Accepted for publication 24 August 2010. Published 14 October 2010.

Growth Stage at Harvest of a Winter Rye Cover Crop Influences Soil Moisture and Nitrogen

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Krueger, E., Ochsner, T., Kantar, M., Sheaffer, C., and Porter, P. 2010. Growth stage at harvest of a winter rye cover crop influences soil moisture and nitrogen. Online. Crop Management doi:10.1094/CM-2010-1014-01-RS.

Abstract
Producers may offset the cost associated with winter rye (*Secale cereale* L.) cover cropping by harvesting the rye as forage, but care must be taken to avoid yield suppression of a primary crop induced by soil water and nitrogen depletion by the rye. The objective was to determine the effect of rye growth stage in the spring on the soil moisture and soil nitrogen under a fall-sown cereal rye cover crop. Field studies were conducted in Morris and St. Paul, MN, from September 2007 through June 2008. Soil moisture and soil NO_3-N were monitored for eight rye harvest dates in the spring and summer of 2008. Soil moisture in late April and early May was similar for rye and fallow treatments. At boot stage, rye had depleted soil moisture by 10% and soil NO_3-N by 83% when averaged across locations. Rye reduced soil NO_3-N compared to the fallow at all growth stages. Harvest timing may be an important management tool to conserve soil moisture for the primary crop. Spring N fertilization is likely necessary when a non-legume such as corn (*Zea mays* L.) follows rye.

Introduction
Corn and soybean (*Glycine max* L.) are the most widely grown crops in the Upper Midwest. These annual crops have relatively short growing seasons with active plant growth and significant ground cover for as little as three or four months per year. The result is a landscape that is prone to off-site nutrient transport, increased soil erosion, and loss of soil organic matter. Planting cover crops after corn or soybean is one approach to addressing these concerns. In the Midwest, winter rye cover cropping has been shown to scavenge excess soil NO_3-N (11) and reduce NO_3-N leaching (14,26). Increased surface cover may also reduce soil erosion (16), while the cover crop biomass may help mitigate loss of soil organic matter (15,22). Rye is particularly well suited for use in the Upper Midwest because it grows well after harvest of the main crop in the fall, is winter hardy, and begins regrowth early in the spring (25). In addition, rye tends to reach optimum forage harvest stage sooner than other small grains, which makes it the preferred small grain species for early-season forage production (18).

Producers are often reluctant to plant winter rye because of costs associated with rye management. If the environmental benefits associated with rye production are to be realized, there must be some immediate economic incentive for producers. Including rye as part of a double-crop forage production system may justify its cost. On farm research in the Upper Midwest has emphasized that rye can be an integral component of soil conservation and nutrient management, as well as provide producers a high-quality forage (10). Dairy farmers have reported high rye forage yields and increased milk production when rye is harvested at optimum forage quality and rye silage replaces haylage in the feed ration (4). Livestock producers who rely upon perennial legume forages may also benefit from rye production. Perennial legume forages are susceptible to winter kill in cold weather locations, but the winter hardiness of rye helps ensure adequate spring forage (10). A companion paper to this study quantifies rye forage quality and yield at various growth stages, and offers management recommendations to optimize rye production (13).

Previous research has highlighted challenges associated with double-cropping. In systems designed to maximize biomass production, Crookston et al. (5) reported that double-cropping corn silage after rye in Minnesota decreased corn yield and did not increase total yearly biomass production, while others (20,30) observed double-cropped corn yield was reduced after rye, but total yearly biomass production was increased. In Michigan, Thelen and Leep (29) reported that winter wheat (*Triticum aestivum* L.) or winter rye decreased grain and silage yields of double-cropped corn, but had no effect on soybean yield. Total biomass production was greater for the double-crop system than for corn silage alone. They noted that moisture depletion induced by the cover crop may have impacted subsequent corn grain and corn silage yield and speculated that soil moisture depletion may have been greater as the winter forage crop matured. When corn followed rye in each of these studies, N was supplied to the primary crop at a rate of at least 100 kg/ha in order to avoid N deficiencies. Debruin et al. (6) showed that a winter rye cover crop reduced subsequent soybean yield and cited soil moisture depletion as a possible reason for lost yield.

This previous work suggests that soil moisture and soil NO_3-N depletion induced by the rye may impact yield of a primary crop, but research quantifying the magnitude of depletion at various rye growth stages was not identified. We hypothesize that the effect of the winter rye cover crop on soil moisture and soil NO_3-N available to the subsequent crop will be greater with advanced rye maturity at harvest. Therefore, harvest timing can be used as a management tool to mitigate the negative effect the rye may have on a subsequent crop. The objective of this research was to determine the effect of growth stage at spring harvest of a fall-sown winter rye cover crop on soil moisture and soil NO_3-N.

Description of Experimental Sites

Field studies were conducted at the West Central Research and Outreach Center in Morris, MN, and at the University of Minnesota in St. Paul, MN, from September 2007 through June 2008. At Morris, the soil series was Doland silt loam (fine-loamy, mixed, superactive, frigid Calcic Hapludoll), and at St. Paul, a well-drained Waukegan silt-loam (fine-silty over sandy or sandy-skeletal, mixed, mesic Typic Hapludolls). Based on typical textural analysis for each soil (24), plant available water in the top 60 cm of the soil profile was 10.2 cm at Morris and 10.8 cm at St. Paul. The experimental site at Morris was fertilized with dairy effluent supplying 196 kg/ha available N prior to rye seeding. Plots at St. Paul were fertilized with dairy effluent supplying 154 kg/ha available N in fall 2006. No crop was planted between manure application in 2006 and rye seeding in fall 2007. 'Rymin' rye was seeded on 14 September 2007 at Morris and 5 September 2007 at St. Paul. The plot size at Morris was 18.3 m × 2.3 m, and rye was seeded at a rate of 94 kg/ha with a grain drill at a row spacing of 19.1 cm. The plot size at St. Paul was 4.6 m × 1.8 m, and rye was seeded at 109 kg/ha with a grain drill at a row spacing of 20.3 cm. Weed growth was insignificant in the rye plots but was controlled in fallow control plots with spring tillage and herbicide application. Temperature and precipitation at each site are presented in Table 1. The experimental design was a randomized complete block with four replications. Treatments were fallow or rye with target rye growth stages at harvest, corresponding to 21 (tillering), 31 (stem elongation), 41 (boot development), 51 (head emergence), 61 (anthesis begins), and 81 (dough development) on the Zadok maturity scale (31). No post rye crop was evaluated in this study.

Table 1. Temperature and precipitation for 2008 and long-term (1979-2008) averages for Morris and St. Paul, MN.

Location	Mean monthly temperature (°C)				Mean monthly precipitation (cm)			
	Mar	Apr	May	Jun	Mar	Apr	May	Jun
Morris 2008	-5.3	4.1	12.0	18.0	2.9	7.3	6.0	10.9
Morris mean	-2.6	6.5	13.9	19.1	3.6	5.8	7.3	10.8
St. Paul 2008	-1.4	7.3	13.8	19.9	4.6	10.4	7.1	7.1
St. Paul mean	0.7	8.9	15.5	20.4	4.7	6.9	9.8	11.7

Data Collection and Statistical Analyses

Sample dates and their corresponding rye growth stage are listed in Table 2. Soil samples were collected to a depth of 60 cm using a 1.8-cm inside diameter soil core probe (AMS Inc., American Falls, ID) and subdivided into 0- to 30-cm and 30- to 60-cm fractions. Four cores were collected per plot and combined. In rye plots, two cores were taken from within the row and two from the interrow. Subsamples were air dried for NO_3-N analysis with the remainder of the sample being dried at 105°C for determination of gravimetric soil water content. A 15-g portion of ground sample was extracted with 2.0 mol/liter KCl at a 1:2 soil to solution ratio for NO_3-N analysis. The extract was then filtered through Whatman no. 1 filter paper to obtain a particulate-free extract. Samples were analyzed for the sum of NO_2-N and NO_3-N using the colorimetric method (17) and a flow-through injection analyzer (Lachat, Loveland, CO). Samples for bulk density were collected for each location and treatment. Two samples were collected per plot using a hydraulic soil probe with a core inside diameter of 6.5 cm. The use of a hydraulic probe with a large core diameter resulted in little soil compaction during sampling. Samples were collected to a depth of 60 cm and subdivided into 0- to 30-cm and 30- to 60-cm fractions. Samples were combined and dried at 105°C. The obtained bulk density was used to determine water content as depth of soil water (cm) and NO_3-N as kg/ha.

Table 2. Sampling dates and harvest growth stage at Morris and St. Paul, MN.

Morris		St. Paul	
Sample date	Growth stage*	Sample date	Growth stage*
April 28	25	May 1	21
May 5	25	May 6	31
May 12	32	May 14	40
May 20	38	May 23	47
May 27	43	May 28	56
June 3	60	June 3	59
June 10	63	June 10	64
June 30	79	June 27	81

* Zadoks scale

Statistical analyses were performed in Matlab 7.0, 2004 (The MathWorks Inc., Natick, MA). Data for soil moisture and soil NO_3-N were subjected to analysis of variance (ANOVA) comparing the fallow and rye treatments for each sampling date. Block was considered a random effect and treatment a fixed effect. Statistical significance was evaluated at $P \leq 0.05$.

Multiple regression models were constructed to determine the effect of rye harvest timing, environment, precipitation, and their cross products on soil moisture and soil NO_3-N. Several variables were considered as a measure of harvest timing: date of harvest, accumulated growing degree days (GDD), forage yield, and rye growth stage at the time of harvest. Models were assembled using each of the potential harvest timing variables and the coefficient of determination, R^2, was used to determine which would be included in the full model. Growth stage was chosen because R^2 was greatest for this variable. The use of more than one harvest timing variable was considered, but was not possible as the correlation coefficient (r) indicated a strong linear relationship between them. Growth stage offers advantages in that it may be more broadly applicable than date of harvest, does not require an estimate of yield, and does not require a knowledge or calculation of GDD. Additionally, rye growth stage is an observation that can be quickly made by the producer.

The environment variable in the regression models was the location of the observation: Morris or St. Paul. The precipitation variable was defined as the number of days since a rain event ≥ 1 cm. Alternative definitions of the precipitation variable such as the number of days since the last measurable rain and rain in the previous seven days were also considered, but did not perform as well. Because soil moisture and soil NO_3-N depletion were observed in the rye treatment for both the 0- to 30-cm and 30- to 60-cm depths, data for the multiple regression analyses were combined for a 60-cm profile average. Soil moisture depletion was defined as the difference in depth of soil water (cm) between treatments, while soil NO_3-N depletion was defined as the difference in soil NO_3-N (kg/ha) between treatments.

The variables chosen for the full regression model were then tested for significance using 95% confidence intervals. Reduced models were prepared using only those variables which were significant predictors of soil moisture or soil NO_3-N depletion. Reduced models were then subjected to *F* tests to determine if omitted variables had predictive power, and those with no predictive power were excluded from the final reduced models. Model significance was evaluated at $P \leq 0.001$.

Influence of Rye Growth Stage at Harvest on Soil Moisture

Soil moisture in late April and early May was similar between fallow and rye treatments at all soil depths at both Morris and St. Paul (Fig. 1). Soil moisture depletion in the rye treatment relative to the fallow was first observed at Morris on 20 May when rye had reached Zadoks 36 (stem elongation, 6th node detectable). The difference existed for both the 0- to 30-cm and 30- to 60-cm depths and persisted for the remainder of the study. At St. Paul, soil moisture depletion in the rye treatment was first observed on 14 May at the 0- to 30-cm depth (Zadoks 40, early boot) and 23 May for the 30- to 60-cm depth (Zadoks 46, late boot). Reduction in soil moisture was observed at each subsequent harvest date. The similar early-season soil moisture between treatments was not surprising, given the limited early rye growth and greater than average April precipitation at both Morris and St. Paul. Soil moisture depletion in May and June likely occurred due to both increased transpiration as the rye developed and limited rainfall. May precipitation was below average at both locations, while June precipitation was average at Morris and below average at St. Paul (Table 1). Soil moisture depletion in the 30- to 60-cm fraction indicates that rye root penetration exceeded the top 30 cm of soil. It is generally recommended that rye be harvested at boot stage (Zadoks 40-49) to optimize forage quality and quantity (9,27). Rye was near boot stage on 20 May in Morris and 14 May in St. Paul, at which point moisture had been depleted by 3.0 cm and 1.1 cm, respectively. Observed soil moisture depletion in Morris was equivalent to 6.2% of the growing season evapotranspiration (ET) for corn and 7.0% of the growing season ET for soybean (28). At St. Paul, the observed soil moisture depletion was equivalent to 2.3% and 2.6% of the growing season ET for corn and soybean, respectively (28).

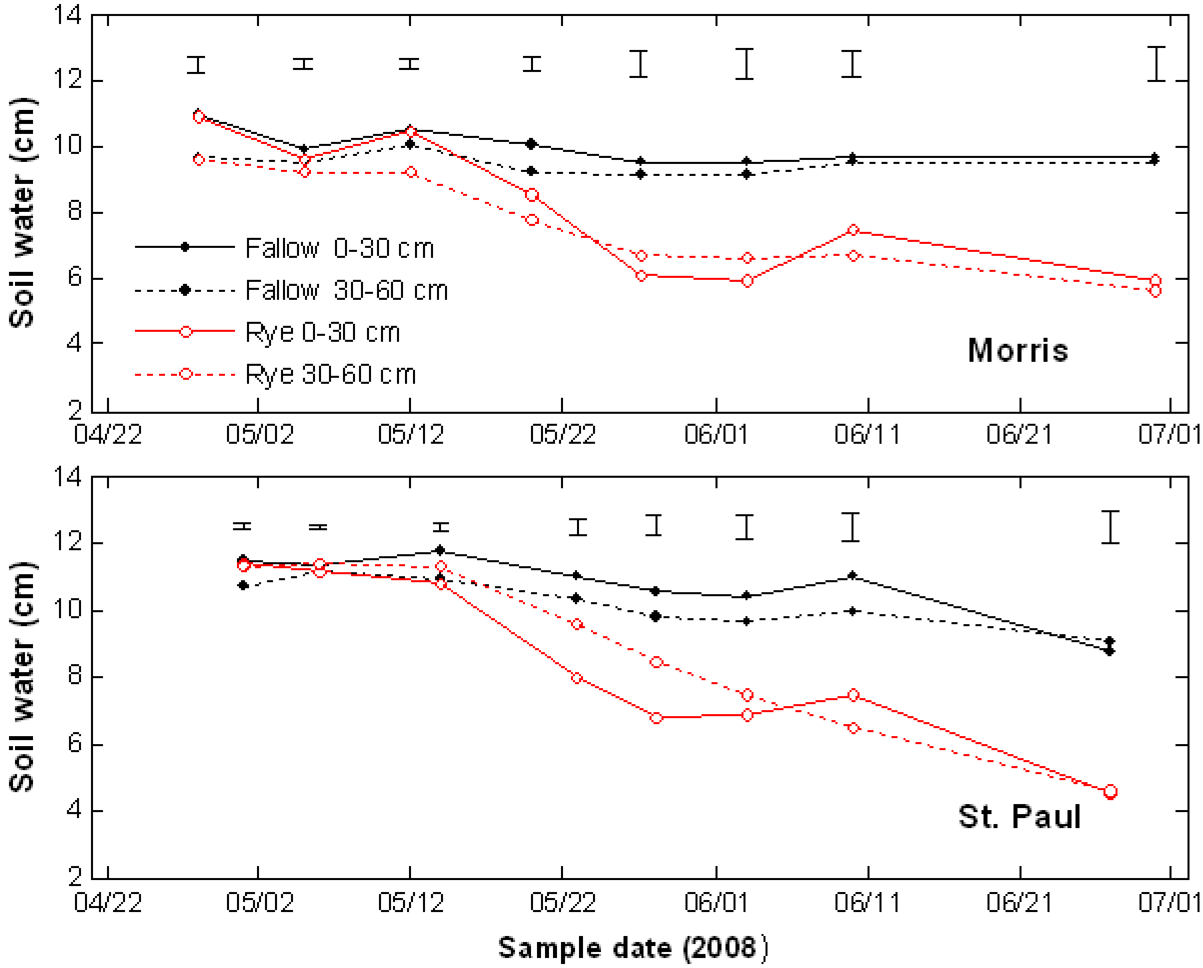

Fig. 1. Soil water (cm) in the 0- to 30-cm and 30- to 60-cm fractions for fallow and rye treatments at Morris and St. Paul, MN. Error bars represent standard error averaged across treatments for each date.

Multiple regression analysis showed that environment was not a significant predictor of soil moisture (Table 3), so data were combined across environments. A reduced model including only growth stage, precipitation, and precipitation × environment explained 84% of the variation in soil moisture. The time series of soil moisture depletion under the rye was well-described by the model with no errors larger than ± 1.6 cm (Fig. 2). These results suggest that soil moisture depletion induced by a rye cover crop can be predicted by rye growth stage and previous precipitation. The signs of partial slopes for growth stage and precipitation indicate that the more mature the rye plant and the more days since the last rain ≥ 1 cm, the greater the difference in soil water between treatments.

The usefulness of a double-cropping system of rye with corn or soybean depends on the ability to produce a subsequent crop with little or no yield loss. The negative impact of soil moisture stress on corn (7,23) and soybean yield (8) is well-established. While the most critical periods of moisture stress for both corn (1) and soybean (19) occur after vegetative development, seeding into a moisture-deficient soil may delay emergence and could increase the likelihood of soil moisture stress later in development. Depending on rye growth stage at harvest and precipitation, the reduction in soil moisture induced by the rye may impair development of the subsequent crop. An earlier rye harvest date may be employed to conserve soil moisture, but forage yield would be reduced.

Table 3. Parameter estimates, 95% confidence intervals, coefficients of determination (R^2), and *F* statistics for the full and reduced multiple regression models. The independent variables are Zadoks growth stage of rye at the time of harvest, days since last precipitation ≥ 1 cm, location, and their cross products. The dependent variable is the difference in depth of water between the rye and the fallow treatments to a depth of 60 cm.

		Parameter est.	95% conf. int.		R^2	*F**
			Lower	Upper		
Full model	Intercept	-4.09	-7.57	-0.61	0.85	52.8
	Growth stage	0.12	0.06	0.18		
	Precipitation	0.42	0.17	0.67		
	Environment	-0.39	-2.85	2.07		
	Growth stage × precipitation	-0.0004	-0.0050	0.0043		
	Growth stage × environment	0.03	-0.02	0.07		
	Precipitation × environment	-0.20	-0.33	-0.06		
Reduced model	Intercept	-4.48	-5.51	-3.45	0.84	103.4
	Growth stage	0.15	0.14	0.17		
	Precipitation	0.32	0.17	0.47		
	Precipitation × environment	-0.14	-0.21	-0.07		

* Significant at the P < 0.001 level.

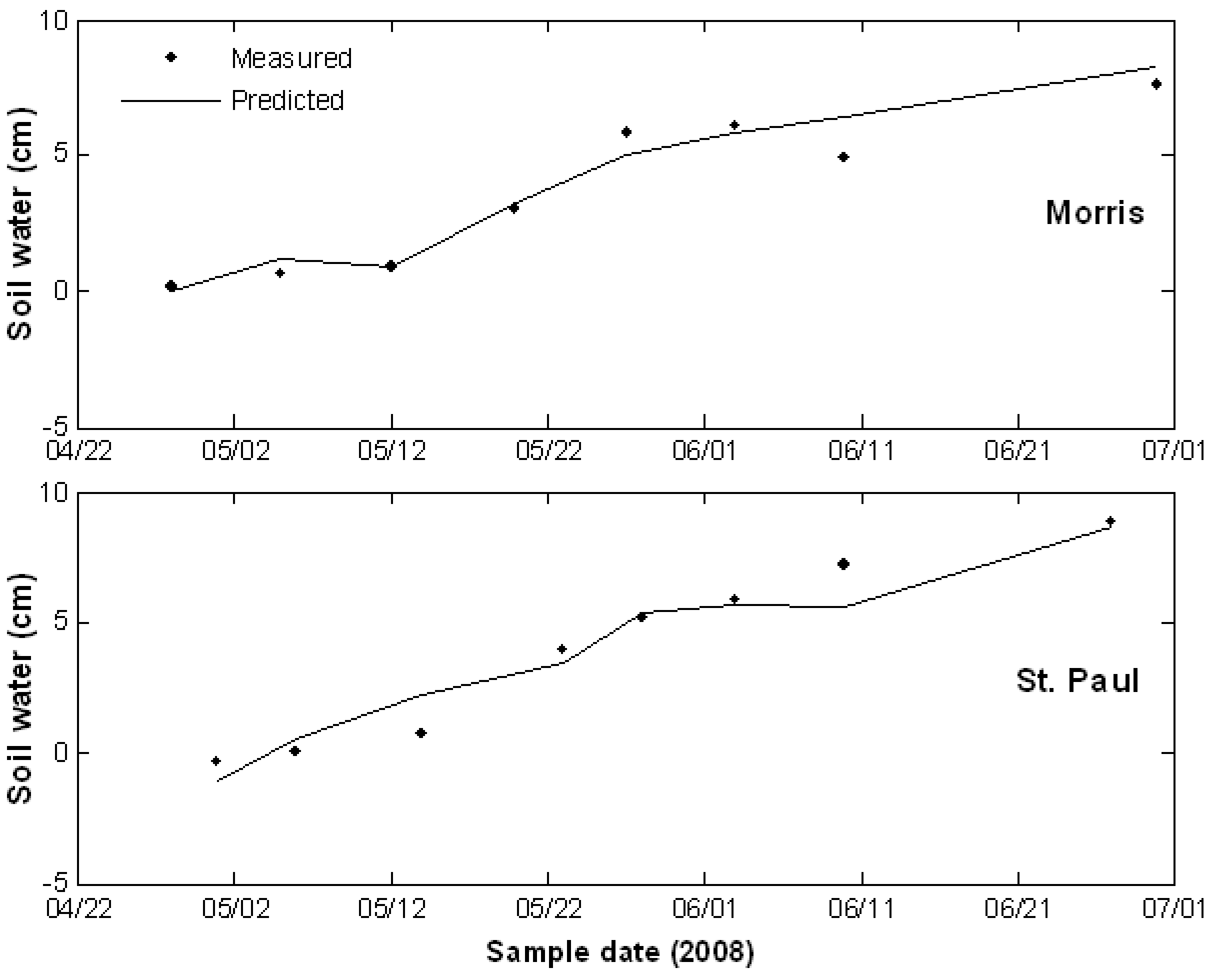

Fig. 2. Measured and predicted difference in depth of soil water to 60 cm (fallow-rye). The data are presented individually by location for clarity.

The growth characteristics of soybean may make it better suited to follow rye than corn. Soybean has been shown to have both a shallower maximum depth of rooting and a greater proportion of the root system near the soil surface than corn (3), with soil moisture use occurring at shallower depths for soybean (2). This suggests that soybean is less reliant on stored soil moisture and more reliant on within season precipitation than corn. Additionally, growing season evapotranspiration has been shown to be greater for corn than soybean (28) indicating that the total water requirement for soybean is less than corn and that soybean may be less likely to experience moisture stress from initial soil moisture depletion induced by the rye.

Influence of Rye Growth Stage at Harvest on Soil Nitrate

Unlike soil moisture, where there was no treatment effect in April and early May, a reduction in soil NO_3-N in the rye treatment relative to the fallow was observed as early as the first harvest (Fig. 3). On 28 April at Morris, soil NO_3-N in the 0- to 30-cm depth had been reduced by 75% (89.0 kg/ha) after rye (Zadoks 25, tillering). Differences were first observed in the 30- to 60-cm depth on 12 May at rye stem elongation (Zadoks 32) when a reduction in soil NO_3-N of 56% (42.2 kg/ha) was observed. Results were similar for St. Paul with a soil NO_3-N reduction after rye of 84% (65.4 kg/ha) in the 0- to 30-cm depth and 81% (179 kg/ha) in the 30- to 60-cm depth on 14 May (Zadoks 40, rye booting).

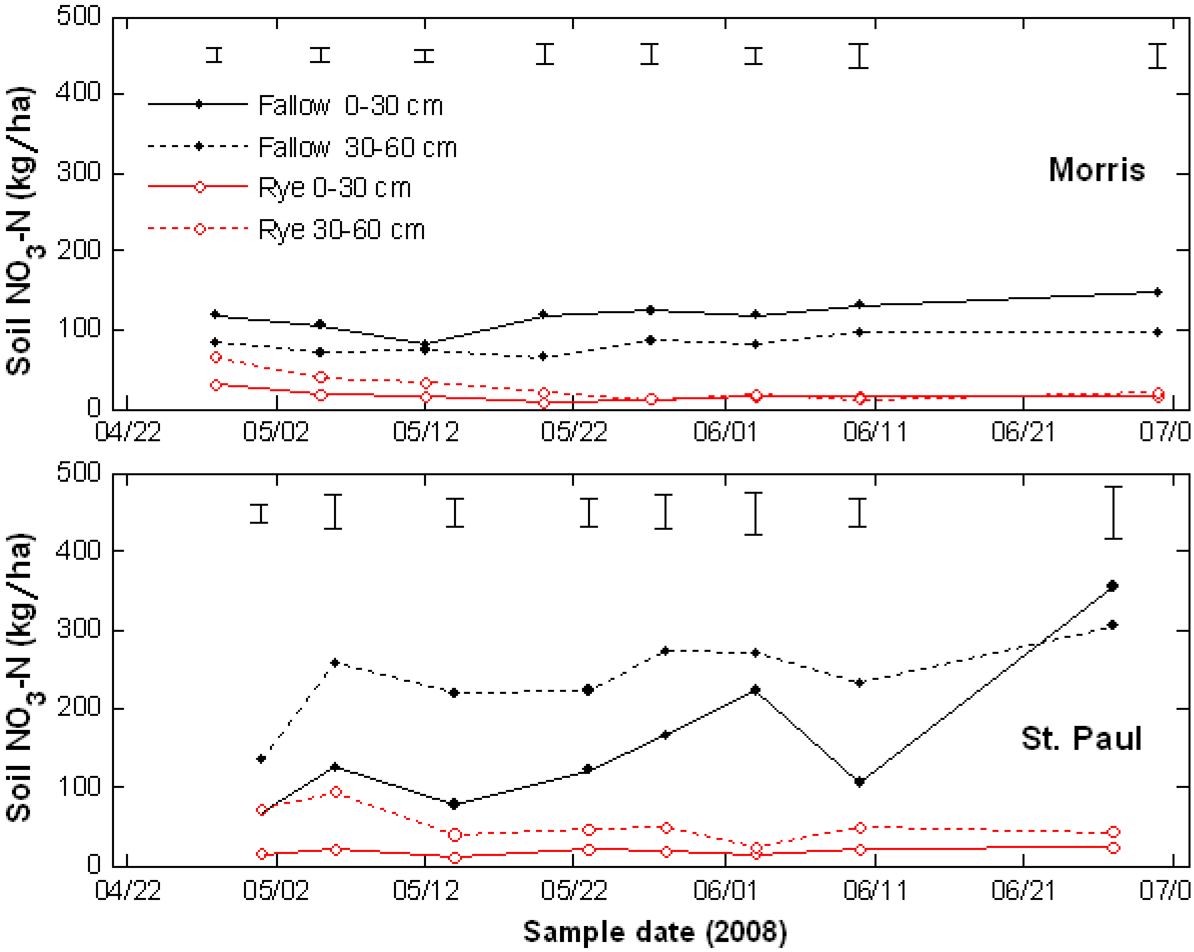

Fig. 3. Soil NO_3-N (kg/ha) in the 0- to 30-cm and 30- to 60-cm fractions for fallow and rye treatments at Morris and St. Paul, MN. Error bars represent standard error averaged across treatments for each date.

The large early-season reduction in soil NO_3-N corresponds well with previous work. Stute et al. (2007) reported spring soil NO_3-N reduction after rye of 50% (27), while Jewett and Thelen (2007) reported spring soil NO_3-N reduction of 43% (11). When rye reached boot stage, soil NO_3-N was reduced by 160 kg/ha from 0 to 60 cm compared to fallow at Morris and 245 kg/ha at St. Paul. Regardless of harvest timing, these data suggest if rye is followed by corn, supplemental nitrogen will be required to meet the N requirements of the corn crop (21). Previous work in Minnesota showed a greater than 30% decrease in corn yield for a similar reduction in available soil NO_3-N (12).

Initial multiple regression analysis of combined data from Morris and St. Paul revealed that environment affected soil NO_3-N; therefore, data were modeled separately for the two locations. At Morris, the final reduced model showed that growth stage and precipitation explained 68% of the variability in soil NO_3-N (Table 4). The time series of soil NO_3-N depletion under the rye at Morris was well-described by the model with no errors larger than ± 15 kg/ha (Fig. 4). These results suggest soil NO_3-N depletion induced by a rye can be predicted by growth stage and precipitation. The positive partial slope for growth stage indicates that the depletion in soil NO_3-N increases as the rye matures. The positive partial slope for precipitation suggests that as time increases between precipitation events, the difference in soil NO_3-N becomes larger. This may occur because samples collected after periods of limited precipitation tended to occur later in the season when the rye had more thoroughly depleted soil NO_3-N. The intercept corresponds roughly to the NO_3-N depletion induced by the rye before May.

Table 4. Parameter estimates, 95% confidence intervals, coefficients of determination (R^2), and *F* statistics for the full and reduced multiple regression models. The independent variables are Zadoks growth stage of rye at the time of harvest, days since last precipitation ≥ 1 cm and their cross product. The dependent variable is the difference in soil NO_3-N (kg/ha) between the rye and the fallow treatments to a depth of 60 cm for Morris, MN.

		Parameter est.	95% conf. int.		R^2	F*
			Lower	Upper		
Full model	Intercept	47.5	-2.27	97.3	0.69	20.4
	Growth stage	1.86	0.85	2.85		
	Precipitation	1.48	-7.4	10.4		
	Growth stage × precipitation	0.06	-0.15	0.27		
Reduced model	Intercept	37.8	3.96	71.6	0.68	31.2
	Growth stage	2.09	1.54	2.64		
	Precipitation	3.79	1.58	6.01		

* Significant at the $P < 0.001$ level

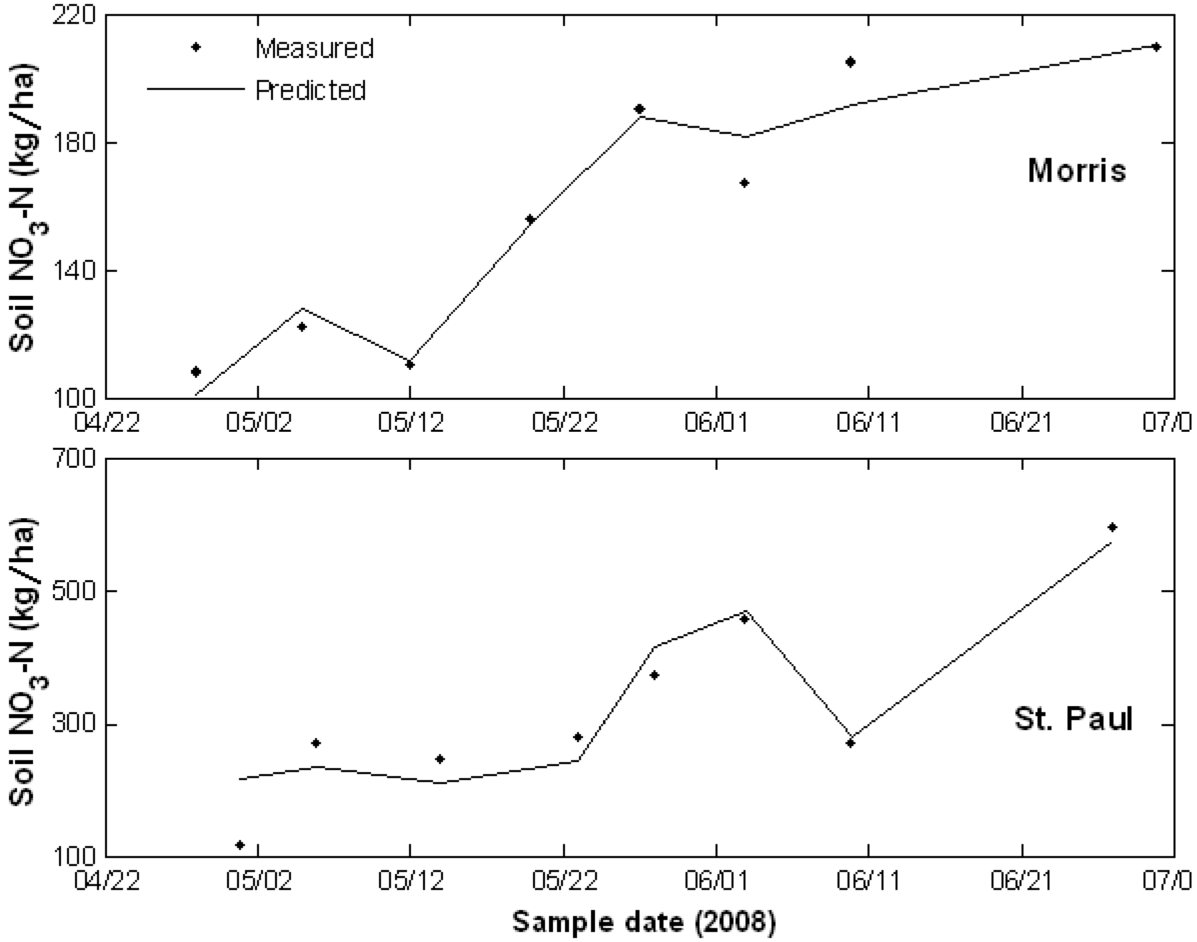

Fig. 4. Measured and predicted difference in soil NO_3-N to 60 cm (fallow-rye).

At St. Paul, precipitation and the growth stage × precipitation interaction accounted for 67% of the variability in soil NO_3-N in the final reduced model (Table 5). Measured soil NO_3-N depletion under rye showed a large deviation (99 kg/ha) from the model for the 1 May harvest, but errors were no larger than 44 kg/ha for subsequent harvest dates (Fig. 4). Surprisingly, rye growth stage was not a significant predictor of soil NO_3-N depletion at St. Paul. This may result from greater week-to-week variability in measured soil NO_3-N at St. Paul than Morris, despite Morris receiving more than 40 kg N/ha as dairy effluent more than St. Paul. It is not known how much of this variability results from natural processes, such as mineralization and leaching, and how much may be due to other factors, such as sampling strategy.

Table 5. Parameter estimates, 95% confidence intervals, coefficients of determination (R^2), and *F* statistics for the full and reduced multiple regression models. The independent variables are Zadoks growth stage of rye at the time of harvest, days since last precipitation ≥ 1 cm, and their cross product. The dependent variable is the difference in soil NO_3-N (kg/ha) between the rye and the fallow treatments to a depth of 60 cm for St Paul, MN.

		Parameter est.	95% conf. int.		R^2	F*
			Lower	Upper		
Full model	Intercept	251.7	31.2	472.3	0.67	18.6
	Growth stage	0.38	-4.14	4.90		
	Precipitation	-29.1	-52.45	-5.68		
	Growth stage × precipitation	0.60	0.17	1.02		
Reduced model	Intercept	269.2	201.4	336.9	0.67	28.9
	Precipitation	-30.7	-43.9	-17.4		
	Growth stage × precipitation	0.63	0.42	0.83		

* Significant at the $P < 0.001$ level.

The relationship between growth stage of rye at harvest and soil NO_3-N is not as strong as that for growth stage and soil moisture. This may be because much of the soil NO_3-N depletion induced by the rye occurred in the fall and spring prior to the initiation of sampling in this experiment and thus is not accounted for in the regression models. This is not true for soil moisture since spring snow melt and precipitation likely replenished any soil moisture depletion that may have occurred in the fall. This has agronomic implications. Waiting to harvest until rye reaches boot stage may come at the cost of additional soil NO_3-N depletion, but some depletion of soil NO_3-N will likely occur no matter when rye is harvested. Following the rye with a non-legume would require additional fertilizer application in the spring regardless of rye growth stage at harvest. While fertilizer was fall applied in this study, another strategy for minimizing the effect of the double-crop on soil NO_3-N may be to apply fertilizer in the spring rather than the fall.

Conclusion

Winter cover cropping can be employed in a corn-soybean rotation to mitigate some of the environmental concerns associated with the corn-soybean cropping system. The producer may regain some of the cost of cover cropping by harvesting the rye as forage. However, the soil moisture and NO_3-N depletion induced by rye may result in yield suppression of a primary crop. The focus of this research was to identify the relationship between rye growth stage at harvest and soil moisture and nitrogen status. Rye depleted soil moisture in this study beginning at or near boot stage. Reduced soil NO_3-N after rye was observed from first sampling (Zadoks 25, tillering) in late April and throughout the remainder of the study. These findings suggest that a successful double-cropping system requires skillful management. Soil moisture depletion may be avoided if rye is harvested early, but this comes at the cost of rye yield. Another strategy is to monitor precipitation and adjust harvest timing accordingly, allowing the rye to reach boot stage if conditions permit. Depletion of soil NO_3-N may be expected regardless of harvest timing. Supplemental nitrogen will be required when following rye with corn, even in systems where fertilizer has been fall applied. A spring soil nitrogen test may aid in determining application rate. In general, soybean may be a better option to follow rye than corn. Soybean relies more upon within-season precipitation and has a lower water demand than corn making soybean less susceptible to the effects of moisture depletion. Since soybean is a legume, the impact of reduced soil NO_3-N would be less on soybean than corn.

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