Rye Cover Crop and Gamagrass Strip Effects on NO$_3$ Concentration and Load in Tile Drainage

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A significant portion of the NO$_3$ from agricultural fields that contaminates surface waters in the Midwest Corn Belt is transported to streams or rivers by subsurface drainage systems or "tiles." Previous research has shown that N fertilizer management alone is not sufficient for reducing NO$_3$ concentrations in subsurface drainage to acceptable levels; therefore, additional approaches need to be devised. We compared two cropping system modifications for NO$_3$ concentration and load in subsurface drainage water for a no-till corn (*Zea mays* L.)-soybean (*Glycine max* [L.] Merr.) management system. In one treatment, eastern gamagrass (*Tripsacum dactyloides* L.) was grown in permanent 3.05-m-wide strips above the tiles. For the second treatment, a rye (*Secale cereale* L.) winter cover crop was seeded over the entire plot area each year near harvest and chemically killed before planting the following spring. Twelve 30.5 × 42.7-m subsurface-drained field plots were established in 1999 with an automated system for measuring tile flow and collecting flow-weighted samples. Both treatments and a control were initiated in 2000 and replicated four times. Full establishment of both treatments did not occur until fall 2001 because of dry conditions. Treatment comparisons were conducted from 2002 through 2005. The rye cover crop treatment significantly reduced subsurface drainage water flow-weighted NO$_3$ concentrations and NO$_3$ loads in all 4 yr. The rye cover crop treatment did not significantly reduce cumulative annual drainage. Averaged over 4 yr, the rye cover crop reduced flow-weighted NO$_3$ concentrations by 59% and loads by 61%. The gamagrass strips did not significantly reduce cumulative drainage, the average annual flow-weighted NO$_3$ concentrations, or cumulative NO$_3$ loads averaged over the 4 yr. Rye winter cover crops grown after corn and soybean have the potential to reduce the NO$_3$ concentrations and loads delivered to surface waters by subsurface drainage systems.

WITHIN the Midwest Corn Belt, NO$_3$ concentrations in surface waters often exceed the 10 mg N L^{-1} maximum contaminant level for drinking water set by the United States Environmental Protection Agency (USEPA) (USEPA, 1992; Jaynes et al., 1999: Mitchell et al., 2000). Excessive NO$_3$ in the Mississippi River has been identified as a leading cause of hypoxia in the northern Gulf of Mexico (Rabalais et al., 1996). Numerous studies at the field and watershed scale have shown that a significant proportion of the NO$_3$ in surface waters in the Midwest comes from agricultural land used for corn and soybean production (David et al., 1997; Goolsby et al., 1999; Jaynes et al., 1999). These studies indicate that subsurface drains (tiles), which are commonly installed in the Midwest on soils with seasonally high water tables (Zucker and Brown, 1998), are one of the primary pathways for transport of NO$_3$ from agricultural fields to surface waters.

The corn–soybean rotation is the predominant cropping system in the Midwest Corn Belt. Attempts to reduce NO$_3$ losses to surface waters in this region have focused on N fertilizer management. Numerous studies have shown that NO$_3$ losses can be substantial in the soybean year of the rotation when no N fertilizers are applied or in the corn year when N fertilizers are applied at less than the economic optimum rate (Baker et al., 1975; Gast et al., 1978; Jaynes et al., 2001; Dinnes et al., 2002). Thus, fine-tuning N fertilizer management to reduce application rates, which is the obvious first step, will probably not reduce NO$_3$ losses to acceptable levels, and additional management practices are needed.

One of the reasons that fertilizer management alone does not solve the problem is that most of the NO$_3$ losses to drainage water or deep percolation occur between maturity and canopy development of the corn and soybean crops (Kladivko et al., 1999; Cambardella et al., 1999; Brouder et al., 2005). In other words, most of the losses occur during the fall, winter, and spring when the corn and soybean crops are not taking up water and nutrients. Small grain winter cover crops have the potential to increase uptake of NO$_3$ and water during this period in the Midwest Corn Belt. Winter cover crops have been shown to reduce NO$_3$ losses in areas of the country where the winter climate is relatively mild and humid and where most of the NO$_3$ losses occur during the winter (Brandi-Dohrn et al., 1997; Herbert et al., 1995; McCracken et al., 1995; Meisinger et al., 1991). In much of the Midwest Corn Belt, the potential growing season between harvest and planting of corn and soybean is short and cold, and the soil is frozen for much of the time. Although there are many possible winter cover crops, small grains such as oat (*Avena sativa* L.), wheat (*Triticum*

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Abbreviations: DOY, day of year; USEPA, United States Environmental Protection Agency; UTM, Universal Transverse Mercator.

aestivum L.), or rye seem to have the best potential as winter cover crops for Midwest corn–soybean rotations (Snapp et al., 2005). Small grains grow well at cool temperatures, the seed is relatively inexpensive, they can be successfully established by overseeding late in the growing season or by direct planting after harvest, and they are easily killed with tillage or herbicides before planting the next crop (Kessavalou and Walters, 1997; Johnson et al., 1998; Strock et al., 2004; Ball Coelho et al., 2005; Snapp et al., 2005).

Information on winter cover crop effects on NO_3 losses from corn–soybean rotations on subsurface drained fields in the Midwest Corn Belt is limited (Dinnes et al., 2002). Strock et al. (2004) observed that a rye winter cover crop after corn reduced drainage volume by 11% and NO_3 loss in drainage water by 13% in Minnesota. For continuous corn in southwestern Ontario, Ball Coelho et al. (2005) found that a rye cover crop maintained groundwater NO_3 concentrations below 10 mg L^{-1} and reduced soil inorganic N by 7 to 55 kg N ha^{-1}. In Indiana, Kladivko et al. (2004) observed a reduction of annual NO_3 loads in drainage water from 38 to 15 kg ha^{-1} (61% reduction) after reducing N fertilizer rates and planting a winter wheat cover crop after corn. Rasse et al. (2000) in Michigan found that a rye cover crop after inbred corn lines fertilized at 202 kg N ha^{-1} reduced leaching losses of NO_3 by 35 and 65 kg N ha^{-1} in 2 yr. Feyereisen et al. (2006) used a simulation model and predicted that a rye cover could reduce NO_3 drainage losses by an average of 7.4 kg N ha^{-1} in southwestern Minnesota. Thus, a small grain cover crop after corn can substantially reduce NO_3 losses to drainage water or deep percolation. However, because substantial losses of NO_3 can also occur in subsurface drainage water in the late winter and early spring after a soybean year when no fertilizer has been applied (Jaynes et al., 2001), additional information is needed regarding small grain winter cover crops planted in each year of a corn–soybean rotation.

Another approach to reducing NO_3 losses in tile drainage from agricultural fields is to plant perennial crops rather than corn and soybean. Perennial crops reduce NO_3 losses because they generally have greater annual evapotranspiration and N uptake than annual grain crops (Randall et al., 1997). Randall et al. (1997) observed that alfalfa (*Medicago sativa* L.) or a mixture of alfalfa and perennial grasses reduced the NO_3 lost in subsurface drains over 4 yr by over 96% compared with a corn–soybean rotation. It is not feasible to replace annual crops with perennial crops on a large percentage of the hectares in the Midwest Corn Belt that are annually planted with corn or soybean. A possible alternative to solid stands of perennial crops is to plant perennial grasses or legumes in narrow strips directly over subsurface drain tiles within fields planted annually to corn or soybean (Russelle et al., 2006). It is unknown whether strips of perennial plants over subsurface drain tiles can remove enough water and NO_3 from the soil and from water flowing to the drain tiles to significantly reduce NO_3 losses.

New management approaches are needed to reduce NO_3 losses to subsurface drainage systems in corn–soybean rotations in the Midwest Corn Belt. Winter cover crops and perennial grasses have the potential to reduce drainage and take up soil N between harvest and planting of corn and soybean crops. No field study in the Midwest Corn Belt has examined the effectiveness of rye cover crops planted every year in a corn–soybean rotation. Similarly,

planting permanent perennial grass strips above subsurface drain tiles to reduce NO_3 losses has not been tested. Therefore, the objective of our study was to measure the effects of rye winter cover crops planted each year and a permanent gamagrass strip on NO_3 concentrations and loads of subsurface drainage water collected over 4 yr of a corn–soybean rotation in central Iowa.

Materials and Methods

A field study was initiated in 1999 in a 3.7-ha field 8.0 km northwest of Ames, IA in Boone County (42.05° N, 93.71° W) with two predominant soils (Andrews and Diderikson, 1981): Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) and Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). Field plots were laid out in a randomized complete block design with four replications. Each plot was 30.5 m wide by 42.7 m long. The site contains 24 plots arranged in six groups or rows (four plots per group) with a field access space between groups. Twelve of the 24 plots were used for this experiment.

In August of 1999, pre-existing drain pipes at the site were cut and blocked. A 25.4-cm diameter drain tile was installed around the perimeter of the site to reduce subsurface flow into the plots. A trench was excavated between groups of plots, and a plastic sheet was installed to a depth of 1.83 m before backfilling with soil to act as a flow barrier. A perforated, 7.62-cm-diameter corrugated drainage tile was installed 1.2 m below the soil surface and lengthwise down the center of each plot. Drainage from each plot was conducted from the edge of the plot by solid plastic tile to one of three large, covered, underground pits. Within each pit, drainage from eight plots was collected in eight dedicated sumps that a sump pump emptied when the water level exceeded a preset level. Flow from each pump went through a combination electrical and mechanical totalizing flow meter; flow volume versus time was recorded with a data logger. Cumulative annual drainage was calculated by summing the yearly discharge volume from each plot and dividing by the plot area.

Flow-weighted water samples were collected in plastic sample jars connected by a small-diameter tube to each sump pump outlet such that a proportional sample was collected each time water was pumped. Water samples were returned to the laboratory on a weekly or shorter basis, depending on tile flow rate, and refrigerated in the laboratory at 4°C until analysis. Water samples were analyzed for NO_3 using a Lachat Autoanalyzer (Zellweger Analytics, Lachat Instrument Division, Milwaukee, WI). Nitrate was quantitatively reduced to NO_2, and the NO_2 concentration was determined colorimetrically (Keeney and Nelson, 1982). The method quantitation limit was 0.5 mg NO_3–N L^{-1}, and standard laboratory quality control procedures were used. Mass of NO_3 in drainage water from each plot was calculated by multiplying the NO_3 concentration of a flow-weighted water sample by the volume of water discharged during the time the sample was collected. Cumulative annual NO_3 load from each plot was calculated by summing across all samples in a calendar year. Annual flow-weighted NO_3 concentrations were computed by dividing the cumulative annual load by the annual drainage volume.

During 2000 we began to monitor and troubleshoot the drain-

age sampling system and to initiate three treatments within a corn–soybean management system: rye winter cover crop, gamagrass strip, and control (no rye cover crop or gamagrass strip). The rye cover crop treatment consisted of a cereal rye (cv. 'Rymin') winter cover crop overseeded into the standing grain crop in late summer (Table 1) at 3.7×10^6 seeds ha^{-1} (2001 and 2002) or drilled after harvest 2.5×10^6 seeds ha^{-1} (2003 and 2004) across the entire plot area. A rye cover crop was attempted in 2000, but the resulting stand was poor because of dry conditions. The rye was chemically killed with glyphosate [N-(phosphonomethyl) glycine] applied at 1.12 kg a.i. ha^{-1} 6 to 12 d before planting of the main crop each spring. The gamagrass treatment was a 3.05-m-wide strip above the drainage tile that was planted with eastern gamagrass seed at 12.0 kg ha^{-1} on 1 May 2000 and on 30 Oct. 2000 (offset from first planting) with a seven-row plate planter with 0.38-m row spacing. Additional plugs of eastern gamagrass were added in spring 2001 to fill in the strips. The gamagrass strips were not completely filled in until October 2001. The control treatment was a normal corn–soybean management system without a rye winter cover crop or a gamagrass strip. Because the gamagrass and winter cover crop treatments were not successfully established until fall 2001, only data from 2002 through 2005 are discussed in this article.

The corn–soybean cropping system was established in 2000 with management typical for central Iowa. Fertilizer rates, management dates, and sampling dates are listed in Table 1. Weed control was maintained with typical pre-emergence herbicides in corn and with glyphosate in soybean in conjunction with glyphosate-resistant soybean cultivars. For the most part, the field plots were managed as a no-till system. However, plots were deep ripped after tile installation on 16 Nov. 1999 and disked on 8 Mar. 2000. All plots were disked on 25 Apr. 2002 because of subsidence above the tile lines. Soybean and corn were slot planted with a five-row, 0.76-m row width, John Deere 7100 planter (Deere and Co., Moline, IL) with bubble coulters. The soybean cultivars, 'Northrup King S19–90' (Northrup King Co., Minneapolis, MN) and 'Stine 2250' and 'Stine 2289–4' (Stine Seed Co., Adel, IA) were planted at 445 000 seeds ha^{-1} in early- to mid-May in 2001, 2003, and 2005 (Table 1). Corn was planted at 79 000 seeds ha^{-1} in late April using 'Pioneer 34B23' (Pioneer Hybrid International Inc., Johnston, IA) in 2002 and 'Pioneer 34B24' in 2004. A liquid starter fertilizer (ammonium polyphosphate; 10–34–0) was applied in-furrow during planting at rates of 112 kg ha^{-1} ($N = 11.2$ kg ha^{-1}; $P = 16.6$ kg ha^{-1}) in 2002 and 130 kg ha^{-1} ($N = 13.0$ kg ha^{-1}; $P = 19.2$ kg ha^{-1}) in 2004. A sidedress application of N fertilizer as liquid urea-ammonium nitrate was applied in the corn years with a spoke-wheel fertilizer injector (Baker et al., 1989) at 224 kg N ha^{-1} (30 May 2002) and at 217 kg N ha^{-1} (21 May 2004). This N fertilizer application rate is high but is not unusual for this area. Dry P and K fertilizers were applied in 2000, 2003, and 2004, when soil tests indicated that levels were low. On 27 Mar. 2000, potassium sulfate was surface broadcast at 224 kg ha^{-1} (K = 97 kg ha^{-1}). On 30 Oct. 2003, diammonium phosphate and potassium chloride were banded with a coulter applicator at 88 kg ha^{-1} ($N = 16.1$ kg ha^{-1}; $P = 18.1$ kg ha^{-1}; K = 44.7 kg ha^{-1}). On 8 Nov. 2004, potassium sulfate was surface broadcast at 67 kg ha^{-1} (K = 29 kg ha^{-1}). In

Table 1. Management and sampling dates.

| | Main crop | | | | |
Parameter	2001 Soybean	2002 Corn	2003 Soybean	2004 Corn	2005 Soybean
Main crop planting date	10 May	25 Apr.	12 May	28 Apr.	6 May
Cover crop planting date	20 Aug.	10 Sept.	2 Oct.	6 Oct.	–
Cover crop kill date	–	17 Apr.	6 May	16 Apr.	25 Apr.
Main crop harvest date	27 Sept.	30 Sept.	30 Sept.	4 Oct.	30 Sept.
Sidedress N fertilizer application	–	30 May	–	21 May	–
Total N applied for crop year	–	235 kg ha^{-1}	–	246 kg ha^{-1}	–
Fall soil sampling	15 Nov.	4 Nov.	13 Nov.	3 Nov.	29 Sept.

2001, 2003, and 2005, soybean grain yields were determined using a modified combine with a weigh tank and moisture meter mounted inside the combine grain storage tank (Colvin, 1990) by harvesting the entire plot area (except for the gamagrass strips) and dividing total grain weight by harvested plot area. In 2002, corn yield was determined by harvesting the entire area of each plot (except for the gamagrass strips) and weighing the grain in a weigh wagon with load cells and taking samples to measure grain moisture. In 2004, because a wind storm had knocked down corn in some areas of the plots, undamaged corn in four strips 2.29-m wide and 42.67-m long from each plot were harvested with the modified combine with weigh tank. The remaining area was bulk harvested. All corn and soybean shoot residues were left on the soil surface after harvest. Yields were calculated based on harvested plot area and were adjusted to 0.155 and 0.130 g g^{-1} grain moisture for corn and soybean, respectively.

Cover crop shoot dry matter samples were collected in the spring of each year within a day of glyphosate application (Table 1). Three samples were taken from each plot by clipping at the soil surface all the rye plants found within a sampling frame 0.76 m wide and 0.50 m long. For each sample, the frame was centered on a row of the previous main crop so that the 0.76-m side of the frame was perpendicular to the row direction. Gamagrass samples were taken in a similar manner. Samples were dried at 40°C, weighed, and ground. Ground samples were analyzed for C and N content using the dry combustion-GC method (Scheppers et al., 1989) with an EA1112 Flash NC Elemental analyzer (Thermo Electron Corp., Waltham, MA). Shoot dry weights were calculated on total plot area basis. That is, for the gamagrass samples, which came from a strip that covered 10% of the plot area, the dry weights per unit sampling area were divided by 10.

Residual soil inorganic N was measured in the fall (Table 1) after harvest by taking three soil cores in each plot 1.20 m long and 38 mm in diameter using a soil probe fitted with a removable acetate liner and pushed into the soil with a hydraulic ram. Cores were taken at random locations within the plot but were not taken from within the gamagrass strips or from above the drainage tile. The core and liner were removed from the soil probe, capped at each end, and stored at −10°C until processing. The frozen soil cores were sectioned into 0.15-m depth increments, removed from the liners, thawed, passed through an 8-mm sieve, and mixed by hand. Two 20-g subsamples were taken from each depth increment for determination of inorganic N and water content. Water content was determined by the change

Table 2. Average monthly air temperature and total precipitation 2001–2005.

Month	Air temperature						Total precipitation					
	2001	2002	2003	2004	2005	1951–2005 Avg.	2001	2002	2003	2004	2005	1951–2005 Avg.
	°C						mm					
Jan.	−5.6	−1.1	−5.6	−7.2	−7.8	−7.4	28	7	7	19	26	19
Feb.	−7.8	−1.1	−6.1	−5.0	0.0	−4.1	33	26	13	36	47	23
Mar.	−1.1	0.6	2.2	5.6	3.3	1.9	28	10	29	96	35	51
Apr.	13.3	10.6	11.1	11.7	12.8	10.0	96	95	112	61	82	88
May	16.7	15.0	15.6	16.7	15.6	16.2	190	130	122	208	111	115
June	21.1	23.3	20.0	20.0	23.3	21.2	50	81	150	91	124	127
July	24.4	24.4	23.3	22.2	24.4	23.3	48	150	168	50	104	102
Aug.	23.3	21.7	23.3	19.4	22.2	22.0	74	209	25	132	171	106
Sept.	16.7	19.4	16.7	20.0	20.6	17.8	149	38	100	34	111	80
Oct.	11.1	8.3	12.2	12.2	12.2	11.4	65	79	24	46	9	59
Nov.	9.4	2.2	2.2	5.6	5.0	2.8	36	6	110	80	49	43
Dec.	−0.6	−1.1	−1.7	−2.2	−6.6	−4.4	10	0	31	12	24	24
Jan.–Dec.†	10.1	10.2	9.4	9.9	10.6	9.2	807	831	891	865	893	837

† Values for the Jan.–Dec. periods are averages for the period for air temperature and totals for the period for precipitation.

in weight by drying one of the two subsamples at 104°C for 48 h. The second subsample was weighed, mixed with 100 mL of 2 *M* KCl, shaken, and filtered. The filtrate was analyzed for nitrate (NO_3+NO_2) and ammonia using a colorimetric method (Keeney and Nelson, 1982) and flow injection technology (Lachat Instruments, Milwaukee, WI). Total inorganic N to a depth of 1.2 m was calculated by assuming a bulk density of 1.25 g cm^{-2} based on typical bulk density for uncompacted surface layer for these soils (Andrews and Diderikson, 1981) for all depth increments.

Monthly precipitation totals and average monthly air temperatures were calculated from daily values collected at the Iowa State University research farm located 5.4 km southwest of the study area (Herzmann, 2006) (Table 2).

The experimental design was a randomized complete block design with four blocks or reps. Data for individual years were analyzed separately and combined for the combined years analysis. Data for individual years were analyzed for treatment and block effects using PROC ANOVA procedure (SAS Institute Inc., 1999). Data for all 4 yr were combined and analyzed for year, treatment, block, and year-by-treatment effects using the PROC MIXED procedure (SAS Institute Inc., 1999) with years as a repeated mea-

Table 3. Rye cover crop and gamagrass shoot dry matter, shoot N concentration, and total shoot N for 2002–2005.

Year	Gamagrass			Rye		
	Shoot dry weight	Shoot N concentration	Total shoot N	Shoot dry weight	Shoot N concentration	Total shoot N
	Mg ha^{-1}	g N kg^{-1}	kg N ha^{-1}	Mg ha^{-1}	g N kg^{-1}	kg N ha^{-1}
2002	–	–	–	2.43A†	22.7C	55.8B
2003	1.46aA	13.0bA	18.8aA	0.25bC	36.5aA	9.3bC
2004	2.02aA	12.9bA	25.5bA	1.48aB	32.8aAB	48.5aB
2005	1.48bA	10.8bA	16.0bA	2.74aA	27.8aBC	76.5aA
Avg.	1.65a	11.9b	19.1b	1.73a	30.0a	47.5a

† Numbers within a row (for a specific measurement) followed by the same lowercase letter and numbers within a column followed by the same uppercase letter are not significantly different as indicated by Tukey's test at the 0.05 probability level.

sure. Tukey's test at the 0.05 probability level was used to compare treatment or year means when the ANOVA indicated significant effects at the 0.05 probability level (SAS Institute Inc., 1999).

Results and Discussion

Weather

Average monthly air temperatures and total monthly precipitation for 2001 through 2005 are shown in Table 2. Data for 2001 are included because the cover crop treatment was planted in fall 2001, soil inorganic N samples were taken in fall 2001, and the drainage in 2002 was dependent to some extent on precipitation in 2001. In general, average monthly temperatures (Table 2) in 2001 to 2005 did not vary greatly from the long-term average or among years. Some exceptions were November 2001, which was 6.6°C above average; December 2001 through February 2002, which was warmer than average; March 2004, which was 3.7°C above the average; October 2002, which was 3.1°C below average; and September 2003, which was 2.7°C or more colder than September in the other years. June, July, and August 2004 had cooler than average temperatures and generally were cooler than the other 3 yr.

Annual precipitation in 2003, 2004, and 2005 was greater than 55-yr average and was slightly below average in 2002. Precipitation ranged from 56 mm above average in 2005 to 6 mm below average in 2002 (Table 2). The year preceding the study (2001) had annual precipitation that was 30 mm below average. In 2002, much of the precipitation occurred in July (48 mm above average) and August (103 mm above average). In 2003, April, May, June, July, and November had above-average precipitation, ranging from 7 to 67 mm above average. May and August in 2004 and July, August, and September in 2005 also had above-average precipitation. In general, soil water availability for soybean and corn growth was favorable in all 4 yr, with no obvious signs of plant water stress.

Rye Cover Crop and Gamagrass Shoot Dry Matter and Nitrogen Uptake

The rye cover crop grew most in 2005 and 2002 and least in 2003 (Table 3). The rye cover crop in 2005 followed a corn crop, and the rye in 2002 followed a soybean crop. There is nothing apparent in the average temperature and precipitation data (Table 2) that explains the greater cover crop growth in these 2 yr. In 2002, rye was overseeded into standing corn in early September. The rye seed germinated but did not survive and establish well because precipitation was 42 mm below normal and average temperature was slightly above normal in September 2002. As a result of the poor stand, rye cover crop dry matter in the spring of 2003 was very low. Because of the poor establishment and growth of the rye in 2002 to 2003, subsequent rye cover crops were planted with a grain drill after corn and soybean harvest. From previous experience (Johnson et al., 1998), we knew that rye cover crops can be established reliably with overseeding into a standing soybean crop in mid to late August. Johnson et al. (1998) reported that shoot dry weight of rye

overseeded into soybean averaged 1.87 Mg ha^{-1} over 3 yr, which is comparable to the 1.96 Mg ha^{-1} average for the 2 yr after soybean in this study. Overseeding of rye cover crops into corn can be successful in Minnesota (Porter, personal communication, 2005) and in Ontario (Ball-Coelho et al., 2005) but apparently requires cooler temperatures and more rainfall than we had in central Iowa in 2002. Strock et al. (2004) observed rye dry weights ranging from 0.5 to 2.7 Mg ha^{-1}, with an average of 1.4 Mg ha^{-1} for rye drilled after corn harvest in Minnesota. These results are similar to those observed in our experiment for rye following corn. Rye cover crop shoot N concentration varied from 36.5 to 22.7 g N kg^{-1} and seemed to decrease as shoot dry weight increased (Table 3), which was also similar to the results of Strock et al. (2004). Cover crop shoot N accumulation was greatest in 2005 and least in 2003 and ranged from 76.5 to 9.3 kg N ha^{-1}. Even though 2003 had the greatest shoot N concentration, shoot N accumulation was very low in 2003 because of the poor cover crop stand and growth.

Gamagrass is a warm season grass and grows actively in Iowa from mid-May through September. Gamagrass shoot dry weight was calculated based on the entire plot area, even though the gamagrass strip covered only 10% of the plot area. Gamagrass shoot dry weight varied from 1.46 to 2.02 Mg ha^{-1} but did not vary significantly among years (Table 3). Measurements were not taken in 2002. Even though the gamagrass strips covered only 10% of the plot area, gamagrass shoot dry weights were greater than cover crop shoot dry weights in 2003 and not significantly different in 2004. In 2005, the cover crop produced more shoot biomass. Gamagrass shoot N concentrations were considerably lower than those of the rye cover crop. Thus, total N accumulation by the gamagrass shoots was much less than that taken up by the rye cover crop in 2004 and 2005 but greater than cover crop N uptake in 2003 because of poor cover crop growth.

Corn and Soybean Yields

Corn (2002 and 2004) and soybean (2003 and 2005) grain yields are shown in Table 4. Yearly averages for corn and soybean yields in the plots were greater than the Boone county average each year (National Agricultural Statistics Service, 2006). In 2002, the corn grain yield of the cover crop treatment was significantly less than that of the control. Our previous research (Johnson et al., 1998) had shown that a corn yield reduction commonly occurred after a rye cover crop killed immediately before planting. In 2004, the corn grain yield was significantly greater than in 2002, and there were no significant differences among treatments. There were several differences between 2002 and 2004 that may have contributed to the treatment effects in 2002 but not in 2004. In 2002, rye cover crop shoot biomass averaged 2.43 Mg ha^{-1} compared with 1.5 Mg ha^{-1} in 2004. Additionally, in 2002 the rye cover crop was killed with an herbicide 8 d before corn planting and then incorporated with shallow tillage on the day of planting, whereas in 2004 the rye was killed 12 d before planting and not incorporated. The light tillage was performed at planting in 2002 to level the plots because of minor subsidence above the tile lines. Thus, the greater rye biomass, the incorporation of rye residues, and the shorter period between rye kill and corn planting may have contributed to the lower corn yields for the rye treatment in 2002. Soybean yields

Table 4. Average main crop grain yields for treatments 2002–2005.

| Year | Main crop | Main crop grain yield | | | |
		Control	Gamagrass	Rye	Avg.
		——————Mg ha^{-1}——————			
2002	corn	12.4a†	12.1a	11.2b	11.9B
2003	soybean	2.7a	2.4a	2.7a	2.6D
2004	corn	13.3a	13.1a	13.3a	13.2A
2005	soybean	4.5a	4.2a	4.2a	4.3C

† Numbers within a row followed by the same lowercase letter and numbers within a column followed by the same uppercase letter are not significantly different as indicated by Tukey's test at the 0.05 probability level. Comparisons between years were only made between similar crops.

were not significantly reduced after the rye cover crop or in the harvested area of the gamagrass plots. Strock et al. (2004) also found that a rye cover crop did not reduce soybean yields in Minnesota. Although the gamagrass treatment did not significantly reduce corn or soybean yields of the harvested area (i.e., not including the gamagrass strip), the gamagrass strip reduced the harvested area by 10% in this experiment. Thus, one disadvantage of planting gamagrass strips above tile lines is that the area occupied by the strips is not producing harvestable grain yield. The gamagrass strips, however, could be harvested for forage.

End-of-Season Soil NO$_3$

Soil cores were taken after harvest each year and analyzed for soil NO$_3$ and NH$_4$. Substantial amounts of inorganic N to a depth of 1.2 m were present in all 4 yr (Table 5). In all years, only a small percentage of the soil inorganic N was in the form of NH$_4$ (data not shown). The least amount of inorganic N was found in 2001, which was significantly less than the inorganic N present in the other 4 yr. In 2001, soybean was planted in the experimental area, no N fertilizer was applied in that year, and September rainfall was well above average (Table 2). No significant treatment differences in soil inorganic N levels were found except in 2001. In that year, the cover crop treatment had less inorganic N in the soil profile to the 1.2-m depth than the control and gamagrass treatments. In 2001, the rye cover crop was overseeded into the soybean crop in late August and had adequate time to grow and take up N before the soil samples were taken in mid-November. In contrast, the rye cover crop did not germinate and establish very well with overseeding in 2002 and was drilled after corn or soybean harvest in early

Table 5. Total inorganic N to a depth of 1.2 m after harvest for 2001–2005.

| Year | Total soil inorganic N† | | | |
	Control	Gamagrass	Rye	Avg.
	——————kg N ha^{-1}——————			
2001	27.6a‡	27.8a	13.7b	23.0B
2002	61.7a	49.3a	26.5a	45.8A
2003	52.9a	54.6a	44.2a	50.6A
2004	94.6a	59.6a	70.4a	74.9A
2005	65.3a	46.2a	82.9a	64.8A
Avg.	60.4a	47.5a	47.5a	

† Total inorganic N to a depth of 1.2 m was calculated by assuming a bulk density of 1.25 g cm^{-2} for all depth increments.

‡ Numbers within a row followed by the same lowercase letter and numbers within a column followed by the same uppercase letter are not significantly different as indicated by Tukey's test at the 0.05 probability level.
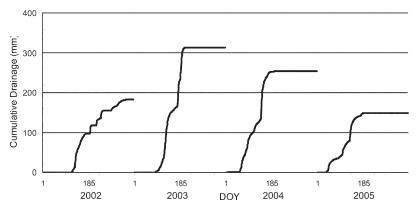
Fig. 1. Cumulative drainage for a control treatment plot over 4 yr, 2002–2005.

October in 2003 and 2004. Because soil samples in the gamagrass treatment plots were taken outside of the gamagrass strips, we did not expect the gamagrass treatment to differ from the control.

Hydrology

In all 4 yr, most of the subsurface drainage occurred in the spring and early summer (Fig. 1 and Table 6). Cumulative drainage reached 5% of the annual total earlier in the year in 2004 and 2005 (before day of year [DOY] 61) than in 2002 and 2003. This was probably the result of above-average precipitation in November of 2003; January, February, and March of 2004; November of 2004; and January and February of 2005 (Table 2). Conversely, cumulative drainage reached 90% of the annual total later in the year in 2002 (DOY 261) than in the other 3 yr, most likely because of substantially above-average precipitation in July

Table 6. Average dates on which 5% and 90% of cumulative drainage were measured and average annual cumulative drainage for 2002–2005.

Year	Control	Gamagrass	Rye	Avg.
		DOY		
Date of 5% of cumulative drainage				
2002	125a†	124a	129a	126A
2003	112a	111a	108a	110B
2004	59a	61a	62a	61C
2005	55a	59a	44a	53C
Avg.	88a	89a	86a	
Date of 90% of cumulative drainage				
2002	262a	260a	260a	261A
2003	191a	191a	191a	191B
2004	155a	152a	154a	154C
2005	147a	144a	151a	147C
Avg.	189a	187a	189a	
		mm		
Cumulative drainage				
2002	227a	158a	209a	197C
2003	346a	235b	301a	294A
2004	248a	221a	253a	241B
2005	175a	109a	139a	141D
Avg.	249a	181a	226a	

† Numbers within a row followed by the same lowercase letter and numbers within a column followed by the same uppercase letter are not significantly different as indicated by Tukey's test at the 0.05 probability level.

2002. In contrast, cumulative drainage reached 90% by DOY 191 in 2003 and by DOY 154 in 2004 and 2005. The drainage season in 2002 started later, lasted longer, and ended later than any of the other 3 yr. In northern Indiana, Brouder et al. (2005) reported that over 6 yr most of the tile drainage occurred in May and June.

Annual cumulative drainage differed significantly among all 4 yr, with 2003 > 2004 > 2002 > 2005. Even though cumulative drainage differed between 2003 and 2005, cumulative annual precipitation did not (Table 2), and soybean crops were grown in both years. In 2003, drainage represented 33% of the total precipitation, and above-average precipitation occurred in four consecutive months (April–July), which coincided with the period when most of the drainage occurred (DOY 110–191) and the time of soybean canopy development. Conversely, in 2005 drainage represented only 16% of the total precipitation and precipitation was well above average in August and September, which was after drainage had stopped and was during or just after the period of maximum water use by the soybean crop.

Neither the rye cover crop nor the gamagrass treatments significantly changed the timing of drainage or reduced cumulative drainage averaged over the 4 yr compared with the control (Table 6). The interaction of year and treatments was significant. The gamagrass treatment had significantly less drainage than the control and cover crop treatments in 2003, which was the year with the greatest cumulative drainage. We had expected that a winter rye cover crop and a gamagrass strip incorporated into a corn–soybean cropping system would increase annual plant transpiration and reduce drainage compared with that of a corn–soybean system without these practices. Even though the reduction of the 4-yr average drainage compared with the control was 9% for the cover crop treatment and 27% for the gamagrass treatment, these differences were not significant because of plot-to-plot variability in drainage. Strock et al. (2004) reported a significant 11% reduction in drainage averaged over 3 yr for a corn–soybean cropping system with a rye cover crop following corn compared with a corn–soybean cropping system without cover crops. Similarly, Logsdon et al. (2002), in a controlled-environment lysimeter study, also observed less drainage with a rye cover crop following soybean.

Nitrate in Drainage Water

The rye cover crop treatment significantly reduced the average annual flow-weighted NO_3 concentration of drainage water by 50% or more compared with the control in each of the 4 yr (Table 7). Additionally, annual flow-weighted NO_3 concentration of the cover crop treatment was below the 10 mg N L^{-1} maximum contaminant level set by the USEPA for drinking water in 2002, 2004, and 2005. In 2003, even though the rye cover crop treatment produced only 0.25 Mg ha^{-1} of rye shoot biomass, the average annual flow-weighted NO_3 concentration of the drainage water for that treatment was 11.8 mg N L^{-1}, which was 12.9 mg N L^{-1} less than that of the control. In the experiment of Strock et al. (2004), the rye cover crop was only planted after the corn phase of the

rotation, yet the cover crop reduction of the annual flow-weighted NO_3 concentration carried over into the spring drainage period of the next corn year in 1 yr of the study. Although the NO_3 concentrations of the gamagrass treatment were numerically less than those of the control in 2 of the 4 yr, the differences were not significant for individual years or averaged over 4 yr. Annual flow-weighted NO_3 concentration of drainage water was significantly higher in 2003, which followed a corn phase and was 11 mo after N fertilizer application in 2002 (Table 7). The year-by-treatment interaction was not significant. Although 2005, like 2003, followed a corn phase and N fertilizer application in 2004, its annual flow-weighted NO_3 concentration was no different than 2002 and 2004. The results for 2005 are contrary to the common expectation that flow-weighted NO_3 concentrations of drainage water will be higher after N fertilizer applications during the corn phase of the corn–soybean rotation than after the soybean phase (Strock et al., 2004). Similarly, Jaynes et al. (2001) reported that monthly flow-weighted NO_3 concentrations peaked shortly after N fertilizer application in the corn phase of the rotation and declined slowly during the soybean phase.

Figure 2 shows the average NO_3 concentrations of the proportional water samples collected throughout 2004. The main N fertilizer application occurred on 21 May 2004 (DOY 142), and NO_3 concentrations of the drainage water increased shortly after this. This increase was most noticeable for the cover crop treatment and the cover crop NO_3 concentration fluctuates around the 10 mg N L^{-1} level for the 30 d after application. During this same period, the gamagrass and control treatment concentrations increased to greater than 20 mg N L^{-1}. The average NO_3 concentration of the cover crop treatment was low before 30 March 2004 (DOY 90), even though there was little visible growth of the cover crop before that time. After DOY 90, when the cover crop was actively growing, the average NO_3 concentration of the cover crop treatment decreased to about 6 mg N L^{-1} and remained at that level until the N fertilizer application, even though the cover crop was killed on 16 April 2004 (DOY 107). The average NO_3 concentration of the gamagrass treatment was also low relative to the control early in the year but quickly increased to the same level as the control. After 19 June 2004 (DOY 171), the average NO_3 concentration of the gamagrass treatment decreased relative to the control until drainage stopped. This midsummer decrease correlated well with active growth period of this warm season grass.

Annual NO_3 load in the drainage water was reduced significantly by at least 50% relative to the control by the rye cover crop treatment in all 4 yr (Table 8). On average the cover crop treatment reduced the annual NO_3 load in the drainage water by 61% or 31.0 kg N ha^{-1}. This reduction in NO_3 mass loss in tile drainage is considerably greater than the 19 kg N ha^{-1} average reduction found by Jaynes et al. (2001) in response to reducing N fertilizer application rates by two thirds. Using a rye cover crop, Strock et al. (2004) reported a 13% reduction in the NO_3 load of drainage water. Kladivko et al. (2004) observed a 60% reduction in drainage water NO_3

Table 7. Average annual flow-weighted NO_3 concentration of drainage water for 2002–2005.

| Year | Flow-weighted NO_3 concentration | | | |
	Control	Gamagrass	Rye	Avg.
	—mg-N L^{-1}—			
2002	19.1a†	23.4a	5.8b	16.1B
2003	24.7a	24.8a	11.8b	20.4A
2004	19.8a	17.4a	9.3b	15.5B
2005	21.6a	17.7a	8.0b	15.8B
Avg.	21.3a	20.8a	8.7b	

† Numbers within a row followed by the same lowercase letter and numbers within a column followed by the same uppercase letter are not significantly different as indicated by Tukey's test at the 0.05 probability level.

load with a winter wheat cover crop and a reduction in fertilizer rates. In both of these studies, the cover crops were planted after the corn phase of the rotation, whereas in our experiment a rye cover crop was planted after both phases of the rotation. In our experiment, it seems probable that the reduction in NO_3 load caused by cover crop treatment was primarily the result of a reduction in NO_3 concentration of the drainage water rather than a reduction in drainage volume. The 4-yr average difference in cumulative drainage between the cover crop and control treatments (23 mm; not significant) would only account for 4.9 kg N ha^{-1}, assuming that the NO_3 concentration was not affected by the cover crop. This accounts for only 16% of the difference in NO_3 loss between the cover crop and control treatments. Thus, it seems likely that the primary mechanism by which cover crops reduced the NO_3 load of the drainage water was through a reduction in the NO_3 concentration of the drainage water resulting from the uptake of soil N. In 3 of the 4 yr, the rye cover crop accumulated more N in shoot biomass than the corresponding reduction in NO_3 load between the control and the cover crop treatment (Table 3). In 2003, however, the cover crop treatment reduced the annual NO_3 load in the drainage water by 47.2 kg N ha^{-1}, but cover crop shoot dry weight was only 0.25 Mg ha^{-1}, and only 9.3 kg N ha^{-1} accumulated in the shoot biomass. Even assuming that the dry weight and N concentration of the rye roots were the same as that of the shoots, which is unlikely (Parkin et al., 2002; Sainju et al., 2005), the total N accumulated in the roots and shoots of the cover crop does not account for the reduction in NO_3 load in 2003. This seems to imply an
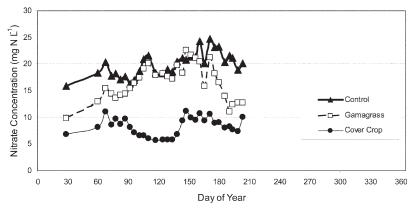

Fig. 2. Average NO_3 concentration of drainage water for control, cover crop, and gamagrass treatments in 2004.

Table 8. Cumulative annual NO₃ load of drainage water for 2002–2005.

Year	Cumulative NO₃ load			
	Control	Gamagrass	Rye	Avg.
	————————kg N ha⁻¹————————			
2002	40.4a†	36.3a	11.2b	29.3C
2003	81.1a	57.3a	33.9b	57.4A
2004	47.2a	37.8a	23.0b	36.0B
2005	34.4a	19.6ab	11.1b	21.7C
Avg.	50.8a	37.7a	19.8b	

† Numbers within a row followed by the same lowercase letter and numbers within a column followed by the same uppercase letter are not significantly different as indicated by Tukey's test at the 0.05 probability level.

effect on N cycling other than accumulation of N in the biomass of the cover crop, but we have no hypothesis for what this effect might be that is supported by the data we collected.

The gamagrass treatment had annual NO₃ loads that were intermediate between those of the control and rye treatments (Table 8). The differences, however, were not significant for individual years or averaged over the 4 yr. Even though the gamagrass treatment significantly reduced drainage in 2003, the NO₃ concentration of the drainage water relative to the control was not reduced, and the NO₃ load was not significantly reduced in that year.

Substantial losses of NO₃ in the drainage water occurred in all 4 yr, especially for the control treatment (Table 8). Average cumulative annual NO₃ load was greatest in 2003, intermediate in 2004, and least in 2002 and 2005. The interaction of years and treatments was not significant. In general, during the 4 yr of this study, the periods of the greatest losses of nitrate coincided with the periods of greatest drainage (Fig. 1 and 3). Substantial NO₃ losses occurred in the springs and early summers of 2002 and 2004, which received N fertilizer in May but followed soybean crops that did not receive N fertilizer (Fig. 3). Nitrate loads in 2004 were significantly greater than in 2002 and probably reflect the greater cumulative drainage in 2004 (Table 6). The cumulative NO₃ losses of the springs and early summers of 2003 and 2005, which followed corn crops that received applications of N fertilizer in the previous May, differed by a factor of two. The corn crop of fall 2004 averaged 13.2 Mg ha⁻¹ compared with 11.9 Mg ha⁻¹ in fall 2002, but the soil inorganic N was greater in fall 2004 than in fall 2002. Cumulative drainage was significantly greater in 2003 than in 2005.
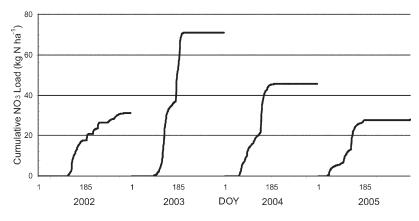
Thus, it seems that the greater drainage in 2003 may have been the primary factor contributing to the greater cumulative annual NO₃ losses in 2003 compared with 2005. Because substantial NO₃ losses occurred in all 4 yr and fertilizer was only applied in two of those years, we assume that some of the NO₃ lost in drainage water came from soil mineralization. In Illinois, David et al. (1997) observed that NO₃ losses in tile drainage were strongly related to cumulative drainage and high drainage events within a given year. They also concluded that, for their study watershed, mineralized soil N was the source of a substantial portion of the N lost in drainage water and that NO₃ concentrations in drainage water would be relatively high even without N fertilization.

Conclusions

A gamagrass strip 3.05 m wide centered over the subsurface drain tiles and covering 10% of the plot surface area did not significantly reduce cumulative drainage, the average annual flow-weighted NO₃ concentrations, or cumulative NO₃ loads averaged over the 4 yr. The gamagrass strip did reduce cumulative drainage in 2003. It is possible that the permanent perennial strip would have been more effective if it had been established for longer period or if the strip above the drain tiles had been wider than 3.05 m. Eastern gamagrass is a warm-season perennial grass, and perhaps a cool-season grass or a perennial dicot that grows more actively in the early spring would have been more effective. We are unsure as to how the permanent vegetation strip should be managed to reduce NO₃ losses to subsurface drains. Thus, a permanent perennial strip above subsurface drain tiles did not significantly reduce NO₃ losses in drainage water in this experiment, but it may be possible to improve the effectiveness of this management practice with different species, increasing the width of the strip, or changing management. Gamagrass strips in corn–soybean production fields would remove the area occupied by the strips from grain production and would complicate field operations, especially herbicide application.

A rye winter cover crop grown after corn and soybean has the potential to significantly reduce the NO₃ loads and concentrations of drainage water delivered to surface waters by subsurface drainage systems in the Midwest Corn Belt. Averaged over 4 yr, the rye cover crop reduced flow-weighted NO₃ concentrations by 59% and loads by 61%. In this experiment, it seems likely that the reduction in NO₃ loads and concentrations was caused by N uptake by the cover crop. Before there is widespread adoption of winter cover crops in the Midwest Corn Belt, problems such as costs of establishment, logistical conflicts, and availability of seed need to be overcome. Also, rye winter cover crops can reduce corn yields and may establish or grow poorly in some years. We believe that management of rye winter cover crops can be improved to address these problems. For example, only a few cultivars of rye have been evaluated in field experiments for their biomass production or their effect on the following corn crop. Additionally, earlier burndown of the cover crop relative to corn planting may have

Fig. 3. Cumulative NO₃ load of drainage water for a control treatment plot over 4 yr, 2002–2005.

explained why there was no corn yield reduction in 2004 in our study. Lastly, timing and methods of cover crop establishment can be improved to reduce year-to-year variability of stand establishment and to increase cover crop growth.

Acknowledgments

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