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Cropping system and nitrogen dynamics under a cereal winter cover crop preceding corn

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Abstract

Cereal rye (*Secale cereale* L.) has been identified as a potential nitrogen (N) management tool when used as a winter cover crop (WCC). However, N deficient corn (*Zea mays* L.) has often been observed when preceded by a cereal rye WCC, resulting in yield reductions and deterring the integration of WCC into cropping systems of the Corn Belt. The objectives of this study were to assess soil N availability and plant N status throughout the corn growing season under various combinations of cereal rye kill date and N-fertilizer strategy in Illinois. Cereal rye WCC was killed three (KT1), two (KT2), and one (KT3) weeks prior to optimal corn planting, and N-fertilizer strategies included combinations of N splits (early and late) and N strategies (at planting, divided between planting and V6, or at V6). Although initial reductions in soil mineral N were observed in cereal rye WCC plots at planting of corn, soil mineral N among all cereal rye kill date and early N strategy plots was improved by the V6 stage and remained equal throughout the growing season. Corn under the latest cereal rye kill date in combination with its total N-fertilizer (160 kg N ha^{-1}) allotted at V6 had lower N contents by the R1 stage than any other kill date, N strategy combination. Relative corn N deficiencies and grain yield reductions were not observed unless cereal rye kill date was delayed to one week before optimal corn planting in Illinois (KT3) and N-fertilizer applied in full at the V6 stage of corn development (late N split, V6 strategy). Residual soil nitrate (NO_3-N) remaining post-harvest of corn varied between cereal rye WCC treatments and the fallow control depending on the N strategy employed throughout the season, indicating that N usage and demands of a winter fallow cropping system and cereal rye WCC systems under different residue loads require different N-fertilizer strategies to achieve more efficient N synchrony.

Introduction

Nutrient flow into, within, and out of managed ecosystems has become an issue of much debate among scientists, regulatory agencies, and policy makers both globally and in the USA. Within the Midwestern Corn Belt public concern has been specifically directed at the movement of N out of the row cropping systems of this region and into water sources (Dinnes et al., 2002; Goolsby et al., 2000). Nitrate-N contamination of ground and surface waters can result in public health risks (Goss and Barry, 1995; Nolan and Stoler, 2000; Shanker et al., 2000; Spalding and Exner, 1993) and impairment of aquatic life and recreation in water resources (Keeney, 1982; McIssac et al., 2001) of this region. According to the Environmental Protection Agency's (EPA) 1998 report to Congress, agriculture was determined to be the leading source of water pollution in these water sources throughout the USA (USEPA, 2000). Additionally, the US Geological Survey (USGS) estimates that on average approximately 35% of the total N discharged by the Mississippi River to the Gulf of Mexico is contributed by streams draining the states of Iowa and Illinois (Goolsby et al., 2000).

While better N management in row cropping systems is imperative to maintain safe water supplies both

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within the Corn Belt and downstream of it, the high N demands of these systems in combination with the mobility of N in soils present difficult challenges. The introduction of winter cover crops into these systems has been identified as a beneficial practice for reducing N losses from croplands (Dinnes et al., 2002; Keeney, 1982). In addition, Binder et al. (2000) and Dinnes et al. (2002) propose addressing N losses from intensively cropped systems through increased N-fertilizer use efficiency by synchronizing N application with N uptake curves of the crop throughout the growing season. It is probable that several strategies will need to be employed in combination to achieve efficient N management in these systems.

Cereal WCC in particular have historically been used to achieve soil and water conservation through residual N uptake post-harvest of primary row crops (Ditsch et al., 1993; Rosecrance et al., 2000; Staver and Brinsfield, 1998; Sullivan et al., 1991). Among cereal WCC, cereal rye has been identified as a useful WCC for the Midwestern USA because of its superior winter hardiness, its susceptibility to herbicide kill, and its large, persistent residue production (Moschler et al., 1967; Odhiambo and Bomke, 2001). Additionally, cereal rye has exhibited preeminent abilities for scavenging residual N from agronomic fields (Shipley et al., 1992). This effect can be especially beneficial in temperate climates similar to the Midwestern Corn Belt in the spring during high rainfall periods (Vos et al., 1997).

While the utility of a cereal rye WCC for improving N management in row cropping systems has been broadly reported, crop yield response to their integration has been variable (Bollero and Bullock, 1994; Clark et al., 1997; Vaughan and Evanylo, 1998; Vaughan et al., 2000; Wagger, 1989b). Corn yield deficits, when observed, have been attributed to reduced stands caused by poor seed-soil contact (Eckert, 1988) or allelopathic toxicity due to phytotoxins present during early decomposition of WCC residues (Barnes and Putnam, 1986), reductions in soil moisture content with excessive WCC growth (Bollero and Bullock, 1994), or a scarcity of available soil N for the corn crop brought about by the immobilization of available N during decomposition of cereal rye residues (Clark et al., 1997; Ruffo, 2001; Wagger, 1989b). When N availability to corn has been limiting in the past, enhancements have been observed with earlier kill dates of cereal rye WCC (Vaughan and Evanylo, 1998). However, little work has been done on combining cereal rye WCC kill dates with N-fertilizer application timing strategies to further improve the synchrony of N availability to the N needs of corn in this type of cropping system.

The objective of this study was to assess the effects of cereal rye WCC kill date and N-fertilizer application timing on soil N availability, N uptake by corn, and grain yield when corn is preceded by a cereal rye WCC.

Materials and methods

Field site

Field experiments were conducted in 2001 and in 2002 at Urbana, Illinois (40° 05′27″ N, 88° 13′42″ W; elevation 224 m above sea level) on a Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoquoll). Average annual precipitation of the study site is 1,041 mm year^{-1}, 48% of which occurs from October to March (during the WCC growing season).

Experimental design and crop management

The experiment was a split-split-plot arrangement in a completely randomized block design with four replications, where early and late applied N (N splits) were the main plots, rye kill dates the subplots, and N-fertilizer application strategies (N strategies) the sub-subplots. The sub-subplots were 6.0 m × 4.5 m in size and corn row-width was 76 cm.

Nitrogen-split treatments (N splits) were early (applied 23 March 2001 and 22 March 2002) and late (no N-fertilizer applied pre-planting of corn). Winter cover crop treatments included three cereal rye kill dates and a fallow control. Cereal rye was no-till drilled on 20 October 2000 and 8 October 2001 at 90 kg ha^{-1} and was killed with glyphosphate (N-(phosphonomethyl) glycine) on 13 April 2001 and 5 April 2002 (KT1), 23 April 2001 and 15 April 2002 (KT2), and 30 April 2001 and 23 April 2002 (KT3). Glyphosphate-resistant corn (DeKalb DKC 60-17) was planted on 9 May 2001 and 22 May 2002 into the cereal rye residue, which remained on the soil surface post kill throughout the corn growing season. Sub-sub-plot treatments included three N strategies: N-fertilizer applied at planting only (P), N-fertilizer applied at planting and V6 (P+V6), and N-fertilizer applied at V6 only (V6). N-fertilizer applications were carried out one day following corn planting and/or identification of the sixth fully expanded leaf (V6). Developmental stages of corn were determined according to Ritchie et al. (1997). All sub-subplots received a total of 160 kg N ha^{-1} N-fertilizer as ammonium sulfate, which was surfaced applied by hand. Bollero and Bullock (1994) calculated a mean economically optimal fertilizer rate of 152 kg N ha^{-1} for corn following a cereal rye WCC in Illinois. The 160 kg N ha^{-1} rate was divided among N splits (early and late) and the different N strategies (P, P+V6, and V6). Early split plots received 80 kg N ha^{-1} in March (pre-planting) with the remaining 80 kg N ha^{-1} applied at P, P+V6 (40 kg ha^{-1} at planting and 40 kg ha^{-1} at V6), or V6, while the late split plots received all 160 kg N ha^{-1} at P, P+V6 (80 kg ha^{-1} at planting and 80 kg ha^{-1} at V6) or V6, with no application pre-planting. Corn was harvested on 3 October 2001 and 1 October 2002.

Soil sampling methods

Two soil cores (1.5 cm in diameter) were taken from each sub-subplot to a depth of 30 cm at planting of corn, the V6 stage of corn development, and the R1 stage of corn development (the identification of visible silks). Soil cores at planting and V6 were taken prior to any N-fertilizer application at these times. Additionally, one soil core was taken using a 4 cm diameter soil Giddings probe from each sub-subplot following corn harvest (7 November 2001 and 10 October 2002) to a depth of 90 cm at 0–30, 30–60, 60–90 cm increments. Soil samples were weighed fresh, dried for 48 h at 35 °C in forced air dryers to constant temperature, and reweighed. Soil bulk density was estimated by oven drying (105 °C) a sub-sample of the forced-air dried sample, adjusting for moisture content, and dividing by the total core volume. All samples were ground to pass a 1 mm sieve. Soil sub-samples were extracted in 2M KCl for colorimetric determination of total soil mineral N. Nitrate-N determination was done by cadmium reduction and ammonia (NH_4-N) determination by the salicylate method (Keeney and Nelson, 1982). Total soil mineral N was calculated by adding NH_4-N + NO_3-N. Only NO_3-N was measured in the post-harvest samples as it is the form that would be most readily lost from the system due to leaching at this time of year.

Plant sampling methods

Cereal rye biomass was estimated by sampling an area of 0.5 m^2 at each kill date from each sub-subplot. Biomass was dried at 65 °C to constant temperature, weighed and ground to pass a 1 mm sieve in preparation for total N analysis. Total N was determined through the Kjeldahl wet digestion method (Bremner and Mulvaney, 1982). Chlorophyll meter readings (CMR) were taken with the Minolta SPAD-502 meter at the V6 stage of corn development and the R1 stage in both years. Readings were taken on the uppermost fully expanded leaf with a visible collar at V6 and from the ear leaf at R1 as suggested by Binder et al. (2000) and Blackmer (1992). Readings taken at V6 were done prior to any N-fertilizer application at this time. Corn above-ground biomass samples were taken at the R1 stage. Three plants were removed from each sub-subplot, dried at 65 °C, weighed, and ground to pass a 1-mm sieve. Total N of corn plant tissue were determined using a modified Dumas method on a LECO CHN-2000. Corn grain yields were estimated by harvesting the entire length of the two central rows with a plot combine and adjusting to Mg ha^{-1} at 15.5% moisture.

Statistical analysis

Soil NO_3-N, NH_4-N, and total mineral N content, CMR, plant biomass, N concentration and content, and grain yield were analyzed using the MIXED procedure of SAS (SAS, 2000) with cereal rye WCC kill date, N split, and N strategy as fixed effects and block and year as random effects. All variables were inspected for the assumption of normality using the UNIVARIATE procedure of SAS (SAS, 2000). Soil NO_3-N, NH_4-N, and total mineral N content data were found to be not normally distributed and were transformed using logarithm base 10. Normality was attained through these transformations. All soil data was then back transformed for presentation in tables. Post-harvest soil NO_3-N content data was analyzed using the repeated measures option of the MIXED procedure with sampling depth as an additional fixed effect in the model. The covariance structure type selected was unstructured based on AIC criteria (Littell et al., 1996) and investigation of the variance covariance structure of the experimental model. Significant effects are discussed both at the 0.05 and 0.10 probability levels. Only those effects which were significant at these respective levels are included in the tables and discussed in the results. Least square means for fixed effects were separated using appropriate standard errors at $\alpha = 0.05$ and $\alpha = 0.10$, as suggested by Carmer and Walker (1988) and Carmer et al. (1989) for combined experiments. As years and all interac-

Table 1. Variance component estimates for the random components of the statistical model presented for each plant and soil variable

Random effect	Plant variance estimates						
	Cereal rye				Corn		
	DM	N content	CMR (V6)	CMR (R1)	DM (R1)	N content (R1)	Grain yield
Year	0.265	1264.80	0	1.891	249.60	66.48	8.727
Block (year)	0	143.04	0	0.010	86.74	1.984	0.039
Year X N split	0	0	0	0	0	0	0
Year X kill date	0.008	626.65	0.371	0	0	0	0
Year X N strategy	0	27.55	1.060	0.630	0	0	0.031
Residual	0.046	0.916	1.438	2.074	0.678	1.088	1.095

	Soil variance estimates									
	Planting			V6			R1			Post-harvest
	NH_4-N	NO_3-N	Total	NH_4-N	NO_3-N	Total	NH_4-N	NO_3-N	Total	NO_3-N
Year	0.013	0.039	0	0	0.007	0.007	0.170	0	0.010	0
Block (year)	0	0	0	0	0	0	0	0	0	0.008
Year X N split	0.0004	0	0.003	0.003	0	0	0	0.0039	0	0
Year X kill date	0	0	0	0	0	0	0.002	0	0	0.002
Year X N strategy	0	0	0	0.001	0	0	0.001	0.0015	0	0
Year X depth	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.035
Residual	0.005	0.022	0.008	0.047	0.037	0.033	0.041	0.030	0.021	N/A

V6 and R1 represent growth stages of corn as defined by Ritchie et al. (1997). DM: dry matter. CMR: Chlorophyll meter readings.

tions with years were considered random, the means of the fixed effects are combined over years. In addition, variance component estimates of the random effects were calculated using the MIXED procedure of SAS (SAS, 2000) and their contributions for each variable relative to their respective residuals are presented in Table 1.

Results

Weather conditions for the rye and corn growing seasons

The temperature and precipitation trends of the 2000–2001 and 2001–2002 rye growing seasons were both divergent from each other as well as from the 30 year monthly averages reported by the Illinois State Water Survey (Figure 1). The most notable divergences among the monthly trends of the 2000–2001 rye season were the low relative precipitation (364 mm vs. the 30 year average of 502 mm), especially that of March and April 2001 which can be critical months for biomass accumulation of WCC in Illinois, and the relatively low temperatures observed in the previous December, which was the second coldest since 1888, of that growing season. In contrast, the 2001–2002 cereal rye season provided relatively high precipitation (543 mm) accompanied by comparatively mild observed temperatures. The 2001 and 2002 corn growing seasons in Illinois were similar, although the high precipitation of April and May 2002 led to a three week delay in corn planting that year and June and July 2002 were relatively dry months.

Table 2. Cereal rye dry weight biomass (DM) and N content as affected by the main effects of N split and kill date; and N content as affected by the N split X kill date interaction in Urbana, Illinois

	N split			
	Early		Late	
Kill date	DM Mg ha^{-1}	N content kg ha^{-1}	DM Mg ha^{-1}	N content kg ha^{-1}
KT1	0.68	26.1	0.67	24.3
KT2	1.53	65.9	1.20	39.3
KT3	2.66	80.5	2.29	53.6

DM: LSD$_{\alpha=0.05}$ for kill date = 0.25. N content: LSD$_{\alpha=0.05}$ for the kill date X N split interaction = 12.2.

Variance contributions of the model's random effects

For completion, the contributions of the model's random effects are presented in Table 1. For all almost all dependent variables, the effect of year had the

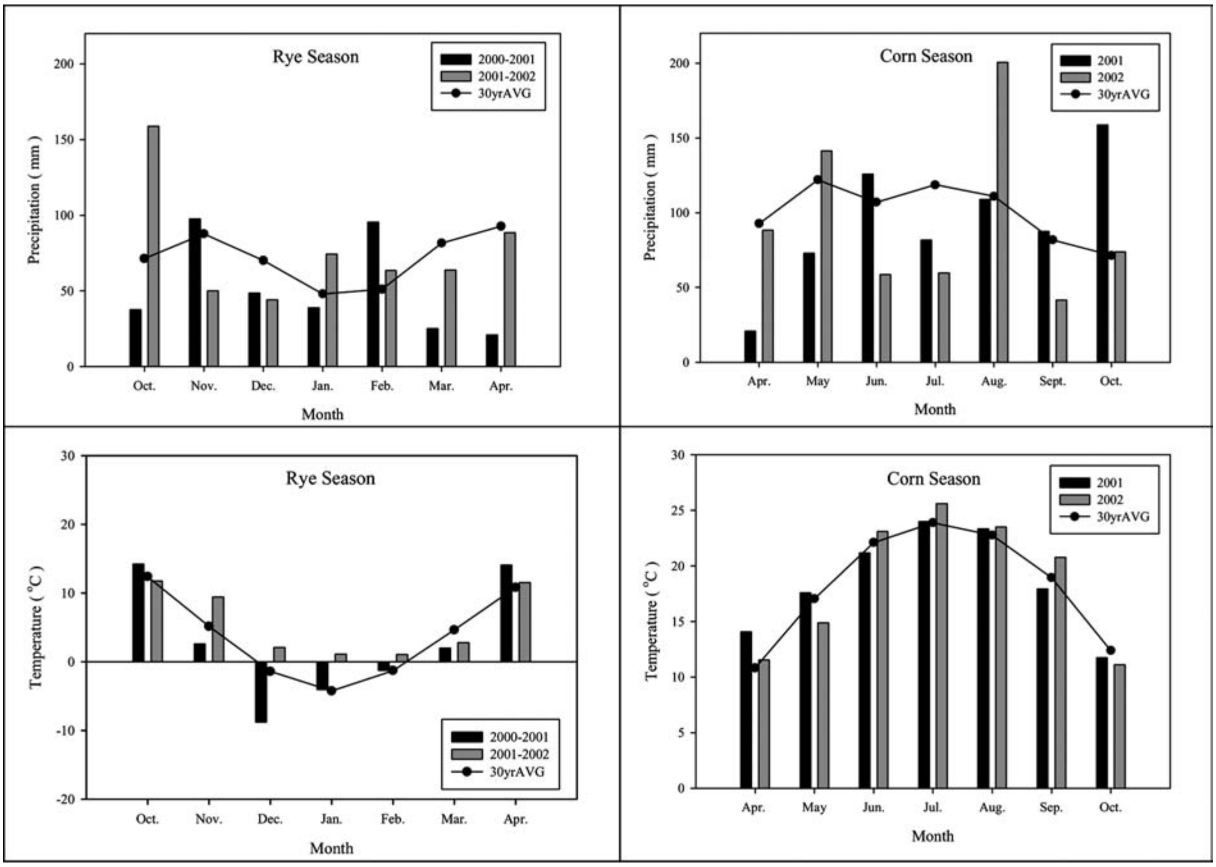

Figure 1. Weather conditions for cereal rye and corn growing seasons for 2001 and 2002 compared to the 30 year average in Urbana, Illinois.

largest variance contribution relative to their respective residuals. These contributions suggest that most of the random variability in the model was due to the fact that the weather conditions were different between the two years. In addition, the contributions of all interactions with years were substantially lower than the effect of year. Thus, dependent variables responded similarly to the fixed effects over the two years.

Cereal rye biomass production and N uptake

Significant differences in cereal rye biomass production were observed due to the main effects of kill date ($P < 0.01$) and N split ($P < 0.01$) (Table 2). Significant differences in N uptake of cereal rye were also observed due to the main effects of kill date ($P < 0.06$) and N split ($P < 0.0001$), and the interaction of kill date X N split ($P < 0.0001$). Cereal rye biomass production and N uptake significantly increased both with delay in kill and N-fertilizer additions in March (early N split). The significant interaction of N split X kill date was attributed to a difference in the magnitude of cereal rye N uptake with delay in kill date under the two N splits (Table 2).

Soil mineral N content throughout the corn growing season

Total soil mineral N content at the time of corn planting was significantly affected by the main effects of N split ($P < 0.09$) and rye kill date ($P < 0.01$) (Table 3). Differences in soil mineral N were due to differences in NO_3-N content since NH_4-N did not show differences among cereal rye WCC kill dates and the fallow control. The fallow control plots contained the highest total soil mineral N content with values decreasing in the cereal rye plots with delay in kill date (Table 3). There were no other significant fixed effects or interactions in the model.

Significant differences in total soil mineral N content by V6 were only observed under the main effect of N strategy ($P < 0.01$) (Table 4). Total soil mineral N, NH_4-N, and NO_3-N content were significantly higher under the P and P+V6 strategies than V6 .

Table 3. Total soil mineral N, NH_4-N, and NO_3-N contents at corn planting as affected by the main effects of kill date and N split in Urbana, Illinois

Main effect	NH_4-N	NO_3-N	Total soil mineral N
Kill date	Log_{10} kg N ha^{-1} (kg N ha^{-1})		
Fallow	1.41 (25.7)	1.57 (37.2)	1.81 (64.6)
KT1	1.41 (25.7)	1.47 (29.5)	1.77 (58.9)
KT2	1.40 (25.1)	1.32 (20.9)	1.70 (50.1)
KT3	1.38 (24.0)	1.10 (12.6)	1.59 (38.9)
N split			
Early	1.43 (26.9)	1.51 (32.4)	1.81 (64.6)
Late	1.36 (22.9)	1.22 (16.6)	1.63 (42.7)

Soil NH_4-N: $LSD_{\alpha=0.05}$ for kill date = 0.07 and $LSD_{\alpha=0.10}$ for N split = 0.05.
Soil NO_3-N: $LSD_{\alpha=0.05}$ for kill date = 0.13 and $LSD_{\alpha=0.10}$ for N split = 0.08.
Total soil mineral N: $LSD_{\alpha=0.05}$ for kill date = 0.09 and $LSD_{\alpha=0.10}$ for N split = 0.10.
Note: All LSD values are presented as Log_{10} kg N ha^{-1}.

Table 4. Total soil mineral N, NH_4-N, and NO_3-N contents at corn V6 stage of development as affected by the main effect of N strategy in Urbana, Illinois

	NH_4-N	NO_3-N	Total soil mineral N
N strategy	Log_{10} kg N ha^{-1} (kg N ha^{-1})		
P	1.70 (50.1)	2.15 (141.3)	2.29 (195.0)
P + V6	1.46 (28.8)	2.08 (120.2)	2.18 (151.4)
V6	1.36 (22.9)	1.78 (60.3)	1.94 (87.1)

Soil NH_4-N: $LSD_{\alpha=0.05}$ = 0.15.
Soil NO_3-N: $LSD_{\alpha=0.05}$ = 0.13.
Soil total mineral N: $LSD_{\alpha=0.05}$ = 0.13.
Note: All LSD values are presented as Log_{10} kg N ha^{-1}.

In addition, NH_4-N was significantly higher under P than P+V6, due to the greater ammonia-based N-fertilizer inputs applied at planting and concurrent mineralization occurring under these inputs.

Total soil mineral N content at R1 was significantly affected by the main effects of N split ($P < 0.07$) and N strategy ($P < 0.03$) (Table 5). Total mineral N was highest under the V6 strategy, followed by P+V6 and P, which were not different from each other. Differences were dictated by NH_4-N indicated higher mineral N availability under management strategies with N-fertilizer inputs provided in part or in full at the V6 stage of development (Table 5).

Table 5. Total soil mineral N, NH_4-N, and NO_3-N contents at corn R1 stage of development as affected by the main effects of N split and N strategy in Urbana, Illinois

	NH_4-N	NO_3-N	Total soil mineral N
Main effect	Log_{10} kg N ha^{-1} (kg N ha^{-1})		
N split			
Early	1.65 (44.7)	1.94 (87.1)	2.17 (147.9)
Late	1.72 (52.5)	2.04 (109.6)	2.26 (182.0)
N strategy			
P	1.58 (38.0)	2.01 (102.3)	2.17 (147.9)
P + V6	1.68 (47.9)	1.99 (97.7)	2.20 (158.5)
V6	1.79 (61.7)	1.97 (93.3)	2.27 (186.2)

Soil total mineral N: $LSD_{\alpha=0.10}$ for N split = 0.08 and $LSD_{\alpha=0.05}$ for N strategy = 0.07.
Soil NH_4-N: $LSD_{\alpha=0.10}$ for N split = 0.14 and $LSD_{\alpha=0.05}$ for N strategy = 0.17.
Soil NO_3-N: $LSD_{\alpha=0.10}$ for N splot = 0.11 and $LSD_{\alpha=0.05}$ for N strategy = 0.26.
Note: All LSD values are presented as Log_{10} kg N ha^{-1}.

Table 6. Chlorophyll meter readings (CMR) at corn V6 stage of development as affected by the N split X N strategy interaction in Urbana, Illinois

N split	N strategy	CMR
Early	P	51.6
	P + V6	50.8
	V6	48.7
Late	P	51.3
	P + V6	49.2
	V6	42.8

$LSD_{\alpha=0.05}$ = 3.21.

Chlorophyll meter readings

Chlorophyll meter readings (CMR) taken at V6 were significantly affected by the main effects of N split ($P < 0.02$) and N strategy ($P < 0.05$) and the N split X N strategy interaction ($P < 0.003$) (Table 6). This interaction is due to the significant difference between the early and late N splits under the V6 strategy (Table 6). The sub-subplots under the latter treatment combination had not received any N-fertilizer up to the point of CMR data collection at V6. Chlorophyll meter readings taken at the R1 stage of corn development were not significantly different across all main effects and interaction terms in the model.

Table 7. Corn dry weight biomass (DM) and N content at the R1 stage of development as affected by the main effects of kill date and N strategy in Urbana, Illinois

	N strategy					
	P		P + V6		V6	
Kill date	DM Mg ha^{-1}	N content kg ha^{-1}	DM Mg ha^{-1}	N content kg ha^{-1}	DM Mg ha^{-1}	N content kg ha^{-1}
Fallow	8.53	124.42	7.53	102.74	6.85	97.87
KT1	7.30	105.96	6.92	98.15	6.50	95.48
KT2	6.78	97.27	7.69	108.49	6.20	89.41
KT3	6.39	93.37	6.52	96.94	4.90	72.30

DM: $\mathrm{LSD}_{\alpha=0.05}$ for kill date = 0.84 and $\mathrm{LSD}_{\alpha=0.05}$ for N strategy = 0.79. N content: $\mathrm{LSD}_{\alpha=0.10}$ for the kill date X N strategy interaction = 15.91.

Corn biomass and N content at the R1 stage of development

Both plant biomass and total N content of corn at R1 were significantly affected by the main effects of kill date ($P < 0.01$ and $P < 0.03$, respectively) and N strategy ($P < 0.01$ and $P < 0.02$, respectively) (Table 7). Nitrogen content was also affected by the kill date X N strategy interaction ($P < 0.07$). Differences in corn N content were primarily a function of biomass differences, as the N concentration of plants did not differ across all treatment combinations (data not shown). The highest corn N content was observed in the fallow control under the P strategy of N-fertilizer application and the lowest content was observed under KT3 with the V6 strategy of N-fertilizer application. Corn succeeding cereal rye at KT3 biomasses in combination with late applied N-fertilizer received its N needs too late in its development to achieve equivalent biomasses and N contents by R1 to other treatment combinations. However, all other kill date, N strategy combinations result in similar N contents by R1, with the fallow, P strategy combination resulting in the highest corn N content.

Grain yields

Corn grain yield was affected by the main effects of N split ($P < 0.09$), kill date ($P < 0.10$), N strategy ($P < 0.10$) and the interaction of N split X N strategy ($P < 0.0003$) (Table 8). Corn grain yields were equivalent among the fallow control and earlier kill dates (KT1 and KT2), but were significantly reduced under KT3. Additionally, the late N split, V6 strategy combination led to significant reductions in grain yield (Table 8).

Post harvest soil NO_3-N

Soil NO_3-N content post-harvest was significantly affected by the main effects of N split ($P < 0.01$), N strategy ($P < 0.02$), and depth of sampling ($P < 0.0001$), as well as the interactions of kill date X N strategy ($P < 0.001$), and N split X depth ($P < 0.03$) (Table 9). Soil NO_3-N content remaining after corn harvest was significantly higher under the late N split (61.8 kg ha^{-1}) than the early N split (41.4 kg ha^{-1}), with the significant N split X depth interaction reflecting a difference in magnitude of response between N splits among sampling depths (Table 9). The significant interaction between kill date X N strategy was due to a difference in response to N strategy observed under the fallow control versus the trend observed among the WCC kill dates (Table 10). For the fallow control plot, post-harvest NO_3-N content was greatest under the P strategy, which was significantly higher than V6 and P+V6, while all WCC plots contained more NO_3-N under the P+V6 strategy than V6 and P, although the P+V6 strategy only resulted in significant differences under KT1 and to a lesser extent under KT2. For KT3, all N strategies were statistically equal (Table 10).

Discussion

Total soil mineral N content results showed that N immediately available for uptake by the corn plants at the time of planting is less in WCC plots, decreasing further with delay in kill date (Table 3). This was explained by the accumulation of cereal rye biomass and plant N content with delay in kill date (Table 2). Decreases in total soil mineral N contents in the WCC plots indicated uptake of soil NO_3-N into WCC bio-

Table 8. Corn grain yield as affected by the main effect of kill date and the N split X N strategy interaction in Urbana, Illinois

Effect		Grain yield Mg ha^{-1}
Kill date		
Fallow		7.31
KT1		7.30
KT2		7.10
KT3		6.42
N split	N strategy	
Early	P	7.29
	P + V6	7.42
	V6	7.16
Late	P	7.71
	P + V6	7.14
	V6	5.41

LSD$_{\alpha=0.10}$ for kill date = 0.62. LSD$_{\alpha=0.05}$ for N split X N strategy interaction = 0.77.

Table 9. Post harvest soil NO$_3$-N content as affected by the main effect of depth and the depth X N split interaction in Urbana, Illinois

	N split		
	Average	Early	Late
Depth (cm)	Log$_{10}$ kg N ha^{-1} (kg N ha^{-1})		
0–30	1.55 (35.5)	1.46 (28.8)	1.65 (44.7)
30–60	0.98 (9.5)	0.89 (7.8)	1.07 (11.7)
60–90	0.71 (5.1)	0.68 (4.8)	0.73 (5.4)

LSD$_{\alpha=0.05}$ for depth = 0.18. LSD$_{\alpha=0.05}$ for the depth X N split interaction = 0.20.
Note: All LSD values are presented as Log$_{10}$ kg N ha^{-1}.

Table 10. Post harvest soil NO$_3$-N content as affected by the kill date X N strategy interaction in Urbana, Illinois

	N strategy		
	P	P + V6	V6
Kill date	Log$_{10}$ kg N ha^{-1} (kg N ha^{-1})		
Fallow	1.56 (36.3)	1.03 (10.7)	1.11 (12.9)
KT1	1.02 (10.5)	1.66 (45.7)	1.11 (12.9)
KT2	0.94 (8.7)	1.16 (14.5)	1.10 (12.6)
KT3	1.04 (11.0)	1.14 (13.8)	1.00 (10.0)

LSD$_{\alpha=0.05}$ = 0.20.
Note: All LSD values are presented as Log$_{10}$ kg N ha^{-1}.

mass. Kessavalou and Walters (1999) observed that measured cereal rye N uptake was nearly equivalent to observed reductions in spring residual soil NO$_3$-N. Similar soil NO$_3$-N reductions with delay in kill date of cereal rye WCC were observed in both fertilized (early N split) and unfertilized (late N split) rye. However, the application of N-fertilizer during cereal rye growth (early N split) improved soil NO$_3$-N content at planting across all kill date treatments.

By V6 any soil mineral N differences due to the cereal rye WCC at any kill date were overcome by the application of N-fertilizer at planting and/or the intrinsic mineralization capacity of the soil, which is reflected in the lack of significance due to kill date at this time of sampling. The P and P+V6 strategies resulted in statistically higher total soil mineral N contents than V6 (Table 4). The lower mineral N contents under the V6 strategy are expected since these plots would have either received no N-fertilizer up until this time or 80 kg N ha^{-1} in late March (approximately three months prior to the V6 sampling date). In contrast, the plots under the P and P+V6 strategy would have received a portion of their N-fertilizer allotment at planting, increasing the total mineral soil N content under these treatments, respectively.

Additionally, the CMR of corn plants at V6 indicate no differences in N status across all treatment combinations with the exception of the late N split, V6 strategy combination (Table 6). The mean value of CMR under the late N split, V6 strategy (42.8) fell below the proposed critical CMR (43.5) for determining corn responsiveness to N-fertilizer at V6 suggested by Jemison and Lytle (1996), and thus improvements in N status of the late N split, V6 strategy corn at R1 compared to V6 were expected with V6 strategy N-fertilizer additions at this time. In addition, chlorophyll meter readings at V6 were significantly correlated with grain yields ($r = 0.50$, $P < 0.001$), indicating that CMR taken at this time are a usable index for determining corn responsiveness to additional N-fertilizer inputs and grain yields under the conditions of cereal rye WCC systems. Although soil mineral N data at V6 would indicate considerably more available N for the P and P+V6 strategies, this is not necessarily reflected in the CMR of the corn plants at this time for which five of six treatment combinations were not statistically different (Table 6). The only treatment combination that did show relative corn N deficiencies in CMR taken at V6 (late N split, V6 strategy) also resulted in less grain yield (Table 8).

By R1 total soil mineral N content was significantly higher among late N split plots and highest under the V6 strategy, followed by P+V6 and V6, with differences dictated by soil NH_4-N contents, as soil NO_3-N did not differ among strategies at this time. Total soil mineral N content differences observed at this time and previously at V6 were a function of N-fertilizer application time, as no differences in soil mineral N due to WCC at any kill date were found. Ammonia-N contents comprised a substantial portion of available soil N in this study as was also reported by Vaughan and Evanylo (1999) in corn following a cereal rye WCC. However,split applications of ammonia-based N-fertilizer in this study override any differences in potential soil N mineralization/immobilization due to decomposition of the cereal rye residues at any kill date. Chlorophyll meter readings at this time indicated no treatment-based differences in plant N status. However, significant differences were observed for plant N content. These differences were due to differences in corn biomass rather than N concentration (Table 7). Reductions in corn biomass production following the introduction of a cereal rye WCC are consistent with the findings of Kuo et al. (2000), who also observed decreased corn biomass under the initial use of cereal rye as a WCC preceding corn. The initial decreases observed by Kuo et al. (2000) were attributed to reduced soil N availability in the system with the introduction of the WCC. However, over the nine year span of their study, increases in corn biomass production were observed and correlated with increases in available soil organic N due to the presence of the decomposing cereal rye WCC over repeated seasons, indicating that N availability improves with persistent use of the WCC.

In our study, the lower N content of the plants under KT3 and the V6 strategy at the R1 stage was in agreement with lower grain yields (Table 8). Binder et al. (2000) found significant differences in N uptake of corn when N-fertilizer was applied on or after V6, showing that N deficiencies can be severe enough to prevent full recovery of grain production when N-fertilizer application is delayed until V6. Both the N content and yield losses observed in the KT3, V6 strategy plots indicate that a similar effect has occurred in this study. Additionally, while CMR at R1 indicated equivalent plant N status across all treatment combinations, plant biomass differences (and likewise N contents) showed that biomass accumulation of the corn plants was hindered early in the growing season when rye kill date and N-fertilizer application were both delayed, perhaps limiting the capacity for N uptake regardless of N-fertilizer made available later in the season.

The grain yield results of this study indicated that maintaining corn yields following the use of cereal rye as a WCC is feasible for Illinois producers under several management strategies investigated in this study. Corn grain yield losses were not exclusively observed as a result of the integration of cereal rye WCC into the cropping system as they have been in the past (Bollero and Bullock, 1994; Ruffo, 2001) in this region. Corn grain yield results imply that KT1 and KT2 would allow for adequate biomass accumulation of rye for retrieval of residual fertilizer N, while minimizing any potential yield losses that might be observed with cereal rye biomass at the quantities observed by KT3. Ditsch et al. (1993) documented 57–76% recovery of residual fertilizer N and Shipley et al. (1992) observed 71% recovery under equivalent cereal rye biomasses. Additionally, Raimbault et al. (1991) concluded that a time interval of two weeks between cereal rye kill date and corn planting in no-till systems may play an important role in reducing the amount of phytotoxins present during the early decomposition of rye residues that may have harmful effects on the following emerging crop (Barnes and Putnam, 1986). Although phytotoxic effects were not specifically investigated in this study, corn plant parameters indicate that N availability and N-fertilizer application timing dictate the status of the corn crop following a cereal rye WCC. N split and N strategy (the N-fertilizer application treatments) were the only the significant effects for corn plant parameters, while the presence of the cereal rye WCC and its date of kill did not result in smaller or N deficient plants unless unsupplimented by N-fertilizer. It is our belief that the primary mechanism through which a cereal rye WCC may negatively affect corn is through N immobilization, unless management decisions are made to improve the synchrony of N application timing to N demand of the corn crop.

Table 9 illustrates the distribution of soil NO_3-N in the soil profile after harvest of corn. With 70% of soil NO_3-N content remaining in the top 30 cm and readily available for uptake by a WCC after corn harvest, the benefits of planting a cereal WCC at this time for N scavenging purposes were evident. Clearly, more soil NO_3-N remains throughout the profile in plots under the late N split than the early N split, indicating that N-fertilizer may have been used more efficiently throughout the growing season when it was applied in part pre-planting of corn and either uptaken during cereal rye growth in the WCC plots or subject to early season losses in the case of the fallow control. The lack of significance of kill date indicates that post-harvest remaining soil NO_3-N is not affected by the preceding WCC under the N-fertilizer rate applied in this study. Brandi-Dohrn et al. (1997) observed similar results over the course of a 3 year study in Oregon and concluded that any reduction in NO_3-N leaching achieved using a cereal rye WCC was due to its presence throughout the winter and not to a reduction in inorganic N remaining at corn harvest. However, the interaction between N strategy and kill date in this study indicates that when a WCC is incorporated into the system in combination with various N strategies, N-fertilizer usage and likewise post harvest soil NO_3-N can differ from that of a winter fallow system (Table 10). Remaining soil NO_3-N was significantly lower in the P+V6 and V6 strategies under the fallow control than the P strategy, implying that either a split or late N-fertilizer application may be a more effective N management strategy for minimizing the likelihood of losses at the end of the season. Whereas, in the WCC plots, the P and V6 strategies resulted in significantly lower post harvest NO_3-N contents among N strategies for KT1 and KT2 and equal post harvest NO_3-N contents for KT3. Although both the P and V6 strategies of N-fertilizer application resulted in equivalent post-harvest NO_3-N in WCC plots, late applied N-fertilizer imparts yield risks at larger cereal rye biomasses, and thus the V6 strategy should not be encouraged in a cereal rye WCC system, despite the fact that it resulted in equal remaining post-harvest NO_3-N.

Conclusions

Based on the soil and plant N status assessments of this study, a cereal rye kill date less than two weeks before planting should be avoided as a management practice when combined with an N-fertilizer application solely at the V6 stage of development. This treatment combination led to reduced corn biomass, lower N uptake, and consequently, lower grain yields. While delaying N-fertilizer application to the V6 stage of corn development may increase fertilizer use efficiency by the corn plant, this delay, in combination with a preceding late killed cereal rye WCC, is too N limiting for corn yields in Illinois. Although N immobilization in the soil was not specifically measured in this experiment, any detrimental effects attributed to the high N demands of rye decomposition were not reflected in the N status of the corn plants or grain yields under earlier kill dates or KT3 as long as supplemental N-fertilizer was supplied either pre-planting or at planting of corn. The use of a cereal rye WCC under a kill date similar to KT1 or KT2 in combination with an early N application strategy results in minimal remaining soil NO_3-N post harvest of corn among management strategies employed in this study and further decreases the likelihood of unnecessary N losses from the cropping system.

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