Cover Cropping to Reduce Nitrate Loss through Subsurface Drainage in the Northern U.S. Corn Belt

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ABSTRACT

Despite the use of best management practices for nitrogen (N) application rate and timing, significant losses of nitrate nitrogen (NO_3^-–N) in drainage discharge continue to occur from row crop cropping systems. Our objective was to determine whether a autumn-seeded winter rye (*Secale cereale* L.) cover crop following corn (*Zea mays* L.) would reduce NO_3^-–N losses through subsurface tile drainage in a corn–soybean [*Glycine max* (L.) Merr.] cropping system in the northern Corn Belt (USA) in a moderately well-drained soil. Both phases of the corn–soybean rotation, with and without the winter rye cover crop following corn, were established in 1998 in a Normania clay loam (fine-loamy, mixed, mesic Aquic Haplustoll) soil at Lamberton, MN. Cover cropping did not affect subsequent soybean yield, but reduced drainage discharge, flow-weighted mean nitrate concentration (FWMNC), and NO_3^-–N loss relative to winter fallow, although the magnitude of the effect varied considerably with annual precipitation. Three-year average drainage discharge was lower with a winter rye cover crop than without ($p = 0.06$). Over three years, subsurface tile-drainage discharge was reduced 11% and NO_3^-–N loss was reduced 13% for a corn–soybean cropping system with a rye cover crop following corn than with no rye cover crop. We estimate that establishment of a winter rye cover crop after corn will be successful in one of four years in southwestern Minnesota. Cover cropping with rye has the potential to be an effective management tool for reducing NO_3^-–N loss from subsurface drainage discharge despite challenges to establishment and spring growth in the north-central USA.

Hypoxia in the Gulf of Mexico has been indirectly linked to the load of nutrients delivered to the gulf by the Mississippi River (Rabalais et al., 2001). According to Alexander et al. (1995) the Upper Mississippi River basin, which includes a portion of Minnesota, contributes one-third of the total NO_3^-–N load in the Mississippi River. In agricultural regions, effluent from subsurface drainage systems has been identified as a major source of nitrate (NO_3^-) entering surface waters (David et al., 1997; Fenelon and Moore, 1998). Excess N in the soil profile may become immobilized and incorporated into organic compounds, or remain in the NO_3^- form and become susceptible to leaching (Gast et al., 1978; Baker and Johnson, 1981; Angle et al., 1993). In agricultural watersheds where artificial drainage is practiced, subsurface tile-drainage systems are used to increase crop productivity and reduce the risk of lowered crop yields from root zone water stress during wet years. However, these drainage systems serve as pathways through which nitrogen can be transported to streams and rivers (Cooper, 1993). Nitrate losses through subsurface tile drainage under row crop systems in the Corn Belt often are in the range of 20 to 100 kg N ha^{-1} yr^{-1} (Kladivko et al., 1991; Randall et al., 1997; Davis et al., 2000).

Cover cropping in the off-season months offers a potential solution for reducing NO_3^- leaching losses, because it can increase the amount of time the land is covered with growing vegetation. Growing cover crops remove water and nitrogen from the soil profile through transpiration and nitrogen uptake. Cover crops also have the potential to reduce soil erosion, increase soil organic matter, and suppress weed growth (Lal et al., 1991; Bowman et al., 1998). Cover crop effectiveness is related to successful stand establishment and biomass production. Stand establishment may be impeded by lack of soil moisture or adequate rainfall after seeding, reliable methods of seeding, or herbicide carryover.

Low temperatures in autumn and spring and excessive moisture in the autumn result in poor rye establishment and low dry matter yield and N uptake. Kessavalou and Walters (1997) reported low rye biomass production in one out of three years in a study in Nebraska. They attributed plant growth delay and reduced dry matter yield to below-average autumn and spring temperatures. Eckert (1988) was unable to establish a rye cover crop following corn harvest at one of two locations in Ohio due to wet autumn conditions. In contrast, Ranells and Wagger (1996) attributed higher rye biomass production in one of two years to favorable autumn precipitation and temperatures.

Cereal rye has been recognized for its potential as a scavenger of residual soil N following corn (Wagger and Mengel, 1988; Staver and Brinsfield, 1990; Reicosky and Warnes, 1991). Staver and Brinsfield (1998) observed NO_3^-–N concentrations in root zone leachate of <1 mg L^{-1} under conditions where cereal rye was planted following corn harvest in Maryland, USA. Cereal rye possessed a greater capacity to conserve residual soil nitrogen and reduce the potential for NO_3^- leaching compared with leguminous cover crops in Georgia, USA (Shipley et al., 1992). Nitrate nitrogen concentrations of leachate under corn–cereal rye were consistently lower compared with leachate collected under corn–winter fallow conditions in Georgia, USA (McCracken et al., 1994). In Iowa, researchers reported success in limiting NO_3^-–N leaching losses to <5.6 kg ha^{-1} during the non-

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Abbreviations: FWMNC, flow-weighted mean nitrate concentration; RSN, residual soil nitrate.

growing season following overseeding rye or a rye–oat (*Avena sativa* L.) mix into soybean during the growing season (Parkin et al., 1998). Success is due, in part, to water use by the rye during late fall and early spring (Prueger et al., 1998).

Much of the information on the use of cover crops in the USA comes from research in the Pacific northwest, mid-Atlantic, and southeast regions with warm, humid climates where soils remain unfrozen and the majority of nutrient losses occurs during the winter (Ditsch et al., 1993; Kuo et al., 1997; Ranells and Wagger, 1997; Clark et al., 1997; Staver and Brinsfield, 1998). Low rainfall and cool temperatures during autumn present challenges to establishing cover crops in the northern Corn Belt and successful cover crop establishment to achieve water quality goals following corn has not been evaluated. Our objective was to determine whether an autumn-seeded winter rye cover crop following corn would reduce NO_3^-–N losses through subsurface tile drainage in a corn–soybean cropping system in the northern Corn Belt (USA) in a moderately well-drained soil.

MATERIALS AND METHODS

This study was conducted from 1998 through 2002 on a moderately well-drained Normania clay loam soil at the University of Minnesota Southwest Research and Outreach Center located near Lamberton in Redwood County, southwestern Minnesota. The climate is interior continental with cold winters (−9°C) and moderately hot summers (21°C) with occasional cool periods. Total annual precipitation of 670 mm is adequate for corn and soybean production without irrigation, because 74% of this falls during the growing season from April to September. Subsurface tile drainage is necessary on most soils to optimize production practices with spring-seeded crops.

Subsurface tile-drainage systems (perforated, plastic 10-cm-diameter tube) were installed in 1972 in 15 individual 13.7- by 15.3-m plots with separate drain outlets. Subsurface tile-drainage lines were spaced to simulate 28-m spacing and buried 1.2 m deep. Individual plots were isolated to a depth of 1.8 m by trenching and installation of 12-mil-thick plastic sheeting. Soil characteristics and details of subsurface drain line installation were given by Gast et al. (1978).

This study was initiated in the autumn of 1998, and involved two cropping systems, including two phases of both cropping systems each year, replicated four times in a randomized complete block design. Treatments were performed on 16 plots, 15 with and 1 without subsurface tile drainage. One of the cropping phases without a rye cover crop contained only three replications. The two cropping systems included 2-yr rotations of (i) soybean–winter fallow then corn–winter fallow, (ii) corn–winter fallow then soybean–winter fallow, (iii) soybean–winter fallow then corn–cereal rye, and (iv) corn–cereal rye then soybean–winter fallow. Crop phases for the standard corn–soybean cropping system with no rye cover crop were labeled as either corn or soybean. Crop phases for the cropping system with a rye cover crop were labeled as $corn_{rye}$, or $_{rye}soybean$. A $corn_{rye}$ label indicated a rye cover crop was planted after corn grain harvest. The $_{rye}soybean$ label indicated that soybean was planted and grown after rye was terminated in spring. Corn and soybean were planted in 76-cm rows perpendicular to the drainage lines. Urea (134 kg N ha^{-1}) was broadcast-applied for corn each spring and incorporated within 24 h by disk cultivation. Fertilizer P and K rates for corn were determined from soil samples collected in autumn. Weeds were controlled using labeled rates of herbicides. Corn and soybean grain yields were measured at physiological maturity by harvesting four 12.2-m-long rows using a two-row combine.

Cereal rye as a cover crop was planted on 1 Oct. 1998, 29 Sept. 1999, and 4 Oct. 2000. 'Rymin' rye was seeded with a John Deere (Moline, IL) 752 no-till drill at 180 kg ha^{-1} into standing corn residue within 5 d after corn harvest. Cover crops were chemically desiccated on 30 Apr. 1999, 11 Apr. 2000, and 16 May 2001. Rye biomass samples were collected before chemical desiccation from four 0.3- by 0.3-m quadrats per plot with cover crops. This procedure was used to estimate cumulative cover crop production since planting. Rye samples were clipped at the soil surface, oven-dried for 48 h at 60°C, and weighed to estimate aboveground dry matter yield and nitrogen uptake. Samples were initially coarse-ground, mixed in a blender for 1 min, and subsampled into a 100-mL brown plastic bottle. Samples were reground in a cyclone mill with a 1-mm screen. Bottles were then placed in a plastic 120-L drum and tumbled for 15 min at 15 rpm to thoroughly mix the samples. Total N was determined with a Foss (Eden Prairie, MN) Model 6500 calibrated near infrared spectrometer scanning monochrometer.

Soil samples were collected in autumn, before rye planting, and spring, immediately before rye desiccation, to measure residual nitrate in the soil profile. Soil cores (3.8-cm diameter) were collected with a hydraulic probe to a 1.5-m depth in 30-cm increments. Three cores were collected from each plot and combined into a single sample at each depth. Soil samples for NO_3^-–N analysis were air-dried, ground to pass a 2-mm sieve, and analyzed using the colorimetric Cd-reduction method after 2 *M* KCl extraction. For calculation purposes, soil bulk density was assumed to be 1.3 Mg m^{-3}.

Rainfall was measured daily approximately 1 km from the experimental site. Tile water flow rates were determined daily, except Saturday and Sunday, by manually measuring the amount of water flowing from each subsurface drainage line during a 1-min interval. Leachate samples were collected manually in plastic bottles for NO_3^-–N analysis three times per week when flow exceeded 10 mL min^{-1}. Daily flow rate and NO_3^-–N concentration were estimated by linear interpolation between measurement dates. Leachate samples were stored frozen until subsequent laboratory analysis. Leachate was analyzed for NO_3^- + nitrite (NO_2^-)–N using the Cd-reduction method. Data are reported for (NO_3^- + NO_2^-)–N as NO_3^-–N, because we assumed the concentration of NO_2^- to be negligible. Total NO_3^-–N flux through a tile-drainage system was calculated by multiplying the interpolated daily NO_3^-–N concentration by the corresponding interpolated daily flow volume. Flow-weighted mean NO_3^-–N concentrations were calculated by dividing the sum total NO_3^-–N flux for the period of interest by the sum total flow volume for the same period of interest.

The probability of having weather conditions favorable to autumn rye establishment and spring growth was determined using 41 yr of precipitation and temperature data collected at a weather station near the experimental site. The periods of interest were October through December during cereal rye establishment after corn harvest and early autumn growth and March through May encompassing early spring growth and cover crop termination before soybean planting. Precipitation data for a 3-mo period were totaled and then subtracted from the 41-yr average for the same time period. For example, precipitation during October through December 1998 totaled 140 mm was subtracted from the 41-yr average of 102 mm resulting in a 38-mm surplus. The same procedure was used for average temperature. The resulting coordinate pairs were plotted. The likelihood of having favorable conditions for es-

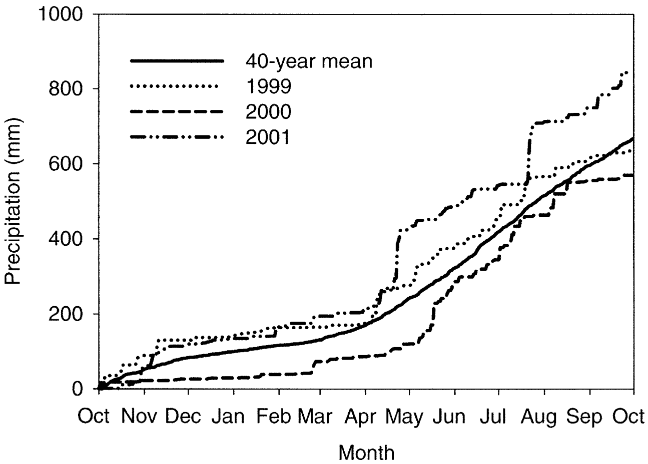

Fig. 1. Long-term mean monthly precipitation (1961–2001) and mean monthly precipitation for the period 1999–2001 at Lamberton, MN, plotted as hydrologic years (e.g., 1 Oct. 1998 through 30 Sept. 1999).

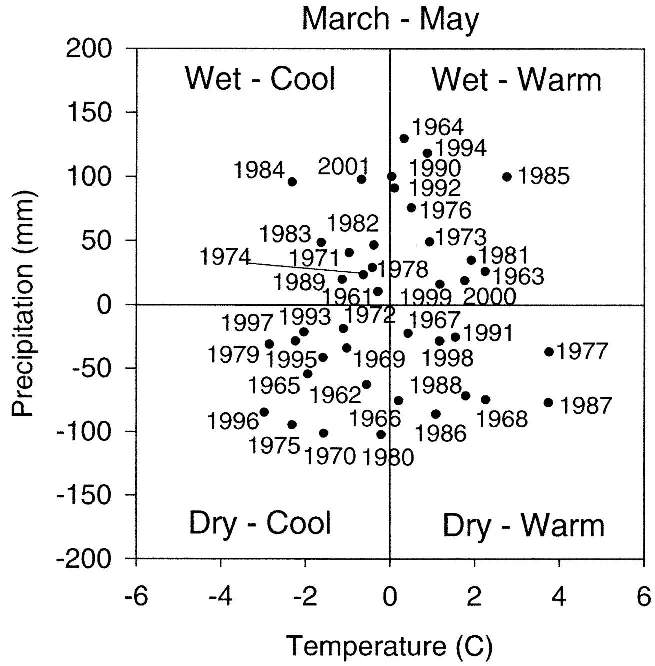

Fig. 2. Departure from the 41-yr total average precipitation versus departure from the 41-yr average air temperature for (a) October through December and (b) March through May at Lamberton, MN.

tablishing and growing a cereal rye cover crop was calculated by totaling the number of years with weather conditions similar to autumn 1998 and spring 1999, respectively, and dividing each total by 41 yr.

Statistical analyses were conducted using SAS (SAS Institute, 1989; Littell et al., 1996) MIXED procedures. For this analysis, crop phase was the fixed component and year was the random effect. Repeated measures analysis was used to account for temporal correlations between responses and application of an appropriate covariance structure so that computations and inferences about fixed effects were valid. Mean values and standard errors were determined using least square methods. Pre-planned orthogonal contrasts were used to evaluate inter- and intra-year variation between means of the different treatments. All statistical tests were performed at the $\alpha = 0.10$ level of significance.

RESULTS AND DISCUSSION

Precipitation

Precipitation, given on a hydrologic year basis, was highly variable during the 3-yr study period (Fig. 1), including a below-average year (2000), an average year (1999), and an above-average year (2001). Air temperature was also variable during the study period (Table 1). At this northern U.S. location, a combination of warmer than normal air temperatures and near-average precipitation in autumn and spring is conducive to winter cover crop establishment and growth. In contrast, lower than normal air temperatures coupled with either unusually wet or below normal precipitation at cover crop planting could result in poor cover crop stand establishment. Similar conditions in spring would also result in poor cover crop growth. This 3-yr study period provided an opportunity for field evaluation of cover cropping in the northern Corn Belt under contrasting growing conditions.

Weather conditions during autumn 1998 and spring 1999 were favorable for establishing and growing a cereal rye cover crop. Weather conditions at the Southwest Research and Outreach Center similar to those in autumn 1998 occurred nine times during the 41-yr period of record and spring conditions similar to those in 1999 occurred 11 times (Fig. 2). The probability of favorable conditions for establishing and growing a cereal rye cover crop for these two time periods and from this limited data set was 25%.

Corn and Soybean Yield and Rye Biomass Production

Corn and soybean grain yields were influenced by weather conditions and planting dates. Corn and soybean yield varied from year to year, but within each year, there were no statistically significant differences among cropping systems (Table 2). The cropping system with a rye cover crop following corn showed no yield disadvantage for the subsequent soybean crop. Yield

Table 1. Long-term mean monthly temperatures (1961–2001) and mean monthly temperatures for the period 1999–2001 at Lamberton, MN.

	Mean monthly temperature								
Year	September	October	November	December	January	February	March	April	May
	°C								
41-yr Mean	16	9	0	−8	−11	−8	−1	7	15
1998–1999	19	11	2	−4	−12	−3	1	8	16
1999–2000	16	8	5	−4	−10	−3	4	7	16
2000–2001	15	10	−2	−15	−7	−13	−4	7	15

Table 2. Mean corn and soybean yield by cropping system in tile-drained plots at Lamberton, MN.

Crop phase	Yield 1999	Yield 2000	Yield 2001
	Mg ha^{-1}		
Soybean	2.7a (0.2)†	3.5a (0.2)	3.1a (0.2)
Rye and soybean‡	2.7a (0.2)	3.4a (0.2)	3.1a (0.2)
Corn	10.0a (0.3)	9.8a (0.2)	7.4a (0.3)
Corn and rye§	9.6a (0.2)	9.7a (0.2)	7.6a (0.2)

† Values within parentheses are standard errors of the mean. Values within a column followed by the same letter are not different at the 0.1 probability level of significance using planned orthogonal contrasts. Yields within a row are for the listed crop phase.
‡ Soybean planted and grown after rye termination in spring.
§ Rye cover crop planted after corn grain harvest.

variability among years was attributed to differences in weather conditions. In 1999, moderately late planting (14 May) and abnormally dry conditions late in the growing season contributed to low soybean yields. In 2000, early planting (5 May) and timely growing season precipitation contributed to high soybean yields. In 2001, very late planting (29 May) coupled with cool, wet early season growing conditions limited soybean yields. Corn was planted within 2 d of soybean each year. In Minnesota, corn and soybean planting generally occurs from 15 April to 15 May and 1 May to 30 May, respectively. Dates of planting overlap for corn and soybean and they vary from year to year depending on weather conditions. Weather conditions and planting dates did not adversely affect corn yields in 1999 and 2000, but considerable corn yield loss occurred in 2001 due to cool and wet early-season growing conditions that delayed corn germination, and modest stalk lodging after high winds later in the season.

Similar to grain yields, cover crop biomass production and N content of the biomass were influenced by weather conditions. Cover crop biomass yield varied from year to year, with 1998–1999 having considerably more biomass than 1999–2000 or 2000–2001 (Table 3). As rye biomass production decreased, N concentration in the biomass increased. Growing conditions in autumn 1998 were favorable for rye cover crop establishment and growth (Table 1, Fig. 1). Above-normal precipitation and temperatures during March and April resulted in vigorous cover crop aboveground biomass production in 1999. Abnormally dry conditions during autumn 1999 through spring 2000 limited cover crop biomass production in 2000, while abnormally cool conditions during early spring coupled with late snow melt limited cover crop biomass production in 2001.

Table 3. Mean rye biomass production and nitrogen concentration in tile-drained plots at Lamberton, MN.

Year	Dry mass	N concentration
	Mg ha^{-1}	%
1998–1999	2.7 (0.2)†	2.5 (0.2)‡
1999–2000	1.0 (0.1)	2.7 (0.1)
2000–2001	0.5 (0.1)	3.8 (0.4)

† Values within parentheses are standard errors of the mean.
‡ The 1999 N concentration data are estimated.

Residual Soil Nitrate Nitrogen

Residual soil nitrate (RSN) in the 0- to 1.5-m soil profile for spring and autumn varied among years and within each year as well as among cropping phases (Table 4). In Table 4, residual soil nitrate values within a column are for the crop year (January–December). Significant differences in RSN between crop phases occurred in spring and autumn 1999. Favorable climatic conditions promoted vigorous rye growth in spring 1999, resulting in significant reductions in RSN in the soil profile. Autumn RSN levels from 1999 resulted in typical carryover of soil NO_3^-–N from 1999 to 2000. Near normal growing season precipitation (Table 1, Fig. 1) coupled with favorable conditions for N mineralization resulted in high levels of RSN in the soil profile in fall 2000 (Table 4). Above average precipitation during autumn 2000 through spring 2001 resulted in considerable loss of NO_3^-–N from the soil profile with drainage discharge for all cropping systems.

Drainage Discharge

Subsurface tile-drainage discharge began in mid- to late March and continued, sometimes sporadically, until late July or early August all three years of the study. Drainage discharge was influenced by annual precipitation and cropping system (Table 5). Data within columns are for the calendar year. Losses within a year reflect spring losses from the previous crop and early summer losses from the current crop. Cover cropping with rye reduced drainage discharge relative to winter fallow, although the magnitude of the effect varied with annual precipitation. Near normal precipitation in autumn 1998 (Fig. 1) through spring 1999 resulted in sufficient soil water recharge of the soil profile and typical drainage discharge during 1999. Abnormally dry conditions in autumn 1999 through spring 2000 resulted in reduced soil water recharge of the soil profile and limited drainage discharge during 2000. Drainage discharge occurred on only 14 d during late May and early June 2000, and coincided with heavy rainfall events. Above-average precipitation in autumn 2000 through spring 2001 resulted in excess soil water in the soil profile and considerable drainage discharge during 2001.

Cover cropping with cereal rye significantly reduced drainage discharge during 1999 for the subsequent $_{\text{rye}}$soybean crop phase compared no cover crop for when favorable weather conditions existed for rye establishment (1998) and biomass production (1999) (Table 5). Three-year average drainage discharge was higher for soybean compared with both crop phases that included a rye cover crop after corn ($p = 0.06$) (Fig. 3). Associated error bars are large due to considerable year-to-year variation in precipitation and subsequent drainage discharge between 1999 and 2001. Introducing a cereal rye winter cover crop after corn reduced subsurface drainage by 11% during a conventional 2-yr corn–soybean cropping system at this location. Rye presumably reduced drainage discharge through water uptake and evapotranspiration.

Table 4. Residual NO_3^-–N in the 1.5-m soil profile as influenced by crop phase at Lamberton, MN.†

	1998	1999		2000		2001
Crop phase	Autumn	Spring	Autumn	Spring	Autumn	Spring
	kg ha^{-1}					
Corn	82a (3)‡	60ab (2)	60a (4)	61a (10)	108a (5)	55a (2)
Soybean	67a (2)	73a (2)	58ab (4)	67a (7)	91a (4)	68a (1)
Corn and rye§	66a (4)	72a (1)	53ab (4)	56a (4)	99a (3)	75a (1)
Rye and soybean¶	69a (1)	28b (4)	40b (2)	58a (12)	102a (2)	60a (2)

† Date are for listed calendar year.
‡ Values within parentheses are standard errors of the mean. Values within a column followed by the same letter are not different at the 0.1 probability level of significance using planned orthogonal contrasts. Residual soil nitrate values within a row are for the listed crop phase.
§ Rye cover crop planted after corn grain harvest.
¶ Soybean planted and grown after rye termination in spring. No rye was planted before soybean in autumn 1998.

Nitrate Nitrogen Concentration and Loss

The FWMNC and quantity of NO_3^-–N discharged with drainage water varied with annual precipitation (Table 5). Losses within a year reflect spring losses from the previous crop and early summer losses from the current crop. For example, NO_3^-–N loss from the soybean crop phase includes spring losses after the previous corn crop and early summer losses from the current soybean crop. The 3-yr average NO_3^-–N loss in drainage discharge was significantly higher for soybean than corn, $_{rye}$soybean, and corn$_{rye}$ (p = 0.004) (Fig. 4). Similar NO_3^-–N loss from corn (i.e., the loss during the hydrologic year following soybean during which corn is grown) for both cropping systems is not unexpected since residual soil NO_3^-–N tends to be lower following soybean than corn in a conventional cropping system (Table 4). Compared with a conventional corn–soybean cropping system with no cover crop over the 3-yr period, NO_3^-–N loss was reduced by 13% by adding a rye cover crop.

Depending on cropping phase and year, FWMNC from subsurface tile drainage ranged from 1 to 19 mg L^{-1} (Table 5). Significant differences between cropping phases occurred in 1999 and 2000. Notwithstanding variations in annual precipitation and drainage discharge, FWMNC values remained relatively consistent among cropping phases from year to year except during 2000, a year of unusually low drainage discharge.

Nitrate nitrogen losses measured in drainage discharge ranged from 0 to 54 kg ha^{-1} (Table 5). Because N fertilizer was applied in spring, this timing may have decreased NO_3^-–N loss from drainage discharge compared with autumn-applied N fertilizer, a common management practice in southwestern Minnesota. Over a 5-yr period in Minnesota, NO_3^-–N losses in drainage discharge from a conventional corn–soybean cropping system totaled 436 kg ha^{-1} for fall-applied N and 362 kg ha^{-1} for spring-applied N (Randall et al., 2003). Significant differences in NO_3^-–N loss between cropping phases occurred in two of three years in our study. The greatest NO_3^-–N loss was found in drainage discharge in soybean after corn in 1999 and 2001 (Table 5). Above-average precipitation, higher drainage discharge, and higher RSN (Table 4) contributed to the greatest NO_3^-–N loss in drainage discharge occurring during 2001 for all cropping phases. Higher RSN was attributed to a combination of carryover of unused fertilizer from the previous dry year and mineralization. Potential soil mineralization was not measured in this study, but our results are similar to those of Randall (1998), who found RSN buildup during dry years and large NO_3^-–N loss and high flow volume from subsurface drainage in subsequent wet years.

CONCLUSIONS

Our objective was to determine whether a rye cover crop following corn in the corn–soybean cropping system in Minnesota, USA, reduced NO_3^-–N loss in subsurface drainage discharge. Averaged across three years, the cropping system with a rye cover crop reduced subsurface drainage discharge by 11% and NO_3^-–N loss in subsurface drainage discharge by 13% compared with the cropping system with no cover crop in this study. Within certain years, relative to precipitation and temperature, rye cover cropping reduced RSN, drainage discharge, FWMNC, and NO_3^-–N loss. Extremes in temperature and precipitation in autumn and/or spring can

Table 5. Drainage discharge and total NO_3–N concentrations and losses from two crop rotations at Lamberton, MN.†

	1999			2000			2001		
Crop phase	Drainage	Concentration‡	Loss	Drainage	Concentration‡	Loss	Drainage	Concentration‡	Loss
	mm	mg L^{-1}	kg ha^{-1}	mm	mg L^{-1}	kg ha^{-1}	mm	mg L^{-1}	kg ha^{-1}
Corn	185a (19)	13b (2)	24b (4)	9.40a (2)	12a (2)	1.20a (0.3)	464b (54)	11a (2)	46a (4)
Soybean	189a (21)	19a (2)	35a (4)	0.25b (2)	17a (3)	0.04b (0.3)	506a (60)	10a (2)	54a (4)
Corn and rye§	166a (19)	14b (2)	24b (4)	0.10b (2)	2b (2)	0.00b (0.3)	428b (54)	12a (2)	46a (4)
Rye and soybean¶	147b (19)	12b (2)	18b (4)	0.30b (2)	1b (2)	0.00b (0.3)	463b (54)	11a (2)	53a (4)

† Values within parentheses are standard errors of the mean. Values within a column followed by the same letter are not different at the 0.1 probability level of significance using planned orthogonal contrasts. Discharge, nitrate nitrogen concentration, and loss values within a row are for the listed crop phase. Data in a year reflect spring losses from the previous crop and early summer losses from the current crop.
‡ Concentrations are flow-weighted mean values.
§ Rye cover crop planted after corn grain harvest.
¶ Soybean planted and grown after rye termination in spring.

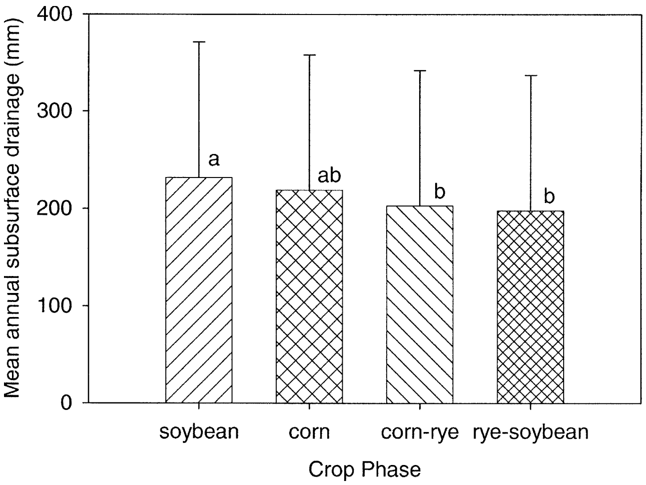

Fig. 3. Mean annual subsurface drainage discharge as influenced by cropping phase with and without a winter rye cover crop from 1999 to 2001 at Lamberton, MN. Error bars represent standard errors of the least-square means of treatments. Letters above the bars represent statistically significant groups. Treatments with the same letter are not different (*t* test, pairwise comparison, $\alpha = 0.1$).

significantly improve or reduce cover crop establishment and biomass production in the northern Corn Belt. Data from southwestern Minnesota suggest that winter rye will be a successful cover crop for reducing NO_3^-–N losses in one of four years. Some of this relatively low success rate is due to years with low leaching potential, while the remainder is due to inadequate rye establishment and growth. Research is in progress to predict cover crop establishment and growth in Minnesota.

Cover cropping has the potential to be a useful management tool for reducing NO_3^-–N loss from subsurface drainage discharge, given appropriate weather and management considerations. Not every farm operation or every production field will require or benefit from the use of cover cropping. There are cost and logistical obstacles to overcome before widespread adoption and implementation of cover cropping. However, as farm managers and policymakers contemplate management options for improving water quality while maintaining farm enterprise profitability, the benefits of winter cover cropping for improved water quality should be considered.

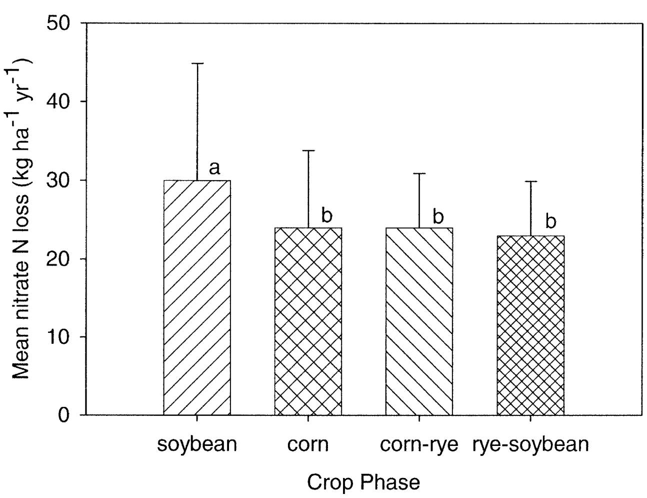

Fig. 4. Mean annual NO_3^-–N loss in drainage discharge as influenced by cropping phase with and without a winter rye cover crop from 1999 to 2001 at Lamberton, MN. Error bars represent standard errors of the least-square means of treatments. Letters above the bars represent statistically significant groups. Treatments with the same letter are not different (*t* test, pairwise comparison, $\alpha = 0.1$).

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