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Corn Nitrogen Fertilization Requirement and Corn–Soybean Productivity with a Rye Cover Crop

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Winter rye (*Secale cereale* L.) cover crop (RCC) has potential to reduce NO_3–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 rate. Treatments were no-RCC and RCC with six fertilizer N rates (0–225 kg N ha^{-1}) applied to corn in a no-till corn–soybean (CS) rotation at four Iowa sites in 2009 through 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. In the no-N control, the RCC reduced soil profile NO_3–N by 15 kg N ha^{-1} only at time of RCC control before corn planting. 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 plant N uptake efficiency (PUE) was reduced at low N rates with RCC, but not above the EONR. Soybean yield was not affected by RCC. Results indicate N fertilization rate should be the same with or without RCC. Improvement in RCC systems and management could make RCC a more viable practice within no-till corn and soybean production.

Abbreviations: CS, corn-soybean; DM, dry matter; EONR, economic optimum nitrogen rate; NDVI, normalized difference vegetative index; NUE, nitrogen use efficiency; PAN, plant available nitrogen; PUE, plant nitrogen uptake efficiency; RCC, rye cover crop; SOM, soil organic matter; YEONR, yield at economic optimum nitrogen rate.

Environmental concerns related to crop N fertilization is an ongoing issue (USEPA, 2007), including reducing N in surface waters related to hypoxia in coastal surface waters (Hoorman et al., 2009; Kladivko et al., 2014). Nitrogen application rate to corn is an important factor in regard to cropping system profitability and NO_3 loss. Applying only the optimal N rate will not stop NO_3 loss, nor necessarily achieve the drinking water standard (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 rate or timing (Hatfield et al., 2009). Therefore, additional in-field practices are needed to reduce NO_3 losses (Sainju and Singh, 2008).

Nitrate losses in tile drainage water from corn production systems can range from 7 to 68 kg N ha^{-1} yr^{-1} (Lawlor et al., 2007), and with most values ranging from 29 to 56 kg N ha^{-1} yr^{-1} (Sawyer and Randall, 2008). 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 NO_3 loss (Staver and Brinsfield, 1998; Qi and Helmers, 2010; Drury et al., 2014; Acuña and Villamil, 2014). Studies

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conducted in the Midwest region of the USA show that cover crops can reduce NO_3 loss from 7 to 65 kg N ha^{-1} (Dabney et al., 2010; Kaspar et al., 2012; Malone et al., 2014). Cover crops also have potential to improve C sequestration, nutrient cycling, soil internal drainage, and help reduce runoff, soil erosion, and weed pressure (Franzluebber, 2005; Hoorman, 2009, Olson et al., 2010; Bernstein et al., 2011; Mirsky et al., 2013; Tabaglio et al., 2013). 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, reduced crop yields, and seed availability (Raimbault et al., 1990; Johnson et al., 1998; Reddy, 2001; Dabney et al., 2001; Thelen and Leep, 2002; Andraski and Bundy, 2005; Kramberger et al., 2009; Reese et al., 2014). 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 increasingly 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 NO_3 loss reduction in cold northern climates due to better fall and early spring growth (Shipley et al., 1992; Parkin et al., 2006), with RCC as a common cover crop choice (Ranells and Wagger, 1997; Ruffo et al., 2004; Kladivko et al., 2014). 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 grain and silage yield decreases have been reported with use of RCC (Raimbault et al., 1990; Kessavalou and Walters, 1997; Thelen and Leep, 2002; Singer and Kohler, 2005; McDonald et al., 2008; Kramberger et al., 2009; Salmerón et al., 2011; Krueger et al., 2012; Reese et al., 2014). A 15% corn yield increase was observed in 2 out of 3 yr in a study conducted on sandy soils in Wisconsin with no N application to the 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 the RCC (Thelen and Leep, 2002; Ruffo et al., 2004; De Bruin et al., 2005; Hoorman et al., 2009). However, soybean yield decreases of 15 to 65% were reported with an RCC, part of the decrease associated with 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 (Raimbault et al., 1990; Dhima et al., 2006; Krueger et al., 2011) and delays corn planting, both of which can reduce corn growth and yield (Wagger, 1989). The effect of RCC on plant available N (PAN) and crop yield can also depend on fertilizer N 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). For soybean, waiting 7 to 15 d to plant after RCC control has resulted in no soybean yield decrease (Thelen and Leep, 2002; Reddy, 2003; Ruffo et al., 2004). Soybean yield decreases have been 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).

With RCC taking up soil NO_3, farmers question if N recycles back to the soil and reduces corn optimal N application requirement, or does it remain unavailable in the RCC biomass or SOM. Since there is an increase in environmental concerns about NO_3–N concentrations in water systems, even at optimal N application rates, and a need for improved N management in regard to water quality (Williams et al., 2007), identifying corn N fertilization requirement in an RCC system is a current need. Previous research with sandy soils in Wisconsin has shown a slight decrease in optimal N rate (Bundy and Andraski, 2005), while other research conducted in Illinois 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 fertilizer N 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). An 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 2 out of 3 yr of a study conducted in Wisconsin (Andraski and Bundy, 2005).

Some research has indicated that N remains in the RCC biomass or 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 application need (Sainju and Singh, 2008; Hashemi et al., 2013), or had no effect on soil supply of PAN and application rate requirement (Kuo and Jellum, 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 optimal N rate.

Nitrogen rate is also a main factor affecting crop NUE, where excess N reduces NUE and efficient fertilization with minimal N loss increases NUE (Meisinger et al., 2008; Raun and Schepers, 2008). Therefore, off-field effects of NO_3 could be reduced if NUE were improved with N rate adjusted for field-specific conditions, such as cover crop influence on corn N application need. Research has not yet fully 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

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

Site	Predominant soil series	Textural class	Soil classification	pH	SOM†	TN†	STP‡	STK‡	NO_3–N§
				0 to 0.15 m					0 to 0.9 m
					g kg^{-1}		mg kg^{-1}		kg ha^{-1}
Ames	Clarion	Loam	fine-loamy, mixed, superactive, mesic Typic Hapludolls	6.4	41	1.8	37 (VH)	172 (H)	13
	Nicollet	Clay loam	fine-loamy, mixed, superactive, mesic Aquic Hapludolls						
Crawfordsville	Mahaska	Silty clay loam	fine, smectitic, mesic Aquertic Argiudolls	6.6	50	2.2	40 (VH)	181 (H)	24
	Nira	Silty clay loam	fine-silty, mixed, superactive, mesic Aquic Argiudolls						
Lewis	Marshall	Silty clay loam	fine-silty, mixed, superactive, mesic Typic Hapludolls	6.4	41	2.1	34 (VH)	239 (VH)	21
Nashua	Floyd	Loam	fine-loamy, mixed, superactive, mesic Aquic Pachic Hapludolls	6.3	48	2.3	23 (H)	148 (O)	12
	Clyde	Silty clay loam	fine-loamy, mixed, superactive, mesic Typic Endoaquolls						

† SOM, soil organic matter; TN, total N.

‡ Soil test P and K. Letters in parentheses indicate soil test category interpretation (Sawyer et al., 2008) with O, optimum; H, high; VH, very high.

§ Soil NO_3–N was summed across the 0- to 0.3-, 0.3- to 0.6-, and 0.6- to 0.9-m sampling depths.

evaluate the effect of an RCC system on corn optimal fertilizer N rate and corn and soybean production.

MATERIALS AND METHODS

Study Sites

A 3-yr (2009–2011) study was conducted at four sites in Iowa, with two field areas at each site. Soils (Table 1) 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 Southeast Research and Demonstration Farm near Crawfordsville (41°12′09″ N; 91°29′31″ W); a well-drained soil formed in loess at the Southwest Armstrong Memorial Research and Demonstration Farm 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 Northeast Research and Demonstration Farm near Nashua (42°55′54″ N; 92°34′37″ W). A CS rotation in a no-till 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 and standard error temperature and total precipitation across 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 arrangement in a randomized complete block, with four replications. The RCC was the main plot (no-RCC and RCC) and six fertilizer N rates applied to corn the split plot (0 to 225 kg N ha^{-1} in 45 kg ha^{-1} increments). A uniform fertilizer N rate was applied to corn at each site in the spring 2008 (agronomic range of 135 to 160 kg N ha^{-1}). For the study years (2009–2011), N was applied as urea-ammonium nitrate solution (UAN, 32% N) with coulter-injection to every other row-space (1.52 m apart) within 2 wk after corn planting and as soil conditions allowed. Individual plot 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^{-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 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 to 2 kg a.i. ha^{-1} of glyphosate [*N*-(phosphonomethyl)glycine]. Across sites and years, RCC control was between Apr. 19 and May 4 before corn planting, and between Apr. 28 and May 20 before soybean planting. The mean intervals between RCC control and corn and soybean planting were 7.3 and 4.5 d, respectively. The intent was to control the RCC in a timely basis and avoid delay in corn and soybean planting. However, delay in RCC control occurred at some site-years due to wet soil conditions. The intent was also to wait a minimum of 7 d after RCC control to plant corn in an attempt to avoid potential negative effects (Dhima et al., 2006), and plant soybean at or within 7 d after rye control.

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 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 oven at 60°C, weighed to estimate RCC biomass DM, and aboveground RCC biomass production adjusted for the sampled area and RCC row width for each site. Samples were ground to pass a 2-mm sieve and a subsample 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 multiplied by aboveground biomass DM.

Corn and Soybean Planting and Harvest

Corn and soybean were planted and managed using cultural practices typical of a no-till 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 RCC and residual crop residue and aid in seed placement. Herbicides and insecticides were used if weed pressure or presence of plant defoliating insects required application. Across sites and 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 sometimes occurred 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 sites and 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 background soil pH, SOM, total N, and soil test P and K at each site. Soil was also sampled by taking five random cores (0–0.9 m in 0.3-m increments) to determine background soil 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 fertilizer N application to determine profile 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 to 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 NO_3 samples collected 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 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}. Six cores per plot were taken in a diagonal pattern across two of the middle soybean rows, with one core from each row and a core 0.2 m from the side of each row. All soil samples were collected by hand with a 0.02-m diam. soil probe. Soil cores were mixed and a subsample saved for analysis.

Soil samples were dried in a forced-air oven at 25°C and ground to pass a 2-mm sieve. Soil pH was determined with 1:1 soil/water ratio, organic C for SOM and total N by dry combustion (LECO CHN-2000 analyzer, LECO Corp., St. Joseph, MI; Nelson and Sommers, 1982), soil test P with colorimetric Mehlich-3, soil test K with 1 mol L^{-1} ammonium acetate and atomic absorption analysis, and NO_3–N with 2 mol L^{-1} KCl 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 NO_3–N amount.

Background soil tests (Table 1) indicated that 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., 2008). The SOM and total N were within the typical range for Mollisols in the Midwest (Soil Survey Staff, 1999). The Mehlich-3 soil tests P and K were in the Optimum to Very High soil test interpretation categories (Table 1; Sawyer et al., 2008). To avoid potential for P and K deficiency and any issue with soil test variability across each site, P and K fertilizers (triple super phosphate and muriate of potash) were broadcast in the fall 2009 if soil test levels were within or near the Optimum interpretation category, with application rate at the estimated crop removal amount for 2 yr of a CS rotation (Sawyer et al., 2008).

Corn Plant Establishment and Canopy Sensing

In 2010 and 2011, the effect of RCC on corn early growth and establishment was evaluated by measuring corn plant height and plant population at the V4 to V7 growth stages. In 5-m length segments of two center rows per plot, plants were counted and plant height measured on 10 random plants from soil surface to the extended leaf tip of the uppermost and fully developed leaf (Warrington and Norton, 1991).

Corn canopy biomass and growth response to RCC and N rate was estimated with a Crop Circle ACS-210 active canopy sensor (Holland Scientific, Lincoln, NE). Corn growth varied across treatments; therefore, 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 to V11 depending

on the N rate. The overall method for canopy sensing was that described by Barker and Sawyer (2010). Approximately 10 VIS and NIR band reflectance values were captured from each plot, the values averaged, and used to calculate a per plot normalized difference vegetative index (NDVI; Gitelson et al., 1996; Teillet et al., 1997).

Soybean Plant Establishment

The effect of RCC on soybean plant establishment was evaluated by measuring soybean plant population at the V1 to 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 subsample collected and weighed. Ears and vegetative subsamples 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. The harvest index for cob and grain was determined from the six plant sample DM, with the area-level cob DM determined from the total plot-level harvested grain DM yield and cob harvest index. Vegetative DM was the difference between total DM and cob plus grain DM. Grain, cob, and vegetative component samples were ground and a subsample 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 multiplied by cob and vegetative DM. Grain N uptake was determined from grain N concentration multiplied by the total harvested grain DM yield. Total aboveground plant N uptake was the summation of cob, grain, and vegetative N. Plant N uptake efficiency, which indicates the efficiency of the system in using available N (Moll et al., 1982; Snyder and Bruulsema, 2007; Wortmann et al., 2011), was used for this study to include both the effect of the RCC and fertilizer N. The PUE was calculated as:

$$\text{PUE} = \frac{\text{Total aboveground plant N uptake (kg N ha}^{-1})}{\text{fertilizer N (kg N ha}^{-1})} \quad [1]$$

Statistical Analysis

Analyses of variance for measured parameters were conducted with PROC MIXED of SAS (SAS Institute, 2009) for a randomized complete block and split-plot arrangement of RCC main plot and N rate split plot. For the analyses, treatments, and their interactions were considered fixed, and replicates, sites, years, and their interactions considered random. When appropriate, differences between treatment means were assessed with the DIFF option in PROC MIXED at $P \leq 0.05$.

To evaluate the site-year mean RCC biomass, RCC N uptake, corn canopy NDVI, grain yield, grain N, total aboveground N uptake, and NUE responses to N rate, PROC REG was used to investigate the quadratic regression model (Eq. [2]), and PROC NLIN the quadratic-plateau model (Eq. [3], Eq. [4]). Models were deemed significant at $P \leq 0.05$ and the model with the smallest residual sums of squares and largest R^2 selected.

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

$$y = a + bx + cx^2,\ x < x_o \quad [3]$$

$$y = a + bx_o + cx_o^2,\ x \geq x_o \quad [4]$$

In these models, y represents the predicted corn response to N rate, x is the fertilizer N rate (kg N ha^{-1}), and a (intercept), b (linear coefficient), c (quadratic coefficient), and x_o (N rate at the join point). The lower and upper 95% confidence limits of model parameters were used to aid model comparison across N rates, with parameters considered not different when estimates were within confidence intervals of equations being compared. Corn EONR for grain yield and yield at the EONR (YEONR) were calculated from each regression model fit to N response (Cerrato and Blackmer, 1990) by solving for x and using a 0.0056 \$ kg^{-1} N/\$ Mg^{-1} corn grain price ratio, derived from \$0.88 kg^{-1} N (\$0.40 lb^{-1} N) and \$157 Mg^{-1} grain (\$4.00 bu^{-1}).

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 RCC biomass production amount 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 (6 vs. 7°C) than normal (normal defined as the historical mean of the prior 16 yr), and 2010 was 2°C warmer (Fig. 1a). For that period, 2009 had 1 cm more precipitation (15 vs. 14 cm), 2010 was drier (only 9 cm), and 2011 had 3 cm less precipitation compared with normal (Fig. 1b).

The weather in late spring and remaining growing season can influence RCC biomass degradation, corn growth and response to N rate, soybean growth, and soil profile NO_3. Temperature in late spring (May and June) was 1°C colder than normal in 2009, whereas 2010 and 2011 were average (19°C); however, 2010 had more precipitation than normal 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 September), 2009 was 2°C colder than normal (19 vs. 21°C) and had slightly more precipitation (29 vs. 24 cm), 2010 was 1°C

warmer than normal and had almost twice as much precipitation (45 cm), and 2011 was somewhat drier (22 cm) than normal.

The weather in the fall can affect profile NO_3, the timing for corn and soybean harvest, and RCC seeding and fall growth. In late September and October, 2009 was 3°C colder and 2010 and 2011 were 2°C warmer than normal (10°C). For that period, 2009 was wetter (16 cm), and 2010 and 2011 were drier (only 2 cm) than normal (6 cm). All years were wetter than normal and included intense precipitation events. In 2009, precipitation was above-normal in August and October, the growing season in 2010 was wet with precipitation well above-normal each month from June through September, and in 2011 precipitation was above-normal in August.

Rye Cover Crop Biomass and Nitrogen Uptake

Each year the RCC was successfully established, but fall growth was low (visually observed but 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 were generally low, and limited by the soil supply of PAN and the short growth period (Table 2). The largest RCC biomass production and N uptake across sites and 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} rate applied to the prior-year corn.

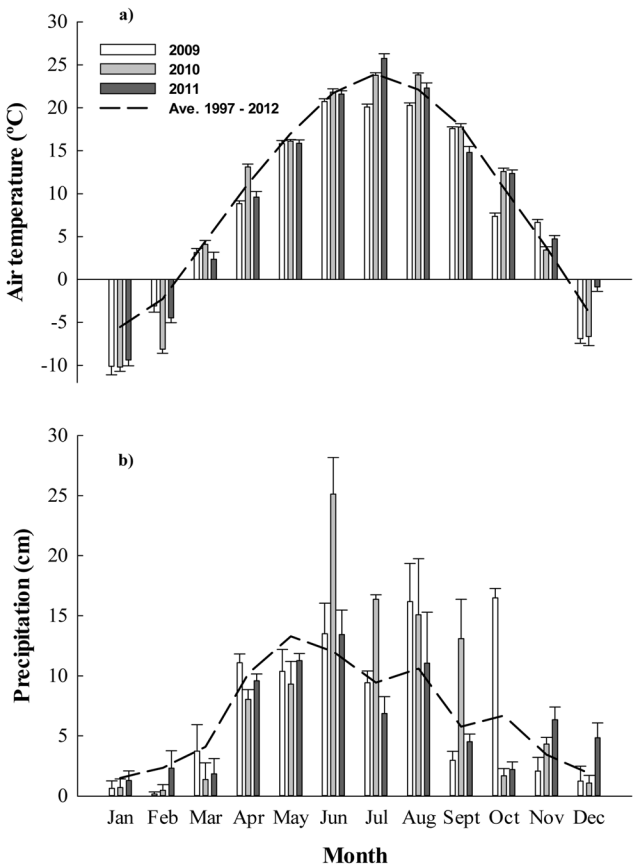

Fig. 1. Mean monthly air temperature (a) and total precipitation (b) across sites (data from Arritt and Herzmann, 2013). Bars represent the standard error across sites.

The RCC biomass DM amount and N uptake before soybean planting in 2009 was low; a result of the cold and wet spring (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. Rye biomass production was the same (average 950 kg ha^{-1}) when the prior-year N rate was <135 kg N ha^{-1}, but increased by 18 and 35% with 180 and 225 kg N ha^{-1}, respectively, and the RCC N uptake was also the same (average 18 kg N ha^{-1}) when the prior-year N rate was <135 kg N ha^{-1}, but increased by 22 and 44% with 180 and 225 kg N ha^{-1}, respectively. In a study conducted on sandy loam soils in southwestern Michigan, 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 affect RCC biomass production or N uptake. They did not recommend using an RCC for scavenging residual NO_3–N when the prior-year corn N rate was ≤100 kg N ha^{-1}. Those results are similar to our findings. Ruffo et al. (2004), on silt loam and silty clay loam soils in Illinois, found that RCC biomass production and N uptake was 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 which promoted RCC growth.

Across sites and years, RCC biomass production before corn planting was lower than RCC biomass before soybean (720 vs. 960 kg DM ha^{-1}), and rye N uptake before corn was <40 kg N ha^{-1} in 10 out of the 12 site-years, with an average of 21 kg N ha^{-1}, which reflected the limited RCC growth. Individual treatment effects on RCC biomass and N uptake are not shown as there were no differences when following soybean. The RCC before corn had on average 2 wk less time to grow in the spring

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.

N rate	Biomass	N uptake
kg N ha^{-1}	kg DM ha^{-1}	kg N ha^{-1}
	2009†	
	500	11
	2010–2011	
0	970‡	18§
45	910	17
90	910	17
135	1020	19
180	1120	22
225	1280	26

† No 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.

‡ RCC biomass N rate significant ($P < 0.05$); with RCC biomass = $960 - 1.52x + 0.0132x^2$, where x = N rate (kg N ha^{-1}), $P = 0.001$, $R^2 = 0.99$.

§ RCC N uptake N rate significant ($P < 0.05$); with RCC N uptake = $18 - 0.037x + 0.00033x^2$, where x = N rate (kg N ha^{-1}), $P < 0.001$, $R^2 = 0.99$.

compared with RCC before soybean due to RCC control at least 1 wk before corn planting, and corn was also planted on average 1 wk before soybean. The timing for RCC control was an attempt to have corn and soybean planting within recommended calendar dates and to avoid delay in planting that might affect yield potential. According to Duiker and Curran (2005), delay of 2 wk in corn planting can result in grain yield losses up to 0.5 Mg ha^{-1}, with other studies across the Corn Belt reporting significant yield reductions with planting delayed after the optimum, ranging from 0.5 to 1.9% yield loss per day (Swanson and Wilhelm, 1996; Lauer et al., 1999; Van Roekel and Coulter, 2011).

Therefore, RCC growth, biomass production, and N uptake were limited by the RCC control timing decision. The above-normal precipitation during the 3 yr of study resulted in low residual NO_3–N (presented later), and therefore RCC growth was limited by N supply. 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

Background Soil Nitrate

The post-harvest soil NO_3–N at initiation of the study was ≤24 kg N ha^{-1} in the top 0.9 m of soil in fall 2008 at all sites (Table 1). This NO_3–N amount was low and indicated 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 from the uniform agronomic N rate applied for the 2008 crop.

Spring Soil Nitrate during the Corn Year

Spring profile NO_3–N was measured only in corn plots with no N application. The NO_3–N was low at the time of RCC control (Table 3), and with 15 kg N ha^{-1} less with RCC than no-RCC. However, there was no difference from the RCC in early June. Soil NO_3–N increased slightly 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; whereas with no-RCC there was a slight decrease (4 kg N ha^{-1} less). In either case, change in soil NO_3–N was not large. The small differences observed in profile NO_3–N between no-RCC and RCC, and between preplant and early June sampling, would be related to low net RCC N cycling, slow SOM N mineralization, corn N uptake, and NO_3–N loss with above-normal precipitation.

Krueger et al. (2011) found that on a silt loam soil in Minnesota PAN was reduced up to 35% after RCC control, and up to 59% after RCC harvest for hay. However, changes in soil NO_3–N during the spring could be influenced more by site-specific N mineralization, soil moisture, and variability in weather conditions than by RCC alone (Andraski and Bundy, 2008; Krueger et al., 2011). Qi et al. (2011) found in Iowa that an RCC reduced NO_3–N concentrations in tile drainage water in March through June, thus having a positive influence on springtime soil NO_3–N loss. The RCC effectiveness depended on N rate applied to the prior-year corn, soil management, and weather patterns.

Post-Harvest Soil Nitrate after Corn

Post-harvest profile NO_3–N after corn was low across all N rates (≤37 kg N ha^{-1}; Table 3), which reflected the above-normal precipitation and large corn yield response to N fertilization. The RCC reduced post-harvest profile NO_3–N by 4 kg N ha^{-1}, a small decrease and potentially a result of soil random variation.

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 rye cover crop (RCC), across sites.

Corn year						Soybean year			
Spring†		Post-harvest				Post-harvest			
RCC	NO_3–N	RCC	NO_3–N	N rate	NO_3–N	RCC	NO_3–N	N rate‡	NO_3–N
	kg ha^{-1}		-- -- -- kg ha^{-1} - -- -- -				-- -- -- kg ha^{-1} - -- -- -		
		2009–2011					2009		
No (preplant)	30a§	No	32a	0	24c	No	33a		
Yes (preplant)	15c	Yes	28b	135	29b	Yes	32a		
No (early June)	26b			225	37a		2010–2011		
Yes (early June)	23b					No	28a	0	28ab
						Yes	28a	135	29a
								225	26b
		Analysis of variance							
Source	*P* > F	Source	*P* > F			Source¶	*P* > F		
Sampling time (ST)	0.076	RCC	0.011			RCC	0.614		
RCC	< 0.001	N rate (NR)	<0.001			N rate (NR)	0.027		
ST × RCC	< 0.001	RCC × NR	0.832			RCC × NR	0.322		

† 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 to V7 growth stages in early June.

‡ The N rate for the fall sampling after soybean corresponds to the 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 analysis of variance corresponds only to 2010–2011.

Table 4. Analysis of variance for the corn responses to rye cover crop (RCC) and fertilizer N rate, across sites and years, 2009–2011.

Source	Canopy NDVI	Plant population†	Plant height†	Grain yield	Grain N uptake	Total N uptake	PUE‡
	P > F						
RCC	<0.001	<0.001	<0.001	<0.001	< 0.001	<0.001	<0.001
N rate (NR)	<0.001	0.861	<0.001	<0.001	< 0.001	<0.001	<0.001
RCC × NR	0.016	0.402	0.325	0.588	0.786	0.554	0.007

† Data only from 2010 and 2011.

‡ PUE, plant N uptake efficiency.

The small RCC effect 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} influenced post-harvest profile NO_3–N more than the RCC (Table 3); however, increases were small especially considering the highest N rate. Some soil NO_3–N differences due to the RCC were measured in the spring, but those differences were small between no-RCC and RCC and would have little effect on corn growth or impact on profile NO_3–N at the end of the growing season.

Post-Harvest Soil Nitrate after Soybean

As found following corn, post-soybean harvest profile soil NO_3–N was low (≤33 kg N ha^{-1}) and not affected by the RCC (Table 3). The N rate applied to the prior-year corn had a small and inconsistent effect, likely due to soil random variation as it would be unlikely for N application to a prior-year corn to have an influence on profile NO_3–N after soybean harvest the following year.

Corn Canopy Sensing and Plant Early Growth

Across sites and years, average corn canopy NDVI values were greater with no-RCC than RCC (0.701 vs. 0.675; P < 0.001; Table 4). The low NDVI values with no or low applied N indicated a decrease in corn stand establishment and growth, N stress, and potential for large response to N application (Table 5 and Fig. 2a). Low NDVI values also reflected years with above-normal precipitation and high N rate requirement. Nitrogen rate increased NDVI values up to the point where response pla-

Table 5. Regression models and parameters describing the corn responses to rye cover crop (RCC) and fertilizer N rate, across sites and years, 2009–2011.

RCC	Model†	Regression parameters					EONR§	YEONR§	R^2	*P* > F
		a	*b*	*c*	Join point	Plateau‡				
					kg N ha^{-1}		kg N ha^{-1}	Mg ha^{-1}		
				Canopy Normalized Difference Vegetative Index (NDVI)						
No	QP	0.646a¶ (0.009)#	0.0013b (0.0004)	-0.000006a (0.000002)	112	0.718	–	–	0.45	< 0.001
Yes	QP	0.607b (0.015)	0.0020a (0.0009)	-0.000011a (0.000008)	87	0.692	–	–	0.27	< 0.001
				Grain yield						
No	QP	5.87a (0.42)	0.0645a (0.0100)	-0.000163a (0.000048)	197	12.21	181	12.20	0.68	< 0.001
Yes	QP	4.67b (0.55)	0.0672a (0.0128)	-0.000166a (0.000060)	202	11.46	185	11.41	0.60	< 0.001
				Grain N uptake						
No	Q	44.4a (4.6)	0.590a (0.096)	-0.00113a (0.00041)	225	120	–	–	0.71	< 0.001
Yes	Q	35.2a (5.3)	0.566a (0.111)	-0.00097a (0.00047)	225	114	–	–	0.66	< 0.001
				Total aboveground plant N uptake						
No	Q	75.4a (6.8)	0.934a (0.144)	-0.00176a (0.00061)	225	196	–	–	0.73	< 0.001
Yes	Q	63.5a (8.5)	0.828a (0.179)	-0.00120a (0.00077)	225	189	–	–	0.65	< 0.001
				N use efficiency (NUE) expressed as plant N uptake efficiency (PUE)						
No	Q	3.13a (0.20)	-0.0197a (0.0034)	0.000044a (0.000012)	225	0.897	–	–	0.74	< 0.001
Yes	Q	2.70a (0.23)	-0.0167a (0.0039)	0.000038a (0.000014)	225	0.860	–	–	0.58	< 0.001

† Q, quadratic regression model; QP, quadratic-plateau regression model. Models fit using site-year means.

‡ Mg ha^{-1} for grain yield, kg N ha^{-1} for grain N and total aboveground plant N uptake, and kg N kg^{-1} N for PUE. The regression model did not reach a plateau for grain N, total aboveground plant N, and PUE, therefore, the highest N rate used for comparison.

§ EONR, economic optimum N rate; YEONR, yield at the economic optimum N rate.

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

Values in parentheses are standard errors.

teaued. The NDVI at all N rates, and the NDVI at the plateau was greater with no-RCC than RCC (0.718 vs. 0.692, respectively), indicating negative effects of RCC on early corn growth and canopy development.

The shape of the NDVI response to N rate was different between no-RCC and RCC (Fig. 2a). Also, the N rate at maximal plant canopy (regression model N rate join point) was 25 kg N ha^{-1} greater with no-RCC than RCC (Table 5). The higher N rate could be an indication of greater N uptake demand due to larger corn biomass with no-RCC, less N needed by corn as a result of the negative effect of RCC, or difference in spring soil NO_3–N with 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, besides an RCC effect on plant growth, resulted in the differential canopy response at the zero and lowest N rate.

Measurement of corn plant height and population at the V4 to V7 growth stages in 2010–2011 confirmed the negative effect of RCC on corn growth and development. The statistical analysis is presented in Table 4, but the data is only summarized here. 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 N rate, with height at 0.76 m with applied N (average of all N rates) and 0.71 m with no applied N. These results indicated that 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.

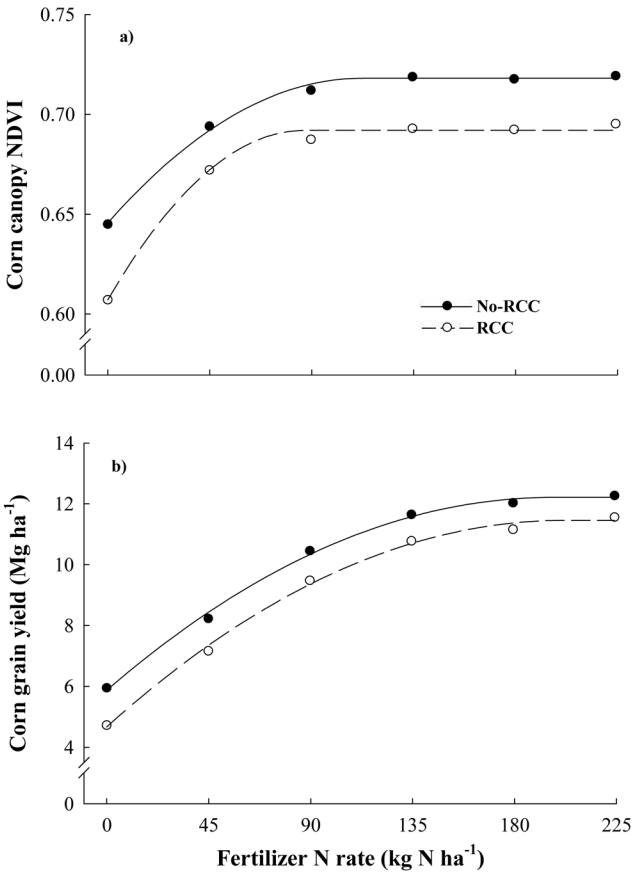

Fig. 2. Corn canopy normalized difference vegetative index (NDVI) (a) and corn grain yield (b) response to rye cover crop (RCC) and N rate, across sites and years. The analysis of variance is presented in Table 4 and regression models and parameters are presented in Table 5.

Decreases in profile NO_3–N due to RCC were minimal in the corn years, and hence the negative effects of RCC on corn establishment and early 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 often related to successful cover crop establishment and biomass production (Strock et al., 2004). However, RCC produced negative crop effects in our study as it reduced corn establishment and early growth.

Corn Yield and Nitrogen Response

Corn Yield

Across N rates, average corn grain yield was greater with no-RCC than RCC (0.95 Mg ha^{-1}; $P < 0.001$; Table 4, Fig. 2b), and was 0.75 Mg ha^{-1} greater at the agronomic maximum N rate (plateau yield; Table 5). No-till cropping systems may benefit from cover crops through decreased soil erosion, increased N recycling, improved soil quality, and increased crop yield (Olson et al., 2010; Moore et al., 2014; 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, 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, plant stand, and grain yield with the intended minimum 7-d waiting period from rye control to corn planting. Duiker and Curran (2005) found that RCC did not reduce corn yield with adequate N (180 kg N ha^{-1}). Zotarelli et al. (2009), however, found that positive effects of RCC on corn yield were greater with no applied N or when applying only 67 kg N ha^{-1}. When 133 kg N ha^{-1} was applied, they found a negative effect of RCC on corn yield.

Results of our study reflected the overall low soil supply of PAN (with no applied N) and need for a high N 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 was confirmed by the relatively small differences in soil profile NO_3–N between no-RCC and RCC.

Corn grain yield decreased as RCC biomass increased. This is shown in Fig. 3 with the 180 kg N ha^{-1} rate, which was chosen as it was close to the optimal N rate across sites and years. 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 7 to 10 d after RCC control, and especially with RCC biomass production >500 kg DM ha^{-1}. These results confirmed the need for developing better agronomic RCC management or different corn production practices to improve early season corn growth and grain yield with the use of an 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, while later corn planting would allow more time for RCC biomass degradation, which conflicts with producers' desire for early corn planting.

Nitrogen Response

Corn grain yield response to N rate was the same with no-RCC and RCC (Table 5 and Fig. 2b). The N rate at the agronomic maximum (plateau yield) was only 5 kg N ha^{-1} lower with no-RCC than RCC. An RCC can potentially increase soil supply of PAN and reduce N rate requirement (Sainju and Singh, 2008). Andraski and Bundy (2005) found a decrease of 30 kg N ha^{-1} in N rate requirement with RCC in 2 out of 3 yr on sandy soils in Wisconsin. However, there was no difference in corn response to N fertilization in our study. Compared with 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 indicate that as the growing season progressed, the difference in corn maximal N rate requirement between no-RCC and RCC decreased in comparison with the canopy sensing results. The N rate at the join point was 25 kg N ha^{-1} greater with no-RCC than RCC at V10 (NDVI results), but this relationship changed with grain yield, where the join point was only 5 kg N ha^{-1} lower with no-RCC than RCC. The NDVI results indicate that the RCC reduced corn biomass production (slowed growth and development), and therefore reduced corn N demand at the time of canopy sensing. However, a difference in corn N requirement was gone at the end of the growing season.

The EONR was only 4 kg N ha^{-1} less with no-RCC than with RCC (Table 5), basically the same optimal N rate. Also, the YEONR was 6% (0.79 Mg ha^{-1}) greater with no-RCC than RCC (Table 5). Compared with the recommended N 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 rate recommendations for corn should not change in an RCC system.

Nitrogen Use Efficiency

The greater corn growth and grain yield with no-RCC than with RCC resulted in greater grain N and total aboveground

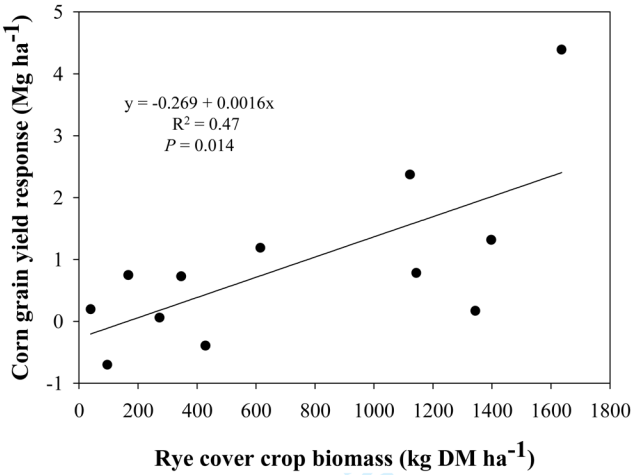

Fig. 3. Corn grain yield response to the rye cover crop (RCC; yield with no-RCC minus yield with RCC) at the 180 kg N ha^{-1} rate. Data points are the means of each site-year and RCC biomass corresponds to biomass at the time of RCC control.

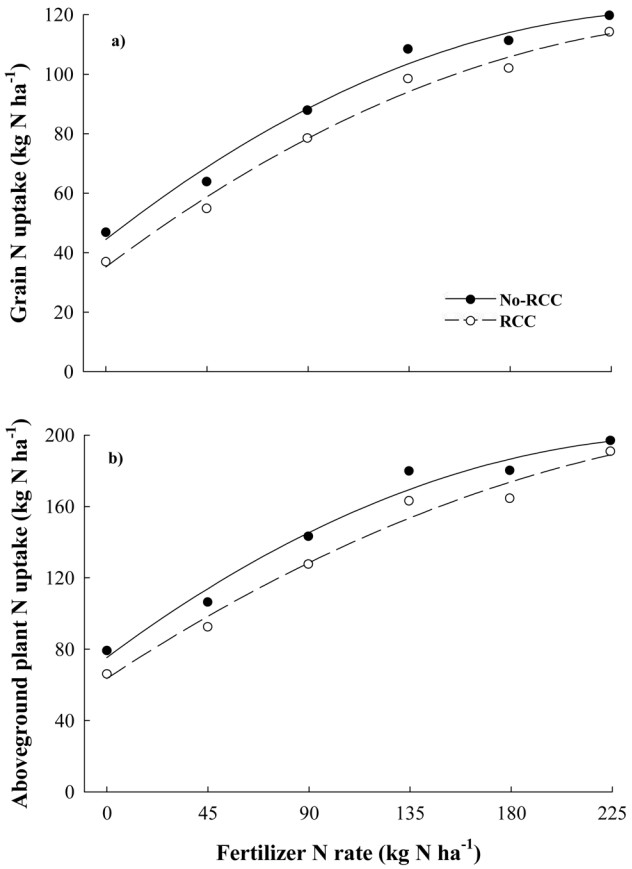

Fig. 4. Corn grain N (a) and total aboveground plant N (b) uptake response to rye cover crop (RCC) and N rate, across sites and years. The analysis of variance is presented in Table 4 and regression models and parameters are presented in Table 5.

plant N uptake at each N rate (Tables 4 and Table 5, Fig. 4), with a mean average of 9 and 14 kg N ha^{-1} greater N, respectively. The N uptake response to N rate was similar with no-RCC and RCC (Fig. 4), as was found for grain yield; however, the grain N and total aboveground plant N uptake did not reach a plateau (Table 5) as for grain yield. 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, and allelopathic effect of RCC on corn growth and development. Zhang et al. (2008) indicated that N uptake and chlorophyll content can be affected by N rate, but sometimes yield is not greatly affected by N treatments, which may explain the response difference between grain yield and N uptake found in our study. Finally, Al-Kaisi and Kwaw-Mensah (2007) indicated that seasonal variability can affect N uptake and that a linear increase of N uptake can result with an increase in N rate, which may or may not be reflected in a concurrent yield increase.

For PUE, the main effect of RCC and N rate, and the interaction, were significant (Table 4). The PUE response to N rate was similar with no-RCC and RCC, and followed a quadratic decreasing trend (Fig. 5). The PUE, as similar for plant N uptake, did not reach a plateau because above-optimal supply may induce a luxury uptake of nutrients, including N (Zhang et al., 2008). Across sites, years, and N rates, PUE was greater for no-RCC than for RCC (1.44 vs. 1.29 kg N kg^{-1} N, respectively). The difference in PUE was greater at lower N rates, but similar when N approached the highest rate, indicating the significant interaction (Table 4 and Table 5). The larger PUE observed with no-RCC than RCC, especially with low applied N, could be a reflection of the greater corn vegetative biomass production with no-RCC than RCC, deficient fertilizer plus soil PAN supply with RCC, and potential change in N cycling with RCC.

Nitrogen use efficiency values generally decline with increasing N rates, and can be fairly low in optimally fertilized systems due to low yield increase per unit of applied N near maximal N response. The PUE helped identify the low corn productivity and low NUE in the RCC system, confirmed the N stress at low N rates, and indicated the differences in corn NUE between no-RCC and RCC. The small difference in PUE between no-RCC and RCC at the high N rate application reflected the corn grain yield plateau (at sufficient N application) above the maximal N response with no-RCC and RCC.

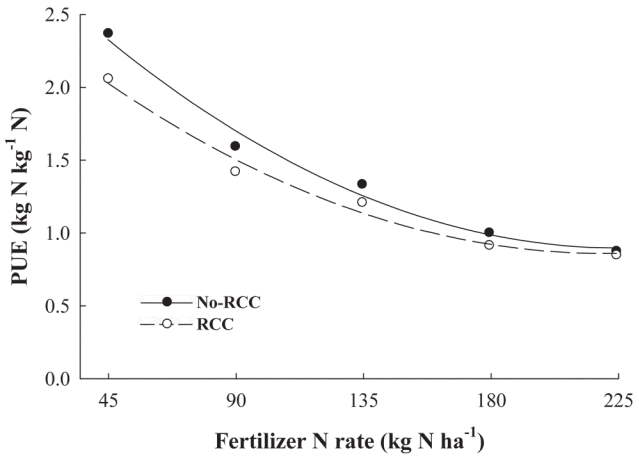

Fig. 5. Plant N uptake efficiency (PUE) as affected by rye cover crop (RCC) and N rate, across sites and years. The analysis of variance is presented in Table 4 and regression models and parameters are presented in Table 5.

Soybean Plant Population and Yield

No difference in soybean early growth between no-RCC and RCC was observed. Plant population was the same for no-RCC and RCC ($P = 0.592$) at the V1 to V2 growth stages (average 337000 plants ha^{-1}). Also, N rate applied to the prior-year corn had no effect ($P = 0.173$) on soybean population (data not shown). 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 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 can be possible (Westgate et al., 2005). Ruffo et al. (2004) found that if RCC control and soybean planting were accomplished on a timeliness basis, there was no decrease in soybean yield. Reddy (2001) also reported that RCC had no detrimental effect on soybean yield with either no-till or conventional till. With winter wheat (*Triticum aestivum* L.) and winter RCCs, Thelen and Leep (2002) reported soybean yield was not reduced when planted 5 to 11 d after rye control, although there were reduced yields of corn and corn silage. It appears that farmers can effectively utilize RCC in CS cropping systems when the RCC precedes soybean in the rotation.

Table 6. Soybean grain yield response to rye cover crop (RCC) and fertilizer N rate applied to the prior-year corn.

N rate	No-RCC	RCC
kg N ha^{-1}	-- -- -- - Mg ha^{-1}- -- -- --	
	2009†	
	4.17	4.19
	2010–2011	
0	4.10	4.07
45	4.01	4.07
90	4.04	3.96
135	4.05	3.98
180	4.02	3.97
225	4.06	4.00
Mean	4.04	4.01
	Statistics ($P > F$)	
Source		
Rye cover crop (RCC)	0.387	
N rate (NR)	0.183	
RCC × NR	0.451	

† No N rate treatments had yet been applied before 2009 and corn in the study areas received a uniform N rate in 2008.

CONCLUSIONS

Despite the RCC being successfully established after corn and soybean harvest, the aboveground RCC biomass and N uptake at the time of control in the spring was low, typically much less than the 1280 kg DM ha^{-1} and 26 kg N ha^{-1} maximum measured across sites and years. The potential for RCC biomass production was limited by the short growing period in early spring before RCC control due to the requirement for timely corn and soybean planting, and by low soil NO_3–N. The RCC decreased profile NO_3–N only in the spring at the time of RCC control, but the reduction was small and did not have an influence on corn N response.

The RCC had no effect on early season soybean plant population or grain yield. Corn early growth and plant stand, however, were decreased with the RCC and resulted in lower corn grain yield compared with no-RCC. At the EONR, corn grain yield was 6% greater with no-RCC than RCC. Also, the negative impact of RCC on corn yield increased as RCC biomass production increased. Early spring RCC control to limit RCC biomass production would decrease the negative effect of RCC on corn production, however, early control would limit RCC N uptake and potentially reduce positive effects on retaining NO_3–N in the soil-crop system.

The RCC did not change corn optimal N application rate as the EONR was 4 kg N ha^{-1} lower with no-RCC than RCC, a small difference considering the inclusion of RCC in the cropping system. As a result of reduced early corn growth and lower grain yield with the RCC, there was lower PUE across N rates and no gain in NUE at the EONR. Results of this short-term study suggested that N application rate for corn in a no-till CS rotation should be the same with or without an RCC. Since there was low RCC N uptake, reduced corn yield and PUE, no change in corn EONR, and no increase in soybean yield, improvement in RCC or CS management is needed for RCC to be a no-till crop production enhancing practice.

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