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Agriculture, Ecosystems and Environment 117 (2006) 39–48
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

Nitrogen losses in runoff from three adjacent agricultural watersheds with claypan soils

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Received 9 May 2005; received in revised form 1 December 2005; accepted 2 March 2006
Available online 18 April 2006

Abstract

Despite improvements in the use of soil conservation practices, crop rotation and managed fertilizer applications, large losses of nitrogen (N) in runoff continue to occur from row-cropped watersheds. Increasing requirements for implementing water quality standards in the United States, has increased pressure for the development of research-based guidelines to reduce N losses from agricultural runoff. The objectives of this study were to examine the effects of management, watershed characteristics, and precipitation on TN and nitrate-N (NO_3^--N) loss over time by comparing losses on three adjacent watersheds with claypan soils. The three adjacent north-facing, corn–soybean rotational watersheds in northeastern Missouri were instrumented with H-flumes, water samplers, and flow-monitoring devices in 1991. Runoff samples from each individual rainfall event between 1991 and 1997 were analyzed for TN and NO_3^--N concentrations. The 7-year mean annual TN losses on the three watersheds ranged from 13 to 19 kg ha^{-1} with a mean of 16 kg ha^{-1}. Nitrate-N losses ranged from 8 to 14 kg ha^{-1} with a mean of 11 kg ha^{-1}. During the study, 67% of the TN was lost as NO_3^--N with a range from 22% in 1997 to 76% in 1996. The mean annual TN losses for corn and soybean years during the study were 30.7 and 5.7 kg ha^{-1}, respectively. Significantly higher loss (57%) of N from watersheds occurred during the period between fall harvest and spring planting when crops were not present (referred to as the ‘‘fallow’’ period in this paper; 86.8 kg ha^{-1}) compared to N losses during the cropping period (64.5 kg ha^{-1}). In 1994, 96% of the annual TN loss and 98% of the annual NO_3^--N loss occurred during the fallow period. In contrast, the lowest fallow period losses of TN (19%) and NO_3^--N (14%) occurred in 1993. The watershed-mean TN and NO_3^--N losses in 1993 alone accounted for 44 and 46% of the total losses observed over the 7-year period because during that year the study area received 142% of the normal precipitation. When the study area received 51% of the annual precipitation before planting in 1996, the TN and NO_3^--N losses accounted for 34 and 38% of the 7-year loss, respectively. Nitrogen fertilizer that was applied in 1993 and 1996 may also have contributed to the observed large losses. The results of this study suggest that the maintenance of a suitable vegetative cover throughout the year could reduce runoff and lower TN and NO_3^--N loss from agricultural watersheds under a corn–soybean rotation.

Keywords: Corn–soybean rotation; Total-N in runoff; Nitrate-N in runoff

1. Introduction

Excessive use of N fertilizer for crop production can cause degradation of water quality (Smith and Cassel, 1991; Conan et al., 2003; Ren et al., 2003). The agricultural sector has been identified as the single largest contributor to non-point source nitrate (NO_3^--N) pollution of surface and ground waters in the Midwestern United States (Hartfield

Abbreviations: NO_3^--N, nitrate-N; TN, total nitrogen; USEPA, United States Environmental Protection Agency

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doi:10.1016/j.agee.2006.03.002

et al., 1999; Jaynes et al., 1999; Burkart and Stoner, 2001). Studies linked increasing concentrations of NO_3^--N in the Mississippi River to hypoxic conditions in the Gulf of Mexico (Turner and Rabalais, 1991; Rabalais et al., 1996; Tomer et al., 2003). Omernik (1977) observed that total nitrogen (TN) concentrations were nearly nine times greater downstream from agricultural lands than downstream from forested areas, with the highest concentration in the Corn Belt States. Heavy fertilizer application also continues to influence ground water N concentrations (Tomer and Burkart, 2003). In northeast Missouri, about 20–25% of shallow farmstead wells have nitrate concentrations exceeding 10 mg L^{-1}, the maximum concentration allowed for drinking water by United States Environmental Protection Agency (USEPA, 1979; Blevins et al., 1996).

Hydrologic response is highly dependent on drainage basin characteristics (Beaulac and Reckow, 1982; Borin et al., 2005) and, therefore, it is important to understand watershed hydrology and its spatial and temporal patterns (Zheng et al., 2004). As land use intensifies, runoff peaks and volumes increase, base flow and response time decrease, and nutrient losses increase. Simple models that use runoff and flow characteristics often predict higher NO_3^--N losses from small watersheds than observed NO_3^--N losses (Caraco et al., 2003). On the other hand, the magnitude of nutrient losses from very large watersheds with diverse agricultural activities may not be easily determined (Beaulac and Reckow, 1982).

The amount of TN and NO_3^--N lost in drainage is directly affected by the amount of runoff volume (Borin et al., 2005). Therefore, understanding of chemical transport in claypan soils is crucial to evaluate potential water contamination from agricultural sources (Kelly and Pomes, 1998). In claypan soils, the depth to the claypan varies across fields (Wang et al., 2003). Perched water in the surface horizons caused by the relatively low hydraulic conductivity of the claypan potentially makes these soils more susceptible to N losses (Motavalli et al., 2003; Seobi et al., 2005). In a 5-year study on claypan soils in north-central Missouri, Ghidey and Alberts (1999) observed that NO_3^--N concentration increased in the surface soil following fertilizer application and less than 5% of the total N applied to the soil was lost via surface runoff. In addition, Blevins et al. (1996), using ^{15}N-labeled fertilizer, showed that claypan soils do not substantially retard NO_3^--N transport to the saturated zone. In a simulated rainfall study, Zheng et al. (2004) observed that during a 90-min run, the NO_3^--N loss was mainly controlled by the near-surface hydraulic gradient. The first recharge event following fertilizer application, irrespective of the time interval between the application and recharge events, transported substantial quantities of NO_3^--N through the claypan to ground water (Kelly and Pomes, 1998).

Control of N loss and maintenance of farm profitability are of increasing national concern (Keeney and Follett, 1991). In the United States, states are required to implement water quality standards based on USEPA guidelines or other scientifically defensible methods (Ice and Binkley, 2003). Such requirements result in increasing pressure for the development of economically and environmentally suitable guidelines to reduce N losses from agricultural runoff. An understanding of the interactions among soils, plant, and management factors at a watershed scale is crucial for the development of effective environmental management practices (Nord and Lyon, 2003). However, few long-term watershed studies have been conducted in the Midwest that provide information on the influence of factors, such as landscape features, precipitation, crop rotation, and timing of N fertilizer application, on N loss. The objectives of this research were to: (1) examine the effects of management and watershed characteristics on TN and NO_3^--N loss over time by comparing losses on three adjacent watersheds with claypan soils; (2) determine the impact of different size runoff events on TN and NO_3^--N loss; (3) evaluate the effects of the timing of rainfall and crop versus fallow period on TN and NO_3^--N losses.

2. Materials and methods

2.1. Watersheds and management

The study was conducted at the University of Missouri-Greenley Memorial Research Center in Knox County, MO, USA (40°01′N, 92°11′W) from 1991 to 1997. Three adjacent north-facing small watersheds designated as "east", "center", and "west" with land areas of 1.65, 4.44, and 3.16 ha, respectively, were instrumented with flumes and flow-measuring and sampling devices in 1991 (Fig. 1). Each watershed is drained by a grass waterway that

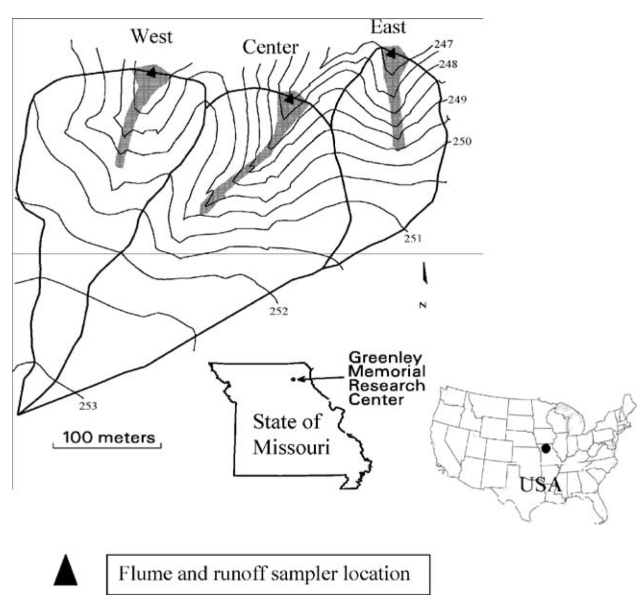

Fig. 1. East, center, and west watersheds with 0.5 m interval contour lines. Numbers represent the elevation in m above sea level. Gray bands indicate location of the grass waterways. Inset maps show approximate location of Missouri State within the United States and the study site location within the State of Missouri.

Table 1
Watershed characteristics and selected soil properties of the study watersheds at the Greenley Research Center

Property	Watershed		
	East	Center	West
Area (ha)	1.65	4.44	3.16
Total slope length (m)	234	425	383
Watershed slope steepness (%)	2.1	1.3	0.9
Depth to the claypan (cm)			
Upper third of watershed	32	23	35
Middle third of watershed	35	22	43
Lower third of watershed	22	20	34
Grass waterway	49	62	57
Soil organic carbon[a] (%)	2.60	2.23	1.93
Soil $pH_{(water)}$[a]	6.7	6.8	7.3
Textural class[a]	Silt loam	Silt loam	Silt loam

[a] Ap horizon.

leads into a concrete approach section and an H-flume. Information on watershed characteristics and soils are presented in Table 1 and has been detailed in Udawatta et al. (2002, 2004), and Seobi et al. (2005).

Briefly, the three watersheds were maintained in a corn–soybean rotation under no-till management with planting in straight rows perpendicular to the slope from 1991 to 1995 and on the contours in 1996 and 1997 (Table 2). The watersheds are underlain by glacial and loess material. Soils are mapped as Putnam silt loam (fine, smectitic, mesic Vertic Albaqualf), Kilwinning silt loam (fine, smectitic, mesic Vertic Albaqualf), and Armstrong loam (fine, smectitic, mesic Aquertic Hapludalf). These soils are characterized by an argillic horizon which occurred between 20 and 62 cm from the surface depending on the landscape position in each watershed (Table 1). The pH of the Ap horizon was between 6.7 and 7.3 and soil organic C content varied between 1.93 and 2.60% (Table 1). The climate in the area is temperate. Thirty-year mean (1961–1990) annual precipitation in the region is 920 mm, of which more than 66% falls from April through September (Owenby and Ezell, 1992).

2.2. Water sampling and analysis

Water sampling and monitoring devices (Teledyne Isco, Inc., Lincoln, NE, USA) were used to collect water samples, record flow and sampling intervals. Flow-measuring devices engaged the sampler in each watershed to withdraw a 135-mL sample of runoff after each 25 m^3 of flow. Due to the difference in individual watershed size and topography, this flow setting for the samplers may have resulted in different minimum amounts of runoff to activate the samplers in each watershed. All samples were flow-weighted and collected for individual storms. After a runoff event, flow, level and sample intake data were downloaded to a laptop computer using the Flowlink software (ISCO, 1998). Water samples were transferred from the field to the laboratory and a composite sample from each watershed for each runoff event was analyzed. All water samples were stored in a refrigerator at 4 °C before analysis.

Water samples were analyzed within 48 h. Total N (USEPA Method 351.2, USEPA, 1979) concentration was determined colorimetrically using a Technicon Autoanalyzer II (Terrytown, NY, USA) on unfiltered samples following a sulfuric acid digestion in a block digester. The concentration of NO_3^--N (USEPA Method 352.2, USEPA, 1979) was also determined with the Technicon autoanalyzer on water samples passed through a Whatman 934-AH glass microfiber filter. Quality control for the Technicon autoanalyzer was maintained by inclusion of blanks and randomly positioning control standards with differing concentrations, duplicate samples and one quality control sample in each run. Nutrient concentrations (mg L^{-1}) were multiplied by the runoff volume (m^3 ha^{-1}) to estimate total discharge (kg ha^{-1}) by runoff event.

2.3. Statistical analysis

Watershed TN and NO_3^--N losses and runoff were analyzed using SAS statistical software (SAS Institute, 1999). Nutrient losses were transformed using square root transformation and used for linear regression analysis to describe relationships between runoff and TN and NO_3^--N loss. Differences between regression coefficients or slopes of any two regressions ($p < 0.05$) were determined by testing the homogeneity of regression coefficients. Regression lines for runoff volume and total nitrogen as well as runoff volume and NO_3^--N were forced to pass trough the origin as there would be no nutrient loss in runoff when there

Table 2
Summary of agricultural activities on the east, center, and west watersheds from 1991 to 1997 at the Greenley Research Center

Year	Crop	Planting date	Field preparation	Planting method	Fertilizer N–P–K (kg ha^{-1})
1991	Corn	20 May	No-till	Straight row[a]	[b]
1992	Soybean	8 June	Field cultivator	Straight row[a]	None
1993	Corn	1 June	No-till	Straight row[a]	160–50–100
1994	Soybean	18 May	No-till	Straight row[a]	None
1995	Soybean	21 June	No-till	Straight row[a]	0–40–120
1996	Corn	25 April, 5 June[c]	No-till	On contour	59–0–0
1997	Soybean	16 May	No-till	On contour	None

[a] Perpendicular to slope.
[b] Information not available.
[c] Replanted, crop failure due to rain.

Table 3
Greenley Research Center monthly and annual precipitation from 1991 to 1997, 30-year mean precipitation (1961–1990), and monthly mean runoff from the three watersheds during the study period

Month	30-year mean PPT[a] (mm)	1991		1992		1993		1994		1995		1996		1997	
		PPT[b] (mm)	RO[c] (mm)	PPT (mm)	RO (mm)	PPT (mm)	RO (mm)	PPT (mm)	RO (mm)	PPT (mm)	RO (mm)	PPT (mm)	RO (mm)	PPT (mm)	RO (mm)
January	34	24		11	0	30	0	9	0	46	0	29	0	13	0
February	30	6		51	8	51	0	61	40	28	0	6	0	120	0
March	73	100		64	0	76	22	12	0	27	0	92	0	49	0
April	82	96	7	89	31	92	52	162	62	127	60	40	0	150	93
May	108	276	194	21	0	133	57	62	13	277	237	285	223	142	78
June	88	43	8	13	0	296	180	57	2	85	41	47	15	68	18
July	114	108	2	259	62	240	109	65	0	154	34	28	0	72	0
August	88	27	0	45	0	95	17	139		136	17	205	39	69	0
September	105	44	0	106	1.5	207	81	67	0	105	1	67	0	58	0
October	81	157	10	62	0	20	18	61	0	21	0	39	0	93	0
November	67	153	35	158	115	47	6	114	32	45	1	45	0	50	0
December	49	28	8	161	42	23	8	54	39	11	0	7	0	36	0
Total year	920	1064		1038		1308		863		1062		888		921	

[a] 1961–1990 monthly mean precipitation.
[b] Precipitation (PPT).
[c] Runoff (RO).

was no runoff. Ranked analysis of variance was used to compare TN and NO_3^--N losses by different runoff volume categories.

3. Results and discussion

3.1. Precipitation and runoff events

The average annual precipitation from 1991 to 1997 was 1021 mm, about 11% greater than the long-term mean. Precipitation during the 7-year study period ranged from 863 mm (94% of normal) in 1994 to 1308 mm (142% of normal) in 1993 (Table 3). Rainfall was above normal during the first 3 years and in 1995. Rainfall amounts were below normal in 1994 and 1996 and the study area received normal rainfall in 1997. The rainfall of the period between fall harvest and spring planting when crop plants were not present (referred to as "fallow" in this paper) varied between 34 and 66% of the annual rainfall with an average of 55% during the study. The greatest number of runoff events occurred in 1993 when the area received 42% more rain than normal.

An average of 110 runoff events occurred on each watershed over the period of the study (Udawatta et al., 2002). However, runoff samples were not collected in all the runoff events because insufficient runoff occurred after some rainfall and some events caused very little runoff or did not activate the sampler. Therefore, during the 7 years, only 67 runoff events in the east watershed, 67 in the center watershed, and 64 in the west watershed produced sample collecting runoff volumes. Lightning damage, equipment settings and malfunction, and presence of debris in the sample line caused differences in sampled events among the watersheds.

3.2. Runoff characteristics and concentration and loss of TN and nitrate-nitrogen

Linear regressions of runoff volume with TN or NO_3^--N losses were significant for the watersheds ($r^2 = 0.56$ and 0.43, respectively, $p \leq 0.05$, Fig. 2A and B). Runoff and TN loss had a better relationship than the runoff volume and NO_3^--N. The slope of the regression line for TN and runoff was (0.0088) larger than the slope (0.0061) for NO_3^--N and runoff. The regression of TN or NO_3^--N concentrations with runoff volume was not significant (Fig. 2C and D). However, Fig. 2C and D shows that most of the small events had higher concentrations of nutrients compared to the larger events. All runoff events with volumes over 500 $m^3\ ha^{-1}$ had less than 25 $mg\ L^{-1}$ nutrient concentrations. The average nutrient concentration decreases with larger runoff events, primarily due to dilution (Black, 1996). However, above-normal rainfall that occurs shortly after fertilizer application cause significant losses of nutrients (Karlen et al., 2005). In the same watersheds, Udawatta et al. (2004) showed that runoff volume accounted for 64–73% of the variability in total phosphorus (TP) loss. However, TN and NO_3^--N losses had weaker relationships with runoff volume than the TP loss. It could be due to the fact that P has more interaction with soil particles compared to N. Fig. 2A and B also shows that the relationships between runoff and TN and NO_3^--N losses were largely determined by a larger number of small runoff events and only a small number of larger events that occurred during the 7-year measurement period.

3.3. Large runoff events and nutrient losses

In general, large rainfall events cause a brief initial high rate of discharge that is an important fraction of the total

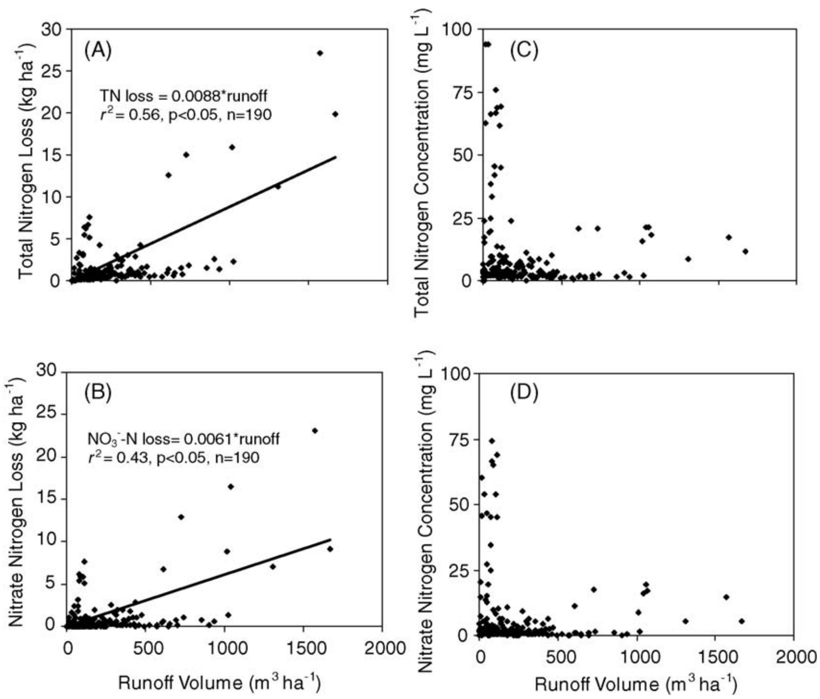

Fig. 2. Relationships between runoff volume and total nitrogen loss (A), nitrate-nitrogen loss (B), total nitrogen concentration (C), and nitrate-nitrogen concentration (D) for the combined data with the three watersheds from 1991 to 1997 at the Greenley Research Center in northeast Missouri.

discharge (Black, 1996). These runoff events remove several magnitudes more TN and NO_3^--N than the small events. During the 7-year study period, eight runoff events with more than 1000 m^3 ha^{-1} runoff volumes removed on average 17.6 and 13.1 kg ha^{-1} TN and NO_3^--N, respectively, across the watersheds (Table 4). The average TN and NO_3^--N losses during the 7-year study were 1.83 and 1.23 kg ha^{-1} per event, respectively, and these losses were significantly different from the losses in the largest eight events. Without the largest eight runoff events, on average, watersheds would lose 1.12 and 0.71 kg ha^{-1} TN and NO_3^--N per event, respectively.

In a P loss study, Quinton et al. (2001) demonstrated that smaller events accounted for a greater proportion of P loss over a 6-year period than infrequent larger events. Morgan et al. (1986) showed that two or three runoff events each year were responsible for substantial annual soil loss in mid-Bedfordshire in the United Kingdom. The same pattern has been observed in the USA (Edwards and Owens, 1991; Udawatta et al., 2004) and Nigeria (Lal, 1976). In a simulated rainfall study in Kentucky, Edwards et al. (2000) observed that runoff N and P was sensitive to the amount and proximity of preceding rainfall. The results of this study also show that individual weather years, such as 1993 and 1996 that generate larger runoff volumes and runoff during fallow periods, account for a high proportion of total TN and NO_3^--N losses. Antecedent soil moisture conditions, ground cover status, fertilizer application and the characteristics of the precipitation, such as the amount of N contained in the rainfall and the frequency, intensity, and quantity of the annual precipitation, and crop yield in the previous year all combine to determine N losses (Kelly and Pomes, 1998; Ghidey and Alberts, 1999; Edwards et al., 2000; Malhi et al., 2001; Quinton et al., 2001; Hofmann et al., 2004; Zheng et al., 2004; Karlen et al., 2005).

Table 4
Number of runoff events and mean losses of total nitrogen and nitrate-nitrogen between 1991 and 1997 from the three watersheds at the Greenley Center by runoff volume

Runoff volume category (m^3 ha^{-1})	Number of runoff events	Total nitrogen (kg ha^{-1})	Nitrate nitrogen (kg ha^{-1})
All events	190	1.83 a	1.23 a
0–200	116	0.88 a	0.63 a
200–500	51	1.87 a	0.60 a
500–1000	15	2.80 a	1.64 a
>1000	8	17.61 b	13.07 b

Values followed by the same letter within a column are not significant at 0.05.

3.4. Nitrate-nitrogen (NO_3^--N) concentration in runoff water

The average NO_3^--N concentration in runoff across the three watersheds was 6.4 mg L^{-1} and was 36% lower than the maximum allowable drinking water concentration of 10 mg NO_3^--N L^{-1} established by the USEPA. However, 9 runoff events out of a total of 64 events had concentrations higher than 10 mg NO_3^--N L^{-1} (Fig. 3). Five events occurred in 1993 and four events occurred in 1996. The average flow-weighted concentration of these nine events was 33.5 mg NO_3^--N L^{-1} and ranged from 11.9 to

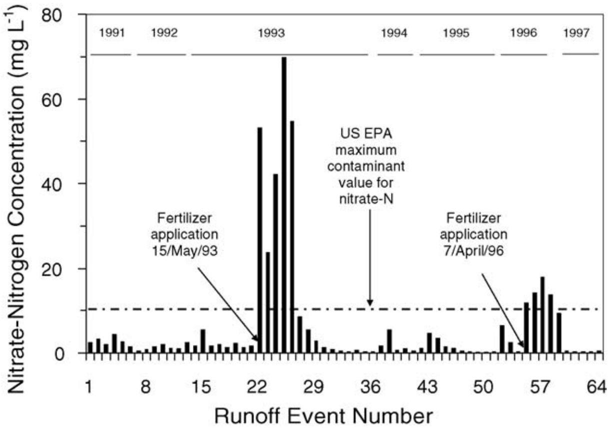

Fig. 3. Flow-weighted mean nitrate-nitrogen concentration by runoff event across the three watersheds during the study period (1991–1997). The horizontal line represents the USEPA maximum allowable nitrate-nitrogen concentration for drinking water.

69.8 mg NO_3^--N L^{-1}. The mean of the largest nine events (33.5 mg L^{-1}) and the grand mean without the largest nine events (1.97 mg L^{-1}) were significantly different ($p \leq 0.05$).

These results corroborate the findings of Castillo et al. (2000) who observed that greater NO_3^--N concentrations in a Midwestern river were associated with storm-generated runoff from agricultural fields. In their study, peak concentrations in the river flow correlated with rainfall. Hofmann et al. (2004) observed that higher concentrations occur in conjunction with higher flow volumes. However, the results of this study show lower mean concentrations of NO_3^--N than the USEPA established values for drinking water and those reported by Tan et al. (2002) in a 5-year study in Canada (11.8 mg L^{-1} for no-till and 13.5 mg L^{-1} for conventionally tilled sites). Only 14% of the events during the 7-year study had concentrations larger than the USEPA standards for drinking water. These higher concentrations were observed during corn years when fertilizer was applied, when precipitation was higher than normal, or when more rain occurred during the fallow period.

3.5. Total nitrogen (TN) and nitrate-nitrogen (NO_3^--N) losses

The annual TN and NO_3^--N losses across the three watersheds were 16.4 ± 3.2 and 11.1 ± 3.1 kg ha^{-1} $year^{-1}$, respectively (Fig. 4A and B). Among the three watersheds, the center watershed had the lowest annual losses of TN (12.9 kg ha^{-1}) and NO_3^--N (8.2 kg ha^{-1}). The east and west watersheds lost 1.5 (19.2 kg ha^{-1}) and 1.3 (17.1 kg ha^{-1}) times more TN than the center watershed. The annual NO_3^--N loss on the east and west watersheds were 14.4 and 10.5 kg ha^{-1}, respectively. The NO_3^--N loss in this study was lower than that reported over a 5-year period in Canada (i.e., 82.3 kg ha^{-1} for no-till and 63.7 kg ha^{-1} for conventionally tilled sites) (Tan et al., 2002).

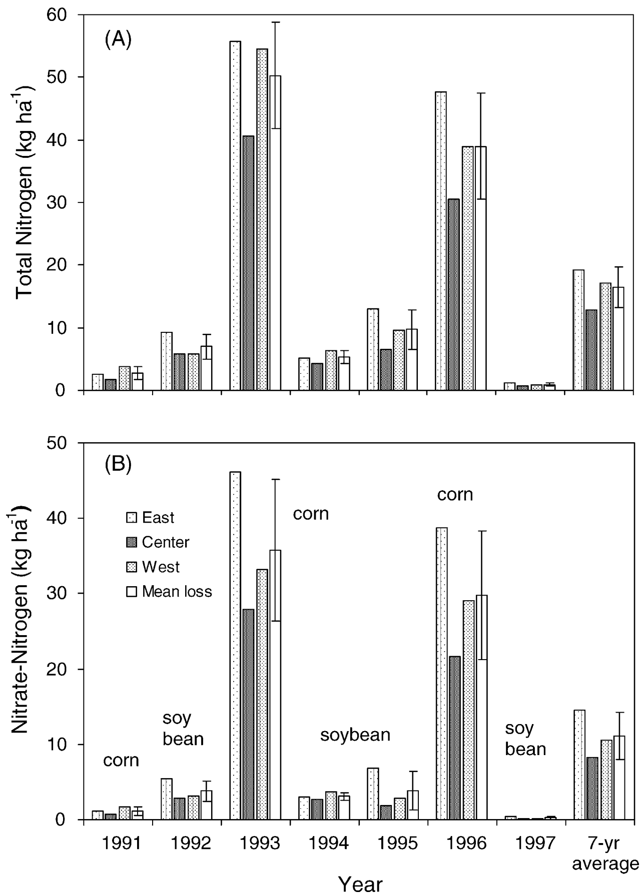

Fig. 4. Annual total nitrogen (A) and nitrate-nitrogen (B) losses for the east, center, and west watersheds and the mean annual losses across all watersheds from 1991 to 1997. Vertical bars indicate $\pm$1S.D. for the mean annual TN losses across all watersheds.

Changes in management practices are a major factor that can lead to reduction in N losses (Delgado, 2002). The grass waterways that were positioned at the bottom of each watershed (Fig. 1) in this research may have reduced the measured loss of N in runoff. The presence of vegetation effectively slows runoff, promotes sediment removal, and increases uptake of nutrients (Dillaha et al., 1989; Schmitt et al., 1999). The center watershed had the longest grass waterway (151 m) compared to 102 and 104 m waterways on the east and west watersheds, respectively. This difference could have possibly reduced N loss from this watershed compared to the other two watersheds.

The annual discharges of TN and NO_3^--N from the three watersheds differed among years (Fig. 4A and B). The three watersheds lost several magnitudes more TN and NO_3^--N in 1993 than the mean annual loss. The TN and NO_3^--N losses in this single year alone accounted for 44 and 46% of the total 7-year losses, respectively. Accounting for the greater N loss experienced during 1993 was that the area received 142% of the normal precipitation during that year (Table 3) and it was a year when N fertilizer was applied to the corn crop (Table 2). In 1996 when the watersheds were planted with corn, N fertilizer was applied on 7 April to supplement crop N requirements. Although precipitation was below normal (−3.5%), watersheds lost an average of 38.9 ± 8.5 kg TN ha^{-1} and 29.7 ± 8.5 kg NO_3^--N ha^{-1} in six runoff events. During this year, watersheds received 59 kg N ha^{-1} in fertilizer and the TN loss was equivalent to 66% of the N applied. About 77% of this was in NO_3^--N form. The TN and NO_3^--N loss in 1996 alone accounted for 34 and 38% of the total 7-year loss, respectively. In this year, 52% of the annual precipitation fell between 1 January and 6 June during the fallow period.

The smallest annual losses of TN and NO_3^--N were observed in 1997 when the area received annual precipitation that was close to the long-term average (Fig. 4). In spite of below normal (−6.2%) precipitation and no N fertilizer application in 1994, the three watersheds had the fifth largest loss that year (5.3 and 3.1 kg ha^{-1} TN and NO_3^--N, respectively). The year 1993 had above normal precipitation and soils were recharged before winter months. Twenty-seven centimeters of precipitation fell before soybeans were planted on 18 May 1994. These conditions are ideal for claypan soils to generate substantial runoff that may transport large amounts of nutrients and sediment (Blanco-Canqui et al., 2002).

The study area received some 15.5% more precipitation than the long-term mean in 1991 and 1995 and 12% more in 1992. The watersheds lost 2.7, 9.7 and 6.9 kg TN ha^{-1} in 1991, 1995 and 1992, respectively. The loss of NO_3^--N during the respective years was 1.1, 3.8 and 3.7 kg ha^{-1}. Although watersheds lost 9.7 kg TN ha^{-1} in 1995, NO_3^--N loss was only 37% of the total loss. No N fertilizer was applied to the soybean crop in 1995 and the previous year (1994) was relatively dry compared to the long-term average precipitation.

Nitrogen losses are largely determined by the amount and intensity of rainfall, soil physical properties affecting drainage and surface runoff, the presence or absence of vegetative cover, and N fertilizer management practices, including the amount and timing of N application (Malhi et al., 2001; Randall and Mulla, 2001; Karlen et al., 2005). Randall and Mulla (2001) reported that the largest losses of N in an agricultural field occurred after frequent precipitation events with above normal precipitation and when crops were not actively growing. In the same watersheds examined in this research, Udawatta et al. (2004) showed that the highest soil phosphorus losses occurred in years with above-normal precipitation and during fallow periods. Bjorneberg et al. (1996) also observed that 45–85% of the annual NO_3^--N loss was through subsurface drainage in continuous corn and corn–soybean rotations.

3.6. Nitrate-nitrogen as a percentage of total nitrogen in runoff

During the 7-year study, approximately 67% of the TN was lost in NO_3^--N form but this proportion varied between 22% in 1997 and 76% in 1996 (Fig. 5). More N was lost in NO_3^--N form during years with greater TN losses. The mean proportion of NO_3^--N to TN in runoff was less than 43% during soybean years (92, 94, 95 and 97) compared to the 63% in corn years (91, 93 and 96). The lowest percentages of NO_3^--N in TN was observed in 1997 (22%) and 1995 (37%) when the watersheds were under soybean. In contrast, two soybean years: 1992 (53%) and 1994 (58%) also lost more than 50% of TN as NO_3^--N. In 1991 (a corn year), the watersheds lost 41% of the TN in NO_3^--N form. The mean percentage of NO_3^--N in TN during corn years excluding 1991 was 73%. In addition to fertilizer application, above normal precipitation conditions may have contributed to the large losses in the NO_3^--N form.

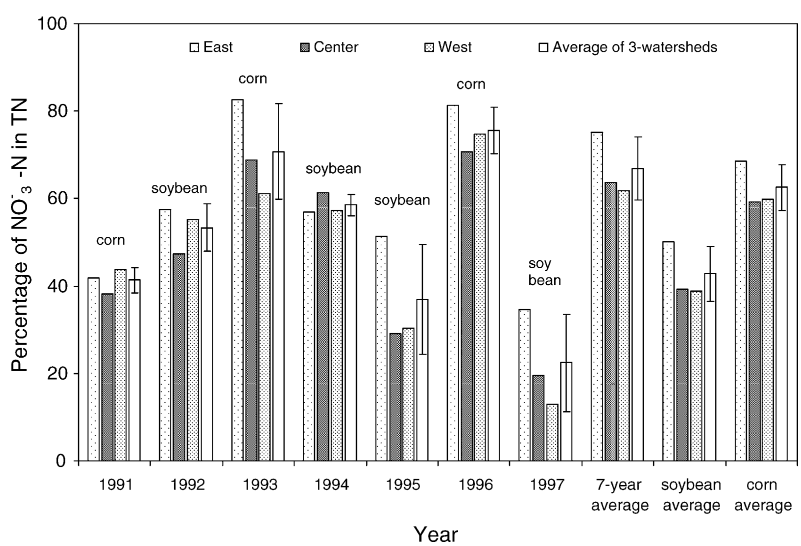

Fig. 5. Percentage of nitrate-nitrogen in total nitrogen in runoff for the east, center, and west watersheds. The mean annual percentages across all watersheds from 1991 to 1997 for the 7-year study period, soybean years, and corn years. Vertical bars indicate ±1S.D. for the mean annual ratio across all watersheds.

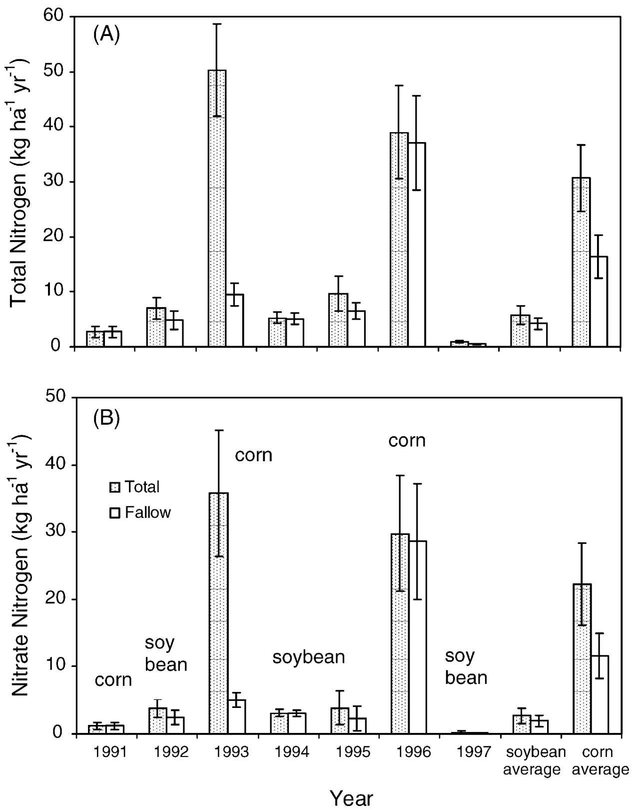

Fig. 6. Mean annual and fallow period losses of total nitrogen (A) and nitrate-nitrogen (B) across the three watersheds from 1991 to 1997. Vertical bars indicate ±1S.D. for the mean annual losses across the three watersheds.

The results of this study suggest that reducing N application alone would not lower N losses in runoff. Other management practices, such as agroforestry or contour grass buffers, may be needed to reduce runoff volume flow rate and excess nutrients from within and below the rooting zone. For example, establishment of grass and agroforestry buffers within watersheds resulted in reduction in runoff loss of non-point source pollutants (Udawatta et al., 2002).

3.7. Crop rotation and fallow period

The loss of TN and NO_3^--N were significantly different between corn and soybean years ($p \leq 0.001$). Mean TN losses in corn and soybean years during the study were 30.7 and 5.7 kg ha^{-1}, respectively (Fig. 6A). Mean NO_3^--N losses in corn and soybean years were 22.2 and 2.7 kg ha^{-1}, respectively (Fig. 6B). Higher average annual losses of TN and NO_3^--N during corn years compared to soybean years could be because N fertilizer was applied to corn and not to soybean. Eghball et al. (2002) observed that long-term fertilizer application did not affect runoff N loss, but significant losses occurred when N was applied just before rainfall. The highest TN and NO_3^--N losses across the three watersheds during a corn year (1993) were 50 and 36 kg ha^{-1}, respectively. The highest TN loss during a soybean year occurred in 1995 (9.7 kg ha^{-1}). These results are consistent with the findings of Kanwar et al. (1997) that NO_3^--N concentrations in runoff were 31–63% lower in a corn–soybean rotation compared to continuous corn.

The annual crop and fallow period TN and NO_3^--N losses were different among years (Fig. 6A and B). The mean annual TN and NO_3^--N fallow period losses across the three watersheds were 71 and 67%, respectively. Approximately 19–100% of the annual TN loss occurred during the fallow period when the soil was free of crops. The greatest fallow period TN and NO_3^--N losses occurred in 1991 followed by 1994. The study was initiated in April 1991 and the reported entire loss for 1991 occurred after the crop was harvested. In 1994, almost all the runoff events occurred during the fallow period, except for a runoff event on May 24. The watersheds received 42% more rain in the previous year (1993). These conditions were favorable for claypan soils to generate significant runoff carrying sediment and organic material. Similar fallow period losses occurred in 1996 before corn was planted. Another study showed that abundant spring rains were the main reason for N loss from corn fields in Iowa (Balkcom et al., 2003). Fallow period loss as a percentage of the total loss was the smallest in 1993 when the area received 55% of the precipitation during the cropping season.

Factors such as season, hydrology, timing and size of N addition govern N losses (Molden and Wright, 1998; Malhi et al., 2001; Karlen et al., 2005). The highest N concentration in runoff in Australia was observed during extensive fallow periods (Hollinger et al., 2001). In Mexico, N loss in runoff was 25 and 6 kg ha^{-1} for no-till without and with 100% residue cover, respectively (Tiscareno-Lopez et al., 2004). The results of this study suggest that greater losses could be prevented by continuous ground cover maintenance or establishment of barriers that reduce flow and runoff volume.

4. Conclusions

The results of this study demonstrate the complex and dynamic nature of the various factors affecting runoff-induced N loss from watersheds with row crop agriculture. Variations in precipitation distribution and changes in agricultural management practices over time affect TN and NO_3^--N losses and concentrations in runoff. This study indicates that the average TN and NO_3^--N losses over a 7-year period generally differed from losses reported for other watersheds in North America with and without the presence of claypan soils. Possible factors affecting observed losses and concentrations in this study were the presence of grass waterways at the base of all three watersheds, the use of no-till, and the crop rotation system that reduced total N fertilizer applications in soybeans years.

Runoff volume and the presence of vegetative ground cover were the main factors that were responsible for the differences in TN and NO_3^--N loss from individual runoff events in the three watersheds. Above average precipitation and precipitation during the fallow periods caused the greatest observed losses of TN and NO_3^--N in runoff. The study suggests that adoption of agricultural practices that can decrease runoff volume, increase infiltration, promote water and N use by vegetation and extend the period of vegetative cover may be the most effective long-term strategy to reduce TN and NO_3^--N losses from agricultural watersheds in the claypan soil region.

Acknowledgements

This research was funded through the University of Missouri Center for Agroforestry under cooperative agreements AG-02100251 with the USDA ARS Dale Bumpers Small Farm Research Center, Booneville, AR and CR 826704-01-0 with the USEPA. The authors wish to thank the Missouri Department of Conservation, the Missouri Department of Natural Resources and Agricultural Extension of the University of Missouri for initial financial support. The results presented are the sole responsibility of the authors and/or the University of Missouri and may not represent the policies or positions of the funding agencies. The authors sincerely appreciate the initial establishment and planning of the research site by Gray Henderson and the field assistance provided by Randall Smoot, Farm Manager, at the Greenley Center.

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