

Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water

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ABSTRACT

Much of the NO_3 in the riverine waters of the upper Mississippi River basin in the United States originates from agricultural land used for corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) production. Cover crops grown between maturity and planting of these crops are one approach for reducing losses of NO_3 . In this experiment, we evaluated the effectiveness of oat (*Avena sativa* L.) and rye (*Secale cereale* L.) cover crops in reducing NO_3 concentrations and loads in subsurface drainage water. The oat fall cover crop was broadcast seeded into living corn and soybean crops before harvest in late August or early September and was killed by cold temperatures in late November or early December. The rye winter cover crop, which had already been used annually for four years, was planted with a grain drill after corn and soybean harvest, overwintered, grew again in the spring, and was killed with herbicides before main crop planting. These treatments were evaluated in subsurface-drained field plots with an automated system for measuring drainage flow and collecting proportional samples for analysis of NO_3 concentrations from each plot. The rye winter cover crop significantly reduced drainage water NO_3 concentrations by 48% over five years, but this was less than the 58% reduction observed in its first four years of use. The oat fall cover crop reduced NO_3 concentrations by 26% or about half of the reduction of the rye cover crop. Neither cover crop significantly reduced cumulative drainage or nitrate loads because of variability in cumulative annual drainage among plots. Both oat and rye cover crops are viable management options for significantly reducing NO_3 losses to surface waters from agricultural drainage systems used for corn and soybean production.

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1. Introduction

The flux of nitrogen (N) from the Mississippi River basin in the central United States is largely responsible for the hypoxic zone in the Gulf of Mexico (Rabalais et al., 1996; Turner et al., 2006; EPA-SAB, 2007). Much of the NO_3 in the surface waters of the upper Mississippi River basin is from agricultural land used for corn and soybean production (Burkart and James, 1999; David and Gentry, 2000; Goolsby et al., 2001; David et al., 2010). Water percolating through these cultivated soils accumulates high loads of NO_3 because these soils contain large quantities of NO_3 from mineralization of organic N that is naturally present in these soils and from

applications of N fertilizers for corn production. Artificial subsurface drainage systems in many agricultural fields further compound the problem by rapidly transporting the NO_3 -laden water to surface waters (Jaynes et al., 1999; Goolsby et al., 2001; Royer et al., 2006; David et al., 2010). Lastly, corn and soybean, grow and take up N and water for only five months of the year, whereas mineralization, percolation, and drainage can continue throughout the year except when the soil is frozen.

Winter cover crops have the potential to reduce NO_3 leaching in corn–soybean rotations by taking up water and NO_3 during the months between corn and soybean maturity and planting (Dabney et al., 2011; Kaspar and Singer, 2011). However, information about their effectiveness in the upper Mississippi River basin is limited (Dinnes et al., 2002; Dabney et al., 2011). Tonitto et al. (2006) in a meta analysis of 69 studies from across the US showed that non-leguminous cover crops reduced NO_3 leaching losses by an average of 70% and the amount of reduction was directly related to cover crop growth. In the upper Mississippi River basin, however, the potential cover crop growing season between harvest and planting of corn and soybean is short and cold and only cold tolerant species like winter rye (*Secale cereale* L.) reliably produce

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Table 1
Crop management dates.

Main crop	2005 Soybean	2006 Corn	2007 Soybean	2008 Corn	2009 Soybean	2010 Corn
Main crop planting date	06 May	4 May	22 May	14 May	22 May	29-April
Oat cover crop planting date	24 August	25 August	27 August	11 September	01 September	20 August
Main crop harvest date	30 September	20 October	26 September	28 October	28 September	16 September
Rye cover crop planting date	30 September	24 October	28 September	29 October	28 September	17 September
Rye cover crop kill date	–	21 April	10 May	29 April	21 May	19-April
Sidedress N fertilizer application	–	19 June	–	19 June	–	09 June
Total N applied for crop year	–	225 kg ha ⁻¹	–	198 kg ha ⁻¹	–	198 kg ha ⁻¹

substantial growth (Snapp et al., 2005). In Iowa, Kaspar et al. (2007) reported that a winter rye cover crop following both phases of a corn–soybean rotation in a no-till system reduced NO₃ losses in drainage water by an average of 61% over four years. In another Iowa study, however Qi et al. (2011), observed no significant effect of a rye cover crop on annual NO₃ losses in drainage water for a fall tillage system. Farther north in Minnesota (Strock et al., 2004), a rye cover crop planted only after corn in a corn–soybean rotation reduced NO₃ losses by 13%, but the rye cover crop had less growth than in the Iowa study. Thus, the potential of winter cover crops to reduce NO₃ losses in fields with subsurface drainage is somewhat uncertain in the upper Mississippi River basin.

Nitrogen taken up by a cover crop is eventually recycled back into the soil in the residues of roots and shoots (Malpassi et al., 2000). This N would eventually be mineralized and then be available for uptake by corn, soybean, or cover crop plants or it could also be lost to leaching. For example, in Denmark, Hansen et al. (2000a) observed more NO₃ leaching losses and more N availability to the main crop (Hansen et al., 2000b) in treatments that had a history of 24 years of a perennial ryegrass (*Lolium perenne* L.) winter cover crop than in treatments that did not. In Canada, Ball Coelho and Roy (1997) observed higher soil NO₃ after corn planting and less NO₃ leaching following a rye winter cover crop during its first three years of use. Two to seven years after the cover crop began (Ball-Coelho et al., 2005), they observed greater corn grain yields and grain N contents following a rye cover crop, but saw no evidence of increased NO₃ leaching or increased organic N accumulation in the soil. Thus, some evidence suggests that continued use of a winter cover crop can increase soil N availability and this may or may not reduce its effectiveness in reducing NO₃ leaching. Therefore, there is a need for additional long-term studies that examine the effectiveness of winter cover crops over time.

One approach to increasing the growing season for a winter cover crop in a corn–soybean rotation is to broadcast cover crop seed onto the soil surface in the standing corn and soybean crops before harvest. Johnson et al. (1998) successfully established both oat and rye cover crops with broadcast seeding into soybeans before harvest in an Iowa study. Similarly, Ball-Coelho et al. (2005) broadcast seeded a rye cover crop into corn before harvest. The main advantage of broadcast seeding before harvest is that the cover crop can begin growing and taking up NO₃ during the 20–30 days between crop maturity and harvest when grain is drying and the main crop is no longer taking up water and N. During this time the soil is still warm, which would promote N mineralization, and any NO₃ in the soil would be more susceptible to leaching because no plant transpiration is occurring. Thus, if cover crops are successfully established with broadcast seeding before harvest, they may be relatively more effective at reducing NO₃ leaching than cover crops established after main crop harvest.

Cover crops have the potential to reduce NO₃ losses to drainage systems and surface waters. No field studies in the upper Mississippi River basin, however, have examined the effectiveness of winter cover crops to reduce NO₃ losses in drainage water after

more than four years of annual establishment. Additionally, the effectiveness of cover crops broadcast seeded before harvest on reducing nitrate leaching has not been tested extensively. The objectives of our study were to: (1) determine whether a rye winter cover crop continues to reduce NO₃ losses in drainage water after more than four years of annual establishment and (2) to determine if an oat cover crop broadcast seeded into corn and soybean crops before harvest can have a measureable impact on NO₃ losses in drainage water.

2. Materials and methods

2.1. Site description

In 1999, separate drainage collection and measurement systems were installed for each of 24 field plots arranged in four randomized complete blocks in a 3.7 ha field 8.0 km northwest of Ames, IA (42.05° N, 93.71° W). The site, its drainage system infrastructure, and previous experiments at the site are also described by Kaspar et al. (2007) and Jaynes et al. (2008). The two predominant soils (Andrews and Diderikson, 1981) on the site were: Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) and Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). Individual plots were 30.5-m wide by 42.7-m long. Only 12 of the 24 plots were used for this experiment with the rest utilized for another experiment in progress and the experiment described by Jaynes et al. (2008). The experiment described in this paper begins in the fall of 2005 and reports on drainage water measurements and sampling for the calendar years 2006–2010.

2.2. Cover crop treatment management

Three treatments were compared in this experiment: a rye winter cover crop, an oat fall cover crop, and a control (no rye or oat cover crop). All three treatments were applied to both phases of a corn–soybean rotation. The rye winter cover crop treatment was a continuation of a treatment that was first established in fall 2000 and consisted of a cereal rye (cv. 'Maton') drilled following harvest (Table 1) at 2.5×10^6 seeds ha⁻¹. The oat (cv. 'Jerry') fall cover crop treatment was a new treatment and was first established in fall 2005. The oat cover crop was broadcast seeded onto the soil surface in the standing corn and soybean crops before harvest in late August or early September (Table 1) at 3.7×10^6 seeds ha⁻¹. The oat cover crop was killed by cold fall temperatures usually in late November to early December when the soil surface begins to freeze. The rye overwintered, grew again in the spring, and was chemically killed with glyphosate [N-(phosphonomethyl) glycine] applied at 1.12 kg a.i. ha⁻¹ 10–15 d before planting of the main crop each spring (Table 1).

2.3. Corn and soybean management

The corn–soybean cropping system was first established in 2000 with corn grown in even-numbered years and soybean in odd

years. This rotation was continued for the current experiment with management typical for central Iowa. Fertilizer rates, management dates, and sampling dates are listed in Table 1. For the most part, the field plots were managed as a no-till system with the last tillage occurring in spring 2002. Weed control was typical for a no-till system using a combination of preemergence and postemergence herbicides for both corn and soybean. Both soybean and corn were planted with a five-row, 0.76-m row width, no-till planter. The soybean cultivars, 'Stine 2289-4' (Stine Seed Co., Adel, IA) in 2005 and 'Harosoy 63' in 2007 and 2009 were planted at 740 000 seeds ha⁻¹ in early- to mid-May (Table 1). Corn was planted at 79 000 seeds ha⁻¹ in late April or early May using 'Pioneer 34A16' (Pioneer Hybrid International Inc., Johnston, IA) in 2006, 'Pioneer 34A20' in 2008, and 'Pioneer 34Y03' in 2010. A liquid starter fertilizer (urea, ammonium hydroxide, phosphoric acid, and potassium hydroxide; 9–18–9) was applied in-furrow during corn planting at a rate of 6 kg N ha⁻¹. Additionally, in 2008 and 2010 a sidedress application of liquid urea–ammonium nitrate at 45 kg N ha⁻¹ was also applied at corn planting. A post-planting sidedress application of liquid urea–ammonium nitrate was applied in corn years with a spoke-wheel fertilizer injector (Baker et al., 1989) in mid June (Table 1) at a rate of 179 kg N ha⁻¹ in 2006 and at 123 kg N ha⁻¹ in 2008 and 2010. Dry P and K fertilizers were applied as subsurface bands in November of 2005, 2007, and 2009 based on soil tests (N contained in P fertilizer; 40 kg N ha⁻¹ in 2005; 24 kg N ha⁻¹ in 2007 and 2009). Total N applied with fall-applied P fertilizers, starters, and sidedress applications was 225 kg ha⁻¹ in 2006 and 198 kg ha⁻¹ in 2008 and 2010 (Table 1).

2.4. Drainage water collection and sampling

The drainage water collection and sampling system was designed to keep the water drained from each plot separate from other plots. Thus, there were four replications of drainage measurements for each treatment. A perforated, 7.62-cm diameter plastic drainage tile was installed lengthwise down the center of each plot at a depth of 1.2 m, such that the distance between tiles in adjacent plots was 30.5 m. Plastic tile without perforations was then used to conduct drainage water from the end of each plot to a separate collection basin. Water was then pumped from each collection basin through a dedicated flow meter and flow volume versus time was recorded with a data logger for each plot. Cumulative annual drainage was calculated by summing the daily flow volume from each plot and dividing by the plot area.

A proportional water sample was collected in a designated sample bottle for each plot every time water was pumped from a plot's collection basin by a small diameter tube connected to the pump outlet pipe. Depending on flow rate, these water samples were retrieved on a weekly or shorter time frame and stored at 4°C until analysis. Water samples were analyzed for NO₃ using a Lachat Autoanalyzer¹ (Zellweger Analytics, Lachat Instrument Division, Milwaukee, WI). Nitrate in samples was reduced to NO₂ and the NO₂ concentration determined colorimetrically (US EPA Method 353.2; US EPA, 1983). The method's lower detection limit for NO₃-N was 0.3 mg N L⁻¹ and standard laboratory quality control procedures were employed. Mass of NO₃ in drainage water was calculated by multiplying the NO₃ concentration of each proportional water sample by the volume of water discharged during the time the sample was collected. Cumulative annual NO₃ load from each plot was calculated by summing the NO₃ mass for all samples in

a calendar year. Annual flow-weighted NO₃ concentrations were computed by dividing the cumulative annual load by the annual drainage volume.

Additionally, as part of the original drainage infrastructure installation, several systems were installed to improve the hydrologic isolation of the site and plots. To reduce subsurface water flow into the site from the surrounding area, a 25.4-cm diameter perforated drain tile was installed around the perimeter of the site. Drainage water from this perimeter tile was kept separate from plot collection system and was routed to the county drainage system. Additionally, within the site a 1.8-m deep plastic-lined trench was installed between each group of four plots to reduce subsurface flow between plots within the site.

2.5. Cover crop shoot samples

Cover crop shoot dry matter samples were collected in early November for oat and in the spring of each year within two days of glyphosate application for rye (Table 1). Three samples were taken from each plot by clipping at the soil surface all cover crop plants found within a sampling frame with internal dimensions 0.76-m wide and 0.50-m long. For each sample the frame was positioned so that the 0.76 m side of the frame was perpendicular to a row of the previous main crop and one row was included in the sampled area. Samples were finely ground and analyzed for N content using the dry combustion-GC method (Scheppers et al., 1989) with an EA1112 Flash NC Elemental analyzer (Thermo Electron Corp., Waltham, MA).

2.6. Corn stalk nitrate samples

Before corn harvest and shortly after corn had reached physiological maturity two stalk NO₃ samples were taken from each plot to evaluate corn N sufficiency (Binford et al., 1990, 1992; Blackmer and Mallarino, 1996). Each sample consisted of the basal stalk segments of five corn plants. Each segment was approximately 0.20-m long and was collected between 0.15 and 0.40 m from the soil surface. Stalk samples were dried at 60°C, ground to pass through a 0.5-mm stainless steel screen, subsampled, and then pulverized in a ball mill. A 0.25 g subsample was mixed with 50 mL of 2 M KCl, shaken, and filtered. The filtrate was then analyzed for nitrate as described for water samples.

2.7. Corn and soybean yield

Soybean and corn grain yields were determined by harvesting the entire plot area, weighing the grain, and measuring grain moisture. Reported grain yields were adjusted to 0.155 and 0.130 g g⁻¹ grain moisture, for corn and soybean, respectively.

2.8. Weather data

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, 2011; Table 2).

2.9. Statistical analysis

The experimental design was a randomized complete block design with three treatments and four blocks. Data for individual years were analyzed for treatment and block effects using PROC ANOVA procedure (SAS, 2010). Data for all five years were combined and analyzed for year, treatment, block, and year by treatment effects using the PROC MIXED procedure (SAS, 2010)

¹ Mention of trade names, company names, or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA-ARS. USDA is an equal opportunity provider and employer.

Table 2
Average monthly air temperature and total precipitation 2005–2010.

Month	Average air temperature (°C)							Total precipitation (mm)						
	2005	2006	2007	2008	2009	2010	1951–2010 average	2005	2006	2007	2008	2009	2010	1951–2010 average
January	−7.8	1.1	−5.6	−8.3	−10.0	−10.0	−7.4	26	16	14	9	25	28	19
February	0.0	−2.8	−8.9	−7.8	−2.2	−8.9	−4.2	47	6	45	18	7	19	22
March	3.3	3.3	6.1	1.1	3.3	3.3	2.1	35	74	81	71	103	55	53
April	12.8	13.3	8.9	8.3	8.9	13.3	10.0	82	109	153	130	116	93	90
May	15.6	16.7	18.9	15.6	15.6	16.7	16.2	111	55	169	216	102	92	115
June	23.3	22.2	22.2	21.1	21.1	22.2	21.3	124	21	52	271	104	284	128
July	24.4	24.4	23.3	23.3	20.6	23.9	23.3	104	141	75	234	70	173	105
August	22.2	22.2	24.4	21.1	21.1	24.4	22.0	172	156	200	53	123	285	111
September	20.6	16.1	20.0	17.8	17.8	18.9	17.8	111	191	48	78	24	167	82
October	12.2	10.0	13.9	11.7	7.8	13.3	11.4	9	63	137	92	186	12	62
November	5.0	4.4	3.3	3.3	6.7	3.3	2.9	49	40	4	66	34	60	43
December	−6.6	1.1	−6.7	−7.8	−6.7	−6.7	−4.5	24	68	49	35	50	18	25
January–December ^a	10.6	11.1	10.0	8.3	8.9	9.4	9.3	894	940	1028	1273	945	1287	856

^a Values for the January through December periods are averages for the period for air temperature and totals for the period for precipitation.

Table 3
Oat and rye cover crop shoot dry matter, shoot N concentration, and total shoot N for cover crops planted in 2005–2009.

Fall of year cover crop planted	Oat			Rye		
	Shoot dry weight (Mg ha ^{−1})	Shoot N concentration (g N kg ^{−1})	Total shoot N (kg N ha ^{−1})	Shoot dry weight (Mg ha ^{−1})	Shoot N concentration (g N kg ^{−1})	Total shoot N (kg N ha ^{−1})
2005	1.54 bA ^a	24.4 aB	36.7 bA	2.44 aA	33.1 aA	80.4 aA
2006	0.32 aC	33.8 aAB	11.1 aB	0.61 aD	28.6 bB	17.1 aC
2007	1.15 aB	27.1 bAB	31.1 bA	1.26 aC	35.9 aA	45.4 aB
2008	0.07 bC	36.0 aA	2.5 bB	0.50 aD	27.6 bB	13.7 aC
2009	0.12 bC	30.1 aAB	3.8 bB	1.73 aB	27.6 bB	47.7 aB
Average	0.64 b	30.3 a	17.1 b	1.31 a	30.5 a	40.9 a

^a 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.

with years as a repeated measure. Tukey's test at the 0.05 probability level was used to compare treatment or year means when the analysis of variance indicated significant effects at the 0.05 probability level (SAS, 2010).

3. Results and discussion

3.1. Weather

Average monthly air temperatures and total monthly precipitation for 2005 through 2010 are shown in Table 2. Although there was some monthly variation from the 60-year normal temperatures during the 6-year period, in general there were no exceptional or consistent deviations. Total annual precipitation, however was above normal in all 6 years and substantially above normal in 2008 and 2010. The period of 2006 through 2010 was the wettest 5 year period during the 60 years of records. Of particular note were the very wet monthly totals for May of 2008; June of 2008 and 2010; July of 2008; August of 2005, 2007, and 2010; September of 2006 and 2010; and October of 2007 and 2009.

3.2. Cover crop shoot dry matter and N content

The oat and rye cover crops used in this study were planted and sampled at different times (Table 1). In three of the five years, the rye cover crop had significantly greater shoot growth than the oat cover crop probably because of spring growth (Table 3). Both oat and rye cover crops planted in fall 2005 and 2007 produced substantial shoot growth because there was good establishment and fall growth as a result of timely September and October rainfall, warmer than normal October temperatures, and a preceding main crop of soybean rather than corn (Tables 1 and 2). Rye planted in

2009 also produced more shoot growth than rye planted in the two corn years, 2006 and 2008. This is partly because of the later planting dates of the rye cover crop in those years (average 27 October; Table 1) compared with the soybean years (average 28 September). Oat planted in 2008 and 2009 had relatively poor establishment and growth because of below normal precipitation in August and September 2008 and in September 2009 (Table 2). Data for cover crops planted in fall 2010 are not shown because the experiment was terminated in December 2010.

The oat cover crop had significantly higher shoot N concentrations than the rye cover crop in three of the five years (Table 3) and in general, shoot N concentrations were greater for smaller and younger plants. The exception to this was for cover crops planted in 2007, for which rye had a greater shoot N concentration than oat and there was no significant difference in shoot biomass. The rye cover crop had significantly greater total shoot N than the oat cover crop in four of the five years. In three years this was due to greater total shoot growth and in 2007 it was due to a greater shoot N concentration. Averaged over the 5 years, the rye cover crop had more than twice the shoot growth and total shoot N as that of the oat cover crop. If only shoot growth and N uptake were to be considered we would expect that a rye cover crop would reduce nitrate losses in tile drainage more than an oat cover crop would.

3.3. Corn and soybean yields

Soybean yields and corn yields are shown in Table 4. Average corn yields in 2006 and 2008 were greater than those in 2010. In 2010 an extremely wet August (Table 2) led to the development of fungal diseases that seemed to cause the corn to mature prematurely and this may have reduced yield. Soybean yields were greater in 2005 than in 2007 and 2009, partly because of a change

Table 4
Average main crop grain yields for treatments 2005–2010.

Year	Main crop	Main crop grain yield (Mg ha ⁻¹)			Average
		Control	Oat	Rye	
2005	Soybean	4.5 a ^a	3.8 b	4.2 a	4.1 C
2006	Corn	13.4 a	12.6 b	13.1 a	13.1 A
2007	Soybean	2.3 a	1.9 b	2.0 ab	2.0 D
2008	Corn	13.3 a	12.8 b	13.5 a	13.2 A
2009	Soybean	2.4 a	2.1 a	2.4 a	2.3 D
2010	Corn	11.1 a	10.5 a	11.1 a	10.9 B

^a 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.

in the soybean cultivar planted in 2007 and 2009 to accommodate another experiment being conducted on the other plots at this site.

Corn and soybean yields of the oat cover crop plots were less than that of the control in the first four years of the experiment, whereas the yields of the rye treatment were not significantly less than the control in any year. Because the oat cover crop treatment was first established in the fall of 2005, the soybean yield reduction in 2005 could not have been caused by a cover crop preceding soybean planting and must have been caused by the cover crop that was broadcast seeded into the 2005 soybean crop in late August. The oat cover crop was seeded using hand-operated broadcast spreaders while walking through the plots and some damage to the soybean plants could have occurred during seeding. Although seeding of the oat cover crop occurred shortly before physiological maturity of both corn and soybean, it seems unlikely that the small newly emerging oat plants competed with soybean and corn plants for water and nutrients.

3.4. Corn stalk NO₃ concentration

Corn stalk NO₃ concentrations for 2006, 2008, and 2010 were all less than 2000 mg N kg⁻¹ (Table 5). Blackmer and Mallarino (1996) divided stalk NO₃ concentration into four categories (low <250 mg N kg⁻¹; marginal 250–700 mg N kg⁻¹; optimal 700–2000 mg N kg⁻¹; and excess >2000 mg N kg⁻¹) related to N availability and corn yield response to N. In fall 2010 stalk NO₃ concentrations were significantly greater than those in 2006 and 2008 and were within the optimal category for corn production. In 2006, the control treatment stalk NO₃ concentrations were in the marginal category and were greater than the oat and rye treatments, which were in the low category. In 2008 the cornstalk NO₃ concentrations were very low and well within the low category. Based on the categories identified by Blackmer and Mallarino (1996) N availability was most likely limiting in 2006 and 2008. Corn yields in 2006 and 2008 were much higher than in 2010 (Table 4), which would have resulted in greater plant demand for N and likely contributed to the low stalk NO₃ values in those years. Thus, the N fertilizers rates applied in 2006, 2008, and 2010 were not excessive, were likely less than optimal in 2006 and 2008, and should not have resulted in excessive residual fertilizer N in any year.

3.5. Drainage flow

In all 5 years a large part of the drainage occurred in spring and early summer (Fig. 1), which is similar to observation made by Helmers et al. (2005) in central Iowa over 15 years. Some drainage, however, occurred throughout the year except for brief periods at the beginning of the year when the ground was frozen and during late summer when the crop canopy and evapotranspiration were near their maximums. This included substantial drainage in late fall in some years, which is unusual for central Iowa (Helmers et al.,

2005), but probably resulted from greater than normal late summer and fall precipitation and high total annual precipitation in these years (Table 2). Total cumulative drainage was relatively high for all 5 years (Table 6) and as mentioned previously this was the wettest 5 year period within the last 60 years. The least drainage occurred in 2006 and 2007 had the most. On average, drainage tended to be a higher percentage of total precipitation in the soybean years (2007 and 2009; 43%) than in the corn years (2006, 2008, and 2010; 30%). Weed and Kanwar (1996) also observed more drainage for soybean than corn in Iowa.

There were no significant differences among treatments for annual cumulative drainage (Table 6). In general, the large variability in cumulative drainage among replications within treatments made it difficult to detect treatment differences if they existed. In the previous study at this site Kaspar et al. (2007) also did not detect an effect of a rye cover crop on cumulative drainage. From 2002 to 2005 cumulative annual drainage ranged from 141 to 294 mm, which is less than annual drainage of all years in the current study except for 2006. In contrast to the studies at this site in central Iowa, Strock et al. (2004) reported that a rye cover crop reduced tile drainage by 11% over 3 years in southern Minnesota. Qi and Helmers (2010) in an outdoor lysimeter study in Iowa observed a 9% reduction in drainage with a rye winter cover crop over 3 years. Similarly, Logsdon et al. (2002) also observed less drainage with a rye cover crop in a controlled environment lysimeter study.

3.6. Nitrate concentration in drainage water

Average annual flow-weighted nitrate concentrations in drainage water were greater in 2006, 2007, and 2008 than in 2009 and 2010 (Table 7). Additionally, average nitrate concentrations of the control treatment in all 5 years (7.1–15.9 mg N kg⁻¹) are much lower than those measured at this same site in 2002–2005, which ranged from 19.1 to 24.7 mg N kg⁻¹ (Kaspar et al., 2007). We hypothesize that the lower NO₃ concentrations in drainage water in 2009 and 2010 and of all years relative to the 2002–2005 period are due to several factors. First, N fertilizer rates applied in this experiment (225 or 198 kg N ha⁻¹) were lower than those applied in the previous experiment at this site (235 and 245 kg N ha⁻¹). Second, the greater than normal precipitation that occurred in 2006–2010, which resulted in greater than normal drainage volumes, probably contributed to reduced nitrate concentrations in drainage water.

Both the rye and oat cover crops significantly reduced average annual flow-weighted NO₃ concentration of drainage water in some years and averaged over 5 years (Table 7). The rye winter cover crop treatment significantly reduced the NO₃ concentration of drainage water in 2006, 2007, and 2008 relative to the control and also reduced NO₃ concentration more than the oat treatment did in 2006. Averaged over five years the rye treatment reduced the NO₃ concentration by 48%. In Minnesota, Strock et al. (2004) observed a 37% decrease in annual drainage water NO₃ concentrations averaged over 3 years. Qi et al. (2011), however, did not

Table 5
Corn stalk nitrate concentration taken in fall shortly before corn harvest for 2006, 2008, and 2010.

Year	Corn stalk NO ₃ concentration (mg N kg ⁻¹)			Average
	Control	Oat	Rye	
2006	374 a ^a	146 b	100 b	207 B
2008	20 a	26 a	20 a	22 B
2010	891 a	1103 a	1368 a	1121 A
Average	428 a	425 a	496 a	

^a 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.

Table 6
Average annual cumulative drainage for 2006–2010.

Year	Cumulative drainage (mm)			Average
	Control	Oat	Rye	
2006	254 a ^a	171 a	203 a	209 C
2007	483 a	437 a	466 a	462 A
2008	456 a	338 a	460 a	418 AB
2009	447 a	329 a	376 a	384 B
2010	485 a	376 a	472 a	444 AB
Average	425 a	330 a	396 a	383

^a 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.

Table 7
Average annual flow-weighted NO₃ concentration of drainage water for 2006–2010.

Year	Flow-weighted NO ₃ concentration (mg NL ⁻¹)			Average
	Control	Oat	Rye	
2006	15.9 a ^a	12.8 a	4.9 b	11.2 A
2007	14.9 a	9.9 b	7.8 b	10.8 A
2008	14.5 a	9.8 b	8.1 b	10.8 A
2009	7.1 a	5.4 a	5.4 a	6.0 B
2010	7.6 a	6.7 a	4.8 a	6.4 B
Average	12.0 a	8.9 b	6.2 b	

^a 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.

observe a significant decrease in annual concentrations with a rye cover crop, but did observe decreases in drainage water NO₃ concentrations over 5 month periods. In our previous study at this site (Kaspar et al., 2007), a rye cover crop reduced NO₃ concentrations by 59% averaged over four years. The reduced effectiveness of the rye cover crop in the present study is probably due in part to the lower drainage water NO₃ concentrations, greater precipitation and drainage, and lower nitrogen fertilizer rates in 2006–2010

than in 2002–2005. However, we cannot rule out that loss of NO₃ resulting from mineralization of rye-derived soil organic matter did not also contribute to the lower effectiveness.

The rye cover crop planted in the fall 2005 produced the greatest shoot biomass and total shoot N (Table 3) and this corresponds to the low drainage NO₃ concentration of that treatment in 2006. Substantial growth of the rye cover crops planted in 2007 and 2009, however, did not seem to reduce NO₃ concentrations any more than

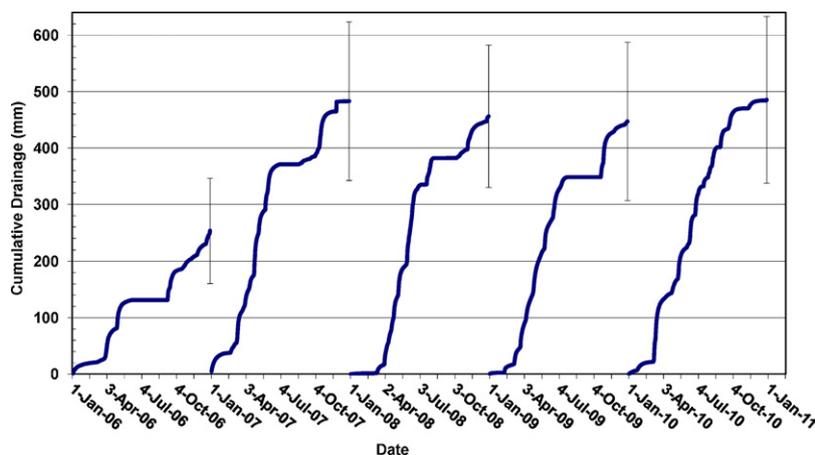


Fig. 1. Average cumulative drainage for the control treatment over time for five years, 2006–2010. Error bars are standard errors of the means ($n=4$) for 31 December of each year.

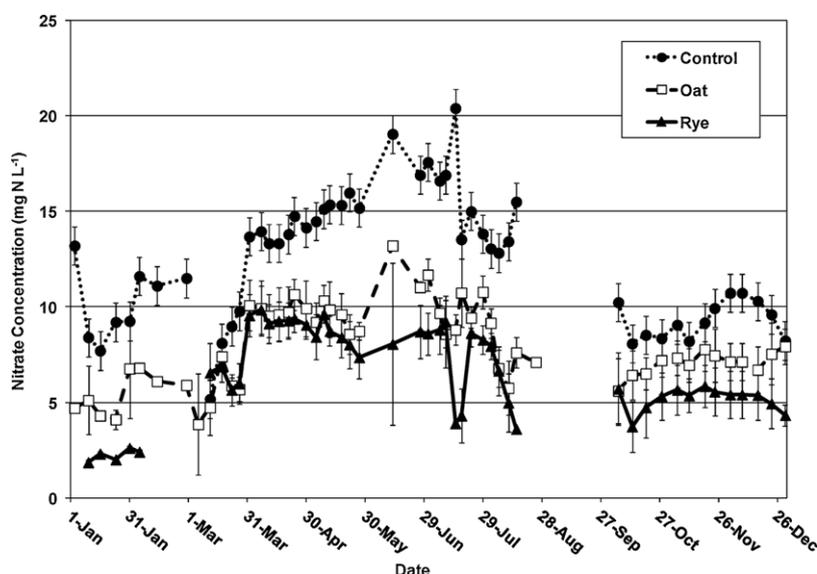


Fig. 2. Average NO_3 concentrations of drainage water for control, oat, and rye treatments in 2008. Error bars are standard errors of the means ($n=4$).

rye cover crops planted in 2006 and 2008, which had much less growth and N uptake. This is similar to results from the previous study (Kaspar et al., 2007) where the amount of rye growth did not always correspond to proportional reductions in NO_3 concentrations within the year that it was terminated and sometimes seemed to affect NO_3 concentrations into the next year. Strock et al. (2004) only planted a rye cover crop following corn in a corn–soybean rotation and also noted that the cover crop reduction of nitrate concentration of the drainage water carried over into the next year. We hypothesize that this time lag and persistence of changes in drainage water NO_3 concentrations in response to cover crops is partly the result of the time it takes for water and solutes to travel from different distances to reach the drainage tiles (Jury, 1975a,b). As a result, NO_3 concentrations in drainage water at any one time are an integration of NO_3 that has traveled very quickly to the tile over short distances and NO_3 that has taken one or more years to travel from the farthest edge of the tile's influence. In contrast to our study, Qi et al. (2011) observed that a rye cover crop treatment only reduced NO_3 concentrations during 5 month periods and not over the entire year. However, the distance between their drainage tiles was 7.6 m compared with 30.5 m in our study.

The oat cover crop treatment significantly reduced drainage water NO_3 concentrations in 2007 and 2008 and reduced the 5 year average concentration by 26%, which was a little better than half as effective as the rye cover crop (Table 7). Averaged over five years the oat cover crop had about 49% of the shoot biomass and 42% of the shoot N uptake of the rye cover crop. Thus, the relative growth of oat roughly corresponds to its relative effectiveness in reducing NO_3 loss in drainage water compared with rye. The oat cover crop was planted on average 38 d earlier than the rye cover crop (Table 1), but grew for a much shorter period of time than the rye cover crop because it winter killed. We had hypothesized that the oat cover crop might be relatively more effective during the early fall because residual fertilizer N may be present and warm soil temperatures encourage N mineralization, but that does not seem to be the case in the years of this study.

The greatest oat growth and N uptake occurred in the falls of 2005 and 2007 and growth in fall 2006 was less than 21% of the growth in 2005. Yet, the oat cover crop did not reduce NO_3 concentration significantly in 2006 (19% numerical reduction) and did reduce it significantly in 2007 (34% reduction). Like the rye cover crop this seemed to indicate that there is not a tight temporal

relationship between cover crop growth and NO_3 concentrations in the next drainage year.

Average NO_3 concentrations of drainage water for the control, oat, and rye treatments over time for 2008 are shown in Fig. 2. All three treatments had some drainage near the beginning of the year and differences in NO_3 concentrations between the control and the cover crop treatments were evident from the beginning. Nitrate concentrations of all treatments increased around 27 March as the soil warmed and after this date the control treatment NO_3 concentrations were consistently above 10 mg L^{-1} until after 25 August when drainage stopped. Even though the rye cover crop was killed on 29 April there is no apparent increase in NO_3 concentrations in response to this event. This again seems to indicate a lag effect. Alternatively, after N fertilizer was applied to the corn crop on 19 June both the control and oat cover crop treatments showed an increase in drainage NO_3 concentration, but the rye treatment did not. After 6 October, which is after the oat planting date but before the rye planting date and corn harvest, both cover crop treatments had lower NO_3 concentrations than the control and the rye treatment was slightly lower than the oat treatment. In general, NO_3 concentrations of both cover crop treatments were less than that of the control for most of the year and for part of the year the rye treatment had lower concentrations than the oat treatment.

3.7. Nitrate load in drainage water

Nitrate loads in tile drainage in 2007 and 2008 (Table 8) were almost twice as great as all other years due to a combination of higher drainage NO_3 concentrations (Table 7) and high cumulative annual drainages (Table 6). The cumulative load did not seem to be strongly related temporally to N fertilizer application in the spring, as 2007 was a soybean year with no N fertilizer application, and 2008 was a corn year with N fertilizer applications. Similarly, Kaspar et al. (2007) observed the greatest NO_3 losses in a year with high cumulative drainage, but no fertilizer application. Thus, although N fertilization was an important factor in tile drainage NO_3 loads, the impact was probably spread out over more than one year and was combined with NO_3 coming from soil N mineralization. Compared with the years 2002–2005 monitored in the previous study (Kaspar et al., 2007), average loads of the control treatment were not that much different (45.9 vs. $50.8 \text{ kg N ha}^{-1}$) even though drainage water NO_3 concentrations were much lower

Table 8
Cumulative annual NO₃ load of drainage water for 2006–2010.

Year	Cumulative NO ₃ load (kg N ha ⁻¹)			Average
	Control	Oat	Rye	
2006	36.0 a ^a	21.6 ab	9.0 b	22.2 C
2007	66.9 a	42.9 a	34.6 a	48.1 A
2008	62.8 a	33.3 a	36.6 a	44.2 A
2009	28.9 a	17.4 a	19.0 a	21.7 C
2010	34.9 a	24.3 a	21.9 a	27.0 B
Average	45.9 a	27.9 a	24.2 a	

^a 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.

in 2006–2010. This may have occurred because the higher drainage volumes in 2006–2010 compensated to some extent for the lower NO₃ concentrations.

In general, the cumulative NO₃ loads in drainage water were not significantly reduced by the cover crop treatments. In 2006, however, the rye cover crop had a lower NO₃ load than the control. Because the rye cover crop significantly reduced NO₃ concentrations relative to the control in 2006, 2007, and 2008 (Table 7) and had no effect on cumulative drainage (Table 6), we can assume that the lack of significant differences for load was partly caused by the high volumes and variability of cumulative drainage. Although the average differences in NO₃ loads between the oat and rye cover treatments and the control (18.0 and 21.7 kg N ha⁻¹, respectively) were not significant, the oat and rye cover crops had accumulated enough N in their shoots on average (17.1 and 40.9 kg N ha⁻¹, respectively; Table 3) to account for these numerical reductions in loads. In the previous study at this site, (Kaspar et al., 2007), a rye cover crop significantly reduced the average annual NO₃ load in drainage water by 61% or 31 kg N ha⁻¹ and accumulated 47.5 kg N ha⁻¹ in its shoot biomass.

4. Conclusion

The rye winter cover crop planted after harvest significantly reduced annual flow-weighted NO₃ concentrations by 48%, but did not significantly reduce loads. Compared with the previous study at this same site there was some reduction in effectiveness of the rye cover crop in reducing NO₃ concentrations of drainage water after 5–9 years of annual establishment of a cover crop. Because N fertilizer rates were reduced and cumulative drainage was so much greater after 2005, it is difficult to totally attribute the reduced effectiveness to recycling of N taken up by the rye cover crop in previous years. Thus, we conclude that the rye winter cover crop remained reasonably effective at reducing NO₃ concentrations in drainage water and widespread adoption of rye winter cover crops in the upper Mississippi River basin has the potential to reduce NO₃ delivered to surface waters by agricultural drainage systems.

The oat fall cover crop broadcast seeded before corn and soybean harvest and killed by cold temperatures in late fall was about half as effective as the rye cover crop in reducing drainage water NO₃ concentrations. Because the oat growth was roughly half as much as that of the rye cover crop, it is reasonable to assume that much of the difference in effectiveness between the two cover crops was probably related to differences in total plant growth.

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