Received: 15 March 2022 | Accepted: 8 July 2022

DOI: 10.1002/cft2.20187

Crop, Forage & Turfgrass Management

RESEARCH

Crop Management

Corn yield response to starter nitrogen rates following a cereal rye cover crop

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Assigned to Associate Editor D. Arnall.

Funding information
Indiana Corn Marketing Council, Grant/Award Number: 00069635; USDA-Hatch, Grant/Award Number: IND010811

Abstract

Cereal rye (*Secale cereale* L.; CR) is promoted as a cover crop as a practice for reducing nitrate leaching losses in the U.S. Midwest. However, early-season nitrogen immobilization during CR decomposition may contribute to yield reductions in corn (*Zea mays* L.). Field trials were conducted at three sites to determine if N as a starter fertilizer could increase the plant N uptake and grain yield of corn following CR. Treatments were a two-way factorial with two cover crop treatments (CR and no CR) and four fertilizer treatments: subsurface banded (2 by 2 inches) at planting as urea ammonium nitrate (UAN) at 0, 25, 50, and 75 lb acre^{-1}. Treatments received the same total N within sites, with the remainder injected between rows at side-dressing as UAN. Nitrogen uptake and yield were unaffected by the starter N × CR interaction in all sites. At one of the sites, CR significantly reduced N uptake and corn yield at the R6 stage by 16 and 4.5% relative to no CR, respectively. Corn yield was unaffected by starter N at two sites, whereas applying 50 or 75 N lb acre^{-1} increased yields compared with 0 and 25 N lb acre^{-1} at the third site. These findings suggest that starter N could increase early-season N uptake but had an inconsistent impact on corn yields. Therefore, further investigations under different soil N conditions are needed to provide insights into how starter N rates can be adjusted to optimize corn yields within a CR system.

1 | INTRODUCTION

Although nitrate makes up a small percentage of the total nitrogen within the soil profile of cropping systems in the U.S. Mississippi River Basin, it is the dominant form of N in subsurface drainage water. Consequently, nitrate export from densely tile-drained row crop production in this region is a leading contributor to the hypoxic zone in the Gulf of Mexico (David et al., 2010). In response, the Mississippi River/Gulf of Mexico Hypoxia Task Force required Corn Belt states to develop state-specific nutrient loss reduction strategies to reduce N loading (USEPA, 2007). Among the in-field strategies listed, cover crops have been identified as one of the most promising practices for achieving the proposed non-point-source nutrient loss reduction goals (Christianson et al., 2018).

Abbreviations: CR, cereal rye; NEP, Northeast Purdue Agricultural Center; SE-1, Southeast Purdue Agricultural Center Site 1; SE-2, Southeast Purdue Agricultural Center Site 2; SMN, soil mineral N; UAN, urea ammonium nitrate; UTC, untreated control.

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TABLE A. Useful conversions

To convert Column 1 to Column 2, multiply by	Column 1 suggested unit	Column 2 SI unit
0.304	foot, ft	meter, m
2.54	inch	centimeter, cm (10^{-2} m)
0.405	acre	hectare, ha
0.405×10^3	acre	square meter, sq m
454	pound, lb	gram, g

Core Ideas

- No interaction of starter N and CR on corn N content and yield was observed at any sites.
- Starter N increased V6-V7 N uptake over no starter but did not always increase yield.
- The impacts of starter N on R6 N uptake and grain yield were inconsistent across sites.
- At one site, CR reduced N uptake and yield by 16 and 4.5% relative to no CR, respectively.

Cover crop planting after cash crop harvest to uptake residual soil inorganic N is an effective in-field conservation practice for reducing nitrate-N leaching losses through tile-drained landscapes (Dinnes et al., 2002; Kladivko et al., 2014). Cereal rye (*Secale cereale* L.; CR) is the most commonly grown cover crop in the U.S. Midwest, partly because of its ability to overwinter, scavenge nutrients, and produce considerable biomass in the spring. Previous studies in this region have shown reductions of 13 to 61% in subsurface drainage nitrate losses with CR (Kaspar et al., 2007, 2012; Ruffatti et al., 2019; Strock et al., 2004). Despite the water quality benefits associated with CR, current data indicate that cover crops are used on less than 0.2% of arable land in the United States. Specifically in Indiana, the state of interest in this study, 8.2% of row cropland is planted to cover crops (USDA-NASS, 2019). Potential corn (*Zea mays* L.) yield reductions following CR are one reason why widespread adoption remains limited (Roesch-McNally et al., 2018).

The mechanisms explaining the yield reduction in the corn crop following CR are not well understood. Previous studies have suggested that yield decreases following CR could result from the CR residue interfering with farm equipment, creating an incomplete seed furrow and inadequate seed-to-soil contact, which often results in reduced corn plant populations (Eckert, 1988; Kaspar & Bakker, 2015). Although a planter's performance would decrease with increasing CR residue amounts, a residue threshold has not been well defined. Lower soil temperatures and the allelochemicals released by the CR residue, as well as root seedling disease, may also lead to slower corn emergence and reduced stands (Balkcom et al., 2007; Kurtz et al., 2021). Another important factor causing the yield penalty is the reduction in early-season soil N availability, partly because of competing N demands by soil microbes during the peak of corn N demand and CR residue decomposition (Nevins et al., 2020), resulting in 0.1 to 12% yield reductions (Crandall et al., 2005; Pantoja et al., 2015; Patel et al., 2019).

To potentially minimize or eliminate early-season corn N stress resulting from net soil N immobilization by CR, previous studies have evaluated individual N management strategies such as the time of application. In a 2-yr study in Illinois, Crandall et al. (2005) found that CR did not affect corn yields when N fertilizer was either applied at planting or split between planting and side-dressing (growth stage V6), but CR significantly reduced yields when all the N was applied at the V6 growth stage. Over a 3-yr study period, Preza-Fontes et al. (2021) also found no corn yield penalty from CR when N was split-applied between planting and side-dressing. In contrast, Patel et al. (2019) evaluated the potential of applying starter N (30 lb N acre^{-1}) to corn following CR in Iowa over 3 yr and found that starter N did not increase corn yield despite consistently increasing early corn growth.

The use of starter fertilizers is a common practice in corn production across much of the U.S. Midwest (Quinn et al., 2020). With this practice, nutrients are applied near the seed at planting with the goal of increasing early-season plant growth and nutrient uptake. In the case of N fertilizer, applying it 2 inches beside and 2 inches below the seed (2×2) allows for greater flexibility in terms of source and rate (Niehues et al., 2004; Rutan & Steinke, 2018). Compared with no starter, previous studies have reported improved corn yield with starter applications of between 10 and 40 lb N acre^{-1} (Niehues et al., 2004; Rutan & Steinke, 2018; Scharf, 1999; Wolkowski, 2000). However, few studies have quantified how starter N rates influence corn yield following CR. Identifying an optimal starter N rate to minimize yield losses could make the inclusion of CR into a corn cropping system more profitable. This information would be of major importance to encouraging the widespread adoption of CR, leading to a significant reduction in nitrate losses in tile-drained landscapes. Therefore, the objective of this study was to evaluate the effects of starter N rate on plant establishment, N uptake, and grain yield in corn following CR.

2 | MATERIALS AND METHODS

2.1 | Site information and experimental design

This study was conducted from the fall of 2017 through the fall of 2018 at three locations in Indiana. Two field trials

TABLE 1 Selected soil chemical properties at the 0- to 6-inch sampling depth, taken during the spring

Site	Year[a]	pH	STP	STK
			lb acre^{-1}	
SE-1	2017	5.9	18	136
SE-2	2015	6.3	24	96
NEP	2018	6.7	44	254

Note. STP, soil test phosphorus (Frank et al., 1998); STK, soil test potassium (Warncke & Brown, 1998); SE-1, Southeast Purdue Agricultural Center Site 1; SE-2, Southeast Purdue Agricultural Center Site 2; NEP, Northeast Purdue Agricultural Center.

[a] Year that soil samples were taken before the 2018 growing season.

were located at the Southeast Purdue Agricultural Center (SE-1 and SE-2) in Butlerville, IN (39˚01′N, 85˚32′W and 39˚02′N, 85˚31′W, respectively), and one trial at the Northeast Purdue Agricultural Center (NEP) near Columbia City, IN (41˚ 06′N, 85˚ 26′W). The 30-yr average (1991–2020) annual precipitation is 49.3 inches in SE-1 and SE-2, and 39.1 inches in NEP. The predominant soil series are as follows: SE-1, Avonburg silt loam (fine-silty, mixed, active, mesic Aeric Fragic Glossaqualfs), somewhat poorly drained, 1.5% organic matter, and 0 to 2% slopes; SE-2, Cobbsfork silt loam (fine-silty, mixed, active, mesic Fragic Glossaqualfs), poorly drained, 1.3% organic matter, and 0 to 1% slopes; NEP, a well-drained Boyer sandy loam (54% of the experimental area) (coarse-loamy, mixed, semiactive, mesic Typic Hapludalfs) and a moderately well-drained (46% of the experimental area) Glynwood silt loam (fine, illitic, mesic Aquic Hapludalfs), both with 1.8% organic matter and 1 to 6% slopes (Soil Survey Staff, 2021). Soil samples (6 inches in depth) for fertility status were taken every 4 yr in all fields, and P and K fertilizers were applied every year (in the spring) in line with the Tri-State Fertilizer Recommendations (Culman et al., 2020). Soil pH [1:1 (v/v) soil/water mixture], Bray and Kurtz P-1 (Frank et al., 1998), and ammonium acetate-extractable K (Warncke & Brown, 1998) from the 0- to 6-inch depth for each site are shown in Table 1.

All trials had a total of 12 treatments: a two-way factorial combination of two cover crop and six starter fertilizer treatments. Plots were 30 by 200 ft, comprising 12 corn rows spaced at 30 inches. Treatments were replicated four times and arranged in a completely randomized design at SE-1 and SE-2 and a randomized complete block design at NEP to account for the two predominant soil types. The cover crop treatments were CR and no CR. Starter fertilizer treatments (2 by 2 inches below and to the side of the seed) were: N only, applied as urea ammonium nitrate (UAN; 28–0–0 N–P–K) at 0, 25, 50, and 75 lb acre^{-1}, a combination of UAN and ammonium polyphosphate (10–34–0 N–P_2O_5–K_2O) applying 50 lb N acre^{-1} and 15 lb P acre^{-1}, and an untreated control (zero N and P; UTC). However, the effects of 50 lb N acre^{-1} and 15 lb P acre^{-1} on corn parameters were not different from those of 50 lb N acre^{-1} alone at all sites ($p > .05$ of independent pairwise *t*-tests, Supplemental Table S1 and Supplemental Table S2) and thus this treatment was excluded from the dataset, statistical analyses, and the results and discussion.

Treatments (other than UTC) received a total of 200 lb N acre^{-1} at SE-1 and SE-2, and 260 lb N acre^{-1} at NEP, which is the agronomic optimum N rate for these locations (Camberato & Nielsen, 2019). Side-dressed N as UAN was injected between rows at the V6-V7 growth stage (Abendroth et al., 2011). Except for the UTC, sulfur was applied as ammonium thiosulfate (12–0–0–26 N–P–K–S) in each starter and the side-dressed applications at a rate of 5 and 10 lb S acre^{-1}, respectively, and this was factored into the total N rate.

2.2 | Cover crop and corn management

All sites were in a corn–soybean [*Glycine max* (L.) Merr.] rotation. Cereal rye was no-till drilled after the soybean harvest in 2017 at 60 lb acre^{-1} in 7.5-inch rows at all sites (Table 2). The CR cover crop was terminated in spring 2018 by spraying 1.5 to 2.5 lb a.i. acre^{-1} of glyphosate [*N*-(phosphonomethyl)glycine] and saflufenacil [*N*-(2-chloro-4-fluoro-5-[3-methyl-2,6-dioxo-4-(trifluoromethyl)−3,6-dihydro-1(2*H*)-pyramidinyl]benzoyl)-*N*-isopropyl-*N*-methylsulfamide]. Before termination, aboveground biomass was randomly collected from a 2.7-ft^2 area at two random locations in each CR plot (a total of 24 samples per site). Samples were dried at 140 ˚F in a forced-air oven until a constant weight, ground to pass a 1-mm screen with a Wiley mill (Arthur H. Thomas Co.), and analyzed for total N and C via combustion via a Flash 2000 Elemental Analyzer (Thermo Fisher Scientific).

Corn was planted 2 to 3 wk after CR termination across sites, with 30-inch row spacing and a target seeding rate of 32,000 seeds acre^{-1} (Table 2). 'Pioneer P1197' was used at SE-1 and SE-2, whereas 'Becks Hybrids 5140HR' was used at NEP. The planters at each location were equipped with row cleaners, coulters, a 2- by 2-inch fertilizer system, and closing wheels. Starter N fertilizer was applied at planting and side-dressing at 26 to 38 d after corn planting (growth stage V6–V7). Aboveground corn dry matter and N uptake were determined at the V6 to V7, R1 to R2, and R6 growth stages. For each sampling event, plants in each plot were counted in three representative 6-ft sections of the row to estimate the plant population. At each of these three locations, there were typically between 10 and 12 plants; and the first five plants in each row section were clipped at ground level and aggregated to determine the plant dry matter and N content. At R6, plants were separated into ear and stover (stalk, leaves, tassel, and ear husks) fractions for weighing and N analysis. Plant

TABLE 2 Summary of management practices and soil and plant sampling in the field trials

Field operation	SE-1	SE-2	NEP
Cover crop planting	26 Sept. 2017	18 Oct. 2017	17 Oct. 2017
Cover crop termination	13 Apr. 2018	3 May 2018	2 May 2018
Corn planting + starter N	9 May 2018	17 May 2018	25 May 2018
V6–V7 corn sampling	4 June 2018	14 June 2018	27 June 2018
Side-dressed N application	7 June 2018	18 June 2018	2 July 2018
R1–R2 corn sampling	9 July 2018	17 July 2018	31 July 2018
R6 corn sampling	15 Sept. 2018	15 Sept. 2018	22 Sept. 2018
Corn harvest	9 Oct. 2018	9 Oct. 2018	19 Oct. 2018

Note. SE-1, Southeast Purdue Agricultural Center Site 1; SE-2, Southeast Purdue Agricultural Center Site 2; NEP, Northeast Purdue Agricultural Center.

samples were dried at 140 ˚F in a forced-air oven until a constant weight, ground to pass a 1-mm screen, and analyzed for total N as described above. Aboveground N content at the V6 to V7 and R1 to R2 stages was estimated by multiplying the stover's dry matter and its N concentration. At R6, total N content was estimated by summing N content in the stover and grain (grain dry matter derived from yield monitor data × grain N%).

Corn was harvested with commercial combines equipped with GPS-enabled grain yield monitors (Table 2). The middle six rows in each plot were harvested to avoid destructive sampling areas and obtain a full combine header pass. Before harvest, the yield monitor was calibrated following the setup and calibration steps for the AgLeader Yield Monitor Manual (AgLeader). The resulting yield data were cleaned using ArcMap Software v10.7 (ESRI Inc.) by removing observations within 50 ft of the ends of each plot to remove potential errors of carryover from plot to plot (Sudduth et al., 2012).

2.3 | Weather and soil N measurements

Weather data for all sites were retrieved from the Indiana State Climate Office (https://climate.agry.purdue.edu). Composite soil samples, which were eight 1-in diameter cores to a depth of 1 ft, were randomly collected from each plot for NO_3–N and NH_4–N determination on the same date as corn planting in all sites (Table 2). Samples were air-dried for 7 d and ground to pass a 2-mm sieve. Inorganic N was extracted with 2 M KCl (5 g of soil in 50 mL extractant, shaken for 30 min), filtered (Whatman filter paper No. 46; Sigma-Aldrich, Inc.), and stored frozen until analysis. Samples were analyzed for NO_3–N and NH_4–N concentrations with an AQ2 Discrete Analyzer (Seal Analytical). Soil NO_3–N and NH_4–N content (lb acre^{-1}) were calculated with the bulk density from the Web Soil Survey (Soil Survey Staff, 2021) for the predominant soil series in the field and the volume of soil in an acre furrow slice to a 1-ft depth. Soil mineral N (SMN) was estimated as the sum of NO_3–N and NH_4–N.

2.4 | Statistical analysis

At SE-2, corn data from four plots were removed from the analysis because of excessive early-season weed pressure and standing water that resulted in poor corn establishment and development, which was documented by aerial imagery collected with an unmanned aerial vehicle (data not shown). ANOVA for the effects of cover crop, starter N rate, and their interaction was conducted for each site via the PROC GLIMMIX procedure in SAS v9.4 (SAS Institute). Given that the UTC lacked a starter N rate, data from UTC were excluded from the ANOVA and mean separations to maintain a balanced experimental design. Data for SE-1 and SE-2 were analyzed as a completely randomized design, whereas the data for NEP were analyzed as a randomized complete block design with block as a random effect. The main effects and all interactions were considered significant at $\alpha \leq .05$. The least-square means were compared via Fisher's LSD method with the LINES option.

3 | RESULTS AND DISCUSSION

3.1 | Weather conditions

Total annual precipitation varied by location and was 2.2% (50.3 inches) greater than the 30-yr average at SE-1 and SE-2, with the most precipitation occurring in February (6.3 inches) and June (8.1 inches) (Table 3). In contrast at the NEP site, annual precipitation was 29.5 inches compared with the 30-yr average of 39.1 inches, with nearly all months having below-normal precipitation. During the corn growing season (from planting to physiological maturity), SE-1 received 17.5 inches, SE-2 received 17.2 inches, and NEP received 14.8 inches of precipitation. Below-average air temperatures were recorded during early winter (December and January) and late spring (March and April) at SE-1 and SE-2. In addition, the average air temperatures in February and May were 39.9 and 71.1 ˚F compared to the 30-yr average of 35.6

TABLE 3 Deviation from the 30-yr average (1991–2020 normal) of mean monthly total precipitation and air temperature for October 2017 to September 2018

	Precipitation				Air temperature			
	SE-1 and SE-2		NEP		SE-1 and SE-2		NEP	
Season	30-yr	2017–2018	30-yr	2017–2018	30-yr	2017–2018	30-yr	2017–2018
	inches				˚F			
Cover crop growing season								
Oct.	3.5	+1.7	2.9	–0.8	56.5	+0.5	52.1	+3.2
Nov.	3.8	+2.2	3.0	+0.1	45.2	–0.4	39.9	+0.9
Dec.	3.7	–1.8	2.4	–2.3	35.7	–3.1	29.5	–2.7
Jan.	3.4	–0.9	2.5	–2.5	31.5	–3.9	24.0	+0.3
Feb.	3.2	+3.2	2.0	+0.4	35.6	+4.3	27.0	+4.2
Mar.	4.2	+0.6	2.6	–0.7	44.8	–5.2	36.9	–2.7
Apr.	5.3	–1.3	3.8	–1.6	55.5	–7.2	48.6	–6.3
Corn growing season								
May	4.9	–1.7	4.3	–1.0	64.3	+7.4	59.8	+11.3
June	5.1	+3.0	4.6	–0.6	72.1	+1.4	69.1	+1.9
July	4.5	–0.5	3.9	–0.5	75.2	–0.1	72.3	+1.0
Aug.	4.5	–1.4	4.1	+2.1	74.0	+0.3	70.4	+1.9
Sept.	3.3	–2.1	3.0	–2.2	67.4	+2.3	63.8	+3.0
Annual	49.3	+1.0	39.1	–9.6	54.8	–0.3	49.5	+1.3

Note. SE-1, Southeast Purdue Agricultural Center Site 1; SE-2, Southeast Purdue Agricultural Center Site 2; NEP, Northeast Purdue Agricultural Center.

TABLE 4 Average (± SE) cereal rye cover crop aboveground biomass, nitrogen and carbon concentration (conc.), total N and C content, and C/N ratio before termination

Site	Biomass	N conc.	C conc.	N content	C content	C/N ratio
	tons acre^{-1}	%		lb acre^{-1}		
SE-1	0.48 (± 0.10)	2.5 (± 0.4)	38.5 (± 7.9)	20 (± 5)	372 (± 76)	18/1 (± 4)
SE-2	0.52 (± 0.11)	1.9 (± 0.4)	38.3 (± 7.8)	19 (± 4)	395 (± 81)	21/1 (± 4)
NEP	0.65 (± 0.13)	2.3 (± 0.5)	38.5 (± 7.9)	29 (± 7)	497 (± 101)	17/1 (± 3)

and 64.3 ˚F, respectively, at SE-1 and SE-2. Above-average mean air temperatures were also observed for most of the year at NEP, particularly in May. In contrast, average temperatures were below the long-term average in December, March, and April at NEP.

3.2 | Cereal rye biomass, N and C analysis, and spring soil N

Cereal rye was managed for the best agronomic performance of the subsequent corn crop, being terminated when the plants were 6 to 12 inches tall or about 2 wk before corn planting (Midwest Cover Crop Council, 2014). At CR termination, aboveground biomass ranged from 0.48 to 0.65 tons acre^{-1} across sites, with 30% greater biomass at NEP than at SE-1 and SE-2 (Table 4). Nitrogen concentration was greatest at SE-1, followed by NEP and SE-2. Consequently, the greater biomass and N concentration resulted in higher N content at NEP than at SE-1 and SE-2. The C concentration was nearly constant regardless of the biomass amounts; therefore, the C/N ratio was altered by N concentration, with the highest C/N ratio at SE-2, followed by SE-1 and NEP. The dry matter, N content, and C/N ratio were similar to those reported in previous studies conducted across the U.S. Midwest. For instance, for CR no-till drilled after soybean harvest, CR aboveground biomass and N content ranged between 0.3 and 2.1 tons acre^{-1} and between 11 and 80 lbs N acre^{-1}, respectively (Crandall et al., 2005; Kaspar & Bakker, 2015; Kaspar et al., 2012; Pantoja et al., 2016). Although we did not sample CR roots at termination, it is expected that their root biomass and C/N ratio would be greater than those of the shoots. Martinez-Feria et al. (2016) reported that the CR biomass root/shoot ratio ranged between 0.75 and 1.94 across a 6-yr study. In addition, the authors found that the C/N ratio of CR roots was between 15 to 64% greater than the shoot C/N

TABLE 5 Effects of cereal rye cover crop (CR) on spring soil nitrate (NO_3-N), ammonium (NH_4-N), and soil mineral N (SMN, sum of NO_3-N and NH_4-N) in the upper 1-ft soil

Treatment	Site								
	SE-1			SE-2			NEP		
	lb acre^{-1}								
	NO_3–N	NH_4–N	SMN	NO_3–N	NH_4–N	SMN	NO_3–N	NH_4–N	SMN
CR	18.0b	4.9b	22.8b	24.1b	3.3b	27.5b	14.1b	4.8b	18.8b
No CR	26.4a	4.3a	31.7a	42.8a	4.6a	47.4a	15.4a	5.3a	20.8a

Note. SE-1, Southeast Purdue Agricultural Center Site 1; SE-2, Southeast Purdue Agricultural Center Site 2; NEP, Northeast Purdue Agricultural Center; SMN, soil mineral N. Treatment means within a column followed by different letters are significantly different at $p < .05$ by Fisher's LSD test.

ratio. This would correspond to the estimated root biomass and C/N ratio of CR of between 0.4 and 1.1 tons acre^{-1}, and between 20/1 and 35/1 across sites in this study, respectively.

At corn planting, CR decreased soil NO_3–N, NH_4–N, and SMN content in the upper 1 ft of the soil in all sites relative to the no-CR (Table 5). Changes in SMN were largely caused by differences in the NO_3–N content, since the NH_4–N levels were only 10 to 26% of SMN. Soil NO_3–N was decreased with CR compared with no CR by 32, 44, and 9% at SE-1, SE-2, and NEP, respectively. Similar reductions in spring soil NO_3–N with CR were found in previous studies in this region (Crandall et al., 2005; Krueger et al., 2011; Lacey & Armstrong, 2015; Pantoja et al., 2015; Patel et al., 2019), which, in turn, can reduce the risk of nitrate leaching and loss in tile-drained croplands (Kladivko et al., 2014; Malone et al., 2014). Several studies have shown a 13 to 61% reduction in NO_3–N leaching losses in tile drainage with CR relative to no CR (Kaspar et al., 2007, 2012; Ruffatti et al., 2019; Strock et al., 2004).

3.3 | Plant population and corn N content

Starter and cover crop treatments and their interaction did not affect the early-season plant population at the V6 to V7 growth stage in all sites (Table 5), averaging 31,107 plants acre^{-1} or 892 plants acre^{-1} (2.8%) fewer than the seeding rate. Decreased plant stand has been suggested as one of the factors reducing the yield of corn following CR. However, the impacts of CR on the plant population have been shown to be inconsistent. Eckert (1988) and Kaspar and Bakker (2015) reported 4 to 30% reductions in plant population following CR, probably caused by the interference of CR residue with the planter, leading to inadequate seed furrow closure and seed-to-soil contact (Kaspar & Erbach, 1998). It is possible that increased CR residue impacts planter performance; however, no work has suggested a threshold at which this could occur. In addition, there are various planter attachments available to assist with residue management when planting into undisturbed soil (e.g., coulters, row cleaners, closing wheels, etc.), but further research is necessary to evaluate their effectiveness when planting into CR residue. Similar to our study, no significant difference in plant populations between the CR and no-CR treatments was reported by Otte et al. (2019) and Patel et al. (2019). The latter authors hypothesized that the planters equipped with row cleaners used in their field trials (as we did) probably minimized the interference between CR residue and farm equipment. These results indicate that removing the CR residue from the seed row at planting can eliminate the negative impacts of CR on corn stands.

There are other concerns with the use of CR as a cover crop, such as allelopathy (Duiker & Curran, 2005), seedling root rot disease (Kurtz et al., 2021), and armyworm (*Spodoptera* sp.) (Pantoja et al., 2015). However, these factors were not an issue in our study.

Starter N fertilizer had a significant effect on corn N content at the V6 to V7 stage at all sites (Table 6). In general, applying 25 lb N acre^{-1} or more tended to increase the N content at the V6 to V7 stage compared with no starter in all sites (Figure 1). However, N content at the V6 to V7 stage was not statistically different among 0 and 50 lb N acre^{-1} at SE-1 and 25 lb N acre^{-1} at SE-2 (Figure 1A,B). After side-dressing, when the total N applied was the same for all starter fertilizer treatments, there were no differences in plant N content between no N and starter N (growth stages R1–R2 and R6, $p > .05$). Averaged across treatments, corn N content at the R1–R2 and R6 stages were 186 and 247 lb acre^{-1} for SE-1, 152 and 205 lb acre^{-1} for SE-2, and 127 and 198 lb acre^{-1} for NEP, respectively. These results indicate that corn plants, regardless of the cover crop treatment, were able to recover from early-season N deficiencies when N fertilizer application was delayed until the V6 to V7 stage, right before the period of rapid corn growth and N uptake (Abendroth et al., 2011).

Cereal rye did not affect corn N content at the V6 to V7 and R1 to R2 stages at any site and at the R6 stage at two of three sites (Table 6, Supplemental Table S3). Cereal rye may not have decreased corn N content at the V6 to V7 stage because of the relatively high SMN in the CR treatments at planting: 18.8 to 27.5 lb N acre^{-1} across the three sites, despite CR

TABLE 6 ANOVA (p-values) for the effect of the starter nitrogen fertilizer rate, the cover crop (CC), and their interaction on corn population; N content at the V6 to V7, R1 to R2, and R6 growth stages, and grain yield at three locations during the 2018 growing season

	Population	N content			
Source of variation	**V6–V7**	**V6–V7**	**R1–R2**	**R6**	**Grain yield**
	Pr > F				
SE-1					
Starter N	.76	.03	.81	.93	.57
CC	.94	.88	.08	.002	.01
Starter N × CC	.68	.06	.76	.48	.55
SE-2					
Starter N	.20	.03	.77	.79	.07
CC	.34	.59	.48	.49	.30
Starter N × CC	.49	.47	.99	.49	.93
NEP					
Starter N	.91	.002	.16	.31	<.001
CC	.85	.67	.70	.70	.68
Starter N × CC	.23	.92	.66	.38	.14

Note. SE-1, Southeast Purdue Agricultural Center Site 1; SE-2, Southeast Purdue Agricultural Center Site 2; NEP, Northeast Purdue Agricultural Center.

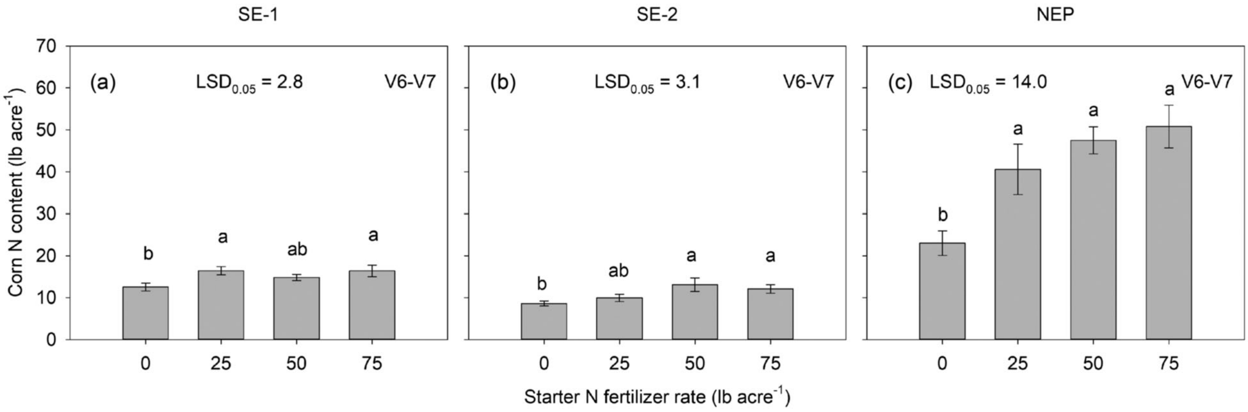

FIGURE 1 Effects of starter nitrogen fertilizer rates (0, 25, 50 and 75 lb N acre^{-1}) on corn N content at the V6–V7 growth stage at three sites during the 2018 growing season. Error bars indicate the SEM. Treatment means within each panel followed by different letters are significantly different at $p \leq .05$ by Fisher's LSD test. SE-1, Southeast Purdue Agricultural Center Site 1; SE-2, Southeast Purdue Agricultural Center Site 2; NEP, Northeast Purdue Agricultural Center

reducing SMN by as much as 19.6 lb N acre^{-1} compared with the no-CR treatment (Table 5). In previous studies where CR reduced early-season corn growth and N content, soil NO_3–N content at corn planting ranged from 3.5 to 13.4 lb acre^{-1} (Crandall et al., 2005; Pantoja et al., 2015).

Although we did not measure soil N during the growing season, independent pairwise t-tests showed that grain yield did not differ between the UTC treatments with and without CR at SE-2 and NEP, suggesting that CR had minimal impacts on soil N (Table 7). At SE-1, however, CR decreased the total N content at the R6 stage by 16% compared with no CR (226 vs. 268 lb N acre^{-1}, respectively). The fact that CR reduced N uptake at the R6 stage but not at the V6 to V7 or R1 to R2 stages indicates that the effects of CR were more pronounced later in the growing season. However, the time of CR decomposition and potential soil N immobilization are still difficult to predict because of the interaction of many factors controlling residue decomposition, such as the residue C/N ratio, soil properties (microbial activity, moisture, and temperature), and the tillage system (Cabrera et al., 2005; Nevins et al., 2020; Thapa et al., 2021). Crandall et al. (2005) found that corn N content at the R1 stage was reduced by terminating the CR 1 wk before corn planting rather than 4 wk before planting (Crandall et al., 2005). Similar to our study, Otte et al. (2019) found that late-terminated CR (1 wk before corn planting) did not decrease the corn N content at the V5 and R2 stages

TABLE 7 Main effects of starter nitrogen rates and cover crop treatments on corn yield at three sites during the 2018 growing season

	Site		
Treatment	**SE-1**	**SE-2**	**NEP**
Starter N	bu acre^{-1}		
0 lb N acre^{-1}	245	201	207b
25 lb N acre^{-1}	248	189	212b
55 lb N acre^{-1}	245	212	231a
75 lb N acre^{-1}	240	188	224a
UTC[a]	81	37	103
Cover crop			
CR	239b	194	220
No CR	250a	201	218
Contrasts			
UTC-CR vs. UTC-No CR	61 vs. 103**	43 vs. 30 NS	101 vs. 105 NS

Note. SE-1, Southeast Purdue Agricultural Center Site 1; SE-2, Southeast Purdue Agricultural Center Site 2; NEP, Northeast Purdue Agricultural Center; CR, cereal rye; UTC, untreated control; NS, not significant ($p > .05$). Treatment means within a column followed by different letters are significantly different at $p < .05$ by Fisher's LSD test; letters are only presented when the treatment effect was significant.

**Significant at $p < .001$.

[a] The UTC treatment was excluded from ANOVA and treatment comparisons and is only shown as a reference point when no N was applied.

compared with no CR, but CR decreased N content at the R6 stage by 12% in 1 of 2 yr. The authors hypothesized that the lower N uptake was the result of the slower N release from the high C/N ratio (48/1) of the CR residue following termination (as evidenced by the lower SMN relative to the no-CR treatment). Krueger et al. (2011) evaluated the impacts of CR on corn silage and found no significant differences in total N content before harvest in plots with or without CR.

3.4 | Corn yield

There was no significant interaction between starter N and cover crop treatment on grain yield at all sites (Table 6). Starter N had a significant effect on grain yield at NEP but not at either SE-1 or SE-2. At NEP, starter rates of 50 and 75 lb N acre^{-1} increased yield by 18.3 bu acre^{-1} compared with 0 and 25 lb N acre^{-1}, which did not differ from each other in yield (Table 7).

It is known that soil properties and weather conditions affect soil N availability and plant N uptake, which, in turn, affect corn's response to N fertilizer (Tremblay et al., 2012). The lack of a corn response to the starter N rate at SE-1 could be attributed to increased soil N supply early in the growing season. It can be hypothesized that the above-normal precipitation and temperature in June at SE-1 and SE-2 resulted in increased mineralization of organic matter and soil N supply, which that coincided with the period of rapid crop growth and N uptake (corn plants reached the VT growth stage by the end of June). These results are similar to those reported by Adeyemi et al. (2020) in southern Illinois. Although their study did not include a 2- by 2-inch starter N treatment, the authors found no difference in corn yield when N was split-applied (preplanting + side-dressing) or all applied as side-dressing in 2018, a year with timely and sufficient rainfall during the growing season. In contrast, the dry and cold soil conditions during the spring at NEP probably decreased the rate of mineralization of the organic matter and slowed N movement to the corn roots. Under low soil N supply conditions, increased starter N rates (at least 50 lb N acre^{-1}) were needed upfront to maintain the yield potential and optimize corn production.

Cereal rye at SE-1 decreased grain yield by 4.5% (averaged across starter N rate treatments) compared with no CR (Table 6), but there were no effects at the other sites. Since we found no reduction in the corn population in all sites, the grain yield reduction at SE-1 can be attributed to the reductions in N uptake during the grain-filling period, which may have resulted from lower SMN availability as a result of microbial immobilization during CR decomposition. This reduction in available SMN was demonstrated by the lower yield of UTC with CR compared with no CR at this site. Grain yield at the other two sites was unaffected by the cover crop treatment. Some works have shown mixed results for CR impacts on corn yield. Previous studies have shown a 0.1 to 12% yield reduction in corn following CR relative to no CR (Crandall et al., 2005; Pantoja et al., 2015; Patel et al., 2019; Ruffatti et al., 2019). In contrast, Snapp and Surapur (2018) found that corn yields were not reduced when following CR over an 8-yr study in Michigan. The authors reported that CR biomass, including the roots, was generally <0.6 ton acre^{-1} and had a C/N ratio between 22/1 and 30/1 over the study period. Other studies have shown that corn grain yield decreased as cover crop biomass and the C/N ratio increased (Finney et al., 2016; Kaspar & Bakker, 2015; Pantoja et al., 2015).

In summary, CR reduced the risk of nitrate leaching losses by decreasing SMN outside the growing season, but its impact on the following corn crop was not consistent across sites. We found that starter N increased early-season crop growth and N uptake relative to having no starter, but it did not always result in greater yields. A better understanding and evaluation of starter N fertilizer under different soil N conditions, which is partly associated with CR management (biomass and N content), is necessary for improving crop productivity in cover crop-based systems.

4 | CONCLUSIONS

In this study, we evaluated the impacts of starter N rates on corn growth and yield following CR, a widely used cover crop in the upper Midwest. Our results showed that CR did not affect early-season plant population and corn N content at the V6 to V7 and R1 to R2 stages at any site. However, CR significantly reduced N content and corn yield at the R6 stage by 16 and 4.5% relative to no CR in one of three sites, respectively. These findings indicate that the effects of CR at this site occurred later in the growing season. Hence, this is an important aspect that needs to be considered when evaluating CR's impacts on corn growth and yield in future research. Regardless of CR's presence, our results showed that starter N can improve early-season corn growth and N uptake relative to no starter; however, it did not always result in greater grain yields. Further research is warranted to evaluate the effects of starter N fertilizer under different soil N conditions, which are partly associated with CR management (biomass and N content). This would provide further insights into how starter N rates can be adjusted to optimize corn yield within a CR system.

ACKNOWLEDGMENTS

This research was supported by the Indiana Corn Marketing Council (Grant Number 00069635) and the USDA-Hatch grant IND010811. The authors thank Corey Lacey and previous members of Dr. Shalamar Amstrong's laboratory for assisting with the field and laboratory work. The authors also thank Joel Wahlman and Alex Helms from the Southeast Purdue Agricultural Center and Stephen Boyer from the Northeast Purdue Agricultural Center for their collaboration in the project and for performing all in-field management applications.

AUTHOR CONTRIBUTIONS

Giovani Preza-Fontes: Formal analysis; Visualization; Writing – original draft. Houston Miller: Data curation; Formal analysis; Investigation; Project administration; Visualization; Writing – review & editing. James Camberato: Formal analysis; Writing – review & editing. Richard Roth: Investigation; Writing – review & editing. Shalamar Armstrong: Conceptualization; Funding acquisition; Investigation; Methodology; Project administration; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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How to cite this article: Preza-Fontes, G., Miller, H., Camberato, J., Roth, R., & Armstrong, S. (2022). Corn yield response to starter nitrogen rates following a cereal rye cover crop. *Crop, Forage & Turfgrass Management*, *8,* e20187. https://doi.org/10.1002/cft2.20187