Nitrate-Nitrogen Losses through Subsurface Drainage under Various Agricultural Land Covers

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Nitrate-nitrogen (NO_3–N) loading to surface water bodies from subsurface drainage is an environmental concern in the midwestern United States. The objective of this study was to investigate the effect of various land covers on NO_3–N loss through subsurface drainage. Land-cover treatments included (i) conventional corn (*Zea mays* L.) (C) and soybean [*Glycine max* (L.) Merr.] (S); (ii) winter rye (*Secale cereale* L.) cover crop before corn (rC) and before soybean (rS); (iii) kura clover (*Trifolium ambiguum* M. Bieb.) as a living mulch for corn (kC); and (iv) perennial forage of orchardgrass (*Dactylis glomerata* L.) mixed with clovers (PF). In spring, total N uptake by aboveground biomass of rye in rC, rye in rS, kura clover in kC, and grasses in PF were 14.2, 31.8, 87.0, and 46.3 kg N ha^{-1}, respectively. Effect of land covers on subsurface drainage was not significant. The NO_3–N loss was significantly lower for kC and PF than C and S treatments ($p < 0.05$); rye cover crop did not reduce NO_3–N loss, but NO_3–N concentration was significantly reduced in rC during March to June and in rS during July to November ($p < 0.05$). Moreover, the increase of soil NO_3–N from early to late spring in rS was significantly lower than the S treatment ($p < 0.05$). This study suggests that kC and PF are effective in reducing NO_3–N loss, but these systems could lead to concerns relative to grain yield loss and change in farming practices. Management strategies for kC need further study to achieve reasonable corn yield. The effectiveness of rye cover crop on NO_3–N loss reduction needs further investigation under conditions of different N rates, wider weather patterns, and fall tillage.

Nitrate-nitrogen (NO_3–N) is a main source of pollution for both shallow groundwater and surface water bodies. Twenty percent of shallow wells sampled in agricultural areas exceeded the drinking water standard of 10 mg N L^{-1} for NO_3–N in the United States (Hamilton et al., 2004). A statewide rural well water survey in Iowa in 1988 and 1989 showed that 18% of Iowa's private rural drinking wells exceeded the USEPA maximum contaminant level (MCL) of 10 mg N L^{-1} for NO_3–N (Kross et al., 1990). Nitrate-N loading from the Mississippi River is suspected to be a main contributor to the hypoxic zone in the Gulf of Mexico (Rabalais et al., 2001). The main source of NO_3–N in the Mississippi River Basin has been linked to subsurface drainage in the Midwest (Lowrance, 1992; Keeney and DeLuca, 1993; David et al., 1997; Zucker and Brown, 1998). The mass of NO_3–N loss is closely related to subsurface drainage volume (Baker et al., 1975; Cambardella et al., 1999), with April, May, and June being found to be the main subsurface drainage period in Iowa. During these 3 mo, nearly 70% of the annual drainage occurred in north-central Iowa (Helmers et al., 2005).

Alternative land covers may change the N input and water and N consumption patterns, which have potential to affect NO_3–N loss through subsurface drainage. Annual cover crops, perennial living mulches, and perennial forage are promising land covers for reducing NO_3–N loss in Iowa because they can grow in the spring when corn and soybean have not been planted or established.

Rye is one of the main annual winter cover crops; it is a cereal that has excellent weather hardiness and the ability to grow on soils with marginal fertility (Bushuk, 2001). Research on the reduction of subsurface drainage and NO_3–N loss by winter rye cover crop, however, is limited in the Midwest. Under a controlled indoor environment, Logsdon et al. (2002) and Parkin et al. (2006) demonstrated reduction of drainage and NO_3–N leaching by winter rye cover crop. Reduction of drainage and soil water content in rye was also observed in a field study using confined nonweighing lysimeters (Qi and Helmers, 2010). In field studies on a plot scale, Strock et al. (2004) found that drainage and NO_3–N loss in rye treatments were reduced by 11 and 13%, respectively. Kaspar et al. (2007) reported that the difference was not significant between cumulative drainage in rye and control treatments, but the rye cover crop decreased the flow-weighted average NO_3–N concentration (FWANC) by 59% and NO_3–N loss by 61%.

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Abbreviations: ADWQ-RDS, Agricultural Drainage Water Quality–Research and Demonstration Site; C, corn; FWANC, flow-weighted average nitrate-nitrogen concentration; kC, kura clover + corn; MCL, maximum contaminant level; PF, perennial forage; rC, rye–corn; rS, rye–soybean; S, soybean.

Living mulches are cover crops planted either before or with a main crop and maintained as a living ground cover throughout the growing season (Hartwig and Ammon, 2002). Living mulches can reduce erosion, suppress weeds, and in the case of legumes, benefit N cycling. Italian ryegrass (*Lolium multiflorum* Lam.), alfalfa (*Medicago sativa* L.), and kura clover are examples of living mulches. With suppression and careful management, kura clover in corn did not reduce the whole-plant biomass and grain yield (Zemenchik et al., 2000) in the north-central United States, especially if herbicide-resistant corn was planted (Affeldt et al., 2004). However, information is quite limited concerning the effect of kura clover with corn system on NO_3–N leaching from tile drains in the Midwest.

Perennial forage grassland has been reported to be the most-effective agricultural land cover in reducing N loss through subsurface drainage (Baker and Melvin, 1994; Randall et al., 1997; Kanwar et al., 2005). Randall et al. (1997) reported that row crop systems showed 1.6 times higher drainage flow and about 35 times higher NO_3–N loss than alfalfa treatment and Conservation Reserve Program (grass-based) system over a 6-yr study in southwestern Minnesota. In Iowa, large-scale prairie restoration from row crop production showed less NO_3–N export in a paired watershed study (Schilling, 2002). Baker and Melvin (1994) documented that the NO_3–N concentration in tile drainage from alfalfa was much lower than that from corn or soybean. Kanwar et al. (2005) reported that reduction of FWANC was significant in alfalfa and strip intercropping systems (corn–soybean–oat [*Avena sativa* L.) compared with conventional corn–soybean rotation, but the reduction of NO_3–N loading mass was offset by elevated drainage flow volume. However, limited information is available concerning the impact of orchardgrass mixed with clovers as perennial forage cover on subsurface drainage and NO_3–N leaching in the Midwest.

To gain a better understanding of the effect of various land covers on NO_3–N loss, a field experiment was conducted in north-central Iowa with conventional corn–soybean rotation, a winter rye cover crop in a corn–soybean rotation, kura clover as a living mulch for corn, and a perennial forage. The objectives of this study were (i) to quantify the spring N uptake and summer crop production under different land covers and (ii) to evaluate the impact of different land covers on NO_3–N in subsurface drainage and the soil profile.

Materials and Methods

Site Description

The field study was conducted at the Agricultural Drainage Water Quality–Research and Demonstration Site (ADWQ-RDS, former Agricultural Drainage Well Site, 42°45′ N, 94°30′ W) near Gilmore City in Pocahontas County, Iowa. Weather data were recorded by an automatic meteorological station at the site. Rainfall patterns and temperature at the site were compared to long-term values (a 30-yr average from 1971 to 2000) determined from readings at the National Climate Data Center stations of Pocahontas (COOP ID 136719) and Humboldt (COOP ID 133985), located 19 km west and east of the research site, respectively. The size of each plot is 38 by 15.2 m. Corrugated plastic drain tiles were installed parallel to the long dimension through the center of each plot and on the borders between plots (7.6-m spacing) at a depth of 1.06 m. Drainage water from each center line was collected in an aluminum culvert with automatic pumping, flow volume monitoring, and water sampling systems. Detailed descriptions of the water pumping and sampling systems can be found in Lawlor et al. (2008).

The field experiment was initiated in the fall 2004, but we excluded results from 2005 from this paper because it was considered a transition year. Land covers, tillage, and seed rates are presented in Table 1. Land cover treatments were (i) conventional corn (DEKALB 50-45)–soybean (Pioneer 92M40-Group 2 middle season) rotation fallowed in winter and spring (C and S), (ii) winter rye cover crop before corn–soybean rotation (rC and rS), (iii) corn with established kura clover as a living mulch (kC), and (iv) perennial forage (PF) of orchardgrass mixed with clovers. The experiment plots were laid out in a completely randomized block design. The field plots were grouped into four blocks by drainage characteristics based on the long-term drainage performance: high, medium-high, medium-low, and low drainage blocks. One plot in each block was randomly assigned to each treatment (6 treatments × 4 blocks). The C and S treatments were rotated every year as were the rC and rS treatments, so the resulting four cropping sequences were CSCS, SCSC, rCrSrCrS, and rSrCrSrC during the 4 yr of study from 2006 through 2009.

In spring, glyphosate was applied in the rC and rS plots to terminate rye growth. Glyphosate-resistant corn and soybean were used, and planting dates were dictated by field conditions. Corn planting in the kura clover plots started in 2007, giving a 2-yr (2005 and 2006) period for kura clover

Table 1. Crop grown, tillage, and seeding rate in conventional corn (C) and soybean (S), rye-corn (rC), rye-soybean (rS), kura clover + corn (kC), and perennial forage (PF) treatments.

Treatment	Land covers		Tillage		Seeding rate
	Spring	Summer	Spring	Fall	
C	fallow	corn	field cultivating	chisel plow	77,000 seeds ha^{-1} for corn
rC	rye	corn	field cultivating	tandem disk	100 kg ha^{-1} for rye and 77,000 seeds ha^{-1} for corn
S	fallow	soybean	field cultivating	tandem disk	439,750 seeds ha^{-1} for soybean
rS	rye	soybean	field cultivating	tandem disk	100 kg ha^{-1} for rye and 439,750 seeds ha^{-1} for soybean
kC	kura clover	kura clover & corn†	no-till	no-till	13 kg ha^{-1} for kura clover
PF	perennial forage	perennial forage	no-till	no-till	9.0 kg ha^{-1} for red clover, 0.6 kg ha^{-1} for ladino clover and 4.5 kg ha^{-1} for orchardgrass

† Corn was planted in kura clover plots 2007, 2008, and 2009, not in 2006.

to establish according to recommended management. After corn planting, the entire kura clover plots were suppressed by glyphosate in 2007 and the plots were band sprayed in 2008 and 2009. Commercial-grade 28% aqueous ammonia-nitrogen was applied at 140 kg N ha^{-1} in the spring closely following corn emergence to corn field including C, rC, and kC plots. The application rate is within the recommended rates of 112 to 168 kg N ha^{-1} for corn following soybean (Blackmer et al., 1997). Nitrogen fertilizer was applied mid-row to corn with a conventional knife applicator. For weed control in all corn and soybean plots, glyphosate was subsequently applied twice more during the growing season, as dictated by weed pressure. To determine the crop yield, 12 rows of corn and soybean out of 20 rows in each plot were harvested by a combine. Grain seed was weighed and sampled to determine water content of the seeds for each pass. Forage plots were mowed and baled once or twice a year but were not grazed by animals. Similar operations were followed in all years; agronomic timing details are included in Table 2.

Biomass and Soil NO_3–N

Aboveground rye shoots were sampled weekly from early April until chemically desiccated with glyphosate. Weekly sampling of kura clover and forage shoots coincided with rye sampling and continued until late June. From July until early October, corn and soybean were sampled once every 3 wk. Row crops such as rye, corn, and soybean were sampled along a 30-cm-long section at four randomly selected locations; kura clover and forage were sampled using a 30-by-30-cm area randomly selected at three locations in each plot. Samples were dried at 60°C for a week for dry biomass determination. Corn ears and stalk were separated for the analysis of N concentration while each of other crops was grounded and analyzed for the plant as a whole. The N concentration in biomass was analyzed in the Soil Plant Analysis Laboratory at Iowa State University by the dry combustion method using a TruSpec CN Analyzer (LECO Corp., MI).

In 2007 to 2009, soil cores with a 2-cm diameter were sampled for soil NO_3–N analysis at three times: early spring (before the start of spring cover growth), late spring (right before corn or soybean planting), and late fall (after corn and soybean harvest). In each plot, soil cores were extracted by a JMC soil sampler (Clements Associations Inc., Newton, IA) at four evenly distributed locations along the plot diagonal at three depths (0–15, 15–30, and 30–60 cm) with samples from each depth being combined. Nitrate-N was extracted from soil samples and was reduced to nitrite (NO_2–N) by passing through a copper/cadmium column. Nitrite is diazotized with sulfanilamide and then reacts with a reagent to form a colored (pink to red) compound, which is subsequently measured by a colorimeter (Lachat QuickChem 8000 Automated Ion Analyzer, Milwaukee, WI).

Subsurface Drainage, NO_3–N Concentration, and NO_3–N Loss

For each plot, a flow meter was used to measure the subsurface drainage flow volume and the meter reading was manually recorded on a weekly or biweekly basis. A fraction of the drainage flow was directed to a 20-L carboy through a plated orifice nozzle for sample collection. The drainage water pumping and water sampling system is documented in Lawlor et al. (2008). Subsamples of the drainage water were collected after approximately every 1.3 cm of drainage flow, and thereafter were stored in a cooler at 4°C until analyzed. Nitrate-N concentration was analyzed in the Wetland Research Laboratory, Iowa State University, through the second-derivative spectroscopy technique (Crumpton et al., 1992). Nitrate–N concentration was multiplied by the representative drainage volume to calculate the NO_3–N loss of each incremental drainage flow in each plot. Cumulative NO_3–N losses were calculated by summing across all incremental NO_3–N loss in March to June, July to November, and a whole calendar year. Flow-weighted average NO_3–N concentration (FWANC) was calculated by dividing the cumulative NO_3–N loss by the subsurface drainage volume.

Statistical Analysis

The corn–soybean rotation treatments were separately analyzed in corn or soybean phase. Six types of land covers, C, rC, S, rS, kC, and PF, were considered the treatment factor in this study. Crop biomass and yield, N uptake, subsurface drainage volume, FWANC in the subsurface drainage, NO_3–N loss, soil NO_3–N, and the increase of soil NO_3–N were analyzed as a completely randomized block design with the GLIMMIX macro in conjunction with the PROC MIXED procedure in SAS 9.1 software (Littell et al., 2006). Because subsurface drainage may not occur in all plots during the same period, the NO_3–N concentration data were unbalanced. The

Table 2. Agronomic field activity timing.

Activity	2005	2006	2007	2008	2009
Termination of rye followed by corn	30 Apr.	24 Apr.	30 Apr.	6 May	8 May
Field cultivating & corn planting	10 May	4 May	14 May	15 May	19 May
Field cultivating & soybean planting	18 May	10 May	17 May	23 May	20 May
Termination of rye followed by soybean	20 May	16 May	23 May	26 May	31 May
Suppression of kura clover	–†	–	29 May	26 May	14 May
Fertilization to corn	25 May	18 May	5 June	4 June	30 June
Corn & soybean harvest	10 Oct.	7 Oct.	22 Oct.	20 Oct.	3 Nov.
Chisel/disk plow & field cultivating	10 Oct.	10 Oct.	24 Oct.	20 Oct.	–‡
Rye planting	11 Oct.	12 Oct.	25 Oct.	21 Oct.	20 Nov.

† Kura clover was not suppressed in 2005 and 2006 because corn was not planted in kC plots in these 2 yr.

‡ Tillage was not conducted in fall 2009 due to wet weather.

GLIMMIX procedure has advantages in analyzing unbalanced data. Differences between means were analyzed with a probability level of 0.05, and groupings were created with the "lines" option for LSMEANS. Because the rye, kura clover, and forage significantly modified the vegetation pattern in spring, treatment effects of drainage and NO_3–N loss in spring (March–June) and summer and fall (July–November) were also analyzed separately to investigate the seasonal effectiveness of land covers on NO_3–N concentration and loss.

Results and Discussion

Weather

Average monthly precipitation and air temperature for the study period are presented in Table 3. Weather information in 2005 is also included because rye grown in 2006 was planted in fall 2005. Overall, the weather was dryer than normal in 2006 (24% < average precipitation) and 2009 (17% < average), and was wetter in 2007 (28% > average) and 2008 (13% > average).The summers of 2006 and 2007 were much drier than usual. Average air temperature indicated that the weather was warmer in 2006 (14% > average air temperature) and near usual in 2007 (4% > average) but was cooler than normal in 2008 (18% < average) and 2009 (9% < average).

The weather in 2006 during the cover crop growing season from March to early May had higher temperature and more rainfall than the long-term average, which was favorable for the growth of spring land covers. For the corn and soybean growing season from May through August, although it was dryer in 2006 than 2007, reviewing weather data, it is estimated that there was more evaporation in 2007 due to higher wind speed and solar radiation. The calculated reference evapotranspiration in June and July of 2007 was 32 and 10% higher than 2006, respectively. Some abnormal or extreme weather occurred during the experiment years. Of particular note is the occurrence of hail at the site on 24 July 2009, which damaged the crops to various extents. Unusually cold weather was observed in early April 2007, with an average temperature of −0.9°C in the first 10 d of April and −5.1°C on average from 4 to 7 Apr. 2007 with the lowest temperature of −10.0°C observed on 7 April.

Biomass and Nitrogen Uptake of Spring Land Covers

The total aboveground biomass of various vegetation species was significantly different when averaged over the observational years ($p < 0.05$, Table 4). Kura clover produced the highest aboveground biomass in late spring, significantly higher than the forage grasses and rye ($p < 0.05$). The biomass of rye in rS treatment was significantly higher than that of rye in rC treatment ($p < 0.05$). Winter rye cover crop in the rS treatment was killed approximately 20 d later than rC treatment. Within these 20 d, rye in rS treatment accumulated 75% of the total above biomass when averaged across 4 yr.

Table 3. Average monthly precipitation and temperature, 2005–2009.

Month	Precipitation						Air temperature					
	Long-term	2005	2006	2007	2008	2009	Long-term	2005	2006	2007	2008	2009
	mm						°C					
Jan.	23	20	22	45	27	21	−9.3	−8.7	−1.7	−7.9	−10.3	−11.8
Feb.	19	43	19	42	25	37	−5.7	−1.7	−5.7	−11.1	−9.5	−4.1
Mar.	55	27	92	69	45	45	1.0	0.6	1.3	3.8	−1.1	1.9
Apr.	81	89	93	106	90	50	8.6	10.9	11.7	7.4	6.5	8.0
May	99	129	22	90	156	66	15.6	13.6	15.8	18.1	14.1	15.0
June	116	182	47	44	161	74	21.0	22.5	21	21.5	20.3	19.6
July	110	88	10	41	102	128	22.8	22.9	23.2	22.2	22.7	19.4
Aug.	111	45	113	367	81	49	21.3	20.3	21	22.2	18.1	19.4
Sept.	78	104	107	97	65	37	16.7	18.8	14.5	17.9	16.4	17.3
Oct.	57	20	19	119	84	151	9.8	10.8	7.7	12.5	9.8	6.3
Nov.	46	67	46	1	42	23	0.9	2.5	2.1	1.4	1.3	5.6
Dec.	27	33	35	27	48	5	−6.6	−9.3	−1.6	−8	−9.5	−9.2
Jan.–Dec.†	821	846	626	1050	926	684	8.0	8.6	9.1	8.3	6.6	7.3

† Values in the row of Jan.–Dec. are totals for precipitation and averages for air temperature.

Table 4. Total aboveground biomass and N uptake of spring land-cover treatments: rye in rye–corn (rC) and rye–soybean (rS), kura clover in kura clover + corn (kC), and forage in perennial forage (PF).

Crop (treatment)	Aboveground biomass†					Aboveground N uptake				
	2006	2007	2008	2009	Avg.	2006	2007	2008	2009	Avg.
	Mg ha^{-1}					kg ha^{-1}				
rye (rC)	0.91c‡	0.33b	0.15c	0.23c	0.41d	31.3c	11.3c	6.2b	8.2c	14.3c
rye (rS)	2.99b	1.68a	0.68c	1.16b	1.63c	58.8bc	31.8ab	18.0b	24.9b	33.4b
kura (kC)	6.19a	1.65a	3.61a	2.30a	3.44a	151.8a	43.9ab	95.0a	57.4a	87.0a
forage (PF)	5.79a	2.07a	1.99b	1.44b	2.82b	104.4ab	27.2b	27.0b	19.2b	44.4b

† Biomass listed in this table was sampled at the growth termination for rye and early June for kura clover and forage.

‡ Means within years and on average (i.e., within a column) followed by the same letter are not significantly different at the 0.05 probability level.

Aboveground biomass accumulation varied significantly under different weather conditions. Biomass of each spring land cover for 2006 was significantly higher than respective biomass for other years ($p < 0.05$). The rainfall and temperature conditions during early spring 2006 were favorable for establishing spring land covers. During the short period of extreme low temperature in April 2007, clover completely wilted and rye became distorted. Following this cold period, however, the clover came up again and rye grasses gradually recovered. In 2008 when the monthly average temperature was consistently lower than 30-yr average, the growth of all land covers in spring was less than in 2006 despite adequate rainfall. Lower biomass of kura clover in 2007 to 2009 compared with 2006 was the result not only of unfavorable weather conditions but also of suppression by herbicide in late May in 2007 to 2009.

Similar to biomass accumulation, different land-cover species showed significant differences in N uptake in the spring when averaged across 4 yr ($p < 0.05$, Table 4). Kura clover assimilated 87.0 kg ha^{-1} of N in the aboveground biomass, which was significantly higher than the PF with a N uptake of 46.3 kg ha^{-1} ($p < 0.05$). Nitrogen extracted by rye in the rS treatment averaged 31.8 kg ha^{-1} across 4 yr, which was significantly higher than rye in the rC treatment of 14.2 kg ha^{-1} ($p < 0.05$).

Nitrogen uptake by spring land covers was statistically different among years. Nitrogen uptake in spring 2006 was significantly higher than all other years for all land-cover treatments ($p < 0.05$). In the rS treatment, for example, N uptake by rye was 58.8 kg N $ha^{-1}$for 2006, significantly higher than the N uptake of 31.8, 18.1, and 24.8 kg N ha^{-1} for 2007, 2008, and 2009, respectively ($p < 0.05$), even though rye growth in rS was terminated 7 to 15 d earlier in 2006 than in other years.

Corn and Soybean Yield and Nitrogen Uptake

Corn and soybean in the plots with rye as a winter cover (rC and rS) did not show grain yield disadvantage compared with the conventional corn and soybean plots (C and S); however, corn that grew with kura clover as a living mulch (kC) was significantly affected in terms of biomass accumulation and grain production ($p < 0.05$, Table 5). Soil moisture, nutrient, and sunlight competition could be responsible for the poor corn establishment and low grain production in the kC plots. Soil moisture in the top 15 cm in the kura clover treatment was nearly always lower than other corn or soybean plots (Qi et al., 2011). Another reason for poor yields could be the hard soil surface because of the root mass of the kura clover in kC plots. Average soybean grain yield in rS was lower than S, but this was not statistically significant. Hail that occurred in late July 2009 reduced the production of soybean more seriously than corn. Average soybean yield in 2009 was 1.9 Mg ha^{-1}, significantly lower than the average yield of 2.9 Mg ha^{-1} in other years ($p < 0.05$).

The winter rye cover crop did not exert negative impact on total N uptake of subsequent corn and soybean crop based on statistical analysis, but corn planted in kC was affected in terms of N uptake by aboveground biomass. Although the average total aboveground biomass of corn in C and rC was three times more than that of soybean in S and rS, N uptake by corn biomass was only 30% higher than soybean.

Subsurface Drainage

Subsurface tile drainage typically initiated in late March and continued to late fall depending on the rainfall pattern. Statistical tests showed that treatment did not significantly influence annual or seasonal drainage flow volume (data not shown). The average annual drainage from all treatments was 327 mm, which was approximately 40% of average annual rainfall. The percentage of drainage occurring from March to June was about 55% of the annual total, lower than the 15-yr observation of 70% in this region (Helmers et al., 2005). This is likely due to the wet weather in late summer and fall in 2007 and 2009. Overall, the effect of experiment block on drainage was evident, with the average drainage volume from the high block (460 mm) significantly higher than that from the low block (242 mm) ($p < 0.05$).

The subsurface drainage showed large field variability. For example, the mean drainage at ADWQ-RDS site in 2008 was 458 mm, comparable to the drainage of 465 mm at the Lamberton site in 2001 (Strock et al., 2004); however, the averaged standard error of this mean drainage was 128 mm at our site, more than twice as much that of 56 mm at the Lamberton site. Of note is that the monitored center line was assumed to drain 50% of the plot area; the actual drainage area of the center line, however, may vary with the hydrological conditions of the soil. High drainage volume that even exceeded or was close to the annual precipitation could be

Table 5. Average total aboveground biomass, grain yield, and total aboveground N uptake at harvest in conventional corn (C) and soybean (S), rye–corn (rC), rye–soybean (rS), and kura clover + corn (kC).

Crop (treatment)	Total aboveground biomass†					Grain yield					Total aboveground N uptake				
	2006	2007	2008	2009	Avg.	2006	2007	2008	2009	Avg.	2006	2007	2008	2009	Avg.
	Mg ha^{-1}										kg ha^{-1}				
Corn (C)	19.9A‡	13.3A	18.0A	17.9B	17.4A	9.1A	7.4A	9.6A	8.0A	8.4A	234A	145A	211A	200A	199A
Corn (rC)	21.8A	11.6A	18.4A	21.8A	18.4A	7.9A	6.9A	10.1A	7.9A	8.1A	261A	135A	207A	227A	207A
Corn (kC)	–§	3.1B	10.3B	12.7C	8.7B	–	1.0B	4.1B	3.4B	2.8B	–	42b	135B	147B	108B
Soybean (S)	5.6a	5.1a	5.2a	4.2a	5.0a	3.3a	3.0a	3.0a	1.9a	2.8a	201a	185A	174a	124a	171a
Soybean (rS)	5.6a	3.3a	4.2a	3.5a	4.1a	3.0a	2.4a	2.8a	1.9a	2.5a	200a	119A	140a	104a	140a

† Biomass listed in this table was sampled in the late season between late August and late September.

‡ Means within years and on average (i.e., within a column) followed by the same letter are not significantly different at the 0.05 probability level. Capital letters for corn and lowercase letters for soybean.

§ Corn was not planted in kC plots in 2006.

attributed to larger actual drainage area or lateral flow into the plot. Similarly, a smaller actual drainage area and lateral flow loss could lead to an unexpected low flow from the monitored center lines.

NO_3–N Concentration in Subsurface Drainage

Nitrate-N concentration in the tile drainage flow was significantly affected by the land-cover treatments (Table 6). When averaged over 4 yr, annual FWANC in drainage flow from kC and PF treatments was significantly lower than that from all other treatments ($p < 0.05$). Four-year average annual FWANCs in kC and PF treatments were 6.8 and 4.6 mg N L^{-1}, respectively, below the MCL value of 10 mg N L^{-1}. The low NO_3–N concentration in the drainage from PF treatment was mainly attributed to no fertilizer input since 2005. However, N application rate to kC treatments was 140 kg N ha^{-1} in each year from 2007 to 2009, whereas the N concentration in the water drained from this treatment was consistently lower than 10 mg N L^{-1} although the corn N uptake in kC was much less than C and rC treatments ($p < 0.05$). Before N fertilizer application to the corn in the kC plots on 26 June 2007, NO_3–N concentration was lower than in the PF plots, an indicator of more N uptake by kura clover in the kC treatment than grasses in the PF treatment. The increase in NO_3–N concentration in the drainage flow from the kC plots in August 2007 may be attributed to the fertilizer application and low N uptake by corn in kC plots.

Annual FWANC from corn or soybean plots with rye cover crop was not significantly different from the FWANC from conventional corn or soybean systems, although NO_3–N concentration in the rC and rS treatments was lower than C and S in most years. However, significant reduction in NO_3–N concentration by rye was observed on a seasonal basis. In March through June, the FWANC in rC was significantly lower than that in C, and in July through November, the FWANC in rS was significantly lower than that in S ($p < 0.05$). The FWANC in March through June consistently exceeded the MCL of 10 mg N L^{-1} for the corn–soybean rotation plots regardless of winter rye as a cover crop. Nitrate–N concentrations in the soybean phase were slightly lower than in the corn phase with the same spring land-cover situation but not significantly different, which is consistent with other studies (Randall and Vetsch, 2005).

NO_3–N Losses in Subsurface Drainage

The NO_3–N loss through drainage was substantially reduced by kC and PF ($p < 0.05$) but not by rC and rS compared with C and S treatments (Table 7). The significant reductions in NO_3–N concentration from PF and kC treatments resulted in significant reductions in N loss. Average annual NO_3–N loss was 38.1 kg N ha^{-1} for conventional corn–soybean rotation and 38.8 kg N ha^{-1} for corn–soybean rotation with winter rye cover. When averaged across the 4 yr, annual NO_3–N loss from PF was 65% lower than the average of all the corn–soybean rotation treatments ($p < 0.05$). The average annual NO_3–N loss from kC was 40% less than the other two corn treatments (C and rC) with the same N application rate ($p < 0.05$).

Similar to drainage volume, NO_3–N mass losses showed high variability temporally. When averaged across treatments, the annual NO_3–N loss in 2006 was 13.0 kg N ha^{-1}, which was 73 and 69% less than in 2007 and 2008, respectively ($p < 0.05$). Seasonal NO_3–N loss varied over a wide range depending on the precipitation, with the average NO_3–N loss in March through June being 17.4 kg N ha^{-1}, accounting for 54% of the annual NO_3–N loading when averaged across all treatments. This percentage was lower

Table 6. Flow-weighted average NO_3–N concentration (mg N L^{-1}) in subsurface drainage in treatments of corn (C), rye-corn (rC), soybean (S), rye-soybean (rS), kura clover + corn (kC), and perennial forage (PF).

Treatment	2006			2007			2008			2009			Four-yr average		
	Annual	Mar.–June	July–Nov.	Annual	Mar.–June	July–Nov.	Annual	Mar.–June	July–Nov.	Annual	Mar.–June	July–Nov.	Annual	Mar.–June	July–Nov.
C	15.1a†	15.1a	15.3a	13.9a	15.0a	12.7a	13.0a	13.1a	12.1a	13.0a	12.8a	13.1a	13.8a	14.0a	13.3a
rC	15.2a	13.2a	16.8a	11.8ab	12.1bc	11.6a	11.4a	11.4a	10.8a	12.8a	11.9a	13.1a	12.8ab	12.2b	13.1a
S	14.9a	14.7a	14.9ab	12.9ab	14.1ab	12.2a	12.1a	12.1a	11.7a	11.8a	11.9a	11.8a	12.8ab	13.2ab	11.9a
rS	12.3ab	12.4a	8.9b	9.9bc	11.1c	9.5a	12.3a	12.4a	9.8a	11.0a	11.4a	10.8a	11.4b	11.8b	9.7b
kC	7.1c	7.1b	8.4b	7.4dc	2.6d	9.4a	6.1b	6.1b	4.5b	6.8b	6.6b	6.7b	6.8c	5.6c	7.3c
PF	8.4bc	8.5b	6.0b	4.4d	4.6d	4.3b	3.0b	3.1b	2.0b	2.6c	3.4b	2.1c	4.6d	4.9c	3.6d

† Means within years and seasons (i.e., within column) followed by the same letter are not significantly different at the 0.05 probability level.

Table 7. Average annual and seasonal NO_3–N loss (kg N ha^{-1}) through subsurface drainage in treatments of corn (C), rye-corn (rC), soybean (S), rye-soybean (rS), kura clover + corn (kC), and perennial forage (PF).

Treatment	2006			2007			2008			2009			Average		
	Annual	Mar.–June	July–Nov.	Annual	Mar.–June	July–Nov.	Annual	Mar.–June	July–Nov.	Annual	Mar.–June	July–Nov.	Annual	Mar.–June	July–Nov.
C	15.7ab†	14.8ab	0.8a	65.8a	25.4a	40.4a	49.5ab	43.8ab	5.7a	28.3a	5.7a	22.6a	39.8a	22.4a	17.4a
rC	14.5ab	10.4ab	4.1a	62.4a	22.4a	40.0ab	56.2a	53.8a	2.4a	31.1a	7.4a	23.7a	41.1a	23.5a	17.6a
S	18.7a	16.8a	1.8a	49.6ab	19.6a	30.0ab	55.8a	49.4a	6.4a	27.1a	6.8a	20.3a	36.3ab	20.4a	15.9a
rS	14.5ab	13.6ab	0.9a	54.5ab	15.3ab	39.2ab	41.7ab	40.0ab	1.7a	35.3a	5.1a	30.2a	36.5ab	18.5ab	18.0a
kC	6.1b	5.7b	0.4a	39.0ab	5.1b	33.9ab	27.9ab	26.1ab	1.8a	24.0a	5.3a	18.7a	24.2bc	10.6b	13.7a
PF	8.9ab	8.7ab	0.2a	21.0b	7.7b	13.3b	17.8b	15.8b	2.0a	6.0a	3.0a	3.0a	13.4c	8.8b	4.6a

† Means within years and seasons (i.e., within column) followed by the same letter are not significantly different at the 0.05 probability level.

than 90% in 2006 and 2008 when late season drainage was not significant.

Soil Nitrate-Nitrogen

The impact of land cover treatment on soil NO_3–N was evident when averaged over sampling years during 2007 through 2009. Soil with the PF treatment, as a result of no fertilization, showed the lowest soil NO_3–N among all the treatments ($p < 0.05$). Soil NO_3–N in most treatments increased from early to late spring, with the magnitude of the increase being significantly different (Table 8). Compared with S treatment, increase in soil NO_3–N in rS between early and late spring was significantly lower during all the three sampling years ($p < 0.05$). This is an indication that rye in rS plots assimilates the readily available NO_3–N in the soil profile.

Comparison to Other Studies

Less effectiveness of winter rye cover crop in reducing NO_3–N loss could be attributed to the lower fertilization rate at our site compared with the Story County site in Kaspar et al. (2007). The N rates to corn at the Story County site were between 235 and 246 kg N ha^{-1}, approximately 100 kg N ha^{-1} higher than the rate of 140 kg N ha^{-1} at our site. Higher N rates at the Story County site led to higher available NO_3–N in the soil for leaching and rye N uptake in the following spring, which is strongly supported by the high soil NO_3–N and, in particular, drainage NO_3–N concentration in the control treatment in Kaspar et al. (2007). In the control treatments (corn–soybean only), the average NO_3–N concentration in drainage was 21.3 mg N L^{-1} at the Story site, 60% higher than the averaged concentration of 13.5 mg N L^{-1} over C and S treatments at our ADWQ-RDS site. Historical data also showed that NO_3–N concentration in drainage at our site was as high as 23.3 mg N L^{-1} at a N rate of 252 kg N ha^{-1} to corn (Lawlor et al., 2008). High fertilizer rate increased yield and biomass and subsequently would increase N mineralization from crop residue in the next growing season. The lower N rate at our site, combined with lower temperature and later rye planting dates, resulted in less rye biomass accumulation and less N assimilation. Therefore the rye cover crop may be less effective in reducing NO_3–N loss. Average rye shoot N uptake was 47.5 kg N ha^{-1} in Kaspar et al. (2007), more than twice as much as the N uptake of 22.7 kg N ha^{-1} at our site. In addition, a simulation study conducted by Li et al. (2008) showed that NO_3–N loss reduction by rye cover crop was 17.2 kg N ha^{-1} at a N rate of 140 kg N ha^{-1}, while it was 33.2 kg N ha^{-1} at a N rate of 252 kg N ha^{-1}.

Rainfall distribution, which is a major determinant of drainage pattern, may be another factor that affects the efficiency of rye in NO_3–N loss reduction. In Kaspar et al. (2007), on average, 90% of the subsurface drainage occurred before early June (DOY 189), during which rye was mainly growing in the field. However, in our study, only 53% of drainage occurred before the end of June, and 47% of drainage occurred in July through November when rye had been killed. High late-season drainage is not usual for our site. Historical data showed that 70% of drainage occurred in March through June at this ADWQ-RDS site based on a 15-yr observation (Helmers et al., 2005). Late-season drainage could reduce soil NO_3–N levels in the soil profile, leaving less soil NO_3–N for the next year. Furthermore, different tillage managements were applied to these two studies. Kaspar et al. (2007) used no-till while in our study the plots were chisel plowed and disked in fall. Fall tillage would be expected to lead to a later planting date for rye.

Corn yield in the kC treatment was significantly reduced in this study, but other studies reported little or no corn yield loss (Zemenchik et al., 2000; Affeldt et al., 2004). Reasons for differences in corn yield could be multiple and could include rainfall. Rainfall at ADWQ-RDS during May to July was 46 and 18% less than normal in 2007 and 2009, respectively, while it was 33, 101, and 65% more than average in Affeldt et al. (2004). However, although the rainfall in May through July 2008 was 29% more than the long-term average at our ADWQ-RDS site, corn yield in the kC treatment was only 42% of the corn yield in C treatments. This suggested that there may be other factors that result in differences in corn yield such as agronomic management, N rate, soil type, and presence of tile drainage. A more vigorous suppression to kura clover growth in spring may have the potential to increase the yield of corn growing with kura clover as a living mulch (Sawyer et al., 2010). Average spring sampled kura clover aboveground biomass was 3.44 kg ha^{-1}, whereas it was 1.57 kg ha^{-1} in Sawyer et al. (2010).

Table 8. Average soil nitrate in 0- to 60-cm soil layer for early spring (ES), late spring (LS), and late fall (LF) in treatments of corn (C), rye–corn (rC), soybean (S), rye–soybean (rS), kura clover + corn (kC), and perennial forage (PF).

Treatment	2007†				2008				2009			
	ES	LS	LF	LS-ES	ES	LS	LF	LS-ES	ES	LS	LF	LS-ES
	kg N ha^{-1}											
C	42a‡	68ab	49a	25a	42a	70ab	31bc	28ab	43bc	61a	32a	17a
rC	31a	61b	53a	30a	48a	80a	86a	32ab	74a	60a	26ab	–15b
S	57a	87a	43a	30a	44a	82a	41b	37ab	34cd	50ab	25ab	16a
rS	46a	53b	38a	7b	55a	53b	52a	–1c	63ab	37b	24b	–26b
kC	–§	–	–	–	26b	72ab	38b	47a	82a	65a	29ab	–17b
PF	–	–	–	–	8c	21c	6c	13c	17d	18c	10c	1b

† ES = early spring when rye, clover, and forage grass started growing (9 April in 2007, 16 April in 2008, and 23 April in 2009); LS = late spring before fertilization and corn and soybean growing (4 June in both 2007 and 2008, and 10 June in 2009); LF = late fall after corn and soybean harvest (31 October in 2007 and 18 November in both 2008 and 2009); LS-ES = difference between LS and ES.

‡ Means within column followed by the same letter are not significantly different at the 0.05 probability level.

§ Not sampled.

Conclusions

Rye significantly reduced seasonal NO_3–N concentration in drainage flow and soil NO_3–N accumulation in spring, indicating a potential in reducing NO_3–N loss. This study suggested that the effectiveness of N loss reduction by rye could be related to field variability, N fertilization rate, and weather conditions. Planting corn in kura clover living mulch and converting corn–soybean into perennial forage significantly reduced NO_3–N loss and NO_3–N concentration in tile drainage below the MCL of 10 mg N L^{-1} for drinking water. However, better agronomic management is needed to ensure minimal corn yield loss in kura clover under Iowa's weather and soil conditions. At present, there is little economic value for the forage grasses. There would also need to be relatively major changes in farming practices to adopt corn with living mulch and perennial forage cropping systems in the U.S. Corn Belt. Of the three cropping alternatives to the conventional corn–soybean rotation, rye cover crop has potential to reduce NO_3–N in drainage water and not impact yields; however, more work is needed to continue investigation of the effectiveness at different N rates, under a wide range of weather conditions, and with fall tillage.

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