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Effect of corn stover harvest and winter rye cover crop on corn nitrogen fertilization

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Effect of corn stover harvest and winter rye cover crop on corn nitrogen fertilization

by

Jose L. Pantoja

A dissertation submitted to the graduate faculty in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY

Major: Soil Science (Soil Fertility)

Program of Study Committee:
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Ames, Iowa
2013

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DEDICATION

I want to dedicate this dissertation to my family, because their love and support made my graduate work more enjoyable. I also consider all my friends and colleagues as part of my career success, to whom I also dedicate this work. However, I have special appreciation for Cindy C. Lopez, my best friend during my graduate studies.
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† NS, non-significant ($P > 0.05$).

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† NS, non-significant.

† 0N, 135N, and 225N stand for 0, 135, and 225 kg N ha$^{-1}$ applied to the prior-year corn.
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<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CC</td>
<td>continuous corn</td>
</tr>
<tr>
<td>CS</td>
<td>corn-soybean</td>
</tr>
<tr>
<td>EONR</td>
<td>economic optimum nitrogen rate</td>
</tr>
<tr>
<td>GNU</td>
<td>grain nitrogen utilization</td>
</tr>
<tr>
<td>NDVI</td>
<td>normalized difference vegetative index</td>
</tr>
<tr>
<td>NUE</td>
<td>nitrogen use efficiency</td>
</tr>
<tr>
<td>PAN</td>
<td>plant available nitrogen</td>
</tr>
<tr>
<td>PFP</td>
<td>partial factor productivity</td>
</tr>
<tr>
<td>PUE</td>
<td>plant nitrogen uptake efficiency</td>
</tr>
<tr>
<td>RCC</td>
<td>rye cover crop</td>
</tr>
<tr>
<td>RCC-BD</td>
<td>rye cover crop biomass degradation</td>
</tr>
<tr>
<td>RCC-BP</td>
<td>rye cover crop biomass production</td>
</tr>
<tr>
<td>RCC-C</td>
<td>carbon in the rye cover crop biomass</td>
</tr>
<tr>
<td>RCC-FC</td>
<td>rye cover crop following corn</td>
</tr>
<tr>
<td>RCC-FS</td>
<td>rye cover crop following soybean</td>
</tr>
<tr>
<td>RCC-N</td>
<td>nitrogen in the rye cover crop biomass</td>
</tr>
<tr>
<td>SH</td>
<td>stover harvest</td>
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<tr>
<td>YEONR</td>
<td>yield at economic optimum nitrogen rate.</td>
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ACKNOWLEDGMENTS

I want to express my sincere appreciation to Dr. John E. Sawyer for his guidance, for being the major support during the execution of the research projects, and for pushing me to use the logic and practicality while executing research work. I feel privileged of working and learning from Dr. Sawyer, both as student and as an individual. Dr. Sawyer has been an excellent mentor for me to become a better scientist. Without Dr. Sawyer’s support the reached goals would not have been accomplished. Sincere gratitude is extended to my committee members for their friendship and for encouraging me to do my best. Appreciation is extended to Dr. Daniel W. Barker for his support with field work and writing of papers, and to the ISU Research and Demonstration Farms superintendents and personnel for their assistance with field activities and collecting of samples. I also want to thank the personnel of the Department of Agronomy, students, and visiting scholars who have worked with me. Their friendship and support made my work more pleasant.

This dissertation includes results of two research projects. The corn stover harvesting project was supported in part by the ISU Agronomy Department Endowment. The rye cover cropping project is part of a regional collaborative project supported by the USDA-NIFA, Award No. 2011-68002-30190, “Cropping Systems Coordinated Agricultural Project (CAP): Climate Change, Mitigation, and Adaptation in Corn-Based Cropping Systems.” Project Web site: sustainablecorn.org. This project was also supported in part by the Iowa Department of Agriculture and Land Stewardship, Division of Soil Conservation, through funds appropriated by the Iowa General Assembly.
ABSTRACT

Improvement in N management to optimize corn N fertilization requirement and minimize NO$_3^-$-N loss from agricultural fields is an ongoing need for continuous corn (*Zea mays* L.) and corn-soybean (*Glycine max* (L.) Merr.) production systems. This is especially important in Iowa as this state has the largest corn production across the U.S.A. The present dissertation includes two projects that evaluated corn response to N application and optimal fertilization rate. The first project evaluated the effect of corn stover harvest (SH) in continuous corn and the interaction with chisel plow and no-tillage systems; and the second project evaluated the effect of a rye cover crop (RCC) in no-till corn-soybean. For the RCC project, an additional in-field experiment was conducted to help understand the N cycling.

Results of the corn SH project showed that across tillage systems and fertilizer N rates, corn grain yield was 7 and 10% greater with 50 and 100% SH compared to no harvest, respectively. Corn grain yield was also 9% greater with chisel plow than with no-tillage. At the economic optimum N rate (EONR), yield was not influenced by SH with chisel plow, but was 6% greater with each SH rate in no-tillage. The EONR was the same with both tillage systems, but decreased by 22 and 45 kg N ha$^{-1}$ with 50 and 100% SH, respectively. Results indicate, at least on a short term basis, that suggested N fertilization rates should be adjusted when stover is harvested in continuous corn production.

Results of the RCC project showed that the reduced corn grain yield by 6% at the EONR, and increased RCC biomass production resulted in lower corn yield. The EONR was the same with no-RCC and RCC. Soybean yield was not affected by the RCC. The RCC N cycling experiment showed that RCC biomass degradation and N recycling after rye control
consistently decreased over time (total of 105 d after control), following an exponential decay. Nitrogen recycling was faster and more N recycled with RCC following soybean than following corn (22 vs. 14 kg N ha⁻¹, respectively), and was influenced by the RCC C:N ratio. This research indicates that corn N fertilization rate should be the same with or without a RCC system, mainly due to the RCC not recycling a large amount of N. Since there was low RCC N uptake, reduced corn yield, and no change in EONR, improvement in the RCC system or management practices are needed for RCC to become viable in a no-till corn-soybean rotation.
CHAPTER 1. GENERAL INTRODUCTION

Iowa has the largest corn (*Zea mays* L.) production across the U.S.A. Improvement in N management to reduce corn N fertilization requirement and NO$_3^-$–N loss from agricultural fields is an ongoing need for both continuous corn and corn-soybean (*Glycine max* (L.) Merr.) production systems.

Current corn grain prices are providing producers incentive to increase corn acreage and grain yield to meet multiple use demands; such as animal feed, grain ethanol, and recently the developing use of crop stover for cellulosic ethanol. Increasing corn production results in greater N fertilization and creates a need for optimizing N use efficiency in the continuous corn production system. However, information on impacts of corn stover harvest on plant available N, fertilization requirement, and succeeding years of corn production is limited. With the potential use of corn stover by the ethanol industry, producers want to improve profits, but they also want to maintain corn production sustainability. They are also questioning the impact of corn stover harvest on optimal N fertilization, crop nutrient supply dynamics, and yield response to tillage system and N fertilization. In some cases, corn stover harvest could be detrimental for crop production, or interact differently with tillage system. A similar response to corn stover harvest could occur with N fertilization requirement. Crop and soil management practices that maximize not only grain yield, but also have associated N fertilization recommendations tailored to increase crop N use efficiency, are currently required. Providing these tailored recommendations is challenging as corn stover harvest has potential to change nutrient supply dynamics.
Rate of applied N and optimal N fertilization requirement are important factors in regard to net profit in corn production systems. However, applying the optimum N rate does not stop NO$_3^-$-N loss from production fields. Meeting water quality standards is a challenge because NO$_3^-$-N concentrations often exceed the maximum EPA drinking water standard in surface waters, and NO$_3^-$-N transport from cropping fields contributes to hypoxia in the Gulf of Mexico. Iowa has a major role in this situation due to extensive corn and soybean production. These issues have led to increased efforts to develop alternative in-field N management practices to help reduce NO$_3^-$-N loss.

Winter cover crops can utilize residual N remaining after harvest of corn and soybean crops, and therefore help reduce NO$_3^-$-N loss. Due to advantages in regard to establishment, winter hardiness, and rapid growth, winter cereal rye (Secale cereale L.) is a common cover crop choice in the Northern region of the U.S.A. However, despite the benefits of winter rye, questions remain about its effects on crop yields and nutrient recycling, especially N. Is that recycling important, does the N become plant available, does N release from cover crop biomass degradation match the time of corn N uptake demand, is there a substantial N release as rye cover crop biomass degrades, and should corn N fertilization rate be adjusted? These are important issues for corn N fertilization and crop productivity, and only few studies have addressed these questions with application of adequate N fertilization rates and results have been inconsistent. Research has shown no detrimental effect of winter rye on soybean yield, but in some cases has reduced corn yield. The effectiveness of winter rye in reducing NO$_3^-$-N loss, increasing N supply for the annual crop, and improving crop yield may depend upon adequate N fertilization, seasonal variation, and cover crop management. Various agencies are providing incentives to farmers for implementing cover crops in their corn and soybean
fields; therefore, producers are becoming more interested in implementing cover crops, with winter rye as the cover crop of choice.

Effective N management in production fields must enhance crop N use efficiency without reducing crop yield or increasing NO$_3^-$-N loss. Practices such as corn stover harvest and use of winter rye as a cover crop may not necessarily result in NO$_3^-$-N loss reduction. However, optimal N fertilization requirement needs to be addressed in such systems to improve profits and balance the amount of N fertilization for optimum plant growth while minimizing NO$_3^-$-N transport to water systems. Evaluating the effects of corn stover harvest and use of winter rye as a cover crop on crop yield and corn optimal N fertilization requirement is an ongoing need in Iowa.

This dissertation includes two major projects that evaluated optimal N fertilization in corn production systems. The first project evaluated the effect of corn stover harvest in continuous corn, and its interaction with chisel plow tillage and no-tillage systems, on corn response to N fertilization and optimal N fertilizer application rate. The second project evaluated the effect of winter rye as a cover crop on corn and soybean yield, corn response to N fertilization, and optimal N fertilizer application rate. Both projects included multiple sites across Iowa and were conducted for multiple years. For the rye cover cropping project, an additional in-field experiment was conducted to help understand the N availability and recycling after winter rye control in the spring; specifically to estimate the rye biomass degradation, release of N accumulated in the rye cover crop biomass, and subsequent effect on corn optimal N fertilization requirement.

Outcomes of these research efforts are helping address better N management practices in continuous corn and corn-soybean production systems. Results will help increase
the crop N use efficiency, and provide effective in-field N management practices to help meet desired water quality standards. Results will also help crop advisers and farmers properly implement corn stover harvest and use of winter rye as a cover crop, and employ in-field agronomic crop management practices to improve corn N fertilization and use efficiency.

**DISSERTATION ORGANIZATION**

This dissertation contains five chapters. The first chapter is a brief description of the dissertation research. Chapters 2 through 4 are manuscripts describing the executed projects and outcomes of research efforts. These chapters are intended to be published in Agronomy Journal. The titles of the manuscripts are “Corn Response to Nitrogen Fertilization with Varying Stover Harvest and Tillage System”, “Nitrogen Fertilization Requirement for Corn and Crop Yield Response to Winter Rye Cover Crop”, and “Winter Rye Cover Crop Biomass Production, Degradation, and Nitrogen Recycling in a Corn-Soybean Rotation System”. The final chapter (chapter 5) provides a summary of general conclusions for the executed projects.
CHAPTER 2. CORN RESPONSE TO NITROGEN FERTILIZATION WITH VARYING STOVER HARVEST AND TILLAGE SYSTEM

A paper to be submitted to Agronomy Journal

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Abstract

Demand for corn (Zea mays L.) stover is increasing for livestock consumption and bioenergy production. Frequent stover harvest (SH) from fields to meet these needs could impact crop N availability and soil N cycling. A three year study was conducted at two sites in Iowa with continuous corn (CC) to determine the effect of SH rate and tillage system on corn production, response to N fertilization, and optimal N rate. Treatments were 0, 50, and 100% SH, chisel plow tillage and no-tillage, and six N rates from 0 to 280 kg N ha⁻¹. Profile soil NO₃⁻–N concentrations (with no N fertilization) slightly increased from spring preplant to early June with no SH, but were the same with SH post-harvest. Mid-vegetative corn canopy normalized difference vegetative index (NDVI) sensing values were greatest with chisel plow, SH, and N application. The increase in NDVI with SH was less with chisel plow than with no-tillage. Corn grain yield was 9% (0.84 Mg ha⁻¹) greater with chisel plow than
with no-tillage. At the economic optimum N rate (EONR), yield was not influenced by SH with chisel plow, but was 6% greater with each SH rate in no-tillage. The EONR was the same with both tillage systems, but decreased by 22 and 45 kg N ha\(^{-1}\) with 50 and 100% SH, respectively. The greater yield with SH resulted in greater grain N utilization GNU. Results indicate N fertilization should be adjusted with SH in CC.

**Abbreviations:** CC, continuous corn; EONR, economic optimum nitrogen rate; GNU, grain nitrogen utilization; NDVI, normalized difference vegetative index; NUE, nitrogen use efficiency; PAN, plant available nitrogen; SH, stover harvest; YEONR, yield at economic optimum nitrogen rate.

**Introduction**

Demand for corn stover is increasing to meet needs for livestock feed and bedding, bioenergy production, and manufactured products such as wood replacement. These uses are in addition to use of corn grain for feed and ethanol fuel. Developing use of crop stover for cellulosic ethanol has large potential as it could further reduce reliance on fossil fuels (Blanco-Canqui et al., 2006). Total demand for corn grain and stover has resulted in increased corn acreage in the U.S.A., increased CC, and potential for continued increase of cropland in corn production due to demand for stover. This will lead to increased fertilizer use (Sulc and Tracy, 2007), and in conjunction with SH, increased potential for negative effects on water quality and nutrient cycling.

As technology to produce cellulosic ethanol becomes commercially viable, corn SH will likely increase (Wienhold and Gilley, 2010). Of concern is that SH will negatively
impact the soil system, crop productivity potential, and the environment (Varvel et al., 2008). Questions remain as to the net agronomic and environmental effect of SH and rate. Corn SH can potentially reduce soil protection provided by crop residue, reduce soil organic matter (SOM), and alter nutrient cycling. Information on impacts of crop biomass harvest on soil nutrient supply is unclear (Mulvaney et al., 2010). Therefore, corn SH could potentially affect plant N availability and N fertilization requirements. Research is needed to evaluate the effects of corn SH not only on soil biological, chemical, and physical properties, but also on crop nutrient supply dynamics. For example, corn N uptake can be affected by cropping system and N fertilization rate (Zhou et al., 1997).

The determination of optimal N fertilization rate for achieving maximum crop profitability is difficult due to the complexity of N cycling, which can be altered with SH, tillage system, and N fertilization management. Microbial N use to decompose high C:N ratio corn stover, combined with lower soil temperature when crop residue covers the soil, results in decreased yields (Andraski and Bundy, 2008). Soil net N mineralization in CC is lower than in corn-soybean \([Glycine\ max\ (L.)\ Merr.]\) rotation, and net N mineralization also decreases with cold temperatures and continued N fertilization (Carpenter-Boggs et al., 2000). Lower N mineralization results in less soil plant available N (PAN) for corn, which may result in lower yield. Corn SH can differentially change corn biomass production and grain yield response to tillage and N fertilization rate (Coulter and Nafziger, 2008). The agronomic impact of crop SH and tillage system on soil N availability, soil N mineralization, and crop growth are not fully understood (Maskina et al., 1993; Venterea et al., 2006). Reasons for this are limited information and research evaluating these impacts in an integrated or long-term basis. Therefore, short-term experiments can show immediate effects
of tillage and N fertilization on crop productivity and response to N rate, but long-term experiments are required to evaluate the lasting influence of such agricultural practices on soil C and other soil properties (Gollany et al., 2005).

Effective N management must enhance N use efficiency (NUE) without reducing crop yield or increasing N loss to water resources (Andraski and Bundy, 2008). Water quality issues have led to implementation of in-field N management practices that can potentially reduce NO₃⁻–N loss in tile drainage water from production fields. However, practices such as corn SH may not necessarily be positive in relation to NO₃⁻–N loss, because SH can increase NO₃⁻–N concentration in surface runoff (Wienhold and Gilley, 2010). Therefore, it is important to evaluate if soil N supply of PAN, corn NUE, and optimal N fertilization requirement change with SH. Utilizing conservation tillage, increasing NUE, and improving N management can optimize profits, maintain crop production sustainability, and minimize N losses (Torbert et al., 2001; Vetsch and Randall, 2004). As an example, in the upper Midwest U.S.A., biennial chisel plow tillage can reduce fuel cost related to tillage, and maintain crop yield compared with more intensive tillage systems (Venterea et al., 2006).

Farmers have diverse choices of tillage practices for corn production. However, no-tillage is becoming a common choice to conserve soil moisture, reduce farm costs due to less equipment use, reduce water erosion and nutrient runoff, and save labor and time. Depending upon soil conditions, no-tillage may result in greater or lower corn grain yield compared to conventional tillage, but may not change corn response to N fertilization (Vetsch and Randall, 2004). Tillage system does not have as large of an impact on crop N uptake and yield as N fertilization rate, N source, and seasonal variability (Kwaw-Mensah and Al-Kaisi, 2006; Al-Kaisi and Kwaw-Mensah, 2007). Crop production in no-tillage is more successful
and has greater crop yield potential on moderate to well-drained soils compared to poorly drained soils (Bitzer, 1998; Torbert et al., 2001). Part of that yield improvement comes from soil moisture conservation due to soil coverage provided by crop residue.

Follett et al. (2012) found reduced corn yield with SH in no-tillage in a relatively dry environment in Nebraska; and Coulter and Nafziger (2008) in Illinois found lower corn yield with SH in no-tillage compared to tillage in a low precipitation environment, but not with normal precipitation. Therefore, SH could be detrimental for crop production, interact differently with tillage system, or produce a different response to N fertilization rate. Coulter and Nafziger (2008) did not find a difference in EONR between tillage systems with SH when precipitation was adequate, but there was a reduction with no-tillage at a site that had low precipitation. In that study, yield at the EONR (YEONR) was 4% greater with partial or full SH compared to no SH when precipitation was adequate. Corn N fertilization requirement with conversion to no-tillage may be greater until a new N equilibrium is established for that soil-plant system (Raun and Schepers, 2008). Corn production requires tillage practices that maximize corn yield, but also have associated N fertilization recommendations tailored to increase NUE (Mehdi et al., 1999). There is a similar need for optimizing N use in systems with corn SH. The objectives of this study were to determine the effect of SH rate and tillage system on corn production, response to N fertilization, and optimal N rate.
Materials and methods

Study sites

The study was established in fall 2008 and conducted for three years at two sites representing contrasting, but common soils in Iowa. The sites were the Iowa State University Agricultural Engineering and Agronomy Research farm in Central Iowa near Ames (42°00’38” N; 93°44’01” W), and the Armstrong Research Farm in southwest Iowa near Lewis (41°19’53” N; 95°10’60” W). The soil at Ames is a calcareous loamy till with high clay content and poor internal drainage, and the soil at Lewis is a silt loam formed in loess with low clay content and good internal drainage (Table 1). At both sites, corn was grown the year before establishment of the study with an agronomic N rate applied during the spring after corn planting. Monthly mean temperature and total precipitation across the study sites were calculated from data collected at weather stations at each research farm and reported by the Iowa Environmental Mesonet Network (Arritt and Herzmann, 2013).

Experimental design and treatment application

The experiment design at each site was a split-split plot with three replicates. Tillage system was the main plot (chisel plow tillage and no-tillage), corn SH rate the split plot (0, 50, and 100% SH), and fertilizer N rate the split-split plot (0 to 280 kg N ha$^{-1}$ in 56 kg ha$^{-1}$ increments). Plots were 15 m long with eight rows per plot, 0.76 m row spacing. Tillage and SH treatments were arranged as main and split-plots to facilitate treatment application. Treatments remained in the same location each year.

Chisel plow tillage was performed to a 0.15-0.25 m depth in the fall after SH, with spring field cultivation as needed for seedbed preparation. Fertilizer N as urea-ammonium
Nitrate solution (UAN, 32% N) was applied with coulter-injectors to every other row-space (1.52 m apart) within three weeks after corn planting and as soil conditions allowed.

Corn SH was performed after grain harvest by raking and baling. For 50% SH, corn stalks were not mowed, a wheel rake with minimal down pressure was used to rake stalks into windrows, and then the stover was baled. For 100% SH, corn stalks were mowed close to soil surface, the wheel rake set to run on the ground with very high pressure to rake stalks into windrows (raked twice if needed), and then the stover was baled. The intended SH rates were 50% and 100% removal, but the actual rate varied upon soil conditions and equipment effectiveness for SH. On average, 30% (20 to 40% range) of corn stover was harvested for the partial SH treatment (50%), and 80% (75 to 85% range) for the full SH treatment (100%).

To determine the amount of corn stover remaining in the field, two random samples were collected with a square frame (0.093 m$^2$) by replicate in fall 2008, and from plots receiving 0, 168, and 280 kg N ha$^{-1}$ within each tillage system in fall 2009 and 2010. These samples were dried in a forced-air dryer at 60 ºC and weighed. Results were used to estimate the amount of stover remaining in the field on a dry matter (DM) basis (Table 2), and by comparison to the DM amount with no SH, calculate the percentage harvested. In 2008 no treatments were applied, therefore, the amount of corn stover remaining in the field for the 2009 growing season was only due to SH rate. In 2009 and 2010, N fertilization resulted in different amounts of corn stover remaining; however, tillage system did not affect that amount.

**Corn planting and harvest**

Corn was planted on average at 81500 seeds ha$^{-1}$ each year with an adapted corn rootworm (Diabrotica sp.) resistant hybrid at each site. The hybrids were ‘Pioneer 35K33’ at Ames and ‘Pioneer 33W84’ at Lewis. Corn was planted with no-till coulters and row
cleaners to remove crop residue and aid in seed placement. Weed control and cultural practices were typical for the CC system at each site. Corn grain yield was determined by harvesting the middle four rows of each plot with a plot combine and adjusting to 155 g kg\(^{-1}\) moisture.

**Soil sampling and analysis**

Ten random cores per replicate were collected in fall 2008 (0-0.15 m) to determine initial soil pH, SOM, and soil test P and K. Soil was also sampled (0-0.90 m in 0.30 m increments) by taking five cores across each replicate to determine initial soil NO\(_3^–\)–N. After treatments initiation (2009-2011), soil was sampled (0-0.60 m in 0.30 m increments) to determine soil NO\(_3^–\)–N each year in the spring preplant and in early June in plots with no fertilizer N; and in the fall post-harvest (0-0.90 m in 0.30 m increments) in plots receiving 0, 168, and 280 kg N ha\(^{-1}\). Six cores per plot were taken in a diagonal pattern across two adjacent rows, with one core from each row and a core 0.20 m from the side or each row. All soil samples were collected by hand with 0.02 m diameter probe. Soil was mixed and a sub-sample saved for analysis. Samples were dried in a forced-air dryer at 25 °C and ground to pass a 2-mm sieve. Soil pH was determined with 1:1 soil:water ratio, SOM by dry combustion (LECO CHN-2000 analyzer, LECO Corp., St. Joseph, MI) (Nelson and Sommers, 1982), soil test P and K with Mehlich-3 extraction and colorimetric determination, and NO\(_3^–\)–N was determined by 2 M KCl extraction and colorimetric cadmium reduction using a Lachat flow injection analyzer (Lachat Instruments, QuikChem 8500 Series 2, Loveland, CO) (Brown, 1998).

When the study was established, soil pH was neutral to slightly alkaline (Table 1), and therefore no lime application was needed (Sawyer et al., 2011). The SOM was within the
typical range for Mollisols in the Midwest U.S.A. (Soil Survey Staff, 1999). The Mehlich-3 soil test P was in the Low interpretation category at Ames and in the High interpretation category at Lewis; whereas the soil test K was in the Low interpretation category at both sites (Sawyer et al., 2011). To avoid potential for P and K deficiency, and any issue with variation in soil tests across the sites, in spring 2009 the Ames site received a uniform application of 60 kg P ha\(^{-1}\) and 85 kg K ha\(^{-1}\), and Lewis received 65 kg P ha\(^{-1}\) and 60 kg K ha\(^{-1}\). Fertilizer P and K were broadcast applied as triple super phosphate and muriate of potash, respectively.

No N fertilizer or manure was applied across the study areas in the fall or spring before planting.

**Corn canopy sensing**

A Crop Circle ACS-210 active canopy sensor (Holland Scientific, Lincoln, NE) was used to estimate corn canopy biomass or growth response to treatments. Corn growth varied across treatments; however, corn canopy sensing was conducted in all plots when corn receiving 168 kg N ha\(^{-1}\) reached the mid-vegetative (V10) growth stage (Abendroth et al., 2011). At the time of sensing, corn stages varied from V8 - V11 depending upon the fertilizer N rate applied after planting, but not difference between SH rates, tillage systems, or interaction between SH and tillage systems was observed. The ACS-210 active canopy sensor uses a single light emitting diode that emits light at the visible (VIS) 590 nm and near-infrared (NIR) 880 nm wavelengths, and reflected light from the corn canopy is captured by two silicon photodiodes on the sensor of varying spectral ranges (400-680 nm and 800-1100 nm) (Barker and Sawyer, 2010). The sensor was mounted on a mast, positioned mid interrow, and carried by hand through the middle of each plot (0.60 to 0.90 m above the canopy) at a constant speed (1.5 m s\(^{-1}\)). Sensing was conducted between the 0900 and 1500 h daytime,
and reflectance measurements were captured on-the-go with a handheld data logger. Values of the VIS and NIR band reflectance were used to calculate the normalized difference vegetative index (NDVI) for each plot (Gitelson et al., 1996; Teillet et al., 1997), as shown in Eq. [1].

\[
NDVI = \frac{(NIR - VIS)}{(NIR + VIS)}
\]  

[1]

**Corn grain nitrogen utilization**

At physiological maturity (R6) six corn ears were randomly collected from the center rows of plots that received no N fertilization. The ears were dried in a forced-air dryer at 60 °C, grain separated from the cob, milled, and a sub-sample analyzed for total N by dry combustion. Results were used to estimate grain N utilization (GNU), using the grain yield from plot combine harvest as shown in Eq. [2] (Dobermann, 2007).

\[
GNU = \frac{Grain \ yield}{grain \ N \ uptake}
\]  

[2]

In this Eq., GNU is equal to the grain yield in Mg ha⁻¹ reported at 155 g kg⁻¹ moisture, divided by grain N uptake in kg N ha⁻¹. The GNU was determined with no N fertilization so the effect of treatments on soil potential to supply PAN would not be masked by application of fertilizer N.

**Statistical analysis**

Analyses of variance (ANOVA) for the amount of stover remaining in the field, profile soil NO₃⁻–N, corn canopy NDVI, corn grain yield, and GNU were conducted with
PROC MIXED (SAS Institute, 2009). For the analyses, treatments and their interactions were considered fixed, and replicates, sites, years, and their interactions were considered random. Differences between treatments were considered significant at $P \leq 0.05$. Mean comparisons for GNU were performed with Fisher Protected Least Significant Difference (FLSD). To evaluate the corn response to fertilizer N rate for NDVI and grain yield, PROG REG was used to investigate the quadratic regression fit [Eq. 3], and PROG NLIN was used to investigate the quadratic-plateau regression fit [Eqs. 4 and 5]. The quadratic-plateau was the best fit for N response ($P < 0.001$ and the largest $R^2$). For grain yield in both tillage systems with no SH, the segment joint point with the quadratic-plateau was greater than the highest N fertilization rate, therefore, in those cases the quadratic model was used. The lower and upper confidence limits (95%) of model parameters were used to aid in model comparison across fertilizer N rates, with parameters considered not different if their estimates were within the confidence intervals of both equations being compared.

\[
y = a + bx + cx^2 \quad [3]
\]
\[
y = a + bx + cx^2 \text{ if } x < x_o \quad [4]
\]
\[
y = a + bx_o + cx_o^2 \text{ if } x \geq x_o \quad [5]
\]

In these models, $y$ represents the predicted corn response (NDVI or Mg ha$^{-1}$ grain yield) to N fertilization, $x$ is the fertilizer N rate (kg N ha$^{-1}$), and $a$ (intercept), $b$ (linear coefficient), $c$ (quadratic coefficient), and $x_o$ (fertilizer N rate at the joint point) constants. The EONR for grain yield and YEONR were calculated from each regression model fit to the
N response (Cerrato and Blackmer, 1990) by solving for $x$ and using a 0.0056 $\text{kg}^{-1} \text{N}$ to $\text{Mg}^{-1}$ corn grain price ratio.

**Results and discussion**

**Weather**

The weather during the growing season can influence corn residue degradation, corn growth and response to N fertilization rate, and profile soil $\text{NO}_3^-$-N. For both sites, the spring in 2009 (Apr. to June) was 1 °C colder than the recent historical average from the last 16 years and 2010 was 1 °C warmer (Fig. 1a). During the reproductive corn growth stages (July to Sept.) and compared to the average, 2009 was 2 °C colder and 2010 was 1 °C warmer. The temperatures in 2011 were the same as the historical average for the entire season. The amount of precipitation during the spring in 2009 was 5 cm lower than the average (31 vs. 36 cm), 2010 was wetter as it received 5 cm more than the average, and 2011 was somewhat drier than the average (34 cm) (Fig. 1b). From July to Sept., 2009 and 2011 were somewhat wetter than the historical average (28 vs. 26 cm); however, 2010 had much greater precipitation during that period (55 cm). During harvest (Oct.), 2009 was 3 °C colder and 2010 and 2011 were 2 °C warmer than the historical average (11 °C). For that period, 2009 was wetter (17 cm) and 2010 and 2011 were drier (1 cm) compared to the historical average (7 cm). There were intense precipitation events during the three years of the study, and generally the three year period was wetter than the recent historical average.
Soil nitrate

Initial soil nitrate

Both sites had low initial soil NO$_3^-$–N concentrations in the top 0.90 m of soil in fall 2008, with Ames lower than Lewis (Table 1). These low concentrations indicated there was not a large pool of PAN in the soil profile. Therefore, sites were likely to show a corn response to N fertilization. The soil samples were collected before any N treatment had been applied; therefore, reflected background concentrations at each site following the prior corn crop. The N applied across the study areas in the spring 2008 was at a uniform agronomic rate for CC (220 kg N ha$^{-1}$).

Spring soil nitrate

Spring soil nitrate

Soil NO$_3^-$–N concentrations in control plots (no N fertilization) were low in the spring preplant and early June at both depths in the top 0.60 m of soil. Corn SH did not affect soil NO$_3^-$–N when averaged across spring sampling times (Table 3); however, there was a small increase in soil NO$_3^-$–N concentration (0.7 mg kg$^{-1}$ more) from preplant sampling to early June with no SH (Fig. 2), indicating low net N mineralization during that time. Soil NO$_3^-$–N concentrations increased slightly with SH level in the spring preplant, but decreased with SH level in early June (Table 3, Fig. 2). However, changes in soil NO$_3^-$–N from preplant to later spring sampling can be influenced by site-specific N mineralization, and soil moisture and temperature conditions (Andraski and Bundy, 2008).

Across sites, chisel plow increased soil NO$_3^-$–N concentration by only 0.5 mg kg$^{-1}$ compared to no-tillage in both spring preplant and early June sampling, a minor increase considering the differences in soil conditions within both systems. The small differences in soil NO$_3^-$–N between SH rates, tillage systems, and sampling time would be related to the
low overall concentrations, potentially low net N mineralization, corn N uptake (Hatfield et al., 2009), and potentially high NO$_3$–N leaching due to intense precipitation events. Despite having a lower amount of crop residue for soil coverage after SH, the 50 and 100% SH did not appear to affect net N mineralization or cycling into inorganic N during the spring, which was reflected in the low soil NO$_3$–N concentrations.

**Post-harvest soil nitrate**

Post-harvest soil NO$_3$–N concentrations were low and not affected by SH rate or tillage system (Table 3, Fig. 3). If any difference in net N mineralization due to SH or tillage system occurred during the growing season, it was not reflected in the post-harvest soil NO$_3$–N. By the end of the growing season any potential effect from SH on soil NO$_3$–N could have been masked by wet conditions that enhanced the potential for NO$_3$–N loss, high corn yield, and potential for large N response in CC to applied fertilizer N. As is often found, NO$_3$–N concentration decreased with depth (Sainju and Singh, 2008), but N application increased profile NO$_3$–N at all depths, with greatest concentrations in the surface 0-0.15 m depth and with the highest N rate.

Net N mineralization could have been different due to the amount of crop residue remaining with different SH rates, and thus potentially affected profile soil NO$_3$–N (Burgess et al., 2002). However, rate of N mineralization seemed to be not affected at these sites and environments. The lack of major differences in profile soil NO$_3$–N in the spring and fall due to SH indicated the amount of crop residue remaining had little influence on PAN. Although not included as a measurement in the study, soil temperature could play a greater role in microbial processing of high C:N stover, N mineralization and cycling, and corn growth than crop residue alone (Andraski and Bundy, 2008).
**Corn canopy sensing**

Corn canopy NDVI values obtained at the V10 growth stage varied with SH and tillage system (Table 4, Fig. 4). Across site-years, NDVI was greater with SH (0.632, 0.688, and 0.681 for 0, 50, and 100% SH, respectively) and with chisel plow compared to no-tillage (0.674 and 0.646, respectively). The largest increase in NDVI with SH was with no-tillage, where 50 and 100% SH resulted in a large increase in corn growth and canopy development (Fig. 4). These results indicated the effect of SH was greater with no-tillage than with chisel plow, which could be a reflection of surface residue coverage and differential soil temperature affecting corn growth, rather than soil N mineralization and soil supply of PAN, since little change due to SH or tillage was found for spring soil NO$_3^-$–N concentrations.

The NDVI values for control plots (no N fertilization) were lower than plots with N fertilization, indicating some N stress, reduction in plant growth, and potential for large response to N fertilization. Application of N increased the NDVI values up to the point where response plateaued (Table 5, Fig. 4), with the N rate at the joint point of the quadratic-plateau model indicating maximal plant canopy production and N response. These results for corn response to N fertilization were consistent with studies conducted in Iowa to evaluate corn canopy response to N stress and N fertilization rate (Barker and Sawyer, 2010 and 2012).

The N rate at maximum NDVI response with 0 and 100% SH was lower with chisel plow compared to no-tillage, indicating potentially greater soil supply of PAN due to more soil mixing or lower amounts of remaining corn stover. However, the NDVI response was different between tillage systems with 50% SH, and also the N rate where the NDVI plateaued was 60 kg N ha$^{-1}$ greater with chisel plow compared to no-tillage at that SH rate. The response difference was mostly due to varying NDVI values at the 56 kg N ha$^{-1}$ rate.
Corn growth and N uptake are rapid at the mid-vegetative growth stages, especially with adequate soil moisture (Abendroth et al., 2011). It is possible that site-specific differences in fertilizer N availability at the low N fertilization rate, along with different soil moisture and temperature conditions, could have resulted in the variable corn NDVI responses. Coulter and Nafziger (2008) indicated that leaf area index and leaf chlorophyll (Minolta SPAD meter) measured at the R2 growth stage had linear relationships with grain yield, and that those relationships were consistent across SH rates and tillage systems. Those plant measurements were taken at a reproductive stage (R2) of corn development rather than V10. Canopy sensing at mid-vegetative stages should reflect early corn growth stresses from SH and tillage, and therefore potential effects on grain yield, but likely not as related directly to yield level.

Sensing measurements have to be interpreted carefully due to potential plant stresses other than from N fertilization rate (Barker and Sawyer, 2010). Non-nutrient factors affecting corn growth are plant density, soil moisture supply, and temperature (Wilhelm et al., 2004). However, those are also factors that could affect early season corn growth response to SH and tillage. In an Indiana study, fall chisel plow reduced corn stover on the soil surface from 21 to 46%, and the lower residue cover compared to no-tillage resulted in greater soil temperature in the spring, which promoted corn emergence, growth, and N uptake (Hill and Stott, 2000). Other research has found that tillage increased soil temperature compared to no-tillage by 1.2 to 1.4 °C in a cold and wet spring (Licht and Al-Kaisi, 2005). Andraski and Bundy (2008) found a soil temperature increase from 1 to 4 °C in the spring depending upon the amount of SH and soil moisture.
In well drained soils, and with low annual precipitation, there are positive impacts of greater crop residue coverage such as increased biological activity, soil moisture conservation, and stover production (Krupinsky et al., 2007; Coulter and Nafziger, 2008). However, having no SH in our study, especially in the no-tillage system, resulted in reduced early season corn canopy. In the early season, corn SH combined with tillage would increase sunlight reaching the soil surface and hence increase soil temperature and promote water evaporation (Boyd and Van Acker, 2003). These factors would promote faster early season corn growth, especially in wet soils, and likely contributed to the larger canopy NDVI values with SH harvest and chisel plow.

**Corn production and nitrogen response**

**Grain yield**

Differences in weather and soil moisture conditions resulted in variation in corn grain yield at each site-year (individual site-year data not shown). On average, corn grain yield was 3.57 and 2.75 Mg ha\(^{-1}\) greater in 2009 compared to 2010 and 2011 across sites, respectively. Across years, Ames had 1.68 Mg ha\(^{-1}\) less corn grain yield compared to Lewis, likely a reflection of the poorly drained soil at the Ames site.

Across sites, years, and N rates, corn grain yield was greater with SH in both tillage systems, with mean 8.19, 8.75, and 9.04 Mg ha\(^{-1}\) for 0, 50 and 100% SH, respectively (Table 4). Corn yield with no N fertilization was quite low, and lower with no SH compared to 50 and 100% SH rates (Table 5, Fig. 5). These yield responses to SH are different than those reported by Follett et al. (2012) with no-tillage, where a grain yield decrease of almost 0.20 Mg ha\(^{-1}\) occurred with 50% SH compared to no SH at a low 60 kg N ha\(^{-1}\) rate. They associated the yield decrease to a reduction in soil productivity due to less soil organic C.
Also, Varvel et al. (2008) indicated that corn SH may not be sustainable in the long-term, especially in no-tillage systems with low annual precipitation. The larger yield with SH observed in our study was consistent across fertilizer N rates for each tillage system (Table 5, Fig. 5). Across SH rates, chisel plow had greater yield than no-tillage (9.07 vs. 8.24 Mg ha\(^{-1}\)). The influence of SH rate varied between tillage systems, where the increase in yield with SH was constant with chisel plow (0.30 and 0.35 Mg ha\(^{-1}\) between each SH rate), but the increase with no-tillage was greater between 0 and 50% SH than between 50 and 100% SH (0.82 vs. 0.22 Mg ha\(^{-1}\)). These results indicated the greater effect of less crop residue on the soil surface with SH in no-tillage than chisel plow. Corn grain yield was the same with chisel plow and no SH as for no-tillage with 50 or 100% SH (8.76 compared to 8.44 and 8.66 Mg ha\(^{-1}\)). These yield responses again indicated the larger impact of SH, and associated lack of residue mixing into soil, with no-tillage than with chisel plow.

Across tillage systems and N rates, corn SH increased corn grain yield by 0.56 (7%) and 0.85 Mg ha\(^{-1}\) (10%) for the 50 and 100% SH, respectively, compared to no SH. Having full corn stover remaining (Table 2) may help protect the soil, but in the CC production system resulted in reduced early season corn growth and ultimately grain yield, especially for no-tillage. Although corn SH increased corn grain yield in the short-term on these productive soils, that benefit needs to be balanced against the need to maintain soil productivity by reducing soil erosion, providing biomass for SOM maintenance, and enhancing long-term productivity (Wilhelm et al., 2004; Coulter and Nafziger, 2008).

The larger corn yields observed with chisel plow compared to no-tillage could be due to many factors, such as soil physical condition, surface residue level, and soil moisture and temperature. The small increase in spring soil NO\(_3^−\)-N observed with chisel plow compared
to no-tillage with no N fertilization would not have contributed to the difference found in the early season corn canopy sensing values and grain yield. On productive soils in Illinois, grain yield in CC was similar between chisel plow and no-tillage with full or partial SH across five environments with adequate precipitation; however, two environments with low precipitation had greater grain yield with chisel plow than no-tillage with partial or no SH (Coulter and Nafziger, 2008). Andraski and Bundy (2008) reported a 40 kg N ha\(^{-1}\) increase in net soil N mineralization in the top 0.90 m of soil with SH compared to no SH in a well-drained silt loam soil with relatively low precipitation. In our study, however, an impact of SH on profile soil NO\(_3^-\)–N was not observed. Site-specific differences in weather, soil properties, and N immobilization-mineralization could be reasons for contrasting results.

**Economic optimum nitrogen**

Corn SH reduced the EONR in both tillage systems (Table 5). The EONR was the same for each tillage system at each SH rate. The average EONR with 50 and 100% SH was 22 (9%) and 45 kg N ha\(^{-1}\) (18%) less compared to no SH, respectively. Coulter and Nafziger (2008) indicated that reduction in N fertilization rate for corn with SH could be due to less N immobilization. Microbial N demand for high C:N ratio corn stover degradation, associated lower soil temperature, and less N mineralization with no SH would result in a high N fertilization requirement (Halvorson and Reule, 2007), as was found in our study (EONR at 255 kg N ha\(^{-1}\)). That rate is approximately 40 kg N ha\(^{-1}\) more than the rate normally recommended for CC in Iowa with no SH (Blackmer et al., 1997; Sawyer et al., 2006). Since the EONR decreased with SH, N fertilization requirement could be adjusted for specific SH rates in CC.
With chisel plow, the difference in corn grain yield between SH and no SH decreased as fertilizer N rates approached the EONR and the highest applied rate (Fig. 5). This did not occur with no-tillage. Yield across N rates, the maximum N response, and YEONR were consistently greater with chisel plow than no-tillage, with an average 0.68 Mg ha\(^{-1}\) (6%) greater yield with chisel plow. However, the EONR with chisel plow was only 5 kg N ha\(^{-1}\) lower compared to no-tillage across SH rates (Table 5), a small difference considering the major changes in soil disruption and surface residue coverage between the two systems. The maximum difference in EONR between tillage systems was only 9 kg N ha\(^{-1}\) (at 50% SH).

**Grain nitrogen utilization**

Corn SH increased grain yield (Table 5, Fig. 5) and grain N uptake (data not shown). The GNU with no N fertilization was greater with SH \((P = 0.040); 0.1188, 0.1204, and 0.1228 \text{Mg kg}^{-1} \text{N}, for 0, 50, and 100\% \text{SH, respectively (FLSD}_{0.05} \text{ between SH rates at 0.0027 \text{Mg kg}^{-1} \text{N}}.\) There was no effect of tillage system \((P = 0.896)\) or interaction of SH rate and tillage system on GNU \((P = 0.523)\). The increase in GNU with SH indicated a season long effect on soil supply of PAN, probably due to an impact of SH on soil N cycling, less stover for microbial degradation, or a combination with change in soil moisture and temperature. Dobermann (2007) indicated that GNU values are usually equal to 0.06 ± 0.03 \text{Mg kg}^{-1} \text{N with adequate N supply, values > 0.09 \text{Mg kg}^{-1} \text{N indicate N deficiency, and values < 0.03 \text{Mg kg}^{-1} \text{N indicate excess PAN or other factors decreasing yield such as drought stress, heat stress, mineral toxicities, and pests damage. In our study, GNU values were > 0.09 \text{Mg kg}^{-1} when no N was applied, which confirmed crop N deficiency with no N fertilization and an expected large corn response to applied fertilizer N.}
Conclusions

Corn SH and tillage system had a minimal effect on spring profile soil NO$_3^-$–N concentrations, and thus did not appear to differentially affect net N mineralization. Soil NO$_3^-$–N was low across all treatments and sampling times, likely a result of high precipitation across the years of study and high crop yield. Only fertilizer N rate had an effect on post-harvest soil NO$_3^-$–N, where N fertilization resulted in greater NO$_3^-$–N concentrations.

Corn SH, chisel plow, and N application increased corn canopy NDVI sensing values at the V10 mid-vegetative growth stage. The NDVI increase attributable to SH was greater for no-tillage than chisel plow. Despite the lack of corn SH effect on soil NO$_3^-$–N in the spring, SH increased early season corn growth, especially with no-tillage. As with canopy NDVI, corn grain yield was increased with SH, chisel plow, and N fertilization. In no-tillage, the increase in yield with SH was not relatively as large as the increase in canopy NDVI. Across tillage systems and fertilizer N rates, the average yield increase was 7 and 10% for 50 and 100% SH, respectively. The yield increase with SH decreased as N rate increased, and at the EONR, the SH effect on grain yield was minimal with chisel plow and 6% with no-tillage.

The EONR was not affected by tillage system, but SH reduced the EONR by 22 kg N ha$^{-1}$ (9%) and 45 kg N ha$^{-1}$ (18%) with 50 and 100% SH, respectively. The greater yield and increased GNU with SH apparently reflects a change in soil N cycling and a greater season-long soil supply of PAN with SH. The lower optimal N requirement in CC with SH should be accounted for when planning N applications. However, this study was conducted for a relatively short time period, and thus could not determine whether the effect of SH on EONR and GNU would be stable over time, or change if SH and less N fertilizer input occur on a
continual basis. Long-term study is needed to monitor not only SH impacts on corn N response, soil supply of PAN and, needed fertilization N rate, but also potential changes in soil properties that might affect corn production sustainability.

**Acknowledgments**

This project was supported in part by the Iowa State University Agronomy Department Endowment. Appreciation is extended to the Iowa State University Research Farms superintendents and personnel for their support with the establishment of the study and field work.

**References**


Table 1. Site information and initial soil test values for the two study sites, fall 2008.

<table>
<thead>
<tr>
<th>Site</th>
<th>Predominant soil series</th>
<th>Textural class</th>
<th>Soil classification</th>
<th>pH</th>
<th>SOM †</th>
<th>STP ‡</th>
<th>STK ‡</th>
<th>NO₃⁻–N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ames</td>
<td>Canisteo</td>
<td>Silty clay loam</td>
<td>fine-loamy, mixed,</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>superactive, calcareous, mesic Typic Endoaquolls</td>
<td>7.2</td>
<td>51</td>
<td>9</td>
<td>117</td>
<td>2.4</td>
</tr>
<tr>
<td>Lewis</td>
<td>Marshall</td>
<td>Silty clay loam</td>
<td>fine-silty, mixed, superactive, mesic Typic Hapludolls</td>
<td>6.9</td>
<td>41</td>
<td>24</td>
<td>123</td>
<td>5.3</td>
</tr>
</tbody>
</table>

† SOM, soil organic matter.
‡ Mehlich-3 soil test P and K.
Table 2. Corn stover remaining after stover harvest (SH) on a DM basis as affected by SH rate and fertilizer N rate, across tillage systems, sites, and years.

<table>
<thead>
<tr>
<th>N rate kg N ha⁻¹</th>
<th>Stover harvest rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2008</td>
<td>3.29</td>
</tr>
<tr>
<td>2009-2010</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.33</td>
</tr>
<tr>
<td>168</td>
<td>3.26</td>
</tr>
<tr>
<td>280</td>
<td>3.88</td>
</tr>
<tr>
<td>Mean</td>
<td>3.15</td>
</tr>
</tbody>
</table>

Statistical analysis for 2009-2010 (P > F)

<table>
<thead>
<tr>
<th>Source</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage system (TS)</td>
<td>0.193</td>
</tr>
<tr>
<td>Stover harvest (SH)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>N rate (NR)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>TS × SH</td>
<td>0.984</td>
</tr>
<tr>
<td>TS × NR</td>
<td>0.247</td>
</tr>
<tr>
<td>SH × NR</td>
<td>0.004</td>
</tr>
<tr>
<td>TS × SH × NR</td>
<td>0.852</td>
</tr>
</tbody>
</table>
Table 3. Partial ANOVA for soil profile NO₃⁻–N concentrations across site-years.

<table>
<thead>
<tr>
<th>Source</th>
<th>Spring sampling $P &gt; F$</th>
<th>Post-harvest fall sampling $P &gt; F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling time (ST)†</td>
<td>0.012</td>
<td>Tillage system (TS) 0.082</td>
</tr>
<tr>
<td>Tillage system (TS)</td>
<td>0.038</td>
<td>Stover harvest (SH) 0.569</td>
</tr>
<tr>
<td>Stover harvest (SH)</td>
<td>0.860</td>
<td>N rate (NR) $&lt; 0.001$</td>
</tr>
<tr>
<td>Sampling depth (SD)</td>
<td>$&lt; 0.001$</td>
<td>Sampling depth (SD) $&lt; 0.001$</td>
</tr>
<tr>
<td>ST × TS</td>
<td>0.969</td>
<td>TS × SH 0.075</td>
</tr>
<tr>
<td>ST × SH</td>
<td>0.047</td>
<td>TS × NR 0.720</td>
</tr>
<tr>
<td>ST × SD</td>
<td>0.016</td>
<td>TS × SD 0.160</td>
</tr>
<tr>
<td>TS × SH</td>
<td>0.870</td>
<td>SH × NR 0.659</td>
</tr>
<tr>
<td>TS × SD</td>
<td>0.822</td>
<td>SH × SD 0.784</td>
</tr>
<tr>
<td>SH × SD</td>
<td>0.999</td>
<td>NR × SD 0.077</td>
</tr>
<tr>
<td>ST × TS × SH</td>
<td>0.845</td>
<td>TS × SH × NR 0.057</td>
</tr>
<tr>
<td>ST × TS × SD</td>
<td>0.070</td>
<td>TS × SH × SD 0.268</td>
</tr>
<tr>
<td>ST × SH × SD</td>
<td>0.338</td>
<td>TS × NR × SD 0.892</td>
</tr>
<tr>
<td>TS × SH × SD</td>
<td>0.249</td>
<td>SH × NR × SD 0.955</td>
</tr>
<tr>
<td>ST × TS × SH × SD</td>
<td>0.927</td>
<td>TS × SH × NR × SD 0.734</td>
</tr>
</tbody>
</table>

† Sampling time was in spring before corn planting and when corn was at the V5-V6 growth stages in early June.
Table 4. Partial ANOVA for corn canopy normalized difference vegetative index (NDVI) and grain yield response to tillage system, stover harvest (SH) rate, and fertilizer N rate, across site-years.

<table>
<thead>
<tr>
<th>Source</th>
<th>NDVI</th>
<th>Grain yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P &gt; F</td>
<td></td>
</tr>
<tr>
<td>Tillage system (TS)</td>
<td>&lt; 0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>Stover harvest (SH)</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>N rate (NR)</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>TS × SH</td>
<td>&lt; 0.001</td>
<td>0.041</td>
</tr>
<tr>
<td>TS × NR</td>
<td>0.831</td>
<td>0.204</td>
</tr>
<tr>
<td>SH × NR</td>
<td>0.347</td>
<td>0.127</td>
</tr>
<tr>
<td>TS × SH × NR</td>
<td>0.058</td>
<td>0.941</td>
</tr>
</tbody>
</table>
Table 5. Regression models and parameters describing the corn canopy normalized difference vegetative index (NDVI) and grain yield response to tillage system, stover harvest (SH) rate, and fertilizer N rate, across site-years.

<table>
<thead>
<tr>
<th>Stover harvest</th>
<th>Model†</th>
<th>Regression parameters</th>
<th>Canopy NDVI</th>
<th>Grain yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$a$</td>
<td>$b$</td>
<td>$c$</td>
</tr>
<tr>
<td>%</td>
<td></td>
<td>kg N ha$^{-1}$</td>
<td>kg N ha$^{-1}$</td>
<td>Mg ha$^{-1}$</td>
</tr>
<tr>
<td>Chisel plow tillage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>QP</td>
<td>0.5688c$^\dagger$</td>
<td>0.00243a</td>
<td>-0.0000135a</td>
</tr>
<tr>
<td>50</td>
<td>QP</td>
<td>0.6031b</td>
<td>0.00132b</td>
<td>-0.0000045b</td>
</tr>
<tr>
<td>100</td>
<td>QP</td>
<td>0.6191a</td>
<td>0.00177a</td>
<td>-0.0000089ab</td>
</tr>
<tr>
<td>No-tillage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>QP</td>
<td>0.5365c</td>
<td>0.00106b</td>
<td>-0.0000029c</td>
</tr>
<tr>
<td>50</td>
<td>QP</td>
<td>0.5761b</td>
<td>0.00235a</td>
<td>-0.0000137a</td>
</tr>
<tr>
<td>100</td>
<td>QP</td>
<td>0.5940a</td>
<td>0.00156b</td>
<td>-0.0000060b</td>
</tr>
</tbody>
</table>

$^\dagger$ Q, quadratic; QP, quadratic-plateau.
$^\ddagger$ Mg ha$^{-1}$ for grain yield.
$^\S$ EONR, economic optimum N rate; YEONR, yield at the economic optimum N rate.
$^\¶$ Within a column for a measurement and tillage system, regression parameters followed by the same letter are not different as determined by 95% lower and upper confidence limits.
$^\#$ The regression model did not reach the plateau, therefore, grain yield response at the highest N rate was used for comparisons.

| Chisel plow tillage |        |     |     |     |             |            |         |         |
| 0              | Q      | 4.529b | 0.0467a | -0.000080b | 280 | 11.30$^#$ | 256 | 11.21 | 1.00 | < 0.001 |
| 50             | QP     | 4.961a | 0.0486a | -0.000095b | 257 | 11.21 | 228 | 11.13 | 1.00 | < 0.001 |
| 100            | QP     | 5.131a | 0.0543a | -0.000118a | 231 | 11.41 | 207 | 11.34 | 1.00 | < 0.001 |
| No-tillage     |        |     |     |     |             |            |         |         |
| 0              | Q      | 3.230b | 0.0488b | -0.000085c | 280 | 10.25$^#$ | 255 | 10.16 | 1.00 | < 0.001 |
| 50             | QP     | 3.876a | 0.0530ab | -0.000100b | 266 | 10.92 | 237 | 10.84 | 1.00 | < 0.001 |
| 100            | QP     | 4.151a | 0.0562a | -0.000120a | 235 | 10.75 | 211 | 10.68 | 0.99 | 0.001 |
Fig. 1. Mean monthly air temperature (a) and total precipitation (b) across sites (data from Arritt and Herzmann, 2013).
Fig. 2. Spring preplant and early June soil profile NO$_3^-$–N concentrations with no N fertilization as affected by stover harvest (SH) rate and sampling time. Mean across sampling depths, tillage systems, sites, and years. Bars with the same letter within a SH rate are not different ($P \leq 0.05$).
Fig. 3. Fall post-harvest soil profile NO$_3^-$–N concentrations as affected by fertilizer N rate and sampling depth. Mean across stover harvest (SH) rates, tillage systems, sites, and years. Horizontal bars represent the standard error of the mean.
Fig. 4. Corn canopy normalized difference vegetative index (NDVI) response to tillage system, stover harvest (SH) rate, and fertilizer N rate, across site-years. Regression models and parameters are presented in Table 5.
Fig. 5. Corn grain yield response to tillage system, stover harvest (SH) rate, and fertilizer N rate, across site-years. Regression models and parameters are presented in Table 5.
CHAPTER 3. NITROGEN FERTILIZATION REQUIREMENT FOR CORN AND CROP YIELD RESPONSE TO WINTER RYE COVER CROP

A paper to be submitted to Agronomy Journal

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Abstract

Winter rye (Secale cereale L.) cover crop (RCC) has potential to reduce NO₃–N loss from corn (Zea mays L.) and soybean [Glycine max (L.) Merr.] fields. However, RCC effects on annual crop productivity and corn optimal N fertilization requirement are unclear. The objectives were to evaluate corn and soybean yield response to RCC and corn optimal N fertilization rate. Treatments were no-RCC and RCC with six fertilizer N rates (0 to 225 kg N ha⁻¹) applied to corn in a no-tillage corn-soybean (CS) rotation at four Iowa sites in 2009-2011. The RCC biomass and N uptake was low, with a maximum of 1280 kg dry matter (DM) ha⁻¹ and 26 kg N ha⁻¹, respectively. The RCC reduced soil NO₃–N by 15 kg N ha⁻¹ only at time of RCC control before corn planting in the no-N control. Corn canopy sensing, plant height, and plant population indicated more N stress, reduced plant stand, and slower growth with RCC. The RCC reduced corn grain yield by 6% at the economic optimum N rate (EONR). The EONR was the same with no-RCC and RCC, but corn N use efficiency (NUE)
was lower with RCC. Soybean yield was not affected by RCC. Results suggested corn N fertilization rate should be the same with or without RCC. Since there was low RCC N uptake, reduced corn yield and NUE, and no change in corn EONR and soybean yield, improvement in RCC management is needed to be a viable practice for no-till crop production.

**Abbreviations:** CS, corn-soybean; EONR, economic optimum nitrogen rate; NDVI, normalized difference vegetative index; NUE, nitrogen use efficiency; PAN, plant available nitrogen; PFP, partial factor productivity; PUE, plant nitrogen uptake efficiency; RCC, rye cover crop; YEONR, yield at economic optimum nitrogen rate.

**Introduction**

Water quality impairment related to crop N fertilization is an ongoing issue, including meeting the USEPA NO$_3^-$–N drinking water standards (USEPA, 2007) and reducing N that causes hypoxia in coastal surface waters (Hoorman et al., 2009). Corn N fertilization rate is an important factor in regard to cropping system profitability and NO$_3^-$–N loss. Applying only the optimal N rate will not stop NO$_3^-$–N loss, nor necessarily achieve the drinking water standards (Lawlor et al., 2007). Successful development of agricultural systems that benefit water quality have to be more inclusive of several agricultural practices, rather than only N fertilization rate or timing (Hatfield et al., 2009). Therefore, additional in-field practices are needed to reduce NO$_3^-$–N losses (Sainju and Singh, 2008).

Nitrate losses in tile drainage water from corn production systems can range from 7 - 68 kg ha$^{-1}$ y$^{-1}$ (Lawlor et al., 2007), and with most values ranging from 29 - 56 kg ha$^{-1}$ y$^{-1}$
Cover crops have shown potential for uptake of residual N from fertilizers or inorganic N released from degrading soil organic matter (SOM) in the period between annual crops (Strock et al., 2004; Tonitto et al., 2006), thus helping reduce NO₃⁻–N loss. Studies conducted in the Midwest region of the U.S.A. show that cover crops can reduce NO₃⁻–N loss from 7 - 65 kg ha⁻¹ (Dabney et al., 2010; Kaspar et al., 2012). Cover crops also have potential to improve C sequestration, nutrient cycling, soil internal drainage, and help reduce runoff, soil erosion, and weed pressure (Hoorman et al., 2009). Despite their benefits, cover crops have not been widely adopted in the Midwest due to several factors, including increased cost and management, lack of success in nutrient recycling, limited establishment and growth during late fall and early spring, and seed availability (Johnson et al., 1998; Dabney et al., 2001; Andraski and Bundy, 2005). Since C helps to retain nutrients in soil and balances nutrient cycling (Hoorman et al., 2009), and with recent large increase in fertilizer prices, farmers are most interested in cover crops as a means to increase soil C and reduce N fertilization requirement.

Winter adapted cereal cover crops tend to be more effective than legumes in NO₃⁻–N loss reduction in cold northern climates due to better fall and early spring growth (Parkin et al., 2006), with RCC as a common cover crop choice (Ruffo et al., 2004). In addition, RCC has flexibility in establishment, relatively low seed cost, and winter hardiness (Feyereisen et al., 2006). However, research has found differing annual crop yield responses with RCC. Corn yield decreases of 9 - 20% have been reported with use of RCC (Kessavalou and Walters, 1997; Singer and Kohler, 2005; McDonald et al., 2008; Krueger et al., 2012). A 15% corn yield increase was observed in two out of three years in a study conducted on sandy soils in Wisconsin without N fertilization to RCC and with low RCC biomass.
production (Andraski and Bundy, 2005). However, applying N to RCC before control may offset potential yield decreases in corn (Hoorman et al., 2009). Soybean yield is not usually affected by RCC because soybean is a legume, and not another cereal, like corn, following RCC control (Ruffo et al., 2004; De Bruin et al., 2005; Hoorman et al., 2009). However, soybean yield decreases of 15 - 65% were reported with use of RCC, but part of the decrease was associated to late RCC control in the spring and delay in soybean planting (Singer and Kohler, 2005).

Negative effects of RCC on corn yield may be mitigated by timely RCC control in early spring relative to corn planting, but early control reduces RCC growth and residual N uptake. Allowing more time for RCC to grow in early spring increases RCC biomass production and residual N uptake, but also increases the risk of RCC allelopathic effects (Dhima et al., 2006) and delays corn planting, both of which can reduce corn growth and yield (Wagger, 1989). Waiting 7 - 15 d to plant soybean after RCC control resulted in no soybean yield decrease (Reddy, 2003; Ruffo et al., 2004). Soybean yield decreases are more associated with soil water use, especially in dry years or lack of soil recharge, instead of a negative effect of RCC on soybean growth (Singer et al., 2005). The effect of RCC on plant available N (PAN) and yield depend upon N fertilization rate and soil supply of PAN (Duiker and Curran, 2005), RCC management (Sainju et al., 2007), and soil moisture and temperature to promote microbial activity (Hoorman, 2009; Maltas et al., 2009).

With RCC taking up soil NO$_3^-$–N, farmers question if N recycles back to soil and reduces corn optimal N fertilization requirement, or does it remain in the RCC biomass or SOM. Therefore, identifying corn N fertilization requirement in a RCC system is a current need. Previous research with sandy soils has shown a slight decrease in optimal N
fertilization rate (Bundy and Andraski, 2005), while other research with fine textured soils did not show an improvement in N use with RCC (Miguez and Bollero, 2006). The use of a limited number of N fertilization rates in research studies, and studies evaluating the effects of RCC only in the short-term, also limits the ability to discern change in required N rate with RCC (Bundy and Andraski, 2005; Duiker and Curran, 2005; Miguez and Bollero, 2006). A RCC did not enhance N availability to corn in Ontario (Vyn et al., 2000), but on sandy soils, an EONR decrease of 30 kg N ha$^{-1}$ with RCC was reported in two out of three years of a study conducted in Wisconsin (Andraski and Bundy, 2005).

Some research has indicated that N remains in the RCC biomass or it is immobilized by microbes as they decompose high C:N ratio RCC biomass (Dinnes et al., 2002; Krueger et al., 2010; Kaspar and Singer, 2011; O’Reilly et al., 2012). In other research, RCC increased total soil N, which could potentially reduce N fertilization requirement (Sainju and Singh, 2008), or had no effect on soil supply of PAN and corn N fertilization requirement (Kuo and Jellun, 2002). In addition, RCC biomass degradation can result in net N recycling to soil, but a lack of synchrony between the period of maximal crop N demand and N recycling from the RCC biomass can occur (Vaughan and Evanylo, 1998; Hoorman et al., 2009; Snyder and Meisinger, 2012). The contrasting and limited information regarding the effects of RCC on soil N recycling and supply of PAN makes it difficult to determine the potential effect of RCC on corn optimal N fertilization requirement.

Nitrogen fertilization rate is also a main factor affecting crop NUE, with excess N reducing NUE (Meisinger et al., 2008), and efficient N fertilization with minimal N loss increasing NUE (Raun and Schepers, 2008). Ongoing research has not yet answered questions related to the fate of N after RCC control, and impact on corn N use and efficiency.
Therefore, the objectives of this study were to evaluate the effect of a RCC system on corn optimal N fertilization rate and corn and soybean productivity.

**Materials and methods**

**Study sites**

A three year (2009-2011) study was conducted at four sites in Iowa, with two field areas selected at each site. Soils were a moderately well drained soil formed in glacial till at the Agricultural Engineering and Agronomy Research farm in Central Iowa near Ames (42°00’34” N; 93°46’50” W); a poorly drained soil formed in loess on a till plain at the Research Farm in southeast Iowa near Crawfordsville (41°12’09” N; 91°29’31” W); a well-drained soil formed in loess at the Armstrong Research Farm in southwest Iowa near Lewis (41°18’48” N; 95°10’49” W); and a somewhat poorly drained soil formed in loamy sediments with underlying till at the Research Farm in northeast Iowa near Nashua (42°55’54” N; 92°34’37” W) (Table 1). A CS rotation in a no-tillage system was initiated in the spring 2008 at each site, with corn and soybean present each year and rotated between study areas. The year before establishment all sites were tilled, with Ames and Nashua planted to soybean, and Crawfordsville and Lewis planted to corn. Monthly mean temperature and total precipitation across the study sites were calculated from data collected at weather stations at each research site and reported by the Iowa Environmental Mesonet Network (Arritt and Herzmann, 2013).

**Experimental design and treatment application**

The experimental design within each field at each site was a split-plot with four replications. The RCC was the main plot (no-RCC and RCC) and fertilizer N rate applied to
corn the split-plot (0 to 225 kg N ha\textsuperscript{-1} in 45 kg ha\textsuperscript{-1} increments). A uniform fertilizer N rate was applied to corn at each site in the spring 2008 (agronomic range of 135-160 kg N ha\textsuperscript{-1}). For the study years (2009-2011), the N rates were applied as urea-ammonium nitrate solution (UAN, 32% N) with coulter-injectors to every other row-space (1.52 m apart) within two weeks after corn planting and as soil conditions allowed. Plots size was eight crop rows (0.76 m row spacing) in width and 15 m in length at Ames, Crawfordsville, and Lewis; and six rows in width and 18 m in length at Nashua. Treatments remained in the same plot locations.

The RCC cultivar was ‘Wheeler’, and was drill-planted after annual crop harvest at 70 kg ha\textsuperscript{-1} seeding rate. The RCC row spacing was 0.19 m at Ames, 0.18 m at Lewis, and 0.25 m at Crawfordsville and Nashua. The first RCC planting was in fall 2008, with RCC seeding dates during the study varying by site and annual crop harvest timing, and ranged between Sept. 17 and Oct. 28 after corn harvest, and between Sept. 25 and Oct. 20 after soybean harvest. In late Apr. or early in May, as soil conditions permitted and allowing time for spring RCC growth, RCC was controlled with application of 1-2 kg a.i. ha\textsuperscript{-1} of glyphosate [N-(phosphonomethyl)glycine] before annual crop planting. The intent was to control the RCC in a timely basis and avoid delay in annual crop planting. The RCC was controlled at least one week before corn planting in an attempt to avoid potential allelopathic effect of RCC (Dhima et al., 2006), and soybean planting was within a week after RCC control. Across site-years, RCC control was between Apr. 19 and May 4 before corn planting, and between Apr. 28 and May 20 before soybean planting. Delay in RCC occurred at some site-years due to wet soil conditions.
Rye cover crop biomass sampling and analysis

Aboveground RCC biomass was sampled each spring within 3 d before RCC control. In 2009, samples were collected by replicate before corn and soybean planting as no fertilizer N rate treatments had yet been applied, and also by replicate before corn planting in 2010 and 2011. For RCC sampling before soybean planting in 2010 and 2011, samples were collected by fertilizer N rate applied to the prior-year corn. Sampling was performed by placing a square 0.093 m$^2$ PVC frame at six random locations that encompassed two RCC rows, cutting the RCC plants at soil surface, and compositing the RCC biomass from the six locations into one sample. The collected samples were dried in a forced-air dryer at 60 ºC, weighed to estimate RCC biomass DM, and aboveground RCC biomass production adjusted for the sampled area and RCC seeding row width for each site. Samples were ground to pass a 2-mm sieve and a sub-sample was analyzed for total N by dry combustion (LECO CHN-2000 analyzer, LECO Corp., St. Joseph, MI) (Nelson and Sommers, 1982). Total aboveground RCC N was determined from the N concentration times aboveground biomass DM.

Corn and soybean planting and harvest

Corn and soybean were planted and managed using cultural practices typical of a no-tillage CS rotation in Iowa. These included using adapted hybrids and varieties, planting in late Apr. to early May, and using planters equipped with no-till coulters and row cleaners to remove surface residue and aid in seed placement. Herbicides and insecticides were used if weed pressure and presence of plant defoliating insects required application. Across site-years, corn planting was between Apr. 23 and May 18, and soybean planting was between May 4 and May 21. These dates are within the range reported by USDA for Iowa, where
80% of the corn was planted between Apr. 18 and May 18 from 2007-2011, and 80% of the soybean was planted between May 3 and June 4 during the same period (USDA, 2012). As with RCC control, delayed planting occurred at some site-years due to wet soil conditions. Corn grain yield was determined by harvesting the middle four rows of each plot with a plot combine and adjusting yield to 155 g kg\(^{-1}\) moisture. Soybean grain yield was determined by harvesting the middle four or six rows of each plot with a plot combine and adjusting yield to 130 g kg\(^{-1}\) moisture. Across site-years, corn harvest was between Sept. 17 and Oct. 28, and soybean harvest was between Sept. 21 and Oct. 9.

**Soil sampling and analysis**

Ten random soil cores per replicate were collected in fall 2008 (0-0.15 m) to determine initial soil pH, SOM, total N, and soil test P and K at each site. Soil was also sampled by taking five random cores (0-0.6 m in 0.3 m increments) to determine initial soil \(\text{NO}_3^-\)–N (Table 1). For the study years (2009-2011), soil was sampled (0-0.6 m in 0.3 m increments) in corn plots with no N fertilization to determine profile soil \(\text{NO}_3^-\)–N in the spring at the time of RCC control (before corn planting) and in early June when corn plants were at V4-V7 growth stages (Abendroth et al., 2011). In the fall, post-harvest soil samples (0-0.9 m in 0.3 m increments) were collected in corn plots receiving 0, 135, and 225 kg N ha\(^{-1}\). For all soil \(\text{NO}_3^-\)–N samples during the study years, six cores per plot were taken in a diagonal pattern across two corn rows, with one core from each row and a core 0.2 m from the side of each row. Soil profile sampling (0-0.9 m in 0.3 m increments) after soybean harvest in 2009 was conducted by collecting six cores per replicate because no fertilizer N rate treatments had yet been applied, with one core collected from each plot (six total) and 0.2 m away from one of the center soybean rows. In 2010 and 2011, sampling after soybean
harvest was by the prior-year corn plots that received 0, 135, and 225 kg N ha\(^{-1}\). All soil samples were collected by hand with a 0.02 m diameter soil probe. Soil cores were mixed and a sub-sample saved for analysis.

Soil samples were dried in a forced-air dryer at 25 °C and ground to pass a 2-mm sieve. Soil pH was determined with 1:1 soil:water ratio, SOM and total N by dry combustion (LECO CHN-2000 analyzer, LECO Corp., St. Joseph, MI) (Nelson and Sommers, 1982), soil test P and K with Mehlich-3 extraction and colorimetric determination, and NO\(_3^--N\) was determined by 2 M KCl extraction and colorimetric cadmium reduction using a Lachat flow injection analyzer (Lachat Instruments, QuikChem 8500 Series 2, Loveland, CO) (Brown, 1998). Soil NO\(_3^--N\) concentrations were converted to a mass basis by using a uniform soil bulk density of 1.3 g cm\(^{-3}\), a common soil bulk density for Iowa soils (Al-Kaisi et al., 2005), and added across depths to estimate amount of NO\(_3^--N\).

Initial soil tests indicated soil pH was slightly acidic (6.3-6.6) at all sites and no lime was applied because that pH range is considered to be sufficient for CS production in Iowa (Sawyer et al., 2011). The SOM and total N were within the typical range for Mollisols in the Midwest (Soil Survey Staff, 1999). The Mehlich-3 soil test P was in the High to Very High soil test interpretation categories, and the Mehlich-3 soil test K was in the Optimum to Very High interpretation categories (Sawyer et al., 2011). To avoid potential for P and K deficiency and any issue with soil test variability across each site, P and K fertilizer was broadcast applied in fall 2009 if soil test levels were within or near the Optimum interpretation category, with application rate at the estimated crop removal amount for two years of a CS rotation (Sawyer et al., 2011). Specifically, the Ames site received an application of 120 kg K ha\(^{-1}\), Crawfordsville and Lewis were not fertilized, and Nashua
received an application of 50 kg P ha\(^{-1}\) and 120 kg K ha\(^{-1}\). Fertilizer P and K were triple super phosphate and muriate of potash.

**Corn canopy sensing and corn establishment**

Corn growth response to RCC and N fertilization rate was estimated with a Crop Circle ACS-210 active canopy sensor (Holland Scientific, Lincoln, NE). Corn growth varied across treatments; however, corn canopy sensing was conducted in all plots when corn receiving 135 kg N ha\(^{-1}\) reached the mid-vegetative (V10) growth stage (Abendroth et al., 2011). At the time of sensing, corn stages varied from V8 - V11 depending upon the fertilizer N rate applied after planting, but not difference was observed between no-RCC and RCC. The ACS-210 active canopy sensor emits light at the visible (VIS) 590 nm and near-infrared (NIR) 880 nm wavelengths through a single light emitting diode, and reflected light of varying spectral ranges (400-680 nm and 800-1100 nm) from the corn canopy is captured by two silicon photodiodes on the sensor (Barker and Sawyer, 2010). The sensor was mounted on a hand-held mast, positioned mid inter-row, and carried through the middle of each plot (0.6-0.9 m above the corn canopy) at a constant speed (1.5 m \(s^{-1}\)). Sensing was conducted between 0900 and 1200 h daytime, and reflectance measurements were captured on-the-go with a handheld data logger. Reflectance values of the VIS and NIR bands were averaged for each plot and used to calculate the normalized difference vegetative index (NDVI) (Gitelson et al., 1996), as shown in Eq. [1].

\[
NDVI = \frac{(NIR - VIS)}{(NIR + VIS)} \quad [1]
\]
In 2010 and 2011, in addition to the corn canopy sensing, the effect of RCC on corn early growth and establishment was evaluated by measuring corn plant height and plant population at the V4-V7 growth stages. In 5 m length segments of two center rows per plot, plants were counted and plant height measured on ten random plants from soil surface to the extended leaf tip of the uppermost and fully developed leaf (Warrington and Norton, 1991). The effect of RCC on soybean early growth and establishment was evaluated by measuring soybean plant population at the V1-V2 growth stages (Pedersen, 2007). Plants were counted in 1.80 m length segments of two center rows per plot.

**Corn nitrogen uptake and use efficiency**

At physiological maturity (R6) (Abendroth et al., 2011), six corn plants were randomly collected from the center rows (combine grain harvest area) to determine cob, grain, vegetative, and total aboveground plant N uptake. Plants were cut at the soil surface and the ears (without husk) and vegetative (including husk) separated and weighed. The vegetative component was chopped and a sub-sample collected and weighed. Ears and vegetative sub-samples were dried in a forced-air dryer at 60 °C, cob and grain separated, and dry weight of each plant component recorded. Grain weight from the six plants was added back into the combine harvested grain weight. Harvest index (HI) for cob and grain was determined from the six plant sample DM. Plot-level cob DM was determined from the total harvested grain DM yield and cob HI. Vegetative DM was the difference between total and cob plus grain DM. Grain, cob, and vegetative component samples were ground and a sub-sample analyzed for total N by dry combustion (LECO CHN-2000 analyzer, LECO Corp., St. Joseph, MI) (Nelson and Sommers, 1982). Cob and vegetative N uptake was determined from N concentration times cob and vegetative DM. Grain N uptake was determined from
grain N concentration times the total harvested grain DM yield. Total aboveground plant N uptake was the summation of the cob, grain, and vegetative N uptake. The NUE, as a function of soil available N and fertilizer N recovery (Moll et al., 1982; Wortmann et al., 2011), was estimated by calculating the partial factor productivity (PFP) and plant N uptake efficiency (PUE) [Eqs. 2 and 3].

\[
PFP = \frac{Grain \ yield}{fertilizer \ N} \quad [2]
\]

\[
PUE = \frac{Total \ aboveground \ plant \ N \ uptake}{fertilizer \ N} \quad [3]
\]

The PFP is the grain yield in Mg ha\(^{-1}\) reported at 155 g kg\(^{-1}\) moisture divided by the fertilizer N rate in kg N ha\(^{-1}\). The PUE is the total aboveground plant N uptake in kg N ha\(^{-1}\) divided by the fertilizer N rate in kg N ha\(^{-1}\). The PFP indicates how productive is the cropping system in producing grain yield in comparison to nutrient input. The PUE also includes N in the cob and vegetative components, and indicates the efficiency of the system in using applied N (Snyder and Bruulsema, 2007).

**Statistical analysis**

Analyses of variance (ANOVA) for measured parameters were conducted with PROC MIXED of SAS (SAS Institute, 2009). No interaction between site and SH rate was observed for the evaluated variables. For the analyses, or the analyses, treatments and their interactions were considered fixed, and replicates, sites, years, and their interactions were considered random. Differences between treatments were considered significant at \(P \leq 0.05\). Means separation were determined with Fisher Protected Least Significant Difference (FLSD). To evaluate the corn canopy NDVI, grain yield, grain N, and total aboveground N uptake
responses to fertilizer N rate, PROC REG was used to investigate the quadratic regression model [Eq. 4], and PROC NLIN was used to investigate the quadratic-plateau regression [Eqs. 5 and 6]. Models were deemed significant at $P \leq 0.05$ and the model with the largest $R^2$ selected. If the segment joint point with the quadratic-plateau model was greater than the highest applied N rate, the quadratic model was used.

$$y = a + bx + cx^2$$ \hspace{1cm} [4]

$$y = a + bx + cx^2 \text{ if } x < x_o$$ \hspace{1cm} [5]

$$y = a + bx_o + cx_o^2 \text{ if } x \geq x_o$$ \hspace{1cm} [6]

In these models, $y$ represents the predicted corn response (NDVI, grain yield, grain N, or total aboveground plant N uptake) to fertilizer N rate, $x$ is the applied N rate, and $a$ (intercept), $b$ (linear coefficient), $c$ (quadratic coefficient), and $x_o$ (fertilizer N rate at the joint point) constants. The lower and upper 95% confidence limits of model parameters were used to aid in model comparison across N rates, with model parameters considered not different when the parameter estimates were within the confidence intervals of both equations being compared. Corn EONR for grain yield and yield at the EONR (YEONR) were calculated from each regression model fit to response to N fertilization rate (Cerrato and Blackmer, 1990) by solving for $x$ and using a 0.0056 $\text{kg}^{-1}$ N to $\text{Mg}^{-1}$ grain price ratio.

Since the corn EONR for grain yield was close to the 180 kg N ha$^{-1}$ rate (presented later), the grain yield response to RCC (yield with no-RCC minus yield with RCC) at this N rate was estimated for each site-year. PROC REG was used to investigate the linear
relationship between amount of RCC biomass production and corn grain yield response to RCC.

**Results and discussion**

**Weather**

The early spring weather can have the greatest influence on RCC growth, biomass production, and N uptake. Across sites, the early spring (Mar. and Apr.) in 2009 and 2011 was 1 °C colder than the historical average from the last 16 years (6 vs. 7 °C), and 2010 was 2 °C warmer (Fig. 1a). For that period, 2009 had 1 cm more precipitation than the historical average (15 vs. 14 cm), 2010 was drier (only 9 cm), and 2011 had 3 cm less precipitation than the historical average (Fig. 1b).

The weather in late spring and remaining growing season can influence RCC biomass degradation, corn growth and response to N fertilization rate, soybean growth, and profile soil NO$_3$–N. Temperature in late spring (May and June) was 1 °C colder than the historical average in 2009, whereas 2010 and 2011 were the same as the historical average (19 °C); however, 2010 had more precipitation than the historical average during that period (34 vs. 25 cm), especially in June where precipitation was well above-normal. During the reproductive corn and soybean growth stages (July to Sept.), 2009 was 2 °C colder than the historical average (19 vs. 21 °C) and had slightly more precipitation (29 vs. 24 cm), 2010 was 1 °C warmer than the historical average and had almost twice as much precipitation (45 cm), and 2011 was somewhat drier (22 cm).

The weather in the fall can affect profile soil NO$_3$–N, the timing for corn and soybean harvest, and RCC seeding and fall growth. In late Sept. and Oct., 2009 was 3 °C
colder and 2010 and 2011 were 2 °C warmer than the historical average (10 °C). For that period, 2009 was wetter (16 cm) and 2010 and 2011 were drier (only 2 cm) compared to the historical average (6 cm). All years were wetter than the historical average and included intense precipitation events. In 2009, precipitation was above-normal in Aug. and Oct., in 2010 the growing season was wet with precipitation well above-normal each month from June through Sept., and in 2011 precipitation was above-normal in Aug.

**Rye cover crop biomass and nitrogen uptake**

Each year the RCC was successfully established, but fall growth was low (not measured) due to cold temperatures and seeding after corn and soybean harvest. Most RCC growth occurred in early spring, but aboveground RCC biomass production and N uptake was generally low (Table 2). The largest RCC biomass production and N uptake across site-years was 1280 kg DM ha$^{-1}$ and 26 kg N ha$^{-1}$, respectively, and was measured with RCC before soybean planting at the 225 kg N ha$^{-1}$ fertilizer rate applied to the prior-year corn. The RCC growth was also limited by the soil supply of PAN and the relatively short spring period for RRC growth.

The amount of RCC biomass production and N uptake before soybean planting in 2009 was low, and probably a result of the cold and wet spring in that year (Table 2). The RCC biomass production did not have an N rate effect because the prior-year corn received a uniform N application rate. In 2010 and 2011, RCC biomass and N uptake before soybean planting were affected by N rate applied to the prior-year corn (Table 2). Rye biomass production was the same with the prior-year 0-135 kg N ha$^{-1}$ rates (average 950 kg ha$^{-1}$), but the prior-year 180 and 225 kg N ha$^{-1}$ rates increased RCC biomass production by 18 and 35%. Rye N uptake was also the same when the prior-year N rate was 0-135 kg N ha$^{-1}$
(average 18 kg ha\(^{-1}\)), but 180 and 225 kg N ha\(^{-1}\) rates increased RCC N uptake by 22 and 44\%. Rasse et al. (2000) found that RCC had better growth and potential for N accumulation (up to 56 kg N ha\(^{-1}\)) when the prior-year corn received more than 200 kg N ha\(^{-1}\), but lower N rates did not increase RCC biomass production or N uptake. They did not recommend using a RCC for scavenging residual NO\(_3^–\)-N when the prior-year corn N rate is ≤ 100 kg N ha\(^{-1}\).

Those results are similar to our findings. Ruffo et al. (2004) found that RCC biomass production and N uptake can be up to 6100 kg DM ha\(^{-1}\) and 170 kg N ha\(^{-1}\) with application of 270 kg N ha\(^{-1}\) to the prior-year corn. They also noted that warm spring conditions and high SOM N mineralization resulted in greater supply of PAN and promoted RCC growth.

Across sites, years, and N rates applied to corn, RCC biomass production before corn planting was lower than RCC biomass production before soybean (720 vs. 960 kg DM ha\(^{-1}\)). Rye N uptake before corn was < 40 kg N ha\(^{-1}\) in ten out of the 12 site-years, with an average of 21 kg N ha\(^{-1}\), which reflected the limited RCC growth. The RCC before corn had on average two weeks less time to grow in the spring compared to RCC before soybean due to RCC control at least one week before corn planting, and corn was also planted on average one week before soybean. The timing for RCC control was an attempt to have corn and soybean planting within recommended calendar dates and avoid delay in planting that might affect yield potential. According to Duiker and Curran (2005), delay of two weeks in corn planting can result in grain yield losses up to 0.5 Mg ha\(^{-1}\). Therefore, RCC growth, biomass production, and N uptake were limited by the RCC control timing decision. The above-normal precipitation during the three years of study resulted in low residual NO\(_3^–\)-N (presented later), and therefore RCC growth was N supply limited. An alternative to improve fall RCC growth, and potentially overall RCC biomass production and N uptake, would be to
seed the RCC in late summer (Johnson et al., 1998). However, even if fall growth is increased, desire by producers for early corn and soybean planting would still limit RCC growth in early spring.

**Soil nitrate**

*Initial soil nitrate*

Initial post-harvest soil NO$_3^-$–N was ≤ 22 kg N ha$^{-1}$ in the top 0.9 m of soil in fall 2008 at all sites. The low NO$_3^-$–N levels indicated low profile inorganic-N at all sites and potential for large corn response to N fertilization. None of the fields had a manure history or received any N application after the 2008 crop harvest; therefore, the profile NO$_3^-$–N reflected background levels. In 2008, the N applied to corn was at a uniform agronomic rate, and this was also reflected in the low profile soil NO$_3^-$–N.

*Spring soil nitrate during the corn year*

Spring profile soil NO$_3^-$–N was measured only in corn plots with no N fertilization. Soil NO$_3^-$–N was ≤ 30 kg N ha$^{-1}$ in the top 0.6 m of soil at the time of RCC control and in early June (Table 3). Sampling time and RCC treatment (with and without RCC) influenced soil NO$_3^-$–N levels. Soil NO$_3^-$–N was 15 kg N ha$^{-1}$ greater with no-RCC than RCC at time of RCC control, but the difference between no-RCC and RCC was not statistically different in early June. Soil NO$_3^-$–N slightly increased with the RCC from the preplant sampling to early June (8 kg N ha$^{-1}$ increase), indicating some net N recycling to soil in the RCC system. However, in the no-RCC a slight decrease in soil NO$_3^-$–N was observed (4 kg N ha$^{-1}$ less), which could be due to corn N uptake and NO$_3^-$–N loss. In either case, change in NO$_3^-$–N was not large.
Plant available N can be reduced up to 35% after RCC control, and up to 59% after RCC harvest for hay (Krueger et al., 2011). However, changes in soil NO$_3^-$–N during the spring could be more influenced by site-specific N mineralization, soil moisture, and variability in weather conditions than by RCC alone (Andraski and Bundy, 2008). The small differences observed in profile soil NO$_3^-$–N between no-RCC and RCC, and between preplant and early June sampling, would be related to low net RCC and SOM N mineralization, corn N uptake, and NO$_3^-$–N loss due above-normal precipitation.

**Post-harvest soil nitrate after corn**

Post-harvest profile soil NO$_3^-$–N after corn harvest was ≤ 37 kg N ha$^{-1}$ in the top 0.9 m of soil (Table 3). This amount of NO$_3^-$–N was low and reflected the years with above-normal precipitation and large corn yield response to N fertilization. The RCC reduced post-harvest profile NO$_3^-$–N after corn harvest by only 4 kg N ha$^{-1}$, a small decrease considering the differences in soil conditions with no-RCC and RCC, and was likely a result of soil random variation. This result might be expected as the RCC was controlled in the spring and corn growth and N uptake occurred all growing season. Application of 135 and 225 kg N ha$^{-1}$ increased post-harvest profile NO$_3^-$–N by 5 and 13 kg N ha$^{-1}$ compared to no N fertilization, respectively. These are small increases considering the fertilizer N input rate.

Some soil NO$_3^-$–N differences were also measured in the spring, but those differences were small between no-RCC and RCC, would have little effect on corn growth, and little chance of impact on profile soil NO$_3^-$–N at the end of the growing season. Qi et al. (2011) found that RCC reduced NO$_3^-$–N concentrations in tile drainage water from corn fields, but only from Mar. to June, and they indicated that effectiveness of RCC in reducing NO$_3^-$–N loss depended on N fertilization rate applied to the prior-year corn, soil management, and
weather patterns. On the contrary, Krueger et al. (2011) indicated that RCC residue reduced soil moisture up to 16%, and that could have a greater impact on corn growth than soil supply of PAN alone.

**Post-harvest soil nitrate after soybean**

As found after corn harvest, soil NO$_3^-$–N after soybean harvest was low (≤ 33 kg N ha$^{-1}$) and not affected by RCC (Table 3). The N rate applied to the prior-year corn resulted in a small decrease in soil NO$_3^-$–N with the 225 kg N ha$^{-1}$ rate compared to the 135 kg N ha$^{-1}$ rate (3 kg N ha$^{-1}$ less) across 2010-2011. That difference is likely due to soil random variation as it does not make sense for a N application to the prior-year corn to have an effect on profile soil NO$_3^-$–N after soybean the second year, especially when having above-normal precipitation. A RCC has potential to reduce soil NO$_3^-$–N loss in tile drainage water from soybean fields during July to Nov. (Qi et al., 2011). Results of our study, however, showed no difference in soil NO$_3^-$–N after soybean harvest between no-RCC and RCC, and low NO$_3^-$–N concentrations reflected the years with above-normal precipitation.

**Corn canopy sensing and plant early growth**

Across site-years, average corn canopy NDVI values were greater with no-RCC than RCC (0.701 and 0.675, respectively) (Table 4). The low NDVI values with no or low N fertilization rates indicated decrease in corn stand establishment and growth, N stress, and potential for large response to N fertilization (Table 5 and Fig. 2a). Low NDVI values also reflected years with above-normal precipitation and high N fertilization requirement. Nitrogen fertilization increased the NDVI values up to the point where response plateaued. The NDVI plateau was greater with no-RCC than RCC (0.718 vs. 0.692, respectively), indicating negative effects of RCC on early corn growth.
The shape of the NDVI response to fertilizer N rate was different between no-RCC and RCC. Also, the N rate at the maximal plant canopy production (joint point of the quadratic-plateau model) was 25 kg N ha\(^{-1}\) greater with no-RCC than RCC. The greater N rate could be an indication of greater N uptake demand due to larger corn biomass with no-RCC, less N fertilization needed by corn as a result of the negative effect of the RCC, or difference in spring soil NO\(_3^–\)-N with RCC.

The corn response to N fertilization and optimal N fertilization rate at the V10 growth stage were similar to other research conducted in Iowa that evaluated corn canopy sensing response to N fertilization rate (Barker and Sawyer, 2010). The NDVI was less with the RCC at all N rates, with the difference between no-RCC and RCC somewhat larger with no N fertilization and relatively smaller at the 45 kg N ha\(^{-1}\) rate (Table 5 and Fig. 2a). At fertilizer rates from 90 to 225 kg N ha\(^{-1}\), the NDVI was consistently greater with no-RCC than RCC. Rapid corn growth in the early- and mid-growing season results in high plant N uptake requirement (Abendroth et al., 2011), and it is possible that site-specific changes in inorganic N supply (soil and 45 kg N ha\(^{-1}\) fertilizer rate) resulted in the difference in canopy response.

Measurement of corn plant height and population at the V4-V7 growth stages in 2010-2011 confirmed the negative effect of RCC on corn growth and development (Table 4). Plant population was 5% greater with no-RCC than RCC (87000 vs. 83000 plants ha\(^{-1}\)), and plant height was 16% greater with no-RCC than RCC across N rates (0.82 vs. 0.69 m). Corn plant height was also influenced by fertilizer N rate (Table 4), with height at 0.71 m with no N fertilization and 0.76 m with N fertilization (average of all N rates). These results indicated the RCC produced an environment that was detrimental to corn establishment and early growth. Detrimental effects of RCC could be aggravated by or interact with other factors,
such as cold and wet spring conditions, RCC soil surface mulch, poor RCC residue removal from the seed row at planting (occurred at two sites in 2010), and early season insect feeding and plant defoliation for corn planted into the RCC. Armyworm (*Spodoptera* sp.) feeding required insecticide application at two sites in 2010.

Decrease in profile soil NO$_3^-$–N due to RCC was minimal in the corn year, and hence the negative effects of RCC on corn growth could be more associated with the overall rye-corn sequence and changes in soil properties. Cover crop effectiveness in improving annual crop yield is related to successful cover crop establishment and biomass production (Strock et al., 2004). However, RCC produced the opposite effect in our study and reduced corn early growth and establishment.

**Corn yield and nitrogen response**

**Corn yield**

Across N rates, average corn grain yield was 0.95 Mg ha$^{-1}$ greater with no-RCC than RCC (Table 4 and Fig. 2b), and 0.75 Mg ha$^{-1}$ greater at the agronomic maximum N rate (plateau yield) (Table 5). No-tillage cropping systems may benefit from cover crops through decreased soil erosion, increased N recycling, and increased crop yield (Reinbott et al., 2004). That was not the case in our study, where reduced yield was potentially due to an allelopathic effect from the RCC on corn growth or differences in soil properties between no-RCC and RCC during the growing season. Also, the RCC biomass can create a surface mulch that would change soil moisture and temperature patterns and negatively affect corn growth (Dhima et al., 2006). Waiting only 7 to 10 d for planting corn after RCC control has been reported to be enough to avoid the allelopathic effect of RCC on corn growth (Duiker
and Curran, 2005). In our study, however, that was not the case as there was decreased corn early growth, stand, and yield.

Duiker and Curran (2005) found that RCC did not reduce corn yield with adequate N fertilization (180 kg N ha\(^{-1}\)). Zotarelli et al. (2009), however, found that positive effects of RCC on corn yield were greater with no N fertilization or when applying only 67 kg N ha\(^{-1}\). When 133 kg N ha\(^{-1}\) were applied, they found a negative effect of RCC on corn yield. Results of our study reflected the low soil supply of PAN and need for a high N fertilization rate. Krueger et al. (2012) indicated that corn yield decrease with RCC was likely a result of the rye-corn rotation affecting corn growth rather than RCC effects on soil supply of PAN, which could have been the case in our study and confirmed the relatively small differences in soil profile NO\(_3^-\)-N between no-RCC and RCC.

Corn grain yield reduction with RCC was greater as RCC biomass production increased. This is shown in Fig. 3 at the 180 kg N ha\(^{-1}\) rate, which was chosen as it was close to the across site-years optimal N fertilization requirement. Approximately 50% of the site-years had a corn grain yield decrease < 1 Mg ha\(^{-1}\), and 30% a yield decrease > 1 Mg ha\(^{-1}\). This indicated frequent and sometimes large corn grain yield decrease with the intended corn planting one week after RCC control, and especially with RCC biomass production > 500 kg DM ha\(^{-1}\). Results confirmed the need for developing better agronomic RCC management or different corn planting practices in order to improve early season corn growth and grain yield with use of RCC. Examples could be early RCC control and extending the waiting period to plant corn after RCC control. However, early control would limit RCC growth and uptake of residual N, and while later corn planting would allow more time for RCC biomass degradation, that conflicts with producers desire for early corn planting.
Nitrogen response

Corn grain yield response to fertilizer N rate was the same with no-RCC and RCC (Table 5 and Fig. 2b). The N rate at the agronomic maximum rate (plateau yield) was only 5 kg N ha\(^{-1}\) lower with no-RCC than RCC. A RCC can potentially increase soil supply of PAN and reduce N fertilization requirement (Sainju and Singh, 2008). Andraski and Bundy (2005) found a decrease of 30 kg N ha\(^{-1}\) in N fertilization requirement with RCC in two out of three years on sandy soils in Wisconsin. However, we did not find a difference in corn response to N fertilization in our study. Compared to the V10 canopy sensing results, the grain yield response was to a much greater N rate and with no difference between no-RCC and RCC at each N rate. These results indicated that as the growing season progressed, the difference in corn maximal N requirement between no-RCC and RCC decreased in comparison to the canopy sensing results. The fertilizer N rate at the joint point was 25 kg N ha\(^{-1}\) greater with no-RCC than RCC at V10 (NDVI results), but this relationship changed with corn yield, where the joint point was 5 kg N ha\(^{-1}\) lower with no-RCC than RCC. These results indicated that the RCC reduced corn biomass production (slowed growth and development), and therefore reduced corn N demand at the time of canopy sensing.

The EONR was only 4 kg N ha\(^{-1}\) less with no-RCC than RCC (Table 5), a similar optimal N rate. Also, the YEONR was 6% (0.79 Mg ha\(^{-1}\)) greater with no-RCC than RCC (Table 5). Compared to the recommended N fertilization rate for a CS rotation in Iowa (Sawyer et al., 2006), the EONR was approximately 25 kg N ha\(^{-1}\) greater, which reflected the above-normal precipitation received in the years of study. The lack of N rate interaction between no-RCC and RCC could also have been an influence of above-normal precipitation, high C:N ratio of the RCC biomass and low degradation rate, and interaction with N cycling.
Also, the RCC N uptake was low, which would indicate a small potential of RCC to change soil supply of PAN, as was measured. Since there was no EONR difference between no-RCC and RCC, it appears that N fertilization recommendations for corn should not change in a RCC system.

**Nitrogen use efficiency**

The greater corn grain yield with no-RCC than with RCC resulted in greater grain and total aboveground plant N uptake (Table 4), average 9 and 14 kg N ha\(^{-1}\) more across N rates, respectively. However, there was similar grain N and total aboveground plant N uptake response to N rate with no-RCC and RCC (Fig. 4), as was found for grain yield. A difference in response between grain yield and N uptake was that the grain N and total aboveground plant N uptake did not reach a plateau (Table 5). According to Tollenaar et al. (1993), the interaction of factors determining corn response to RCC and N uptake are complex and may be affected by RCC biomass production, available N to facilitate RCC biomass degradation during the growing season, and the allelopathic effect of RCC on corn growth and development.

There was an interaction between RCC and N rates for PFP and PUE indices (Table 4). The PFP and PUE were chosen as NUE indicators because they integrate the use efficiency of the system, which would include both the cover crop system and applied fertilizer N effects. The PFP indicated corn had greater NUE with no-RCC than RCC when fertilizer N was ≤ 90 kg N ha\(^{-1}\), but was not different with greater N rates (Fig. 5a). A similar trend was observed with PUE, except that the PUE was different between no-RCC and RCC when N rate was ≤ 135 kg N ha\(^{-1}\) (Fig. 5b). Across N rates, NUE was greater with no-RCC than RCC. The greater PFP and PUE with no-RCC than RCC at low N fertilization rates
reflected the greater corn biomass production with no-RCC than RCC, deficient fertilizer plus soil supply of PAN, and potential change in N cycling with use of RCC.

Nitrogen use efficiency values typically decline with increasing N fertilization rates, and can be fairly low in optimally-fertilized systems. Optimum PFP values range from 0.04 - 0.08 Mg kg\(^{-1}\) N (Dobermann, 2007); however, PFP values in our study were within that range only with N rate ≥ 135 kg N ha\(^{-1}\), where EONR was near 180 kg N ha\(^{-1}\). Both PFP and PUE helped identify the low corn productivity and NUE in the RCC system, and confirmed the N stress at low N rates. Both indices also indicated the differences in corn NUE between no-RCC and RCC. The lack of difference in corn NUE between no-RCC and RCC with 180 and 225 kg N ha\(^{-1}\) reflected the similar corn grain yield response with no-RCC and RCC at sufficient N fertilization.

**Soybean plant population and yield**

No difference in soybean early growth or stand establishment was observed between no-RCC and RCC \((P = 0.592)\) at the V1-V2 growth stages (average 337000 plants ha\(^{-1}\)). Also, fertilizer N rate applied to the prior-year corn had no effect on soybean population \((P = 0.173)\). The RCC or N rate applied to the prior-year corn had no effect on soybean grain yield (Table 6). Since soybean is capable of symbiotic N fixation, changes in soil supply of PAN or an effect of RCC on N cycling would not be expected to affect yield as soybean could compensate for such changes. Apparently, unlike in corn, the presence of the RCC biomass, degradation products, or early season changes in soil properties due to the RCC did not negatively affect soybean. However, a decrease in soybean plant biomass with late RCC control and delay in soybean planting is possible (Westgate et al., 2005). Ruffo et al. (2004),
however, found that if RCC control and soybean planting were accomplished on a timeliness basis, there is no decrease in soybean yield.

**Conclusions**

The RCC was successfully established each year in the fall after corn and soybean harvest. However, aboveground RCC biomass production and N uptake measured in early spring at time of control was low, less than the maximum across site-years of 1280 kg DM ha\(^{-1}\) and 26 kg N ha\(^{-1}\), respectively. The RCC biomass production was limited by the short growing period in the fall before winter dormancy and early spring before RCC control. The requirement for timely corn and soybean planting to achieve profitable yields, and low profile soil NO\(_3^--\)N, limited the RCC growth and N uptake. The RCC decreased profile NO\(_3^--\)N only in the preplant spring at the time of RCC control, but the reduction was small.

The RCC had no effect on soybean stand establishment and grain yield. Corn early growth and plant stand in the no-tillage CS rotation were decreased in the RCC system, and resulted in lower corn grain yield compared to no-RCC. At the EONR, corn grain yield was 6% greater with no-RCC than RCC. Also, greater RCC biomass production resulted in lower corn grain yield. Extending the waiting period for corn planting after RCC control, or earlier RCC control to limit RCC biomass production, might decrease the negative effect of RCC on corn production. However, early RCC control would limit RCC N uptake and potentially reduce its positive effect on retaining NO\(_3^--\)N in the soil-crop system.

The RCC did not change corn optimal N fertilization requirement. The EONR was 4 kg N ha\(^{-1}\) lower with no-RCC than RCC, a small difference considering the soil changes in the RCC system and detrimental effects of RCC on corn growth and yield. As a result of the
reduced early corn growth and lower yield with use of RCC, there was lower NUE with the RCC across fertilizer N rates and no gain in NUE at the optimal N fertilization requirement. Results suggested that N fertilization rate for corn in a no-tillage CS rotation should be the same with or without use of a RCC.

Since there was low RCC N uptake, reduced corn yield and NUE, and no change in corn EONR and soybean yield, improvement in RCC management is needed for this practice to be more viable in a no-tillage CS rotation. Continued research would help confirm if the effects of RCC on corn and soybean yield and corn optimal N fertilization requirement remain the same or change in the long-term with continual use of the RCC system.

Acknowledgments

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References


Table 1. Site information and initial soil test values for each study site.

<table>
<thead>
<tr>
<th>Site</th>
<th>Predominant soil series</th>
<th>Textural class</th>
<th>Soil classification</th>
<th>pH</th>
<th>SOM$^+$</th>
<th>TN$^+$</th>
<th>STP$^\ddagger$</th>
<th>STK$^\ddagger$</th>
<th>NO$_3^-$-N$^\S$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0-0.15 m</td>
<td></td>
<td>0-0.15 m</td>
<td>0-0.15 m</td>
<td>0-0.15 m</td>
<td>0-0.15 m</td>
<td>0-0.15 m</td>
</tr>
<tr>
<td>Ames</td>
<td>Clarion</td>
<td>Loam</td>
<td>fine-loamy, mixed, superactive, mesic Typic Hapludolls</td>
<td>6.4</td>
<td>41</td>
<td>1.8</td>
<td>37</td>
<td>172</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Nicollet</td>
<td>Clay loam</td>
<td>fine-loamy, mixed, superactive, mesic Aquic Hapludolls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crawfordsville</td>
<td>Mahaska</td>
<td>Silty clay loam</td>
<td>fine, smectitic, mesic Aquertic Argiudolls</td>
<td>6.6</td>
<td>50</td>
<td>2.2</td>
<td>40</td>
<td>181</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Nira</td>
<td>Silty clay loam</td>
<td>fine-silty, mixed, superactive, mesic Aquic Argiudolls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lewis</td>
<td>Marshall</td>
<td>Silty clay loam</td>
<td>fine-silty, mixed, superactive, mesic Typic Hapludolls</td>
<td>6.4</td>
<td>41</td>
<td>2.1</td>
<td>34</td>
<td>239</td>
<td>16</td>
</tr>
<tr>
<td>Nashua</td>
<td>Floyd</td>
<td>Loam</td>
<td>fine-loamy, mixed, superactive, mesic Aquic Hapludolls</td>
<td>6.3</td>
<td>48</td>
<td>2.3</td>
<td>23</td>
<td>148</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Clyde</td>
<td>Silty clay loam</td>
<td>fine-loamy, mixed, superactive, mesic Typic Endoaquolls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^+$ SOM, soil organic matter; TN, total N.

$^\ddagger$ Mehlich-3 soil test P and K.

$^\S$ Soil NO$_3^-$-N was summed across the 0-0.3 and 0.3-0.6 m sampling depths.
Table 2. Aboveground rye cover crop (RCC) biomass production and N uptake at the time of control in the spring before soybean planting as affected by fertilizer N rate applied to the prior-year corn, across sites.

<table>
<thead>
<tr>
<th>N rate (kg N ha⁻¹)</th>
<th>Biomass (kg DM ha⁻¹)</th>
<th>N uptake (kg N ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2009</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>2010-2011</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>970bc†</td>
<td>18c</td>
</tr>
<tr>
<td>45</td>
<td>910c</td>
<td>17c</td>
</tr>
<tr>
<td>90</td>
<td>910c</td>
<td>17c</td>
</tr>
<tr>
<td>135</td>
<td>1020bc</td>
<td>19bc</td>
</tr>
<tr>
<td>180</td>
<td>1120ab</td>
<td>22b</td>
</tr>
<tr>
<td>225</td>
<td>1280a</td>
<td>26a</td>
</tr>
</tbody>
</table>

† No fertilizer N rate treatments had yet been applied before RCC control in the spring 2009 and corn in the study areas received a uniform N rate in 2008.
‡ Means followed by the same letter within a column are not different (P ≤ 0.05).
Table 3. Profile soil NO$_3^-$--N (0-0.6 m for spring samples and 0-0.9 m for post-harvest samples) in corn and soybean crops, with and without RCC, across sites.

<table>
<thead>
<tr>
<th></th>
<th>Corn year</th>
<th></th>
<th>Soybean year</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spring‡</td>
<td>Post-harvest</td>
<td></td>
<td>Post-harvest</td>
</tr>
<tr>
<td>RCC</td>
<td>NO$_3^-$--N</td>
<td>RCC</td>
<td>NO$_3^-$--N</td>
<td>N rate</td>
</tr>
<tr>
<td>No (preplant)</td>
<td>0.076</td>
<td>No</td>
<td>0.011</td>
<td>No</td>
</tr>
<tr>
<td>Yes (preplant)</td>
<td>&lt; 0.001</td>
<td>RCC</td>
<td>&lt; 0.001</td>
<td>RCC</td>
</tr>
<tr>
<td>No (early June)</td>
<td>ST x RCC</td>
<td>0.0001</td>
<td>0.001</td>
<td>0.0001</td>
</tr>
<tr>
<td>Yes (early June)</td>
<td>0.0001</td>
<td>RCC x NR</td>
<td>0.0001</td>
<td>RCC x NR</td>
</tr>
</tbody>
</table>

† The spring sampling was conducted only in corn plots with no fertilizer N. Sampling time was at time of RCC control and when corn was at the V4-V7 growth stages in early June.
‡ The N rate for the fall sampling after soybean corresponds to the fertilizer N rate applied to the prior-year corn.
§ Means followed by the same letter within a column are not different ($P \leq 0.05$).
¶ The partial ANOVA corresponds only to 2010-2011.
Table 4. Partial ANOVA for the corn responses to rye cover crop (RCC) and fertilizer N rate, across site-years.

<table>
<thead>
<tr>
<th>Source</th>
<th>Canopy NDVI</th>
<th>Plant population†</th>
<th>Plant height†</th>
<th>Grain yield</th>
<th>Grain N uptake</th>
<th>Total N uptake</th>
<th>PFP‡</th>
<th>PUE‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rye cover crop (RCC)</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>N rate (NR)</td>
<td>&lt; 0.001</td>
<td>0.861</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>RCC × NR</td>
<td>0.016</td>
<td>0.402</td>
<td>0.325</td>
<td>0.588</td>
<td>0.786</td>
<td>0.554</td>
<td>0.001</td>
<td>0.007</td>
</tr>
</tbody>
</table>

† Data only from 2010 and 2011.
‡ PFP, partial factor productivity; PUE, plant N uptake efficiency.
Table 5. Regression models and parameters describing the corn responses to rye cover crop (RCC) and fertilizer N rate, across site-years.

<table>
<thead>
<tr>
<th>RCC</th>
<th>Model</th>
<th>Regression parameters</th>
<th>Joint point</th>
<th>Plateau</th>
<th>EONR</th>
<th>YEONR</th>
<th>$R^2$</th>
<th>$P &gt; F$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$a$</td>
<td>$b$</td>
<td>$c$</td>
<td>Plateau $^\dagger$</td>
<td>Mg ha$^{-1}$</td>
<td>kg N ha$^{-1}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canopy NDVI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>QP</td>
<td>0.6456a</td>
<td>0.00129b</td>
<td>-0.000058a</td>
<td>112</td>
<td>0.718</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Yes</td>
<td>QP</td>
<td>0.6071b</td>
<td>0.00196a</td>
<td>-0.000113a</td>
<td>87</td>
<td>0.692</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Grain yield</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>QP</td>
<td>5.872a</td>
<td>0.0645a</td>
<td>-0.000163a</td>
<td>197</td>
<td>12.21</td>
<td>181</td>
<td>12.20</td>
</tr>
<tr>
<td>Yes</td>
<td>QP</td>
<td>4.665b</td>
<td>0.0672a</td>
<td>-0.000166a</td>
<td>202</td>
<td>11.46</td>
<td>185</td>
<td>11.41</td>
</tr>
<tr>
<td>Grain N uptake</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>Q</td>
<td>44.4a</td>
<td>0.590a</td>
<td>-0.00113a</td>
<td>225</td>
<td>120#</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Yes</td>
<td>Q</td>
<td>35.2a</td>
<td>0.566a</td>
<td>-0.00097a</td>
<td>225</td>
<td>114#</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Total aboveground plant N uptake</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>Q</td>
<td>75.4a</td>
<td>0.934a</td>
<td>-0.00176a</td>
<td>225</td>
<td>196#</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Yes</td>
<td>Q</td>
<td>63.5a</td>
<td>0.828a</td>
<td>-0.00120a</td>
<td>225</td>
<td>189#</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

$^\dagger$ Q, quadratic regression model; QP, quadratic-plateau regression model.

$^\ddagger$ Mg ha$^{-1}$ for grain yield, and kg ha$^{-1}$ for grain N and total aboveground plant N uptake.

$^\S$ EONR, economic optimum N rate; YEONR, yield at the economic optimum N rate.

$^\text{¶}$ Regression parameters followed by the same letter within a column and measurement are not different as determined by 95% lower and upper confidence limits.

$^\#$ The regression model did not reach the plateau, therefore, grain and total aboveground plant N uptake at the highest fertilizer N rate was used for comparisons.
Table 6. Soybean grain yield response to rye cover crop (RCC) and fertilizer N rate applied to the prior-year corn.

<table>
<thead>
<tr>
<th>N rate kg N ha⁻¹</th>
<th>No-RCC Mg ha⁻¹</th>
<th>RCC Mg ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>4.10</td>
<td>4.07</td>
</tr>
<tr>
<td>45</td>
<td>4.01</td>
<td>4.07</td>
</tr>
<tr>
<td>90</td>
<td>4.04</td>
<td>3.96</td>
</tr>
<tr>
<td>135</td>
<td>4.05</td>
<td>3.98</td>
</tr>
<tr>
<td>180</td>
<td>4.02</td>
<td>3.97</td>
</tr>
<tr>
<td>225</td>
<td>4.06</td>
<td>4.00</td>
</tr>
<tr>
<td>Mean</td>
<td>4.04</td>
<td>4.01</td>
</tr>
</tbody>
</table>

Statistics (\(P > F\))

<table>
<thead>
<tr>
<th>Source</th>
<th>(P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rye cover crop (RCC)</td>
<td>0.387</td>
</tr>
<tr>
<td>N rate (NR)</td>
<td>0.183</td>
</tr>
<tr>
<td>RCC × NR</td>
<td>0.451</td>
</tr>
</tbody>
</table>

† No fertilizer N rate treatments had yet been applied before 2009 and corn in the study areas received a uniform N rate in 2008.
Fig. 1. Mean monthly air temperature (a) and total precipitation (b) across sites (data from Arritt and Herzmann, 2013).
Fig. 2. Corn canopy normalized difference vegetative index (NDVI) (a) and corn grain yield (b) response to rye cover crop (RCC) and fertilizer N rate, across site-years. The partial ANOVA is presented in Table 4 and regression models and parameters are presented in Table 5.
Fig. 3. Corn grain yield response (yield with no-RCC minus yield with RCC) at the 180 kg N ha\(^{-1}\) rate. Data points are the means of each site-year and RCC biomass corresponds to biomass at the time of RCC control.
Fig. 4. Corn grain N (a) and total aboveground plant N (b) uptake response to rye cover crop (RCC) and fertilizer N rate, across site-years. The partial ANOVA is presented in Table 4 and regression models and parameters are presented in Table 5.
Fig. 5. Corn partial factor productivity (PFP) (a) and plant N uptake efficiency (PUE) (b) as affected by rye cover crop (RCC) and fertilizer N rate, across site-years. The partial ANOVA is presented in Table 4 and regression models and parameters are presented in Table 5.

† NS, non-significant ($P > 0.05$).
CHAPTER 4. WINTER RYE COVER CROP BIOMASS PRODUCTION, DEGRADATION, AND NITROGEN RECYCLING IN A CORN-SOYBEAN ROTATION

A paper to be submitted to Agronomy Journal

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Abstract

Use of a winter rye (*Secale cereale* L.) cover crop (RCC) in corn (*Zea mays* L.) and soybean (*Glycine max.* (L.) Merr.) fields can change N availability and cycling. The objectives were to evaluate RCC biomass production (RCC-BP), degradation (RCC-BD), and N recycling in a no-tillage corn-soybean (CS) rotation. For two years at four sites aboveground RCC was sampled in the spring before control to determine RCC biomass dry matter (DM), C, and N uptake. To evaluate RCC-BD and remaining RCC C and N, samples were collected, put into nylon mesh bags, placed on the soil surface, and collected at specific times for 105 d. Treatments included RCC following soybean (RCC-FS) and corn (RCC-FC), and N rate applied to the prior-year corn for RCC-FC. The RCC-BP was N limited with low N uptake (highest at 44 kg N ha⁻¹) due to low profile soil NO₃⁻–N. Averaged across site-years, the greatest RCC-BP was with RCC-FC that received 225 kg N ha⁻¹ (1280 kg DM ha⁻¹).
but the greatest RCC N uptake was with RCC-FS (27 kg N ha$^{-1}$). The RCC-BD and N consistently decreased over time following an exponential decay. An average 62% biomass DM of RCC-FS and RCC-FC was degraded after 105 d; however, N recycling was greater for RCC-FS than for RCC-FC (22 vs. 14 kg N ha$^{-1}$, respectively), and was influenced by the RCC C:N ratio. The RCC did not recycle a large amount of N, which limited potential as an N conserving management practice.

**Abbreviations:** CS, corn-soybean; PAN, plant available nitrogen; RCC, rye cover crop; RCC-BD, rye cover crop biomass degradation; RCC-BP, rye cover crop biomass production; RCC-C, carbon in the rye cover crop biomass; RCC-FC, rye cover crop following corn; RCC-FS, rye cover crop following soybean; RCC-N, nitrogen in the rye cover crop biomass.

**Introduction**

Understanding crop biomass degradation and nutrient cycling dynamics in cropping systems is critical for efficient resource management (Schomberg et al., 1994). Nitrate can accumulate in soils with N fertilization of cereal crops (Jacinthe et al., 2000). Despite the use of in-field practices to reduce NO$_3^-$–N loss, such as N fertilization rate and timing, significant NO$_3^-$–N losses in drainage discharge occur from cropping systems (Strock et al., 2004). Since NO$_3^-$–N is the primary form related to issues with N in water systems, management of N inputs for optimal crop production while minimizing NO$_3^-$–N loss continues to be a challenge (Dinnes et al., 2002). Therefore, improving nutrient use efficiency, crop production profits, and drinking water quality are ongoing needs in the Midwest region of the U.S.A. In this region, corn N fertilization can result in residual soil inorganic N that can be transported to
water systems, with losses at recommended N fertilization rates for corn between 29 and 56 kg N ha\(^{-1}\) (Sawyer and Randall, 2008). Nutrient management is more challenging for N than other plant nutrients because of its complex cycle and the speed at which N can transform to different chemical forms. Nitrogen cycling can be also affected by tillage system, soil drainage, crop type, N fertilization rate and source, time of N application, soil organic matter (SOM), inorganic soil N, slope, and precipitation and temperature patterns (Dinnes et al., 2002).

The potential NO\(_3^–\)-N loss between growth cycles of annual crops creates an opportunity for use of cover crops as an alternative management practice to reduce NO\(_3^–\)-N leaching (Kaspar et al., 2001). Cover crops function by taking up inorganic soil N and holding it in organic forms (Staver and Brinsfield, 1998). Therefore, cover crops have potential to improve N cycling in agricultural fields (Tonitto et al., 2006; Kaspar and Singer, 2011). Additional benefits from cover crops include reduction in soil erosion (Kaspar et al., 2001), weed pressure (Dhima et al., 2006), and increase in SOM (Sainju et al., 2005). However, the largest problem with cover crops in the Midwest is the cold and generally short period for growth between harvest and spring planting of annual crops (Dinnes et al., 2002). Due to winter hardiness and its potential to utilize residual soil NO\(_3^–\)-N, winter cereal rye is often used as a cover crop in the northern corn belt of the Midwest region (Feyereisen et al., 2006).

Despite the potential benefits of RCC, information about its effects on annual crop productivity and effective N recycling is unclear. Rye cover crop effectiveness in reducing NO\(_3^–\)-N loss and improving N cycling still needs to be addressed when using different N fertilization rates, tillage systems, and with variable weather patterns (Qi et al., 2011). The
The negative effects of RCC on corn growth and yield makes farmers reluctant to use RCC or to give it adequate time to grow in the spring. Lamarca (1996) found that when accumulated cereal cover crops biomass was less than 3000 kg DM ha$^{-1}$, the strongest negative effect on corn growth was for four weeks after cover crop control; however, greater cover crop biomass resulted in extended negative impact on corn growth. Therefore, farmers attempt to reduce the negative effect of RCC on corn with early control in the spring, which allows timely corn planting, but reduces RCC growth and N uptake. Early control also allows more time for RCC-BD and N recycling (Kaspar and Singer, 2011). However, that practice would diminish the RCC potential to scavenge residual NO$_3^-$–N. Extending the waiting
period could result in late corn planting, something farmers prefer to avoid due to potential yield loss (Duiker and Curran, 2005).

Due to concerns about NO$_3^-$–N delivery to the Gulf of Mexico and the need for meeting local drinking water standards (USEPA, 2007; Hoorman et al., 2009), programs providing incentives to farmers for implementing RCC as an in-field management practice are increasing. Farmers are also increasingly interested in in-field management practices that can help reduce NO$_3^-$–N losses as they increase understanding of their role in improving water quality.

Predicting plant biomass degradation requires knowledge of environmental factors and chemical and physical composition of the biomass (Collins et al., 1990). To have success in N recycling and supply of PAN to annual crops from RCC-BD, that N availability needs to be synchronized with annual crop N uptake (Kaspar and Singer, 2011). The RCC-BD and N recycling are mainly a function of air temperature (Farsad et al., 2011; Brennan and Boyd, 2012), biomass quality (Gregory et al., 1985; Ma et al., 1999), cropping history of the field (Parkin et al., 2002), and soil moisture (Schomberg et al., 1994). The RCC N recycling is also a function of C and N availability for microbes rather than their total amount in the RCC biomass (Ruffo and Bollero, 2003b). Steiner et al. (1994 and 1999) indicated that both air temperature and soil moisture need to be combined when developing models to describe crop biomass degradation. However, Collins et al. (1990) considered the use of time in first-order kinetics functions (exponential decay) as an accurate and by far the simplest approach to evaluate degradation of crop biomass in crop fields.

When adopting RCC as a management practice in corn production systems, farmers question the potential supply of PAN to corn from RCC-BD. Is that recycling important or
substantial, does the N become plant available and if so, does it match the time of corn N uptake demand, and should corn N fertilization requirement be adjusted? To investigate these questions, the objectives of this study were to evaluate RCC-BD and N recycling after spring RCC control in a no-tillage CS rotation.

Materials and methods

Study sites

The study was conducted in 2010 and 2011 at four Iowa sites. The predominant soils at each site were a Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludolls) and a Nicollet clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) at the Agricultural Engineering and Agronomy Research farm in Central Iowa near Ames (42°00′34″ N; 93°46′50″ W); a Mahaska silty clay loam (fine, smectitic, mesic Aquertic Argiudolls) and a Nira silty clay loam (fine-silty, mixed, superactive, mesic Aquic Argiudolls) at the Research and Demonstration Farm in southeast Iowa near Crawfordsville (41°12′09″ N; 91°29′31″ W); a Marshall silty clay loam (fine-silty, mixed, superactive, mesic Typic Hapludolls) at the Armstrong Research Farm in southwest Iowa near Lewis (41°18′48″ N; 95°10′49″ W); and a Floyd loam (fine-loamy, mixed, superactive, mesic Aquic Pachic Hapludolls) and a Clyde silty clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) at the Research and Demonstration Farm in northeast Iowa near Nashua (42°55′54″ N; 92°34′37″ W). At Ames the soils are moderately well drained and formed in glacial till, at Crawfordsville the soils are poorly drained and formed in loess on a till plain, at Lewis the soil is well-drained and formed in loess, and at Nashua the soils are somewhat poorly drained and formed in loamy sediments with underlying till. Weather data was
collected at weather stations at each research site and reported by the Iowa Environmental Mesonet Network (Arritt and Herzmann, 2013).

**Treatment application**

This study was conducted within a multi-site project evaluating corn and soybean grain yield response to RCC and corn optimal N fertilization requirement with and without use of a RCC. Full details of the study methods can be found in chapter 3. Specific treatment information pertinent to the current study is presented here. Two adjacent study areas were selected at each site in the spring 2008 and a no-tillage CS rotation initiated. The RCC treatment (with and without RCC) was the main plot. For the corn year, six N rates (0 to 225 kg N ha\(^{-1}\) in 45 kg N ha\(^{-1}\) increments) were applied to individual plots as urea-ammonium nitrate solution (UAN, 32% N) within two weeks after corn planting and within each RCC treatment. The RCC cultivar was ‘Wheeler’ and was drill-seeded in the fall after soybean and corn harvest at a rate of 70 kg ha\(^{-1}\). The RCC seeding dates were between Sept. 25 and Oct. 9 for RCC-FS, and between Sept. 17 and Oct. 28 for RCC-FC. For the study presented here, only plots with the RCC were used.

**Soil sampling and analysis**

Soil was sampled by hand for profile soil NO\(_3^-\)–N determination with a 0.02 m diameter soil probe in fall 2009 and 2010 (0-0.9 m in 0.3 m increments) after soybean and corn harvest and before or at RCC seeding. Sampling after soybean harvest in 2009 was by collecting six cores per replicate (RCC main plot) because no fertilizer N rate treatments had yet been applied to the prior-year corn, with each core collected from each plot (six total) and 0.2 m away from one of the center soybean rows. In 2010 sampling following soybean was by prior-year corn plots that had received 0, 135, and 225 kg N ha\(^{-1}\) (hereafter 0N, 135N, and
Sampling after corn harvest was by each plot that received 0N, 135N, and 225N the prior-spring and by collecting six cores per plot in a diagonal pattern across two corn rows, with one core from each row and a core 0.2 m from the side or each row. Soil cores were mixed and a sub-sample saved for analysis. Collected soil was dried in a forced-air dryer at 25 °C, ground to pass a 2-mm sieve, and NO$_3^-$–N was determined by 2 M KCl extraction and colorimetric cadmium reduction using a Lachat flow injection analyzer (Lachat Instruments, QuikChem 8500 Series 2, Loveland, CO) (Brown, 1998). Concentrations were converted to a mass basis, and added across depths to obtain the total soil NO$_3^-$–N to 0.9 m depth. A common soil bulk density for Iowa soils of 1.3 g cm$^{-3}$ was used for that conversion (Al-Kaisi et al., 2005).

**Rye biomass sampling and analysis**

In the spring, the aboveground RCC biomass was sampled (0.093 m$^2$ PVC square that encompassed two RCC rows at six random locations) within 3 d before RCC control to determine RCC-BP, and accumulated C and N (considered time zero). Sampling dates are shown in Table 1. The RCC plants were cut at the soil surface from within the frame and composited from the six locations into one sample. For the RCC-FS, biomass sampling was conducted by replicate because no N was applied to soybean, whereas for RCC-FC sampling was by each plot that received 0N, 135N, and 225N.

Additional RCC biomass was collected from each plot/replicate and that biomass was split into three sub-samples, fresh weight recorded, put into nylon mesh bags, and the bags placed on the soil surface in the middle of corresponding prior-soybean replicates or corn plots. The amount of RCC biomass placed into the mesh bags varied depending on the amount of RCC-BP at each site-year, but the study intended to have 100-300 g of fresh RCC biomass.
biomass in each bag. The mesh bags covered on average 0.06 m$^2$ when placed on an undisturbed no-tillage soil surface. Placement was away from farm equipment traffic patterns to avoid damage during planting of the annual crop and N application to corn. One set of bags was collected at 21, 63, and 105 d. In a few cases some soil was mixed with the RCC biomass sample, but was carefully removed by hand before weight recorded. The RCC biomass samples collected at time zero, and the remaining RCC biomass in each mesh bag at each sampling time, were dried in a forced-air dryer at 60 ºC and weighed to estimate the RCC-BP (at time zero) and the amount of remaining RCC biomass DM at each sampling time. The initial amount of RCC biomass DM measured at time zero was adjusted to an area basis for RCC row spacing, and then that amount per area used for RCC-BD after time zero.

All samples, including samples collected at time zero, were ground to pass a 2-mm sieve and a sub-sample analyzed for total C and N by dry combustion (LECO CHN-2000 analyzer, LECO Corp., St. Joseph, MI) (Nelson and Sommers, 1982). The amounts of remaining RCC biomass DM, C in the RCC biomass (RCC-C), and N in the RCC biomass (RCC-N) at each sampling time were calculated on an area basis by relating the fraction that remained in the mesh bag to the amount per area determined at time zero. The C:N ratio of all RCC biomass samples was calculated by dividing the amount of C by the amount of N on an area basis.

**Statistical analysis**

Analyses of variance (ANOVA) for measured parameters were performed with PROC MIXED (SAS Institute, Cary, NC). For all analyses, replicates and years were considered random. For the analyses of profile soil NO$_3^-$-N, RCC-BP, total C, total N, and C:N in the RCC biomass DM, site was considered fixed for RCC-FS and RCC-FC, and N
rate applied to the prior-year corn was also considered fixed for RCC-FC. For the analysis of RCC-BD, RCC-C, RCC-N, and C:N ratio in the remaining RCC biomass DM, sampling time was a fixed factor. Means separation were determined with Fisher Protected Least Significant Difference (FLSD) and differences between treatments were considered significant at $P \leq 0.05$.

The relationship between C:N ratio and N concentration of the RCC biomass DM at time zero and across site-years was fit to the power regression model [Eq. 1] using PROC NLIN of SAS. The exponential decay regression model [Eq. 2] was fit using PROC NLIN for RCC-BD, RCC-C, and RCC-N as proposed by Collins et al. (1990). The exponential model fit was by site for RCC-FS, by site and by fertilizer N rate applied to the prior-year corn for RCC-FC, and across site-years for both RCC-FS and RCC-FC. PROC REG was used to fit the quadratic decay model for the C:N ratio of remaining RCC biomass DM [Eq. 3] across site-years. The coefficient of determination ($R^2$) for each model was calculated, and models were deemed significant at $P \leq 0.05$.

$$Y = ax^{-b} \quad [1]$$

$$Y_t = Y_0e^{-kt} \quad [2]$$

$$Y = a + bx + cx^2 \quad [3]$$

In the power regression model, $Y$ represents the predicted N concentration (g N kg$^{-1}$), $x$ is the C:N ratio in the RCC biomass DM, and $a$ and $b$ are constants of the model. In the exponential decay model, $Y_t$ is the remaining RCC biomass DM, RCC-C, or RCC-N (kg ha$^{-1}$) at time $t$ (d); $Y_0$ is the predicted initial RCC biomass DM, RCC-C, or RCC-N (kg ha$^{-1}$) at $t =$
\(0; e\) is the exponential constant with an approximate numerical value of 2.7182; and \(k\) is the relative decomposition rate coefficient \((d^{-1})\). The parameters of the power and exponential models were considered significant if the 95% confidence intervals did not encompass zero (Ruffo and Bollero, 2003a). In the quadratic model, \(Y\) represents the predicted C:N ratio in the remaining RCC biomass DM, \(x\) is time \((d)\), and \(a, b,\) and \(c\) are the intercept, linear coefficient, and quadratic coefficient of the regression model.

An ANOVA across years was used to investigate significance of site for RCC-FS, and site and fertilizer N rate applied to the prior-year corn for RCC-FC, on estimated amount of initial \((Y_0)\) RCC biomass DM, RCC-C, and RCC-N, and on the relative degradation rate coefficient \((k)\) for RCC-BD, RCC-C, and RCC-N. Since \(k\) was not affected by site, results were summarized across site-years. Also, an ANOVA analysis indicated a significant interaction for biomass C:N ratio between sample time and RCC-FS and RCC-FC with each fertilizer N rate applied to the prior-year corn, therefore an FLSD \((P = 0.05)\) was calculated to indicate treatment differences at each sampling time.

**Results and discussion**

**Weather**

The weather in late fall and early spring can influence RCC growth, RCC-BP, and accumulation of total C and total N. The amount of precipitation can also affect crop productivity and post-harvest profile soil NO\(_3\)–N. The time after RCC planting in the fall (late Sept. to late Nov.) was cold in 2009 and 2010 (average \(\leq 11^\circ\)C) at all sites, and October 2009 was wet due to twice as much precipitation received that month at all sites compared with the historical average of the last 16 years (Fig. 1). The early spring (Mar. and Apr.) in
2010 was on average 2 °C warmer than the historical average at all sites, whereas 2011 was 2 °C colder at three out of the four sites. During that period, Ames was drier than the historical average in 2011, Crawfordsville was drier in 2010, and Lewis and Nashua did not receive any precipitation in Mar. any year. The weather after RCC control can affect RCC-BD and nutrient cycling. During the time the mesh bags were in the field (late Apr. to early Aug.), 2010 was 1 °C warmer than the historical average at all sites and received more precipitation than the historical data each month, especially with high precipitation in June and Aug. at Ames, and in June at Crawfordsville. In 2011, precipitation was near the historical average during that period at all sites, but July and Aug. were 2 °C warmer compared to the historical average.

**Post-harvest soil nitrate**

Post-harvest profile NO$_3^-$–N in the top 0.9 m of soil was < 55 kg N ha$^{-1}$ at all sites after soybean and corn harvest, with most instances being much less than that (Tables 2 and 3). Profile soil NO$_3^-$–N after soybean harvest was lowest at Ames and greatest at Lewis. After corn harvest and across N rates applied to the prior-year corn, NO$_3^-$–N was lowest at Ames and greatest at Nashua. Except for Ames, N fertilization resulted in increased soil NO$_3^-$–N. Across sites, 135N and 225N application increased soil NO$_3^-$–N by 5 and 13 kg N ha$^{-1}$ compared to 0N. The amount of profile soil NO$_3^-$–N after crop harvest highly depends on crop yield, annual precipitation, and weather patterns (Strock et al., 2004). In this study, the low post-harvest profile soil NO$_3^-$–N reflected years with above-normal precipitation and high crop production, and indicated that soil supply of PAN to promote RCC-BP and N uptake was low. However, N rate applied to the prior-year corn slightly increased post-
harvest profile soil NO$_3^-$–N and at most sites would potentially influence RCC-BP and N uptake.

Rye cover crop biomass production and nutrient accumulation

Rye cover crop biomass production

The RCC-BP for RCC-FS and RCC-FC (across N rates applied to the prior-year corn) was greatest at Crawfordsville and lowest at Nashua (Tables 4 and 5, respectively). Crawfordsville was one of the southern sites in this study and had the greatest annual precipitation; therefore, greater RCC-BP can be expected at this site. Nashua was the most northern site and had a shorter spring period for RCC growth. According to Hoorman et al. (2009), accumulation of RCC biomass may result in lower soil temperature in cooler regions and decrease RCC-BP. On average, RCC-BP for RCC-FS was 10% (100 kg DM ha$^{-1}$) less than RCC-FC (across N rates applied to the prior-year corn). The RCC-FS was controlled on average two weeks before control of RCC-FC to reduce the negative effect of RCC on the subsequent corn crop and to allow timely corn planting, which was on average one week before soybean planting.

Despite the lack of increase in soil NO$_3^-$–N with corn fertilizer N application at Ames, the application of 225N to the prior-year corn resulted in a RCC-BP increase (170 kg DM ha$^{-1}$) compared to 0N, but no increase with 135N. At Lewis, there was increased profile NO$_3^-$–N, but no difference in RCC-BP with the prior-year N rate. At no site was there greater RCC-BP with prior-year 135N rate. Although post-harvest profile NO$_3^-$–N was increased with N fertilization to the prior-year corn at most sites, the increases were not large and therefore RCC-BP was not greatly increased from that N. Across site-years, application of 225N increased RCC-BP by 28% (280 kg DM ha$^{-1}$) compared to 0N and 135N.
The RCC-BP was low compared to studies conducted by Ruffo and Bollero (2003a) and Farsad et al. (2011) in the Midwest region. Reasons for low RCC-BP included late seeding in the fall after soybean and corn harvest, cold temperatures in late fall, short spring period for RCC growth, and low post-harvest soil NO$_3^-$-N. Later RCC control in the spring could help increase RCC-BP, but this would reduce soil nutrient supply for the annual crop (Krueger et al., 2011). Brennan et al. (2011) indicated that RCC-BP is also a function of site location and plant density.

**Total carbon and nitrogen**

Total C in the RCC-FS followed the same trend as the RCC-BP and was greatest at Crawfordsville and lowest at Nashua; however, total N was not different between sites (Table 4). Total C in the RCC-FC was greatest at Crawfordsville and lowest at Nashua, the same trend as the RCC-BP; however, total C was not affected by N rate applied to the prior-year corn at Ames, which differed from RCC-BP (Table 5). Total N in the RCC-FC was also greatest at Crawfordsville and lowest at Nashua; however, total N was not affected by N rate applied to the prior-year corn at Lewis, which followed the same trend as RCC-BP and RCC-C. At no site did the 135N rate result in more C or N than with 0N for RCC-FC.

Across site-years, application of 225N increased total C by 30% (120 kg C ha$^{-1}$) and total N by 40% (8 kg N ha$^{-1}$) in the RCC-FC compared to 0N and 135N. The increase in total N with corn N fertilization reflected the difference in residual soil NO$_3^-$-N in the fall after corn harvest (8 - 13 kg NO$_3^-$-N ha$^{-1}$). According to Sainju et al. (2005), RCC is capable of scavenging residual soil NO$_3^-$-N up to 1.2 m depth. Our results indicated that RCC-FC was influenced by residual soil NO$_3^-$-N from the 225N rate; however, the 135N rate apparently did not have enough post-harvest residual soil NO$_3^-$-N to affect RCC growth and N uptake.
Ranells and Wagger (1997) conducted a two year experiment to evaluate N uptake by corn and RCC recovery of residual N with $^{15}$N-labeled fertilizer. They applied 200 kg N ha$^{-1}$ to the corn crop and found that corn plus RCC utilized 75% of the fertilizer; however, RCC recovered only 39% of the residual soil NO$_3^-$-N.

Despite the lower RCC-BP for RCC-FS compared to RCC-FC, that RCC accumulated 6 kg N ha$^{-1}$ more than the RCC-FC across N rates applied to the prior-year corn, and 9 kg N ha$^{-1}$ more than the RCC-FC with 0N. The greater total N in the RCC-FS compared to RCC-FC with 0N also reflected the difference between the two systems in residual soil NO$_3^-$-N after crop harvest (9 kg NO$_3^-$-N ha$^{-1}$ less after corn harvest with 0N). Assuming minimal soil N mineralization in the fall after soil profile sampling, and in the early spring until the time of RCC control, the amount of inorganic soil N for RCC uptake would approximate the amount of post-harvest profile soil NO$_3^-$-N. Based on that N amount, the RCC accumulated an average 87% and 75% of the profile NO$_3^-$-N present, respectively, for RCC-FS and RCC-FC. Results indicated the RCC-FS was somewhat less N limited than the RCC-FC, or the RCC growth was influenced by prior-year corn crop residue, both of which may impact RCC-BD and N recycling during the subsequent growing season.

According to Schomberg et al. (1994), total C and total N affect crop biomass quality (C:N ratio), and Douglas and Rickman (1992) found that N concentration in the crop biomass plays an important role in crop biomass degradation and N cycling.

**C:N ratio in the rye cover crop biomass**

In this study, the C:N ratio in the RCC biomass DM increased slightly with increasing RCC-BP for both RCC-FS and RCC-FC, but decreased with N fertilization to the prior-year corn for RCC-FC at three sites (not Crawfordsville) (Tables 4 and 5). According to Brennan
et al. (2013), the C:N ratio increases through the RCC growth period and with increasing RCC-BP. The RCC-BP at Crawfordsville was three to four times larger than the other sites and the RCC had the highest C:N ratio, which may have resulted in lack of C:N change with N fertilization to the prior-year corn. Across site-years, the C:N ratio was lower for RCC-FS than for RCC-FC, a reflection of the less limited N supply in the RCC-FS system and the shorter spring time for RCC-FS to grow.

Across site-years, C concentration in the RCC biomass DM was the same for RCC-FS and RCC-FC with 0N and 135N (average 410 g C kg⁻¹); however, application of 225N to the prior-year corn increased the C concentration by 7 g C kg⁻¹ (P < 0.001). The increase in C concentration was not large, and was possibly a result of increased RCC-BP with the 225N rate. Across site-years, N concentration in the RCC biomass DM was 8 g N kg⁻¹ greater for RCC-FS than for RCC-FC across N rates applied to the prior-year corn (31 vs. 23 g N kg⁻¹), and 10 g N kg⁻¹ greater when compared to RCC-FC with 0N. Nitrogen fertilization to the prior-year corn increased N concentrations in the RCC biomass and was 21, 23, and 25 g N kg⁻¹ for 0N, 135N, and 225N, respectively (P < 0.001). Vigil and Kissel (1991) indicated that despite an increase of crop biomass, C concentration is fairly constant during the growth season, but not C:N ratio. Our results indicated accumulation of C was similar for RCC-FS and RCC-FC; however, accumulation of N was different depending upon the prior-crop and N rate applied to the prior-year corn.

The C:N ratio in the RCC biomass DM increased with decreasing N concentrations, and was lower with RCC-FS than with RCC-FC (Fig. 2). The lower C:N and greater N concentration in the RCC-FS also confirmed that RCC was less N limited or less influenced by the prior-crop than for RCC-FC. The high $R^2$ of the relationship indicated varying N
concentration is the factor determining the C:N ratio of RCC biomass DM, and that C concentration is constant. The C:N ratio vs. N concentration relationship observed in this study was previously reported by Vigil and Kissel (1991). They indicated that 75% of the N mineralized with crop biomass degradation could be explained by the biomass C:N ratio. According to Brennan et al. (2013), the C:N ratio of RCC biomass DM can be estimated readily by N concentration due to the narrow spread of C concentration. This relationship could be useful for estimating the amount of C added to soil from RCC-BD, thus only needing RCC biomass N concentration measurement.

**Rye cover crop biomass degradation and nutrient recycling**

The RCC-BD with RCC-FS and amount of RCC-C differed by the interaction of site and sampling time (expressed in days) after mesh bags placement in the field; however, amount of RCC-N was only different by time (Table 6). The main effect of site and time was significant for C:N ratio with RCC-FS. The RCC-BD with RCC-FC and amount of RCC-C differed by the interaction of site and time, and also by the interaction of site and N rate applied to the prior-year corn. However, amount of RCC-N was not different with the site and time interaction. Statistical results also showed a significant interaction between site and N rate applied to the prior-year corn for RCC-N. The interaction of time and N rate, and the three way interaction, was not significant for remaining RCC biomass DM, RCC-C, and RCC-N in the RCC-FC. These results indicated that the remaining RCC biomass DM, RCC-C, and RCC-N were the same across sample date for site and N rate applied to the prior-year corn. The interactions of site and time, and time and N rate, were significant for the C:N ratio with RCC-FC. The microbial use of available C for RCC-BD can result in potential N mineralization (Ruffo and Bollero, 2003a), and since N concentration is the driving factor for
changes in the C:N ratio with RCC-BD (Vigil and Kissel, 1991), N recycling patterns and rates are not necessarily the same as for RCC-BD or C recycling.

The exponential decay model described the RCC-BD, RCC-C, and RCC-N across the 105 d period. Parameter estimates for the exponential decay models and statistics indicating the significance of the models for degradation of RCC-FS and RCC-FC at each site and across years are presented in Tables 7 and 8, respectively. All models were developed with the means of remaining RCC biomass DM, RCC-C, and RCC-N by site for RCC-FS, and also by N rate applied to the prior-year corn for RCC-FC.

The exponential decay models for RCC-BD, RCC-C, and RCC-N with RCC-FS were significant \((P < 0.05)\) for each site and had a \(R^2 \geq 0.95\) (Table 7). The greatest initial RCC biomass DM \((Y_0)\) was estimated at Crawfordsville and the lowest at Nashua, which matched the RCC-BP results measured at time zero. Results also indicated that relative RCC-BD rate \((k)\) was greatest at Crawfordsville and lowest at Lewis. Despite similar annual temperature between the two sites, precipitation was greater at Crawfordsville than Lewis and the increased moisture may have resulted in a greater \(k\) value for Crawfordsville. The decay models for RCC-C and RCC-N indicated that estimated initial amount of RCC-C and RCC-N \((Y_0)\) also matched the total C and N amounts measured at time zero. However, differences in \(k\) for RCC-C was narrower than for RCC-BD. The greatest fraction of RCC biomass DM remaining after 105 d for RCC-FS was at Lewis (52%) and the lowest at Crawfordsville (25%). The difference in RCC-BD between the two sites was due to the different \(k\) for each site. Ruffo and Bollero (2003a) found that by corn harvest, there was still 5% RCC biomass DM remaining on the soil surface, with the amount varying with initial RCC-BP and accumulated C.
As found with RCC-FS, all exponential decay models for RCC-BD, RCC-C, and RCC-N with RCC-FC were significant at each site for each N rate applied to the prior-year corn (Table 8). In all but two cases, the $R^2$ was $\geq 0.90$. Those cases were the RCC-BD and RCC-N with 0N at Crawfordsville. The Crawfordsville site has a poorly drained soil that saturates relatively quickly with high precipitation. That situation may have added variability, which affected RCC-BD and N recycling. The greatest initial RCC biomass DM ($Y_0$) was estimated at Crawfordsville and the lowest at Nashua, which matched the RCC-BP measured at time zero. The $k$ for RCC-BD was within a narrow range (-0.012 to -0.009) for all sites, indicating RCC-BD rate for RCC-FC was similar across sites and N rates applied to the prior-year corn. The decay models of RCC-C and RCC-N showed that estimated initial amount of RCC-C and RCC-N ($Y_0$) also matched the total C and N amounts measured at time zero. However, the range of $k$ for RCC-C and RCC-N was wider than for RCC-BD (-0.017 to -0.010 for RCC-C, and -0.014 to -0.004 for RCC-N). The $k$ for RCC-C with RCC-FC was similar to $k$ for RCC-C with RCC-FS, indicating C recycling over time was the same for both RCC-FC and RCC-FS. However, $k$ for RCC-N with RCC-FC was lower than $k$ for RCC-N with RCC-FS, indicating N recycling was slower for RCC-FC than for RCC-FS. Overall, the estimated $k$ values were similar to those reported by Kaboneka et al. (1997), who conducted an incubation study evaluating corn, soybean, and wheat biomass degradation over 30 d.

The significance of the exponential decay models and $R^2$ for both RCC-FS and RCC-FC were high compared to a similar study conducted by Ruffo and Bollero (2003a) where they sampled RCC biomass that remained on the soil surface across plots. In our study, the models goodness of fit was likely improved due to placement of the RCC biomass into mesh
bags and allocation on the soil surface away from farm equipment traffic patterns, which
avoided RCC biomass damage in the mesh bags from plot activities. The placement of RCC
biomass into soil (buried vs. soil surface) can also create significant changes in $k$, as crop
residues incorporated to the soil degrade faster than those remaining in the soil surface
(Douglas and Rickman, 1992). Our study was conducted in a no-tillage system, and this
could have resulted in slower RCC-BD compared with more intense tillage systems.

Site did not have an influence on $Y_0$ or $k$ for RCC-BD, RCC-C, and RCC-N with
RCC-FS (Table 9). The interaction between site and N rate applied to the prior-year corn
influenced $Y_0$ for RCC-BD and RCC-C, but not RCC-N with RCC-FC. The $k$ was not
influenced by any factor with RCC-FC. Therefore, the net amount of RCC-BD and N
recycling depended upon $Y_0$, but $k$ for RCC-BD and N recycling was the same across sites
and N rates applied to the prior-year corn with RCC-FC. The exponential decay models
across site-years for RCC-BD, RCC-C, and RCC-N with RCC-FS and RCC-FC are shown in
Fig. 3. Results indicated that across site-years and after 105 d, 38% of the biomass DM with
RCC-FS and RCC-FC (across N rates applied to the prior-year corn) still remained in the
field. Across site-years, the net N recycling of accumulated N with RCC-FS (N for the
subsequent corn crop) was 25% (7 kg N ha$^{-1}$), 60% (16 kg N ha$^{-1}$), and 80% (22 kg N ha$^{-1}$) by
21, 63, and 105 d, respectively, after time zero. By the end of the 105 d period and across N
rates applied to the prior-year corn, 64% (14 kg N ha$^{-1}$) of accumulated N with RCC-FC (N
for the subsequent soybean crop) was recycled.

The net N recycling was low for both RCC-FS and RCC-FC, and reflected the low N
accumulation in the RCC biomass DM. Ruffo and Bollero (2003b) indicated that slow
nutrient recycling rates are associated not only with accumulation of high C and low N
compounds, but also with C and N availability for microbial use in RCC-BD and nutrient recycling processes. This can be especially important with cereal crops (with high C:N ratio), as with RCC, compared to legumes. Early cover crop control results in low C:N ratio due to the shorter time to accumulate cellulose, hemicellulose, and lignin (Kaspar and Singer, 2011). The more rapid N recycling with RCC-FS could have been a result of the lower initial C:N ratio in the RCC biomass DM compared with RCC-FC (Tables 4 and 5, Fig. 4). The RCC-FS was controlled two weeks before control of RCC-FC, and hence had less time to grow and accumulate high C:N ratio compounds, which resulted in more rapid and greater N recycling. This is also reflected in the lower C:N ratio over time (Fig. 4). The prior-year corn 225N rate resulted in a lower initial C:N ratio compared to 0N, but since the difference was small, the N recycling was somewhat similar with and without N fertilization to the prior-year corn. As the rate of C and N recycling decreased over time, the C:N ratio became the same with RCC-FS and RCC-FC (Fig. 4), an indication of the low N amount and high C:N compounds remaining in the RCC biomass.

Results suggested that residual NO$_3^-$--N from the fertilizer N applied to the prior-year corn has potential to increase RCC-BP and N uptake with RCC-FC, but not rate of RCC-BD, C or N recycling. Results showed that N recycling from RCC-FS was not large and would have minimal impact on soil potential supply of PAN for the subsequent corn crop and reduction in corn N fertilization requirement. Ruffo and Bollero (2003a) conducted a study in Illinois to evaluate RCC-BD and found that after four to six weeks of corn emergence, RCC-BD recycled only 33% of the accumulated N in the RCC biomass. They concluded that RCC-BD and nutrient recycling are more useful in soil conservation and soil N storage than as an N source for corn production. Using surface-applied $^{15}$N-labeled RCC biomass, Ranells and
Wagger (1997) found that corn recovered only 4% of N recycled from RCC-BD. Garwood et al. (1999) found that a RCC increased total soil inorganic N by 160 kg N ha$^{-1}$ across an eight year study, and concluded that the increase in soil N storage was due to less NO$_3^-$–N loss in tile drainage water with N accumulation in the RCC biomass. Kuo and Jellum (2000) indicated that an increase in total soil N is possible, but in soils with high background levels of SOM, it is difficult to measure that increase with implementation of new crop management practices such as use of RCC. That could be the case in Iowa soils that have high SOM levels. In another study, Kuo and Jellum (2002) concluded that a RCC did not reduce presidedress soil NO$_3^-$–N concentrations compared to fallow and that corn yield was mostly affected by initial amount of profile soil NO$_3^-$–N and N fertilization rate. Our results in this RCC-BD study, and the lack of change in the corn economic optimum N rate with use of the RCC system found in the overall multi-site study (presented in Chapter 3), confirmed that the RCC system had minimal effect on amount of N recycled back to soil and supply of PAN to corn.

**Conclusions**

Across site-years, the RCC-BP and N uptake were not large due to low post-harvest profile soil NO$_3^-$–N and the short spring period for RCC growth. Based on the amount of profile soil NO$_3^-$–N present after annual crop harvest, the RCC did accumulate 87% and 75% of that N, respectively, for RCC-FS and RCC-FC. There were differences in amount of RCC-BP, total C, and total N between sites with RCC-FS, and also between fertilizer N rates applied to the prior-year corn with RCC-FC, but those differences were not large. Nitrogen applied to the prior-year corn at 225N resulted in the greatest RCC-BP (1280 kg DM ha$^{-1}$).
However, accumulated N was greater with RCC-FS (27 kg N ha\(^{-1}\)) than with RCC-FC (21 kg N ha\(^{-1}\) across N rates applied to the prior-year corn), a reflection of the different prior-crop, seeding date, and time for RCC growth in early spring.

An exponential decay model fit the RCC-BD, and C and N recycling. The degradation rate coefficient \((k)\) for RCC-BD and RCC-C was similar for RCC-FS and RCC-FC, and for the different N rates applied to the prior-year corn. However, decay models indicated a greater degradation rate for RCC-N with RCC-FS than with RCC-FC. The low RCC-BP and N uptake, in combination with the relatively slow RCC-BD rate, resulted in a low N recycling amount in all cases. After 105 d, RCC-FS recycled 22 kg N ha\(^{-1}\) (80% of uptake) and RCC-FC recycled only 14 kg N ha\(^{-1}\) (64% of uptake across N rates applied to the prior-year corn) from RCC-BD. The more rapid and largest N recycling with RCC-FS compared to RCC-FC appeared to be associated with a lower initial C:N ratio. Results showed that a RCC can be a good management practice for environmental purposes, that is, accumulate residual soil NO\(_3^\)–N. However, the RCC system in our study did not recycle a large amount of N, which limited potential as an agronomic N management practice.

**Acknowledgments**

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University Research Farms superintendents and personnel for their support with treatment applications and mesh bag collection.

References


Table 1. Calendar dates for rye cover crop (RCC) biomass sampling.

<table>
<thead>
<tr>
<th>Prior-crop</th>
<th>Ames</th>
<th>Crawfordsville</th>
<th>Lewis</th>
<th>Nashua</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybean</td>
<td>Apr. 21</td>
<td>Apr. 19</td>
<td>Apr. 22</td>
<td>Apr. 23</td>
</tr>
<tr>
<td>Corn</td>
<td>Apr. 28</td>
<td>May 09</td>
<td>Apr. 29</td>
<td>May 04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybean</td>
<td>Apr. 29</td>
<td>Apr. 29</td>
<td>Apr. 20</td>
<td>Apr. 28</td>
</tr>
<tr>
<td>Corn</td>
<td>May 09</td>
<td>May 06</td>
<td>May 05</td>
<td>May 07</td>
</tr>
</tbody>
</table>
Table 2. Post-harvest residual soil NO$_3^-$–N in the top 0.9 m of soil at the time of rye cover crop (RCC) seeding after soybean harvest, 2009-2010.

<table>
<thead>
<tr>
<th>Site</th>
<th>NO$_3^-$–N kg NO$_3^-$–N ha$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ames</td>
<td>23c†</td>
</tr>
<tr>
<td>Crawfordsville</td>
<td>32b</td>
</tr>
<tr>
<td>Lewis</td>
<td>42a</td>
</tr>
<tr>
<td>Nashua</td>
<td>27bc</td>
</tr>
<tr>
<td>Mean</td>
<td>31</td>
</tr>
</tbody>
</table>

† Means with the same letter are not different ($P \leq 0.05$).
Table 3. Post-harvest residual soil NO$_3$–N in the top 0.9 m of soil at the time of rye cover crop (RCC) seeding after corn harvest, 2009-2010.

<table>
<thead>
<tr>
<th>N rate $^\dagger$</th>
<th>Ames</th>
<th>Crawfordsville</th>
<th>Lewis</th>
<th>Nashua</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>0N</td>
<td>16a $^\ddagger$</td>
<td>23b</td>
<td>23b</td>
<td>24c</td>
<td>22c</td>
</tr>
<tr>
<td>135N</td>
<td>19a</td>
<td>22b</td>
<td>29ab</td>
<td>39b</td>
<td>27b</td>
</tr>
<tr>
<td>225N</td>
<td>18a</td>
<td>35a</td>
<td>33a</td>
<td>53a</td>
<td>35a</td>
</tr>
<tr>
<td>Mean</td>
<td>18C $^\ddagger$</td>
<td>27B</td>
<td>28B</td>
<td>38A</td>
<td></td>
</tr>
</tbody>
</table>

$^\dagger$ 0N, 135N, and 225N stand for 0, 135, and 225 kg N ha$^{-1}$ applied to the prior-year corn.

$^\ddagger$ Means with the same lower case letter within a column and means across fertilizer N rates with the same capital letter are not different ($P \leq 0.05$).
Table 4. Aboveground rye cover crop (RCC) biomass dry matter (DM), total C, total N, and C:N ratio with RCC following soybean (RCC-FS) at the time of sampling in the spring, 2010-2011.

<table>
<thead>
<tr>
<th>Site</th>
<th>DM</th>
<th>Total C</th>
<th>Total N</th>
<th>C:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ames</td>
<td>1130ab†</td>
<td>455ab</td>
<td>30a</td>
<td>14b</td>
</tr>
<tr>
<td>Crawfordsville</td>
<td>1230a</td>
<td>505a</td>
<td>29a</td>
<td>17a</td>
</tr>
<tr>
<td>Lewis</td>
<td>910ab</td>
<td>370ab</td>
<td>27a</td>
<td>13bc</td>
</tr>
<tr>
<td>Nashua</td>
<td>710b</td>
<td>285b</td>
<td>23a</td>
<td>12c</td>
</tr>
<tr>
<td>Mean</td>
<td>990</td>
<td>405</td>
<td>27</td>
<td>14</td>
</tr>
</tbody>
</table>

† Means with the same letter within a column are not different \((P \leq 0.05)\).
Table 5. Aboveground rye cover crop (RCC) biomass dry matter (DM), total C, total N, and C:N ratio with RCC following corn (RCC-FC) at the time of sampling in the spring, 2010-2011.

<table>
<thead>
<tr>
<th>N rate†</th>
<th>Ames</th>
<th>Crawfordsville</th>
<th>Lewis</th>
<th>Nashua</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry matter (kg DM ha⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0N</td>
<td>760b†</td>
<td>1920b</td>
<td>700a</td>
<td>500b</td>
<td>970b</td>
</tr>
<tr>
<td>135N</td>
<td>770b</td>
<td>2130b</td>
<td>690a</td>
<td>510b</td>
<td>1020b</td>
</tr>
<tr>
<td>225N</td>
<td>930a</td>
<td>2910a</td>
<td>560a</td>
<td>710a</td>
<td>1280a</td>
</tr>
<tr>
<td>Mean</td>
<td>820B†</td>
<td>2320A</td>
<td>650BC</td>
<td>570C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total C (kg C ha⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0N</td>
<td>310a</td>
<td>800b</td>
<td>285a</td>
<td>205b</td>
<td>400b</td>
</tr>
<tr>
<td>135N</td>
<td>315a</td>
<td>885b</td>
<td>280a</td>
<td>205b</td>
<td>420b</td>
</tr>
<tr>
<td>225N</td>
<td>385a</td>
<td>1220a</td>
<td>235a</td>
<td>290a</td>
<td>530a</td>
</tr>
<tr>
<td>Mean</td>
<td>335B</td>
<td>970A</td>
<td>265BC</td>
<td>235C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total N (kg N ha⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0N</td>
<td>16b</td>
<td>28b</td>
<td>15a</td>
<td>12b</td>
<td>18b</td>
</tr>
<tr>
<td>135N</td>
<td>18ab</td>
<td>31b</td>
<td>16a</td>
<td>13b</td>
<td>19b</td>
</tr>
<tr>
<td>225N</td>
<td>25a</td>
<td>44a</td>
<td>15a</td>
<td>20a</td>
<td>26a</td>
</tr>
<tr>
<td>Mean</td>
<td>19B</td>
<td>34A</td>
<td>16BC</td>
<td>15C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C:N ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0N</td>
<td>20a</td>
<td>29a</td>
<td>19a</td>
<td>17a</td>
<td>21a</td>
</tr>
<tr>
<td>135N</td>
<td>18b</td>
<td>29a</td>
<td>18a</td>
<td>15b</td>
<td>20b</td>
</tr>
<tr>
<td>225N</td>
<td>16c</td>
<td>28a</td>
<td>15b</td>
<td>14b</td>
<td>18c</td>
</tr>
<tr>
<td>Mean</td>
<td>18B</td>
<td>28A</td>
<td>17BC</td>
<td>15C</td>
<td></td>
</tr>
</tbody>
</table>

† 0N, 135N, and 225N stand for 0, 135, and 225 kg N ha⁻¹ applied to the prior-year corn.
‡ Means with the same lower case letter within a column and measurement and across fertilizer N rates means with the same capital letter within a measurement are not different (P ≤ 0.05).
Table 6. Partial ANOVA for rye cover crop (RCC) biomass degradation (RCC-BD), C in the RCC biomass (RCC-C), N in the RCC biomass (RCC-N), and C:N ratio with RCC following soybean (RCC-FS) and RCC following corn (RCC-FC), 2010-2011.

<table>
<thead>
<tr>
<th>Source</th>
<th>RCC-BD</th>
<th>RCC-C</th>
<th>RCC-N</th>
<th>C:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCC-FS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site (S)</td>
<td>0.131</td>
<td>0.086</td>
<td>0.195</td>
<td>0.048</td>
</tr>
<tr>
<td>Time (T)†</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>S × T</td>
<td>0.002</td>
<td>0.022</td>
<td>0.501</td>
<td>0.113</td>
</tr>
<tr>
<td>RCC-FC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site (S)</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Time (T)</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>S × T</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>0.174</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>N rate (NR)‡</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>S × NR</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>0.665</td>
</tr>
<tr>
<td>T × NR</td>
<td>0.160</td>
<td>0.129</td>
<td>0.057</td>
<td>0.013</td>
</tr>
<tr>
<td>S × T × NR</td>
<td>0.360</td>
<td>0.470</td>
<td>0.875</td>
<td>0.671</td>
</tr>
</tbody>
</table>

† Mesh bag collection day.
‡ Fertilizer N rate applied to the prior-year corn.
Table 7. Exponential decay model parameters and statistics indicating the significance of models for rye cover crop (RCC) biomass degradation (RCC-BD), C in the RCC biomass (RCC-C), and N in the RCC biomass (RCC-N) with RCC following soybean (RCC-FS) as a function of sample time (days), 2010-2011.

<table>
<thead>
<tr>
<th>Site</th>
<th>RCC-BD</th>
<th></th>
<th></th>
<th></th>
<th>RCC-C</th>
<th></th>
<th></th>
<th></th>
<th>RCC-N</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \hat{Y}_0 )†</td>
<td>( k )‡</td>
<td>( R^2 )</td>
<td>( P &gt; F )</td>
<td>( \hat{Y}_0 )</td>
<td>( k )</td>
<td>( R^2 )</td>
<td>( P &gt; F )</td>
<td>( \hat{Y}_0 )</td>
<td>( k )</td>
<td>( R^2 )</td>
</tr>
<tr>
<td>Ames</td>
<td>1110</td>
<td>-0.0090</td>
<td>0.95</td>
<td>0.005</td>
<td>470</td>
<td>-0.0178</td>
<td>0.98</td>
<td>0.005</td>
<td>31</td>
<td>-0.0154</td>
<td>0.98</td>
</tr>
<tr>
<td>Crawfordsville</td>
<td>1220</td>
<td>-0.0131</td>
<td>0.98</td>
<td>0.003</td>
<td>510</td>
<td>-0.0161</td>
<td>0.98</td>
<td>0.004</td>
<td>29</td>
<td>-0.0113</td>
<td>0.98</td>
</tr>
<tr>
<td>Lewis</td>
<td>920</td>
<td>-0.0062</td>
<td>1.00</td>
<td>&lt; 0.001</td>
<td>385</td>
<td>-0.0146</td>
<td>0.99</td>
<td>0.003</td>
<td>28</td>
<td>-0.0150</td>
<td>0.99</td>
</tr>
<tr>
<td>Nashua</td>
<td>740</td>
<td>-0.0096</td>
<td>0.96</td>
<td>0.005</td>
<td>295</td>
<td>-0.0160</td>
<td>0.98</td>
<td>0.006</td>
<td>23</td>
<td>-0.0163</td>
<td>0.99</td>
</tr>
</tbody>
</table>

† \( \hat{Y}_0 \), estimated initial rye cover crop (RCC) biomass dry matter (DM), total C, or total N.
‡ \( k \), relative degradation rate coefficient.
Table 8. Exponential decay model parameters and statistics indicating the significance of models for rye cover crop (RCC) biomass degradation (RCC-BD), C in the RCC biomass (RCC-C), and N in the RCC biomass (RCC-N) with RCC following corn (RCC-FC) as a function of sample time (days), 2010-2011.

<table>
<thead>
<tr>
<th>Site and N rate‡</th>
<th>RCC-BD</th>
<th></th>
<th></th>
<th>RCC-C</th>
<th></th>
<th></th>
<th>RCC-N</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( Y_0 )</td>
<td>( k )</td>
<td>( R^2 )</td>
<td>( P &gt; F )</td>
<td>( Y_0 )</td>
<td>( k )</td>
<td>( R^2 )</td>
<td>( P &gt; F )</td>
<td>( Y_0 )</td>
</tr>
<tr>
<td>Ames 0N</td>
<td>820</td>
<td>-0.0090</td>
<td>0.89</td>
<td>0.014</td>
<td>335</td>
<td>-0.016</td>
<td>0.95</td>
<td>0.014</td>
<td>18</td>
</tr>
<tr>
<td>135N</td>
<td>770</td>
<td>-0.0060</td>
<td>1.00</td>
<td>&lt; 0.001</td>
<td>325</td>
<td>-0.013</td>
<td>0.98</td>
<td>0.003</td>
<td>18</td>
</tr>
<tr>
<td>225N</td>
<td>990</td>
<td>-0.0101</td>
<td>0.94</td>
<td>0.009</td>
<td>415</td>
<td>-0.015</td>
<td>0.93</td>
<td>0.017</td>
<td>27</td>
</tr>
<tr>
<td>Crawfordsville 0N</td>
<td>1950</td>
<td>-0.0096</td>
<td>0.98</td>
<td>0.002</td>
<td>815</td>
<td>-0.011</td>
<td>0.98</td>
<td>0.002</td>
<td>28</td>
</tr>
<tr>
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<td>2180</td>
<td>-0.0105</td>
<td>0.98</td>
<td>0.003</td>
<td>910</td>
<td>-0.011</td>
<td>0.98</td>
<td>0.003</td>
<td>31</td>
</tr>
<tr>
<td>225N</td>
<td>3010</td>
<td>-0.0097</td>
<td>0.97</td>
<td>0.003</td>
<td>1270</td>
<td>-0.010</td>
<td>0.97</td>
<td>0.004</td>
<td>45</td>
</tr>
<tr>
<td>Lewis 0N</td>
<td>740</td>
<td>-0.0096</td>
<td>0.94</td>
<td>0.008</td>
<td>305</td>
<td>-0.017</td>
<td>0.95</td>
<td>0.013</td>
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</tr>
<tr>
<td>135N</td>
<td>720</td>
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<td>0.005</td>
<td>300</td>
<td>-0.016</td>
<td>0.96</td>
<td>0.012</td>
<td>18</td>
</tr>
<tr>
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<td>250</td>
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<td>0.95</td>
<td>0.011</td>
<td>16</td>
</tr>
<tr>
<td>Nashua 0N</td>
<td>530</td>
<td>-0.0091</td>
<td>0.95</td>
<td>0.006</td>
<td>215</td>
<td>-0.013</td>
<td>0.97</td>
<td>0.006</td>
<td>12</td>
</tr>
<tr>
<td>135N</td>
<td>530</td>
<td>-0.0106</td>
<td>0.98</td>
<td>0.003</td>
<td>215</td>
<td>-0.013</td>
<td>0.97</td>
<td>0.007</td>
<td>14</td>
</tr>
<tr>
<td>225N</td>
<td>730</td>
<td>-0.0117</td>
<td>0.99</td>
<td>0.002</td>
<td>300</td>
<td>-0.014</td>
<td>0.99</td>
<td>0.003</td>
<td>20</td>
</tr>
</tbody>
</table>

‡ 0N, 135N, and 225N stand for 0, 135, and 225 kg N ha\(^{-1}\) applied to the prior-year corn.

‡ \( Y_0 \), estimated initial rye cover crop (RCC) biomass dry matter (DM), total C, or total N.

§ \( k \), relative degradation rate coefficient.
Table 9. Partial ANOVA for fixed effects on estimated initial amount \((Y_0)\) and relative degradation rate \((k)\) of exponential decay models for RCC biomass degradation (RCC-BD), C in the RCC biomass (RCC-C), and N in the RCC biomass (RCC-N) with RCC following soybean (RCC-FS) and RCC following corn (RCC-FC), 2010-2011.

<table>
<thead>
<tr>
<th>Fixed effects</th>
<th>(Y_0) RCC-BD</th>
<th>(Y_0) RCC-C</th>
<th>(Y_0) RCC-N</th>
<th>(k) RCC-BD</th>
<th>(k) RCC-C</th>
<th>(k) RCC-N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site RCC-FS</td>
<td>0.704</td>
<td>0.669</td>
<td>0.826</td>
<td>0.336</td>
<td>0.767</td>
<td>0.348</td>
</tr>
<tr>
<td>Site RCC-FC</td>
<td>0.009</td>
<td>0.012</td>
<td>0.020</td>
<td>0.614</td>
<td>0.206</td>
<td>0.219</td>
</tr>
<tr>
<td>N rate†</td>
<td>0.097</td>
<td>0.107</td>
<td>0.090</td>
<td>0.519</td>
<td>0.177</td>
<td>0.760</td>
</tr>
<tr>
<td>Site (\times) N rate</td>
<td>0.042</td>
<td>0.037</td>
<td>0.393</td>
<td>0.706</td>
<td>0.341</td>
<td>0.469</td>
</tr>
</tbody>
</table>

†Fertilizer N rate applied to the prior-year corn.
Fig. 1. Monthly mean temperature and total precipitation by site and year (data from Arritt and Herzmann, 2013).
Fig. 2. Relationship between the C:N ratio in the rye cover crop (RCC) biomass dry matter (DM) and N concentration at the time of RCC sampling for RCC following soybean (RCC-FS) and RCC following corn (RCC-FC). Data points are the mean of each RCC system at each site and across 2010-2011. The regression line was significant ($P < 0.001$).

† 0N, 135N, and 225N stand for 0, 135, and 225 kg N ha$^{-1}$ applied to the prior-year corn.
Fig. 3. Exponential decay models for rye cover crop (RCC) biomass degradation (RCC-BD), C in the RCC biomass (RCC-C), and N in the RCC biomass (RCC-N) with RCC following soybean (RCC-FS) and RCC following corn (RCC-FC) as a function of time. Data points are the mean of each RCC system across site-years. All regression models were significant ($P \leq 0.05$).

† 0N, 135N, and 225N stand for 0, 135, and 225 kg N ha$^{-1}$ applied to the prior-year corn.
Fig. 4. Quadratic parameters of C:N ratio change with rye cover crop (RCC) biomass degradation (RCC-BD) with RCC following soybean (RCC-FS) and RCC following corn (RCC-FC) as a function of time. Data points are the mean of each RCC system across site-years. All regression models were significant ($P \leq 0.05$), with an $R^2 = 1.0$. Vertical bars indicate the FSLD ($P = 0.05$).

† NS, non-significant.

‡ 0N, 135N, and 225N stand for 0, 135, and 225 kg N ha$^{-1}$ applied to the prior-year corn.
CHAPTER 5. GENERAL CONCLUSIONS

This dissertation included two major projects that evaluated optimal N fertilization in corn production systems. Both continuous corn and corn-soybean rotation are common cropping systems in Iowa. The first project evaluated the effect of corn stover harvest in continuous corn production, and its interaction with chisel plow tillage and no-tillage systems, on corn response to N fertilization and optimal N fertilization rate. The second project evaluated the effect of winter rye as a cover crop on corn and soybean yield, corn response to N fertilization, and corn optimal N fertilization rate. For the cover cropping project, an additional in-field rye cover crop degradation experiment was conducted to help understand the N availability and recycling after rye cover crop control in the spring; specifically to estimate the rye cover crop biomass degradation, release of N accumulated in the rye cover crop biomass, and subsequent effect on corn optimal N fertilization. Both projects had specific objectives and outcomes were used to write manuscripts to be submitted to Agronomy Journal.

The corn stover harvesting project showed an increase in corn grain yield with stover harvest, chisel plow tillage, and N fertilization. Across tillage systems and fertilizer N rates, partial (50%) or full (100%) stover harvest increased corn grain yield by 7% (0.56 Mg ha\(^{-1}\)) and 10% (0.85 Mg ha\(^{-1}\)), respectively. The yield increase with stover harvest decreased as N rate increased. With optimal N fertilization, the corn grain yield increase with stover harvest was minimal in the chisel plow system and 6% (0.68 Mg ha\(^{-1}\)) greater in the no-tillage system. In this project, corn canopy sensing was performed at the V10 mid-vegetative growth stage to evaluate the effect of stover harvest on corn early growth and plant N status. Results
helped identify the positive effects of stover harvest on corn early growth and difference in
response to N fertilization. The grain N use evaluation, measured with harvested corn grain,
reflected a change in soil N cycling and a greater soil supply of plant available N with
implementation of stover harvest. The overall economic optimum N rate was not affected by
tillage system, but partial and full stover harvest reduced the N fertilization requirement by
9% (22 kg N ha\(^{-1}\)) and 18% (45 kg N ha\(^{-1}\)), respectively. The lower optimal N fertilization
requirement should be accounted for when planning N applications in continuous corn
production systems where corn biomass is harvested.

The cover cropping project, in a no-tillage corn-soybean rotation, showed that rye
cover crop biomass production and N uptake were not large across site-years. The low rye
cover crop biomass and N uptake were due to low post-harvest soil NO\(_3\)–N and the short
spring period for rye cover crop growth. In this project, winter rye cover crop did not affect
soybean stand establishment or grain yield in the no-tillage corn-soybean rotation. However,
a decrease in corn early growth and plant stand establishment (estimated with corn canopy
sensing at the V10 mid-vegetative growth stage), plant height, and grain yield with use of
winter rye as a cover crop was observed. Corn yield reduction due to winter rye was 6%
(0.79 Mg ha\(^{-1}\)) at the economic optimum N rate. The optimal N fertilization requirement was
similar with and without use of winter rye as a cover crop, 2% (4 kg N ha\(^{-1}\)) lower with no-
rye compared to the rye cover crop, a small difference considering potential change growth
factors with the rye cover cropping system, such as soil temperature and moisture, and the
detrimental effects from the winter rye on corn growth and yield. Also, the rye cover crop did
not apparently recycle enough N from soil profile NO\(_3\)–N to influence optimal N
fertilization requirement. Across N rates, and as a result of the reduced early corn growth and
lower yield, there was lower N use efficiency with the winter rye cover crop and no gain in N use efficiency at the optimal N fertilization requirement. Results suggested that corn N fertilization requirement in a no-tillage corn-soybean rotation system should be the same with or without use of winter rye as a cover crop.

The additional in-field rye cover crop degradation experiment in the cover cropping project showed differences in amount of rye cover crop biomass production and accumulation of N between sites for rye cover crop following soybean, and also between the prior-year corn N rates for rye cover crop following corn; however, those differences were not large. Across site-years, N applied to the prior-year corn at the 225 kg N ha\(^{-1}\) rate resulted in the greatest rye cover crop biomass production (1280 kg DM ha\(^{-1}\)); however, the greatest amount of accumulated N was with the rye cover crop following soybean (27 kg N ha\(^{-1}\)). An exponential decay model fit the rye cover crop biomass degradation and C and N recycling. The degradation rate coefficient \((k)\) for rye cover crop biomass degradation and C remaining in the rye cover crop biomass was similar following soybean and corn. However, decay models indicated a greater rate for N recycling from the rye cover crop when following soybean than when following corn. The net amount of N recycled depended mainly upon the initial rye cover crop biomass production. Overall, the low rye cover crop biomass production and N uptake, in combination with the relatively slow N release from rye cover crop biomass degradation, resulted in low N recycling. After the 105 d study period, 80% (22 kg N ha\(^{-1}\)) of the N in the rye cover crop biomass when following soybean was recycled, and 64% (14 kg N ha\(^{-1}\)) of the N in the rye cover crop biomass when following corn. The more rapid and largest N recycling from the rye cover crop following soybean appeared to be associated with a lower initial C:N ratio of the rye cover crop biomass. This study showed
that winter rye as a cover crop has potential to be a good management practice for environmental purposes, that is, accumulate residual soil inorganic N. However, the rye cover crop did not recycle a large amount of N, which limited potential as an agronomic N management practice for the corn-soybean rotation system.

Both, the corn stover harvesting project and the rye cover cropping project were conducted for a relatively short period of time, and thus reflect the effect of stover harvest and winter rye cover crop only in a short-term basis. Research in a long-term basis could help determine whether the effect of stover harvest or winter rye cover crop on optimal N fertilization requirement and N use efficiency would remain the same or change after a long-term basis with continual stover harvest or use of winter rye as a cover crop. Also, improvement in management of winter rye cover crop is needed for this agronomic practice to be more viable in a no-tillage corn-soybean rotation system.
BIOGRAPHICAL SKETCH

Jose L. Pantoja was born in Ibarra, Ecuador, in 1982. He was awarded with a full scholarship to study his B.S. in agronomy at the Escuela Agrícola Panamericana – Zamorano, Honduras, C.A., where he graduated in 2005. Between 2005 and 2007, Jose worked at Zamorano, first as a technical assistant of the Soil Testing Laboratory Unit, and then as a student instructor in the Agricultural Services Unit. In 2007, Jose moved to the University of Arkansas, where he pursued his M.S. studies in Crop, Soil & Environmental Science, and graduated in 2009. He arrived to Iowa State University (ISU) in the fall semester of 2009. At ISU, Jose worked with Dr. John E. Sawyer conducting field and laboratory research as part of his Ph.D. studies in the Department of Agronomy. His projects focused on evaluating the effect of corn stover harvest and use of winter rye as a cover crop on corn N fertilization requirement and crop productivity. After finishing his studies at ISU, Jose’s goal was to go back to his home country and participate in the development of agriculture through teaching and executing research projects.