CROPPING SYSTEMS

Soybean Yield as Affected by Biomass and Nitrogen Uptake of Cereal Rye in Winter Cover Crop Rotations

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ABSTRACT

The inclusion of cereal rye (*Secale cereale* L.) as winter cover crop (WCC) following corn (*Zea mays* L.) has been suggested as a valuable nutrient management tool in the typical corn–soybean [*Glycine max* (L.) Merr.] rotation of the U.S. Midwest. However, little information is available on the effects of rye WCC on the soybean crop. The objectives of this study were to quantify biomass and nitrogen (N) uptake of rye WCC and to evaluate the effect of rye WCC on soybean yield. The effects of four rotations (corn/soybean, hairy vetch–corn/rye–soybean, rye–corn/rye–soybean, and hairy vetch + rye biculture–corn/rye–soybean) on soil residual NO_3–N content, rye biomass, N content, and C/N ratio, soil residue cover, soybean light interception, and grain yield were investigated at Urbana and Brownstown, IL. Rye N content was highly correlated with soil residual NO_3–N content ($r = 0.64$, $p < 0.0001$). Rotations that only included hairy vetch (*Vicia villosa* L.) reached maximum N content at lower corn N rates compared with rotations with rye. Soybean light interception at R1, R4, and R6 growth stages and grain yield were not affected by the treatments. Rye WCC planted after corn appears to take up a significant proportion of residual NO_3–N without affecting soybean grain yield, providing an environmental service to the agroecosystem.

The leaching of nitrate (NO_3–N) from agricultural fields into surface and groundwater supplies is a critical problem in the U.S. Midwest (Dinnes et al., 2002). It is generally recognized that residual N from excessive fertilizer application is the most important source of NO_3–N, although soil organic N mineralization does contribute some too. Most of the NO_3–N leaching occurs during the late fall and early spring months when the soil is fallow in the typical corn–soybean rotation of the U.S. Midwest (Owens et al., 1995). Winter cover crops, particularly grasses, can reduce NO_3–N leaching in corn–soybean cropping systems (Meisinger et al., 1991; Meisinger and Delgado, 2002). Brandi-Dohrn et al. (1997) reported a mean 37% reduction in flow weighted NO_3–N for different cropping systems that included WCC compared with winter fallow. McCracken et al. (1994) found that NO_3–N concentration of leachate was almost zero during the fall, winter, and early spring with rye WCC. They also reported that the average loss of N during the winter period was 8.4 mmol N m^{-2} with rye WCC as compared with 145 mmol N m^{-2} with winter fallow.

In the U.S. Midwest, rye is the preferred grass WCC because of its winter-hardiness and its exceptional ability to scavenge residual N (Wagger and Mengel, 1988; Ditsch and Alley, 1991; Shipley et al., 1992; Bollero and Bullock, 1994). In a review paper, Meisinger et al. (1991) reported reductions in the mass of leached N ranging from 59 to 77% with rye WCC compared with no cover crop. The N content of rye WCC is reported to be around 40 kg N ha^{-1} (Wagger and Mengel, 1988), although it can reach up to 120 kg N ha^{-1} (Vaughan and Evanylo, 1999) in field crops rotations. Kessavalou and Walters (1999) concluded that rye N content was close to the reduction in residual soil NO_3–N, and therefore rye N content can be considered a good estimator of the reduction in potentially leachable NO_3–N.

In the long term, the addition of large N and C inputs in the form of WCC biomass to the soil results in higher levels of soil organic matter (OM) and soil total N which increases the productivity of the soil (McVay et al., 1989; Kuo and Jellum, 2000; Sainju et al., 2002). In addition, residue cover provided by grass WCC reduces weed competition (Weston, 1996; Williams et al., 1998) and prevents soil erosion (Langdale et al., 1991; Alberts and Neibling, 1994).

The adoption of rye WCC will be limited if the yield of the cash crops in the cropping system is reduced. There is conflicting information in the literature on this question. Some evidence suggests that rye WCC reduces soybean grain yield mainly by reducing plant stands (Eckert, 1988; Reddy, 2001). Liebl et al. (1992) reported that soybean yield was reduced when soybean was planted 1 week after killing a rye WCC, but yield was not affected when soybean was planted 2 weeks after killing the rye WCC. Other authors (Wagner-Riddle et al., 1994; Swanton et al., 1998) did not find a reduction in soybean yield when rye WCC was killed at least 1 week before planting. Moore et al. (1994) reported greater soybean yield after rye WCC in one out of four environments and a neutral effect in the other three environments.

The objectives of this study were to: (i) quantify biomass and soil mineral N uptake of rye WCC planted after corn and as predecessor of soybean in three different WCC rotations, and (ii) to evaluate the effect of rye WCC on the subsequent soybean yield.

MATERIALS AND METHODS

This 2-yr field study was conducted at Brownstown and Urbana, IL, during 2000 and 2001. At Brownstown the soil is

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Abbreviations: C/S, corn–soybean; OM, organic matter; PAR, photosynthetically active radiation; R-C/R-S, rye–corn/rye–soybean; RV-C/R-S, hairy vetch + rye biculture–corn/rye–soybean; V-C/R-S, hairy vetch–corn/rye–soybean; WCC, winter cover crop.

a Cisne silt loam (fine, smectitic, mesic Vertic Albaqualf) and at Urbana it is a Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquoll). At Brownstown soil total C was 7.5 and 8.1 g kg^{-1}, soil total N was 0.52 and 0.61 g kg^{-1}, and pH was 6.4 and 6.2 for 2000 and 2001. At Urbana soil total C was 14.7 and 12.4 g kg^{-1}, soil total N was 1.02 and 0.83 g kg^{-1}, and pH was 6.0 and 6.3 for 2000 and 2001. All soil samples were taken at a depth of 30 cm. The study was conducted under no-till practices in fields that had been previously in a corn–soybean rotation for at least 5 yr.

The experimental design was a split-plot arrangement of treatments in a randomized complete block with four replications. Main plots (9 m wide by 20 m long) consisted of four rotations and split plots (4.5 m wide by 10 m long) were N fertilizer rates applied to corn. The rotations were (i) corn/soybean (C/S), (ii) hairy vetch–corn/rye–soybean (V-C/R-S), (iii) rye–corn/rye–soybean (R-C/R-S), and (iv) hairy vetch + rye biculture–corn/rye–soybean (RV-C/R-S). Further details on WCC management before corn planting are presented in Ruffo and Bollero (2003). Four N fertilizer rates (0, 90, 180, and 270 kg N ha^{-1}) were surface broadcast applied at the corn V6 stage (Ritchie et al., 1997) as ammonium–nitrate.

Rye was no-till drilled after corn harvest on 14 Oct. 1999 and 27 Oct. 2000 at Brownstown and 5 Oct. 1999 and 20 Oct. 2000 at Urbana. The seeding rate was 90 kg ha^{-1} at both locations. The rye was killed with herbicides (1.1 kg a.i. ha^{-1} of glyphosate [(*N*-(phosphonomethyl)glycine]) in the spring before planting soybean. The rye was killed 2 May 2000 and 3 May 2001 at Brownstown and 1 May 2000 and 2001 at Urbana. In both years, at the time of killing, the rye had already headed at Brownstown and was at the boot stage at Urbana. Soybean was no-till planted using 76-cm row spacing on 17 May 2000 and 15 May 2001 at Brownstown and 8 May 2000 and 9 May 2001 at Urbana.

Rye biomass was sampled right before killing the WCC. Two 0.12 m^2 subsamples of aboveground plant biomass were taken from the three center rows of each experimental unit using electric shears. Plant biomass was dried for 3 d at 65°C, then weighed and ground to pass a 1-mm mesh. Samples were analyzed for N with an automated Dumas instrument (Leco CHN-2000, Leco Corp., St. Joseph, MI). Nitrogen content was calculated as the product of plant biomass and N concentration.

In both years a month after planting soybean the soil residue cover was estimated using the line-transect method. One count per plot was taken with a 15-point (points separated by 30 cm) line-transect (Shelton et al., 1992). The line-transect was placed diagonally to crop rows and counts were taken encompassing the four central soybean rows. Soil residue cover is expressed as percentage of soil cover.

Soil samples were taken 1 d after corn harvest. A sample consisted of three composite cores (1.7 cm diam.) from each experimental unit to a depth of 30 cm. Soil samples were dried for 72 h at 40°C, and then ground to pass a 2-mm mesh. Nitrate–N (NO_3–N) was analyzed by the cadmium reduction method (Keeney and Nelson, 1982). From each experimental unit soil cores to a 30-cm depth were taken with a Giddings probe (4.1 cm in diam.) to estimate the mean soil bulk density. These samples were dried at 105°C for 72 h and weighed. Soil NO_3–N content (g N m^{-2}) was calculated using measured soil bulk density and soil NO_3–N concentration.

Soybean vegetative stages were measured during the season as suggested by Ritchie et al. (1994). To evaluate canopy development, light interception measurements were taken at R1, R4, and R6. Photosynthetically active radiation (PAR, μmol m^{-2} s^{-1}) was measured using a 0.8 m long Sunfleck PAR Ceptometer (Decagon Devices, Pullman, WA). Measurements were taken between 1100 and 1400 h below the canopy and a beam fraction sensor on a tripod measured incident light above the canopy. Light interception (*Li*, %) was calculated as:

$$Li = \left[1 - \left(\frac{\text{PAR below canopy}}{\text{PAR above canopy}}\right)\right] \times 100 \qquad [1]$$

Table 1. Fall soil residual NO_3–N as affected by the location × N rate interaction at Brownstown and Urbana, IL.

	Location	
N rate	**Brownstown**	**Urbana**
kg ha^{-1}	**—— $\log_{10}$ kg N ha^{-1} (kg N ha^{-1})† ——**	
0	**0.93 (8.5)**	**0.71 (5.1)**
90	**0.91 (8.2)**	**0.80 (6.3)**
180	**1.00 (10.0)**	**1.30 (20.0)**
270	**1.20 (15.9)**	**1.80 (63.1)**

† Fisher's protected LSD within Location = 0.12 (α = 0.05) ($\log_{10}$ kg N ha^{-1}).

The two middle rows of each plot were harvested using a small plot combine. Yields were adjusted to 130 g kg^{-1}.

All data were checked for normality using the UNIVARIATE procedure of SAS (SAS Inst., 2000). Soil NO_3–N content data were nonnormal and were transformed using logarithm base 10 and all statistical analyses are based on transformed data. Nontransformed means are presented in the tables.

The statistical model was analyzed using the MIXED procedure of SAS (SAS Inst., 2000). Locations, rotations, and N fertilizer rates were considered fixed factors and years and blocks were considered random factors. Means of significant treatment effects were separated using appropriate standard errors. Orthogonal contrasts between fallow and rotations including WCC were performed to test significant differences between a winter fallow and rotations including rye after corn. All random components were evaluated for their relative contribution and their significance based on their relative size to the residual variance component estimate. Pearson's correlation coefficient was used to evaluate the linear association between rye N content with soil residual NO_3–N content and yield with light interception at R1, R4, and R6 soybean growth stages using the CORR procedure of SAS (SAS Inst., 2000).

RESULTS AND DISCUSSION

Soil Residual NO_3–N Content

The soil residual NO_3–N content data were collected and analyzed to characterize the conditions that preceded the growth and development of rye WCC before the soybean crop. There were significant location × N rate ($p < 0.001$) and location × rotation ($p < 0.001$) interactions for soil residual NO_3–N content (Tables 1 and 2). In addition, there were significant main effects

Table 2. Fall soil residual NO_3–N as affected by the location × rotation interaction at Brownstown and Urbana, IL.

	Location	
Rotation†	**Brownstown**	**Urbana**
	—— $\log_{10}$ kg N ha^{-1} (kg N ha^{-1})‡ ——	
C/S	**1.19 (15.5)**	**1.14 (13.8)**
R-C/R-S	**0.85 (7.1)**	**1.11 (12.9)**
RV-C/R-S	**0.93 (8.5)**	**1.14 (13.8)**
V-C/R-S	**1.09 (12.3)**	**1.16 (14.4)**

† C/S, corn–soybean; V-C/R-S, hairy vetch–corn/rye–soybean; R-C/R-S, rye–corn/rye–soybean; RV-C/R-S, hairy vetch + rye biculture–corn/rye–soybean.

‡ Fisher's protected LSD within Location = 0.10 (α = 0.05) ($\log_{10}$ kg N ha^{-1}).

of N rate ($p < 0.0001$) and rotation ($p < 0.0001$). For all treatment combinations, the magnitude of soil residual NO_3–N content was low except for the one at Urbana following the 270 kg ha^{-1} N rate (63 kg N ha^{-1}). The significant location × N rate is due to a difference in the magnitude of the response of soil residual NO_3–N content to N rate at the two locations (Table 1). As N fertilization rate increased there was a greater proportional increase in soil residual NO_3–N at Urbana than at Brownstown. The high OM content and heavy-textured soils at Urbana as compared with the lower OM content and lighter-textured soils at Brownstown resulted in a higher soil residual NO_3–N content at the 30-cm depth after harvesting. We propose that this difference was due to the higher rate of soil organic N mineralization and less NO_3–N movement at Urbana as compared with Brownstown.

Rotation did not affect soil residual NO_3–N content at Urbana; however, at Brownstown soil residual NO_3–N content after the C/S and V-C/R-S rotations were significantly higher as compared with the R-C/R-S and RV-C/R-S rotations (Table 2). In addition, the C/S rotation had significantly higher soil NO_3–N content than the V-C/R-S rotation. At Brownstown, the rotations that included rye preceding corn (R-C/R-S and RV-C/R-S) each had lower soil residual NO_3–N content than V-C/R-S and C/S. This was probably due to N immobilization that occurred when large volumes of high C/N ratio residue were left on the soil surface (Aulakh et al., 1991; Reeves, 1994; Kuo et al., 1997) and the inherent lower N mineralization potential of the soils at Brownstown as compared with Urbana.

Rye Biomass, Carbon/Nitrogen Ratio, and Nitrogen Content

At killing time, rye biomass ranged from 2200 to 6100 kg ha^{-1}, which is similar to the range reported in other studies (Vaughan and Evanylo, 1999; Odhiambo and Bomke, 2001). In Virginia, Ditsch et al. (1993) reported rye biomass ranging from 2100 to 7100 kg ha^{-1} and in Maryland, Clark et al. (1994) reported maximum rye biomasses of 6400 and 7100 kg ha^{-1}. There were significant responses of rye biomass at killing time to the main effect of location ($p < 0.05$) and the interaction rotation × N rate ($p < 0.014$). At Urbana, rye biomass (4460 kg ha^{-1}) was significantly higher than at Brownstown (3280 kg ha^{-1}), reflecting the general higher soil fertility in Urbana. The response of rye biomass to N rate differed among rotations (Table 3). Rye biomass in the R-C/R-S and RV-C/R-S rotations reached a maximum of 270 kg ha^{-1} N rate, whereas in the rotation V-C/R-S it reached a maximum with 180 kg N ha^{-1}. There were no significant differences for rye biomass between the rotations at 0 kg N ha^{-1} but, with 90 and 180 kg N ha^{-1} the V-C/R-S produced significantly more rye biomass than did either the R-C/R-S or RV-C/R-S. However, at 270 kg N ha^{-1} the rye biomass for RV-C/R-S was significantly larger than that from either R-C/R-S or V-C/R-S.

Shipley et al. (1992) and Ditsch et al. (1993) found that rye biomass increased linearly with the N applied to the previous corn similar to the patterns shown in the R-C/R-S and RV-C/R-S rotations in our study. The plateau that rye biomass reached at 180 kg ha^{-1} N rate in the V-C/R-S rotation suggests a higher availability of mineral N in this rotation compared with R-C/R-S and RV-C/R-S, probably due to enhanced soil organic N mineralization in the spring combined with higher soil residual NO_3–N in V-C/R-S (13.2 kg N ha^{-1}) rotation compared with R-C/R-S (9.5 kg N ha^{-1}) and RV-C/R-S (11.0 kg N ha^{-1}) rotations. As suggested for other crops, N uptake is greater where hairy vetch had been used compared with rye as a WCC predecessor (McCracken et al., 1989).

Table 3. Rye biomass in spring as affected by the rotation × N rate interaction at Brownstown and Urbana, IL.

N rate	Rotation †		
	R-C/R-S	RV-C/R-S	V-C/R-S
kg ha^{-1}		kg ha^{-1}‡	
0	2236	2459	2765
90	2522	2645	3357
180	3782	4306	5716
270	5152	6095	5110

† C/S, corn–soybean; V-C/R-S, hairy vetch–corn/rye–soybean; R-C/R-S, rye–corn/rye–soybean; RV-C/R-S, hairy vetch + rye biculture–corn/rye–soybean.

‡ Fisher's protected LSD within Rotation = 470 ($\alpha = 0.05$). Fisher's protected LSD within N rate = 1080 ($\alpha = 0.05$).

There was a significant location × N rate ($p = 0.06$) interaction on rye C/N ratio (Table 4). This interaction was because at Brownstown there were no significant differences in rye C/N ratio among N rates, whereas at Urbana the higher N rates significantly decreased rye C/N ratios. Rye C/N ratio is generally reported in the range of 25 to 57 (Reeves, 1994). Carbon/N ratio increases with phenological development (Odhiambo and Bomke, 2001) and decreases with N availability (Ditsch et al., 1993). In addition, Ditsch et al. (1993) reported a linear positive response of rye N concentration and thus a decrease in C/N ratio to N fertilizer applied to the previous corn crop. Similarly, in our study higher N rates significantly decreased the C/N ratio at Urbana following a similar pattern as shown for soil residual NO_3–N content. The greater N availability at Urbana from the soil residual NO_3–N and N mineralization allowed for greater N uptake by the rye WCC. It is accepted that as C/N ratio decreases the rate of residue decomposition and N mineralization increase, facilitating nutrient cycling and reducing soil residue cover (Kumar and Goh, 2000).

Rye N content ranged from 35 to 170 kg N ha^{-1} (Ta-

Table 4. Rye C/N ratio in spring as affected by the location × N rate interaction at Brownstown and Urbana, IL.

N rate	Location	
	Brownstown	Urbana
kg N ha^{-1}‡	C/N†	
0	28.2	23.4
90	26.8	22.3
180	26.6	18.6
270	24.5	15.7

† Fisher's protected LSD within Location = 3.9 ($\alpha = 0.05$).

Table 5. Rye N content (kg N ha^{-1}) in spring as affected by the location × N rate interaction at Brownstown and Urbana, IL.

	Location	
N rate	Brownstown	Urbana
kg N ha^{-1}	rye N content, kg N ha^{-1}†	
0	36.6	38.0
90	35.1	55.4
180	54.6	117.9
270	71.4	170.4

† Fisher's protected LSD within Location = 38.0 (α = 0.05).

bles 5 and 6). In general, the literature shows that rye N content ranges from 40 kg N ha^{-1} (Wagger and Mengel, 1988; Bollero and Bullock, 1994; Clark et al., 1997) to 90 kg N ha^{-1} (Ranells and Wagger, 1997; Vaughan and Evanylo, 1999; Odhiambo and Bomke 2001), although it can reach 120 kg N ha^{-1} when planted on a previously fertilized corn field (Shipley et al., 1992; Ditsch et al., 1993) and 296 kg N ha^{-1} after heavily fertilized vegetable crops (Dabney et al., 2001). There was a significant location × N rate interaction ($p < 0.0001$) on rye N content (Table 5). At Brownstown, rye N content did not respond to N fertilizer rate, but at Urbana rye N content significantly increased with N rate, reaching a maximum of 170 kg N ha^{-1} at the 270 kg N ha^{-1} rate. This interaction had the same pattern as soil residual NO_3–N content reflecting the scavenging ability of rye. In addition, the higher soil OM and higher N mineralization potential at Urbana provided for a larger source of available N for the rye and consequently higher N content compared with previous studies (Ditsch et al., 1993; Ranells and Wagger, 1997).

There was a significant correlation ($r = 0.64$, $p < 0.0001$) between soil residual NO_3–N content and rye N content. There was a significant rotation × N rate interaction ($p < 0.1$) on rye N content (Table 6). There were no differences in rye N content among rotations after the 0 and 90 kg N ha^{-1} N rates. In the V-C/R-S rye N content reached a maximum at 180 kg N ha^{-1} and additional N with the 270 kg N ha^{-1} rate had no effect. In contrast, the maximum N content in the RV-C/R-S and R-C/R-S was reached at the 270 kg N ha^{-1} rate. This result suggests greater mineral N availability in the rotation that included hairy vetch before corn (V-C/R-S) and consequently an increase in available N for the rye WCC. Similarly, McCracken et al. (1989) suggested that hairy vetch had a residual effect that increased N uptake of the following crop in rotations that included N fertilizer and WCC.

Table 6. Rye N content in spring as affected by the rotation × N rate interaction at Brownstown and Urbana, IL.

	Rotation †		
N rate	R-C/R-S	RV-C/R-S	V-C/R-S
kg ha^{-1}		kg ha^{-1}‡	
0	35.1	36.5	40.2
90	36.3	47.2	52.3
180	69.8	77.9	110.9
270	121.1	129.4	112.3

† C/S, corn–soybean; V-C/R-S, hairy vetch–corn/rye–soybean; R-C/R-S, rye–corn/rye–soybean; RV-C/R-S, hairy vetch + rye biculture–corn/rye–soybean.

‡ Fisher's protected LSD within Rotation = 40 (α = 0.05). Fisher's protected LSD within N rate = 25 (α = 0.05).

Kessavalou and Walters (1999) concluded that the reduction of soil residual NO_3–N in the spring was almost equivalent to the N content of the rye at killing time. Likewise, Schröder et al. (1996) reported that the reduction in N leaching was similar to the N content of rye and ryegrass at the time of killing. In our study, rye N content showed a great response to N availability and its ability to take up large amounts of soil mineral N.

Soil Residue Cover and Soybean Yield

There was a significant rotation effect on soil residue cover ($p < 0.05$). A linear contrast showed significantly less soil (73% vs. a mean 84%) residue cover for the C/S cropping system as compared with all rotations including rye (V-C/R-S, R-C/R-S, and RV-C/R-S). However, there were no significant differences among the V-C/R-S, R-C/R-S, and RV-C/R-S rotations. There was a significant ($p < 0.01$) location × N rate interaction. At Brownstown (mean 82%), there were no differences in residue cover between N fertilizer rates, but at Urbana soil residue cover significantly increased from 66% with 0 kg N ha^{-1} to 93% with 270 kg N ha^{-1}. Residue cover was higher than 30% in all treatment combinations suggesting that cash-crops in no-till left sufficient amount of residue to meet soil conservation tillage standards (Reeder, 1992). However, rye residue has advantages over cash-crop residues with respect to water infiltration, runoff, and erosion. Kaspar et al. (2001) did not find a significant difference in residue cover between fallow plots (78%) and plots with rye WCC (83%). Nevertheless, they reported that rye WCC significantly increased water infiltration rate, reduced runoff, and reduced erosion compared with the fallow plots. In addition, residue cover reduces weed density and potentially benefits weed control during the soybean growing season (Liebl et al., 1992; Williams et al., 2000). Teasdale et al. (1991) reported that a 1% increase in residue cover between 42 and 97% reduced weed density by 1.37%, reaching a maximum of 75% reduction in weed density.

Light interception at R1, R4, and R6 was not affected by the treatments. At all three growth stages, linear contrasts between C/S and rotations including rye WCC (V-C/R-S, R-C/R-S, and RV-C/R-S) were not significant. Light interception is an effective measurement of canopy size and ultimately determines crop growth rate and yield as demonstrated by the significant correlations between grain yield and LI at R4 ($r = 0.67$, $p < 0.0001$) and R6 ($r = 0.75$, $p < 0.0001$).

Soybean grain yield was not affected by the treatments. Grand mean soybean grain yield was 2.8 Mg ha^{-1}. The variance component of the random effect of year (0.43 Mg^2 ha^{-2}) was 2.5 times larger than the residual (0.17 Mg^2 ha^{-2}). Thus, most of the variation in yields was due to the differences in environmental conditions experienced each year. The small contributions of the variance components year × rotation (0 Mg^2 ha^{-2}) and year × N rate (0.01 Mg^2 ha^{-2}) interactions suggest that the weather conditions affected treatments equally and were the major determinant of grain yield. Linear contrast showed no differences in yield among all rotations. As WCC preceding soybean, rye is reported to reduce (Eckert, 1988; Reddy, 2001; Williams et al., 2000), increase (Warnes et al., 1991; Williams et al., 2000), or not affect grain yield (Wagner-Riddle et al., 1994) depending on rye biomass at the time of killing, the time between killing and soybean planting, and weather conditions.

The lack of significant effect of rye WCC on soybean yield agrees with the results reported by Wagner-Riddle et al. (1994), Swanton et al. (1998), and Reddy (2003), who did not find differences in soybean yield when the soybean crop was planted 1 or 2 wk after rye killing time. The lack of significant differences in LI suggests that rye WCC did not affect soybean stand, which was reported to be the most common cause for negative effects on soybean yield (Eckert, 1988; Reddy, 2001). Positive effects of rye WCC on soybean yield have been attributed to improved weed control (Warnes et al., 1991; Liebl et al., 1992; Williams et al., 2000). We propose that the lack of a positive effect in our study was due to the low weed pressure.

In summary, the large amount of rye biomass produced and its N content which was highly correlated to soil residual NO_3–N content demonstrate that rye WCC planted after corn has the potential to reduce NO_3–N leaching. As the N rate applied to the previous corn crop increased, rye biomass increased up to 6095 kg ha^{-1} and rye N content increased up to 170 kg ha^{-1} without affecting soybean light interception during the growing season and grain yield. The ability of rye to respond to increased N availability combined with other potential benefits—such as soil erosion reduction and improved weed management—provide valuable environmental services when used in the traditional corn–soybean rotation of the U.S. Midwest.

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