---|---|---|---|---|---|---|
| | Till | No-Till | Mean | Till | No-Till | Mean | Till | No-Till | mean |
| | ------------------------------------------------ plants ha$^{-1}$ ------------------------------------------------ | | | | | | | | |
| Starter | 78400 | 82400 | 80400 | 79200 | 81800 | 80500 | 78800 | 82100 | 80400 |
| No Starter | 78900 | 81500 | 80200 | 79200 | 81200 | 80200 | 79100 | 81400 | 80200 |
| Tillage mean | 78700 | 81900 | | 79200 | 81500 | | 78900b† | 81700a | |
| RCC mean | | | 80300 | | | 80300 | | | |

† Only main effect of tillage system was significant, with different letters indicating significant difference ($P \leq 0.10$).

Table 6. Effect of rye cover crop (RCC), tillage system, and starter N on corn pre-harvest plant population, across site-years.

| Starter | RCC | | | No RCC | | | Tillage mean | | Starter mean |
|---|---|---|---|---|---|---|---|---|---|
| | Till | No-Till | Mean | Till | No-Till | Mean | Till | No-Till | |
| | ---------------------------------------- plants ha$^{-1}$ ---------------------------------------- | | | | | | | | |
| Starter | 76900 | 80900 | 78900 | 77700 | 80300 | 79000 | 77300 | 80600 | 79000 |
| No Starter | 77300 | 79500 | 78400 | 77900 | 80122 | 79000 | 77600 | 79800 | 78700 |
| Tillage mean | 77100 | 80200 | | 77800 | 80200 | | 77500b† | 80200a | |
| RCC mean | | | 78600 | | | 79000 | | | |

†Only main effect of tillage system was significant, with different letters indicating significant difference ($P \leq 0.10$).

Table 7. Effect of rye cover crop (RCC), tillage system, and starter N on corn V6 growth stage plant height, across site-years.

| Starter | RCC | | | No RCC | | | Tillage mean | | Starter mean |
|---|---|---|---|---|---|---|---|---|---|
| | Till | No-Till | Mean | Till | No-Till | Mean | Till | No-Till | |
| | ------------------------------------------------ cm ------------------------------------------------ | | | | | | | | |
| Starter | 54 | 52 | 53 | 56 | 53 | 54 | 55 | 52 | 54a† |
| No Starter | 53 | 50 | 52 | 54 | 48 | 51 | 53 | 49 | 51b |
| Tillage mean | 54 | 51 | | 55 | 50 | | 54a | 51b | |
| RCC mean | | | 52 | | | 53 | | | |

† Only main effect of tillage system and starter were significant, with different letters indicating significant difference ($P \leq 0.10$).

Table 8. Effect of rye cover crop (RCC), tillage system, and starter N on corn V10 growth stage normalized difference red edge (NDRE) canopy sensing index, across site-years.

| | RCC | | | No RCC | | | Tillage mean | | Starter |
|---|---|---|---|---|---|---|---|---|---|
| Starter | Till | No-Till | Mean | Till | No-Till | Mean | Till | No-Till | mean |
| Starter | 0.400 | 0.396 | 0.398 | 0.398 | 0.394 | 0.396 | 0.399 | 0.395 | 0.397a† |
| No Starter | 0.394 | 0.394 | 0.394 | 0.394 | 0.388 | 0.391 | 0.394 | 0.391 | 0.393b |
| Tillage mean | 0.397 | 0.395 | | 0.396 | 0.391 | | 0.397 | 0.393 | |
| RCC mean | | | 0.396 | | | 0.394 | | | |

† Only main effect of starter was significant, with different letters indicating significant difference ($P \leq 0.10$).

Table 9. Effect of rye cover crop (RCC), tillage system, and starter N on corn V10 growth stage normalized difference vegetative index (NDVI) canopy sensing, across site-years.

| | RCC | | | No RCC | | | Tillage mean | | Starter |
|---|---|---|---|---|---|---|---|---|---|
| Starter | Till | No-Till | Mean | Till | No-Till | Mean | Till | No-Till | mean |
| Starter | 0.823 | 0.823 | 0.823 | 0.827 | 0.822 | 0.824 | 0.825a† | 0.822a | 0.824A‡ |
| No Starter | 0.820 | 0.810 | 0.815 | 0.824 | 0.808 | 0.816 | 0.822a | 0.809b | 0.816B |
| Tillage mean | 0.822 | 0.816 | | 0.825 | 0.815 | | 0.823A | 0.816B | |
| RCC mean | | | 0.819 | | | 0.820 | | | |

†Interaction of tillage system and starter was significant, with different lower case letters indicating significant difference ($P \leq 0.10$).

‡Main effect of tillage system and starter were significant, with different upper case letters indicating significant difference ($P \leq 0.10$).

Table 10. Effect of rye cover crop (RCC), tillage system, and starter N on corn yield, across site-years.

| Starter | RCC | | | No RCC | | | Tillage mean | | Starter mean |
|---|---|---|---|---|---|---|---|---|---|
| | Till | No-Till | Mean | Till | No-Till | Mean | Till | No-Till | |
| | ---------- | ---------- | ---------- | ---------- Mg ha$^{-1}$ | ---------- | ---------- | ---------- | ---------- | ---------- |
| Starter | 12.6 | 12.4 | 12.5 | 13.0 | 13.0 | 12.8 | 12.8 | 12.4 | 12.6a† |
| No Starter | 12.4 | 12.2 | 12.3 | 12.8 | 12.8 | 12.6 | 12.6 | 12.2 | 12.4b |
| Tillage mean | 12.5 | 12.2 | | 12.9 | 12.9 | | 12.7a | 12.3b | |
| RCC mean | | | 12.4b | | | 12.7a | | | |

† Only main effects of RCC, tillage system, and starter were significant, with different letters indicating significant difference ($P \leq 0.10$).

Table 11. Effect of rye cover crop (RCC), tillage system, and starter N on soybean yield, across site-years. The RCC was inter-seeded only into standing soybean and starter N is applied only at corn planting. None of the treatment effects were significant ($P \leq 0.10$).

| | RCC | | | No RCC | | | Tillage mean | | Starter |
|---|---|---|---|---|---|---|---|---|---|
| Starter | Till | No-Till | Mean | Till | No-Till | Mean | Till | No-Till | mean |
| | ---------- | ---------- | ---------- | ---------- | Mg ha$^{-1}$ | ---------- | ---------- | ---------- | ---------- |
| Starter | 4.30 | 4.38 | 4.34 | 4.40 | 4.33 | 4.36 | 4.35 | 4.35 | 4.35 |
| No Starter | 4.35 | 4.41 | 4.38 | 4.34 | 4.39 | 4.36 | 4.34 | 4.40 | 4.37 |
| Tillage mean | 4.32 | 4.40 | | 4.37 | 4.36 | | 4.35 | 4.38 | |
| RCC mean | | | 4.36 | | | 4.36 | | | |

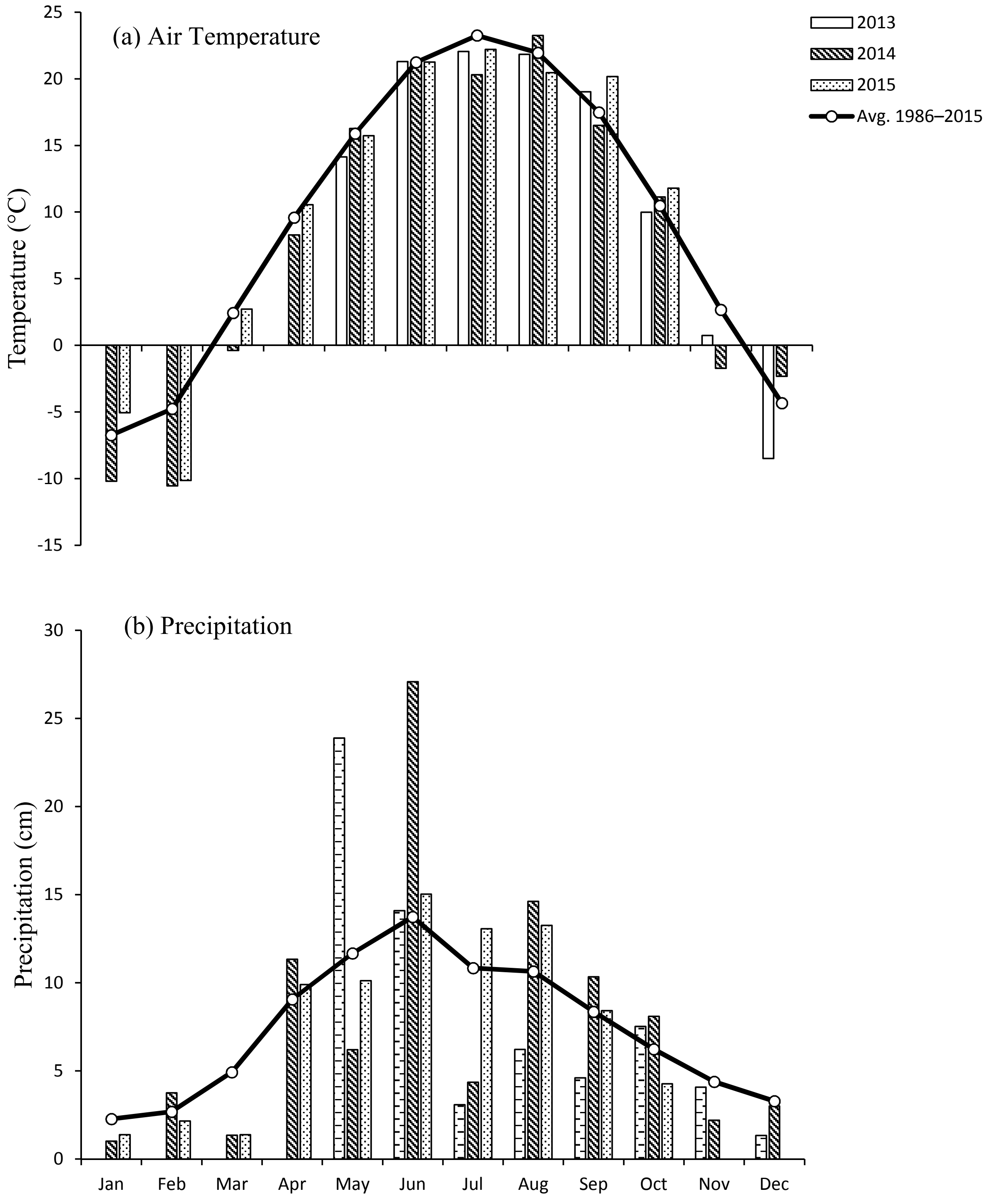


Fig. 1. Monthly mean air temperature (a) and total monthly precipitation (b) across site for each study year and the 30-yr mean (data from Arritt and Herzmann, 2015).

# CHAPTER 4. GENERAL CONCLUSIONS

This thesis included two field studies related to winter cereal rye cover crop use in a corn-soybean rotation, the most common grain crop rotation in Iowa. The first study used a root ingrowth core method to estimate rye cover crop root and shoot partitioning of biomass and nutrient composition (C and N) in a winter rye cover crop at the time of termination in the spring. The second study evaluated the effect of agronomic practices to potentially improve corn yield in a rye cover crop system. Practices were tillage systems (tilled and no-till) and a high starter N fertilizer rate or no starter. Rye was planned to be terminated when small (15-20 cm growth) and at least 2 weeks before corn planting – additional factors to aid in increasing corn response following the rye cover crop. The rye cover crop was aerial broadcast seeded into standing soybean and treatment effects were measured for corn plant population, early vegetative growth, and corn grain yield. In addition, the residual effect of these treatments were determined for soybean grain yield.

The root ingrowth study showed that root biomass production in the rye cover crop following corn and soybean decreased with soil depth, with 50–60% of total rye root biomass in the top 15-cm depth. In rye following soybean, soil depth or the N rate applied to previous year corn did not have any effect on rye root C and N concentration, or C:N ratio. In rye following corn, root C concentration did not change with depth, but root N and C:N ratio varied inconsistently with depth. Carbon concentration was similar in the rye root and shoot, but the N concentration was half or less in the root compared to the shoot. Rye shoot biomass was twice the root biomass, with about 65% of the total plant C and about 80% of the total plant N present in the shoot. This shows that most of the N taken up by the rye cover crop is partitioned to the shoot. This is important as above ground rye cover crop sampling can give a reasonable estimate of rye cover crop total N uptake. Average root total N was 4–6 kg N $ha^{-1}$ versus 20–29 kg N $ha^{-1}$ in the shoot biomass. The average C:N ratio of the rye root (47–52) was 2–3 times higher than the shoot (16–23). Rye cover crop roots, having a C:N ratio higher than approximately 20:1 to 25:1, above which net N immobilization would occur, could lead to initial immobilization of soil inorganic N due to decomposition of rye cover roots after termination. That effect would limit net release of N taken up by the rye cover crop to subsequent grain crops.

In the agronomic practice evaluation study, winter cereal rye was successfully established by aerially broadcast seeding into standing soybean before leaf drop, however, the rye plant stand was not uniform (patchy) and with poor rye growth, especially when there were dry soil conditions in the fall. Rye growth and establishment was better within the tilled system compared to no-till, but the overall rye cover crop biomass was low (154–335 kg dry biomass $ha^{-1}$) with low N uptake (6–13 kg N $ha^{-1}$). These low amounts also reflect the early planned rye termination in the spring. Low biomass production and N uptake would reduce effectiveness as a cover crop, but could improve corn early growth and response to the rye cover crop. The rye cover crop reduced soil $NO_3$–N by 10 and 31 kg $ha^{-1}$ in fall and spring respectively, a larger change than expected because of the low amount of rye growth. Corn stand and early growth was not affected by rye, but there was 2.4% reduction in corn yield in the presence of the rye cover crop. There was a positive corn response from tillage and starter fertilizer on corn early growth, and a higher corn yield with tillage compared to no-till. The high starter N rate increased corn yield by 2% in both tillage systems, with or without the rye cover crop. This is especially important as the main N was sidedress applied after planting. Soybean yield was not affected by the aerially inter-seeded rye, the tilled or no-till system, the starter N applied to previous year corn, or any residual effect of the rye cover crop grown before corn.

Both research studies provided insight into rye cover crop dynamics as related to growth, nutrient uptake, and interaction with subsequent grain crops. Both, however, were conducted over a relatively short period of time. Having data form additional years would help determine the consistency of results across more production seasons. It would be interesting to see if rye root measurements change with different seeding techniques (drilled versus aerial broadcast for example), and in years with high rye cover crop plant establishment and production how that would affect corn growth, development, and yield in response to various agronomic production practices.