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Nitrogen cycling and tile drainage nitrate loss in a corn/soybean watershed

Lowell E. Gentry [a,*], Mark B. David [a], Karen M. Smith [a], David A. Kovacic [b]

[a] Natural Resources and Environmental Sciences Department, University of Illinois, W-503 Turner Hall, 1102 South Goodwin Av., Urbana, IL 61801, USA

[b] Landscape Architecture Department, University of Illinois, 101 Temple Buell Hall, 611 East Lorado Taft Drive, Champaign, IL 61820, USA

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Abstract

Nitrogen (N) in surface waters has been linked to agricultural crop production, and more specifically, to NO_3^- exported by tile drainage. The objective of this study was to evaluate agricultural N pools and fluxes in a seed corn/soybean (*Zea maize* L./*Glycine max* L.) watershed (40 ha) to relate soil inorganic N pools with annual losses of NO_3^- in drainage tiles. During a 2-year period beginning in October 1993, soil samples in the top 50 cm located near the tile systems (predominantly Drummer silty clay loam, fine–silty, mixed mesic Typic Haplaquolls) were analyzed for microbial biomass C and N, inorganic N, and N mineralization rates. Water flow and NO_3^- concentrations were continuously measured in the three drainage tiles. Soil microbial biomass N ranged from 83 to 156 kg N ha^{-1}, and appeared more closely related to soil moisture than soil inorganic N pools. Soil inorganic N ranged from a low of 13 kg N ha^{-1} during the soybean growing season to a high of 115 kg N ha^{-1} after N fertilization. Following good growing seasons in 1993 and 1994, high crop uptake of N resulted in relatively small soil inorganic N pools of 40 and 24 kg N ha^{-1}, respectively, after crop harvest. In 1995, however, when poor growing conditions decreased crop N accumulation, 98 kg N ha^{-1} remained in the watershed after harvest. Based on an average effective drainage area of 30 ha, 38 and 64 kg N ha^{-1} leached out of the watershed through tile drainage for a total of 3.1 Mg N for the 1995 and 1996 water years, respectively. Tile N export from the watershed was greatest during high flow events when there concurrently existed large pools of soil inorganic N in the form of NO_3^-. Differences in annual N export for each tile were the result of a combination of factors including; timing and area of N fertilization, amount and distribution of precipitation, crop uptake of soil derived N, and inorganic N pools remaining after harvest. © 1998 Elsevier Science B.V.

Keywords: Maize; Soybean; Microbial biomass N; Inorganic N; N mineralization; Crop uptake

1. Introduction

As nitrogen (N) fertilizer use and application rates increased in the Midwest throughout the 1960s and 1970s, NO_3^- concentrations in rivers and reservoirs concomitantly increased throughout the region. In

* Corresponding author. Tel.: +1-217-333-1769; fax: +1-217-244-3219; e-mail: l-gentry@uiuc.edu

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tile drained agricultural areas of the Midwest, researchers have linked drainage to surface water N concentrations (Logan et al., 1994; Fausey et al., 1996; Drury et al., 1996; David et al., 1997). Excessive use of N fertilizer for maize production has been implicated in nonpoint source NO_3^- pollution of groundwater (Aldrich, 1984; Schepers et al., 1986; Newbould, 1989). High NO_3^- concentrations in surface and groundwaters have been attributed to agricultural systems that characteristically 'leak' nutrients (Loucks, 1977), coupled with the evidence that N fertilizers are inefficiently used (less than 50% recovery) by monoculture cropping (Keeney, 1982; Blackmer, 1987). Although large amounts of N may be present in soil organic matter, it is normally released too slowly to meet the needs of the growing maize crop (Stanford, 1982; Broadbent, 1984). Inorganic N is added to the soil solution via mineralization and wet deposition. However, the principal means of increasing N availability to crops is by application of nitrogenous fertilizers (DeWilligen, 1986).

The predominant cropping system in Central Illinois is a maize/soybean rotation where only maize production receives N fertilization, at an average rate in Champaign County of 196 kg N ha^{-1} (Champaign County SWCD, 1995, personal communications). However, in Champaign County, approximately 4000 ha are in seed corn production where an average of 135 kg N ha^{-1} is applied (Champaign County SWCD, 1995, personal communications). Compared with maize hybrids, N accumulation by inbreds is typically less than 50%, and yield may only be 25 to 50% of hybrids (Beauchamp et al., 1976). Because of the high price of hybrid seed and the low cost of N fertilizer, the N management strategy of seed corn producers is to ensure that N availability in the soil is nonlimiting (Balko and Russell, 1980). Therefore, in a seed corn production system, there is a greater potential for higher inorganic N pools after harvest than in hybrid maize production. This is the result of the relatively high fertilizer rates combined with lower plant uptake and yields.

In contrast, the soybean crop does not receive fertilizer N and accumulates N through soil uptake and atmospheric N_2 fixation. In a fine textured soil (e.g., silty-clay loam) with 3–5% organic matter, the soybean crop typically accumulates 25 to 50% of its N from atmospheric N_2 fixation (Johnson et al., 1975; Harper, 1987) and uses residual N and mineralized N for the majority of its N requirement (Olsen et al., 1970). Under high N fertility, a greater percent of the N accumulated by the soybean crop is soil derived. Although the addition of N fertilizer does not enhance soybean grain yield, soybean uptake of residual N remaining from the previous maize crop may increase fertilizer recovery and decrease potential N leaching losses. Therefore, N dynamics and crop N accumulation must be evaluated over the entire crop rotation to determine more accurately total N fertilizer recovery.

The objective of this study was to evaluate agricultural N pools and sinks in a seed corn/soybean rotation using a field-size watershed approach to relate soil inorganic N levels with annual losses of NO_3^- in drainage tiles. Investigation was made of the following N pools and fluxes to evaluate the fate of applied fertilizer N: soil microbial biomass N, soil inorganic N, plant uptake of N, and N leaching through drainage tiles.

2. Materials and methods

2.1. Description of agricultural watershed

An agricultural watershed approximately 40 ha in size located 25 km south of Champaign–Urbana, along the Embarras River was selected for study (Fig. 1). It is part of the larger (48,173 ha) Camargo watershed which has been previously studied (David et al., 1997). The watershed size was estimated by determining the extent of subsurface tile drainage combined with an estimate of the effective area of influence of the drain tiles. There were approximately 4275 m of 20.3 cm diameter subsurface drainage tiles in the watershed at a depth between 1 and 1.5 m. The total effective area of influence of drain tiles was calculated to be 100 m (50 m on each side of the tile) based on hydraulic conductivity of soil in the tile drain layer (Kurein et al., 1997).

The tile drainage system extended across two fields (fields 1 and 2) that were owned and operated by two different farmers (Fig. 1). Based on length of tiles in each field, approximately 75% of the subsurface watershed was located in field 2. There were three main tile lines in the two fields: tiles A, B, and

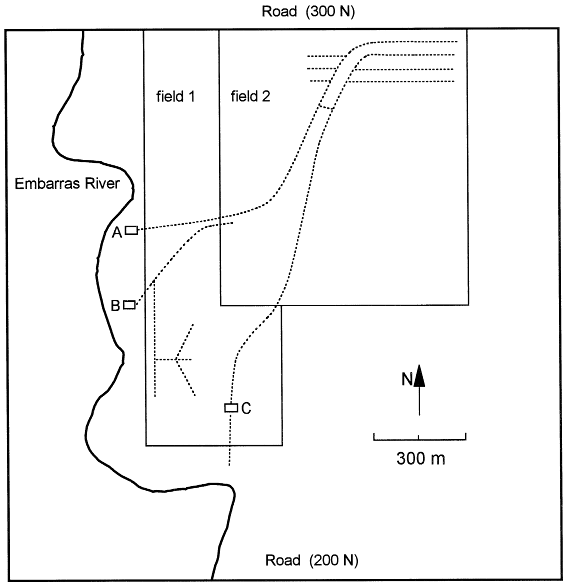

Fig. 1. Agricultural watershed located near the Embarras River, 25 km south of Champaign–Urbana, IL. Drainage tile (dashed lines) and agricultural field locations (solid lines) are shown.

C. Using the estimate for effective area drained and subtracting areas of tile overlap, the three tiles together drained up to a maximum of 40 ha of soil for the two fields. Tiles were randomly positioned in the watershed to facilitate drainage of several large low-lying areas consisting predominantly of Drummer silty clay loam (fine–silty, mixed mesic Typic Haplaquolls). Tile B had an estimated drainage area of 8 ha and was located almost entirely in field 1, whereas tile A (15 ha drainage area) and tile C (17 ha drainage area) drained both fields. Drainage areas for tiles A and C in field 2 merged, overlapped and were joined to increase flow capacity during major runoff events. The drainage area of tile A overlapped tile B in field 1. All overlapping areas of tile drainage were compensated for in drainage area estimates and were considered to have a negligible impact on tile water chemistry.

2.2. Cultural practices

The two farmers were on the same crop rotation (seed corn grown in 1993 and 1995, soybean in 1994) and planting and harvesting dates closely coincided each year. For the 2 years that seed corn was produced in the watershed, the same rate of N fertilizer was applied; however, the timing of application differed as well as the type of fertilizer in 1995.

On November 30, 1992, field 2 was fertilized with anhydrous ammonia at a rate of 135 kg N ha^{-1}. Field 1 received a side-dress application of anhydrous ammonia on June 3, 1993 at the same rate. During the first week in May of 1993, the entire watershed was planted with maize 'Northrup King' inbred parents at a population of 69,000 plants ha^{-1} to produce the hybrid '6822'. On September 8, 1993 the entire watershed was harvested.

In 1994, the watershed was planted with soybean and did not receive N fertilizer. Both fields were planted during the third week in May and harvested during the third week in September. Field 1 was drilled in 20.3 cm rows with 'Pioneer 9392' at a population of 370,000 plants ha^{-1}, and field 2 was planted in 76.2 cm rows with 'ICI D348' at a population of 198,000 plants ha^{-1}.

On February 9, 1995, field 2 received a dilute solution of $(NH_4)_2SO_4$ (6-0-0-6) at a rate 135 kg N ha^{-1}. Field 1 received a side-dress application of anhydrous ammonia on June 3, 1995 at the same rate. As in 1993, the entire watershed was planted with Northrup King inbreds at a population of 69,000 plants ha^{-1} to produce the hybrid 6822. Because of wet conditions, however, planting operations were conducted during the third week in May. On September 10 the entire watershed was harvested.

2.3. Soil sampling and analysis

All soil sampling in the watershed was conducted in Drummer soils located in the area drained by the tile system. In October 1993, six soil sampling sites were located only in field 1 near tiles A and B. In April 1994, six more sampling sites were located in field 2 over tiles A and C. The 12 sampling sites were arranged above the tile system in four transects of three sites each. Transects were located approximately 150 m apart and sites within a transect were 30 m apart. At each field site, transects were sampled for total N, percent organic matter, inorganic N, microbial biomass N, crop yield, and crop N content. It was estimated that the drainage area in field 2 was three times greater than field 1, therefore, a weighted mean of 75/25 was used to determine data for the entire watershed.

From October 6, 1993 to October 9, 1995, transects were sampled once a month except in the winter, for a total of 17 times. At each field site, soil was sampled at three depths (0–10, 10–30, and 30–50 cm) for inorganic N, microbial biomass N, and mineralized N. Inorganic N was extracted from field moist samples using 1 N KCl and analyzed for NO_3^- by cadmium reduction, and NH_4^+ by an automated phenate method, using a Technicon autoanalyzer (APHA, 1989) for both. To determine microbial biomass C and N, field moist soil was fumigated with chloroform and extracted with 0.5 M K_2SO_4 (Brookes et al., 1985). A Dohrmann DC-80 was used to determine dissolved organic C in extracts of fumigated and unfumigated soils. Total dissolved N was determined colorimetrically as NO_3^- after a basic persulfate digestion of extracts (D'Elia et al., 1977). Multipliers of 2.86 (Sparling et al., 1990) and 1.85 (Brookes et al., 1985) were used to convert chloroform labile C and N to microbial biomass pools. Mineralized N was determined using a buried N bag technique where soil cores were placed in polyethylene bags and relocated to incubate at the original soil depth (Eno, 1960; Paschke et al., 1989). Fresh and incubated soil cores were extracted with 1 N KCl, with extracts measured for NO_3^- and NH_4^+. Net N mineralization was estimated as the sum of net changes in NO_3^- and NH_4^+ for each soil sample during the incubation period. All values were corrected for moisture content by oven-drying sub-samples at 105°C for 48 h.

In October of 1994, soil total N and percent organic matter were determined at each field site at four depths (0–10, 10–30, 30–50, and 50–100 cm). Soil was air dried, sieved (2 mm), and sub-samples ground (40 mesh). Moisture content was determined by oven-drying at 105°C for 48 h. Total N was determined on ground samples by Kjeldahl digestion followed by an automated phenate method using a Technicon autoanalyzer. Percent organic matter was determined by the loss-on-ignition method (David, 1988).

2.4. Crop sampling and analysis

At each soil sampling location in the watershed, four female maize plants in 1993 and 1995 and five soybean plants in 1994 were harvested at maturity to determine above-ground plant weight, yield and N content (Heberer et al., 1985). Plant material was analyzed for N using a combustion technique (Fisons NA 2000 N Analyzer).

For maize, the above ground plant material was separated into leaves, stalks, ears, and a reproductive support fraction that consisted of husk, shank and tassel. Leaves and stalks were weighed fresh and mechanically shredded, and a sub-sample dried to a constant weight in a forced-draft oven at 80°C for 48 h. The ears and reproductive fraction were dried as above, before shelling the ear and combining the cob with the reproductive support fraction. Both fractions were redried to constant weight. After drying, all fractions were weighed and ground (2 mm screen) for chemical analysis.

For soybean, only stem, grain and pods were collected because of leaf senescence and loss before grain harvest. Plant fractions were oven-dried at 80°C for 48 h, weighed and ground (2 mm) for chemical analysis. To calculate N accumulation in leaves, a N harvest index value of 80% was used; therefore, 20% of the whole shoot N was estimated to be in the leaves (Harper, 1987).

2.5. Tile flow measurements and water analysis

Continuous monitoring of tile flow began December 21, 1993 for tile A, and flow monitoring equipment for tiles B and C was installed after tile flow had ceased in the summer of 1994. For both the 1995 and 1996 water years, tile flow started in November and ended in August. Duration of tile flow was influenced by seasonal fluctuations in the ground water table in part the result of distribution and amount of precipitation. Precipitation was measured on site by a Campbell Scientific TE525 tipping bucket rain gauge with rainfall data recorded every 30 min by a Campbell Scientific CR10 datalogger.

To monitor tile flow continuously, a weir structure fitted with a combination weir plate (a slot and v-notch for estimating low and moderate flow rates and a crest for high rates) was installed at the end of each tile. Each monitoring station contained a Campbell Scientific CR10 datalogger, Keller PSI pressure transducer, and an ISCO Model 2900 automatic water sampler. The datalogger was programmed to record tile flow every 15 min and calculate a daily average based on the 96 instantaneous flow values recorded throughout the 24 h period. Based on flow characteristics, a volume increment was programmed into the datalogger to best facilitate proportional sampling during a subsurface runoff event for a given tile. The datalogger triggered the water sampler at short enough intervals to collect water during peak flow as well as provide samples on the ascending and descending arms of the flow hydrograph. All water samples and flow data were collected within 24 h after flow events. Based on the hydrograph, selected samples were saved for analysis.

Tile water samples were preserved for storage on the same day as collection, with pH and conductivity determined on unfiltered samples (APHA, 1989). Sub-samples were filtered (1.2 μm glass fiber) and analyzed for NO_3^- by ion chromatography (APHA, 1989). Mass of N load exiting the tile system was determined by multiplying NO_3^- concentrations with actual flow rates and assuming that measured concentrations represented actual concentrations for variable periods of time before and after sampling. Therefore, a NO_3^- concentration could be assigned to every flow rate (based on 15-min intervals) to calculate daily, monthly, and annual N loads.

3. Results and discussion

3.1. Crop yield and N accumulation

The growing seasons in 1993 and 1994 were favorable for high grain yields for both crops, however, seed corn grain yield was less than 1 Mg ha^{-1} in 1995 (Table 1). The 1995 seed corn yield was only 21% of the yield produced in 1993 because of a combination of factors: late planting date, high temperatures at pollination, and low rainfall in July. In 1995, seed corn harvest removed 73% less N from the watershed than in 1993, although whole shoot N accumulation only declined by 37% (Table 1). Because of poor pollination in 1995, more N accumulated in the stover than in 1993. Previous studies have shown that when kernel number is restricted or the ear removed entirely, a higher percentage of N is accumulated in the stalk (Christensen et al., 1981; Jones and Simmons, 1983). Therefore, increased N accumulation in stover is an important temporary N reservoir that may help decrease the potential for N leaching after a poor growing season.

In 1994, the soybean grain yield was 3.2 Mg ha^{-1} and whole shoot N accumulation was 248 kg ha^{-1} (Table 1). Although yield was excellent in 1993, whole shoot N accumulation by the soybean crop was 110% higher than for the seed corn crop. To determine uptake of soil N by the soybean crop, an estimate of 50% was used to account for N accumulation from symbiotic N_2 fixation (Harper, 1987). In 1993 and 1994, it was estimated that both crops accumulated similar amounts of soil derived N (Table 1). However, because of the higher N concentration of the soybean seed, harvested soybean removed nearly 40% more soil derived N from the watershed than did the 1993 seed corn, and over 400% more than the 1995 seed corn crop.

3.2. Soil nitrogen

The predominant soil drained by the tile systems was a Drummer silty clay loam containing approximately 7750 kg of organic N ha^{-1} in the upper 50 cm of soil with a total organic N in the top 1 m of

Table 1
Precipitation (May through August), grain yield, N accumulation, and inorganic soil N in October for the agricultural watershed. Seed corn was grown in 1993 and 1995, and soybean in 1994

Year	Precipitation (mm)	Yield (Mg ha^{-1})	Crop N Accumulation		Soil
			Grain (kg ha^{-1})	Whole shoot (kg ha^{-1})	Inorganic N (kg ha^{-1})
1993	650	4.44	71	118	40
1994	320	3.21	198 (99)	248 (124)	24
1995	400	0.92	19	94	108

[a]Values in parenthesis represent an estimate of soil derived N for 1994 soybean crop.

11,000 kg N ha^{-1}. Although this soil contains a large pool of soil organic N, it is presumed to be released too slowly to satisfy the N needs of the maize crop and, therefore, N fertilizer was applied. The soybean crop, however, accumulated as much soil derived N without N fertilizer as did the excellent seed corn crop of 1993. Assuming 1 to 2% of soil organic N mineralizes annually, 78 to 155 kg of inorganic N in the upper 50 cm would potentially be available to the soybean crop per year. If this rate of N release is combined with the amount of N fertilizer applied for seed corn production, a range of 213 to 290 kg of inorganic N ha^{-1} may have been available to the crop. However, the seed corn crop did not accumulate more soil derived N than the soybean crop, although it possibly had twice as much N available (Table 1). It is hypothesized that N fertilizer may be absorbed by microorganisms before the maize root system is sufficiently developed to compete with microbial uptake of inorganic N.

Microbial biomass N ranged from 1.2 to 2.2% (83 to 156 kg N ha^{-1}) of the total N in the upper 50 cm of soil throughout the duration of the 2-year sampling period from October 1993 to October 1995 (Fig. 2). Based on the 17 sampling dates, the average microbial biomass N was 120 kg ha^{-1}. This large soil microbial N pool was nearly equal to the rate of N fertilizer application. Soil microbes incorporate N fertilizer into their biomass, especially ammoniacal N, temporarily immobilizing it until carbon becomes limiting. Fertilizer N may have increased microbial biomass N immediately after application especially in March 1995. However, soil moisture may have been the overall regulating factor controlling microbial biomass N and C.

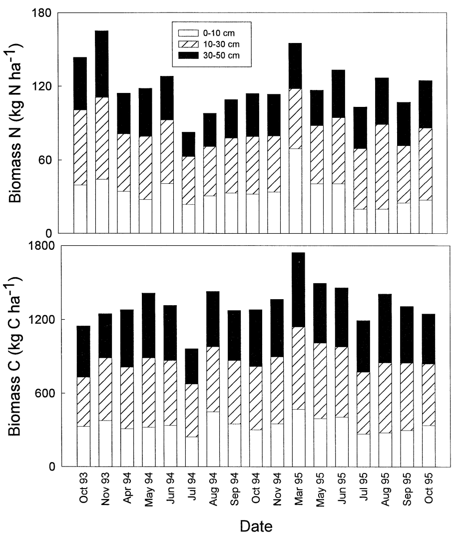

Fig. 2. Mean microbial biomass N and C in the top 50 cm of soil depth in the agricultural watershed sampled from 1993 to 1995 ($n=12$).

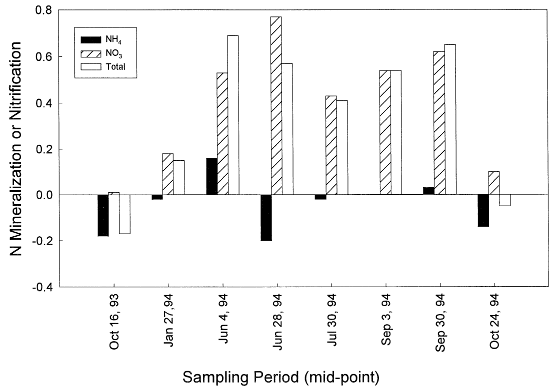

Fig. 3. Mean daily rates of N transformations in the top 50 cm of soil depth in the agricultural watershed sampled from 1993 to 1994. The mid-point of each sampling period is plotted ($n=12$).

Soil microbial C ranged from 900 to 1750 kg ha^{-1} for an average C:N ratio of 10:1. High values of microbial biomass N were not closely associated with high microbial biomass C; however, the lowest microbial biomass C and N occurred simultaneously in July of 1994. This was a period of hot dry weather and the soil moisture dropped from 20 to 12%. The highest microbial biomass C occurred in March of 1995 after fertilization of the watershed and coincided with the second highest microbial biomass N measured during the experiment. Except for this possible response to N fertilization, microbial biomass N or C did not appear to be strongly influenced by available inorganic N.

Soil N mineralization and nitrification rates were estimated throughout the experimental period. Application of N fertilizer greatly increased the variability of soil inorganic N; therefore, the data collected using the buried N bag technique in 1995 were not usable. Total mineralized N for 1994 was 88 kg N ha^{-1} and the estimated mineralization of N for 1995 was 133 kg N ha^{-1}. This estimate for 1995 was calculated by adding the recommended soybean N

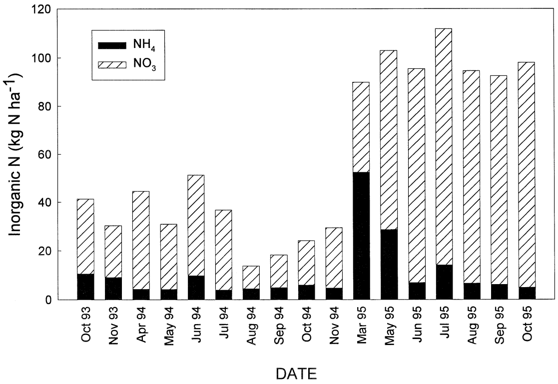

Fig. 4. Mean total inorganic N (NO_3^- and NH_4^+) in the top 50 cm of soil depth in the agricultural watershed sampled during 1993 to 1995 ($n=12$).

credit of 45 kg N ha^{-1} to the total mineralized N in 1994 (Kurtz et al., 1984). During the soybean growing season, net mineralization rates ranged from 0.49 to 0.69 kg N ha^{-1} day^{-1} for a total formation of 66 kg N ha^{-1}, with a period of net N immobilization during the month of October in both 1993 and 1994 (Fig. 3). Most of the mineralized N was as NO_3^- throughout the growing season. Crop root degradation immediately following harvest may have provided sufficient carbon to promote N immobilization, however, an overall dryer year may have limited microbial biomass in the fall of 1994 as compared with 1993.

Overall, microbial biomass (C or N) did not appear to be related to inorganic N pools (both crop years) or to mineralization rates (during the soybean year). From this lack of a relationship it might be assumed that microbial biomass is not important in regulating soil N mineralization rates. Holmes and Zak (1994) also found a similar result, although they were working in a forest soil. They indicated that N availability was primarily controlled by the turnover of microbial biomass, leading to a relatively constant pool of microbial biomass C and N through time (Holmes and Zak, 1994). Microbial biomass in the present soils may have had the same importance.

The soybean crop was estimated to accumulate 124 kg N ha^{-1} of soil derived N in 1994 (Table 1). To account for this amount of soil derived N accumulation, mineralized N, residual N at planting, and wet deposition of N were summed together, providing an estimate of 101 kg of inorganic N ha^{-1} available for plant uptake. It is hypothesized that the difference of 23 kg N ha^{-1} was the result either of an underestimation of total N mineralization during the growing season using the buried N bag technique, or because the contribution of N from atmospheric N_2 fixation to whole shoot N accumulation was closer to 60% instead of 50%.

Nitrogen fertilizer was applied for seed corn production to ensure N fertility was not a limiting factor. The inorganic N level in the soil during the 2-year sampling period ranged from a low of 13 kg ha^{-1} in August of 1994 to a high 112 kg ha^{-1} in July of 1995 (Fig. 4). The lowest inorganic N level for the watershed coincided with the period of peak uptake of soil N by the soybean crop. The highest inorganic N level was determined on July 17, 1995 after field 1 received a side-dress application of N. However, inorganic N levels for the entire watershed were greater than 90 kg ha^{-1} from March 21 to October 9, 1995 from N fertilization of field 2 in February. Inorganic N pools were more than 140% higher after grain harvest in 1995 than after harvest in 1993 (Table 1). Because of the harsh environmental conditions in 1995, crop N accumulation was

Table 2
Annual precipitation, tile flow, and nitrate export from the watershed for 1994–1996 water years

Water year[a]	Precipitation (mm)	Tile flow m^3 yr^{-1}			Tile nitrate export kg yr^{-1}		
		A	B	C	A	B	C
1994	970	79,520			698 (9.0)		
1995	790	29,135	12,694	54,874	374 (12.3)	105 (8.0)	675 (14.1)
1996	930	57,688	18,960	94,155	860 (14.5)	237 (12.3)	837 (8.8)

[a]Water year refers to the period from October 1 of the previous year to September 30 of the identified water year.
Values in parentheses are flow-weighted mean NO_3–N concentrations (mg N l^{-1}).

restricted and apparently little of the fertilizer N was used by the crop.

3.3. Precipitation, tile flow, and NO_3^- leaching

In 1993, Champaign County received a record annual rainfall with the total for Champaign–Urbana at 1480 mm. During the growing season of 1993, the watershed received over 650 mm of precipitation that produced substantial tile flow throughout the summer. At that time weekly grab samples and instantaneous flow measurements were made, but water and N budgets were not determined. Until continuous flow and proportional sampling were initiated for tile A in December of 1993, data from weekly grab samples were used to complete the 1994 water year (October 1, 1993 to September 30, 1994). Continuous flow was not monitored for tiles B or C during the 1994 water year. Although precipitation for water years 1994 and 1996 were similar, tile A flow was 38% higher in 1994 (Table 2). This higher flow was the result of frequent heavy rains throughout the summer and autumn of 1993 which caused continuous tile flow during that year. During the subsequent water years, the watershed received more typical annual rainfall amounts and tile flow cessation occurred for all tiles from August through October.

In general, all three tiles responded similarly to precipitation events producing similar flow hydrographs (Fig. 5), although the magnitude of flow was different among the tiles because of the source areas drained. When comparing annual tile drainage during the same water year, the three tiles varied greatly in flow, ranging from 12,694 to 54,874 m^3 yr^{-1} (159 to 323 mm yr^{-1}) in the 1995 water year and 18,960 to 94,155 m^3 yr^{-1} (237 to 554 mm yr^{-1}) during 1996 (Table 2). The range of annual precipitation among the three water years was 180 mm with a high of 970 mm in 1994 and a low of 790 mm in 1995. However, annual flow for tile A was nearly three-fold higher during the 1994 water year compared with 1995. These data suggest that tile flow was a function of area drained as well as timing and distribution of precipitation.

Nitrogen export from the watershed via NO_3^- leaching through tile lines was closely associated with high flow events (Figs. 5 and 6). During the

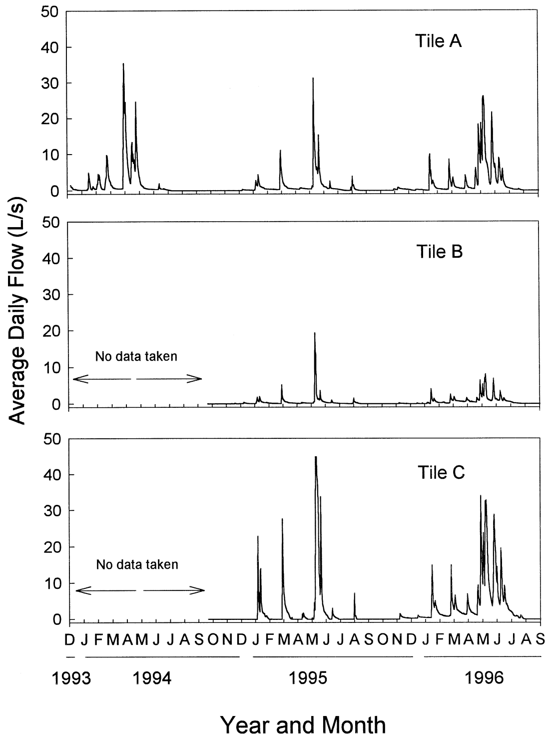

Fig. 5. Daily flow rates for agricultural drainage tiles sampled during the 1994 to 1996 water years.

1995 water year which produced the least subsurface runoff of the 3 years evaluated, nearly all the NO_3^- exported for the entire year leached during record rainfall in May. During this high flow period, NO_3^- export for tile C was as much as 148 kg N in 1 day. To further illustrate the importance of NO_3^- movement during high flow events, only nine days of flow contributed 75% of the annual N export of 675 kg for tile C. In contrast, during the water year 1996, when there were nearly twice as many high flow events, a total of 45 days were required to contribute 75% of the annual N export of 837 kg. This large difference in flow patterns and N loss per day for tile C, suggested that NO_3^- leaching is controlled by complex interactions between inorganic N pools, and frequency and magnitude of high flow events (Lowrance, 1992; Patni et al., 1996).

High tile flow events are responsible for most of the annual N loss, however, the amount of soil inorganic N influences NO_3^- concentrations in tile water. Although drainage water in tiles A and C

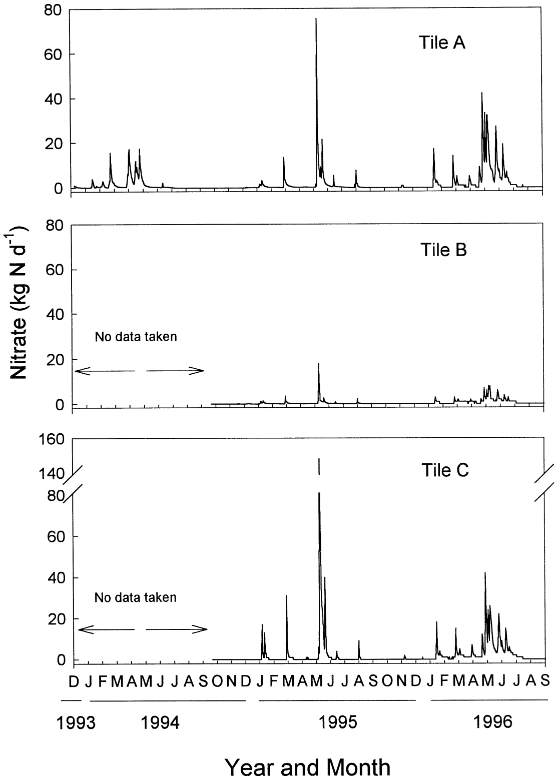

Fig. 6. Daily NO_3^- export for agricultural drainage tiles sampled during the 1994 to 1996 water years.

were of similar NO_3^- concentrations during high flow events in May of 1995, the flow rate for tile C was typically more than twice as high. During the month of May, tiles A and C exported 230 kg and 616 kg of N, respectively, and N loss was a function of flow rates. However, in preliminary sampling during the 1994 water year (data not shown) and flow proportional sampling during the 1996 water year, NO_3^- concentrations of tile C were always less than tile A. The consistently higher flow of tile C may have been responsible for diluting NO_3^- concentrations below that of tile A. During the spring of 1995 after only field 2 was fertilized, the NO_3^- concentrations were similar. Although both tiles A and C originate in field 2, based on the annual N export, it is hypothesized that tile C receives a higher proportion of drainage water from field 2 than does tile A.

The highest tile NO_3^- concentrations observed during this study were 49 and 43 mg N l^{-1} for tiles A and C, respectively, during a high flow event on May 19, 1995. During this same event, NO_3^- concentrations of tile B did not exceed 13 mg N l^{-1}. Tile B was located almost entirely in field 1 which had not yet been fertilized on May 19. There was a substantial tile flow event in early March and NO_3^- concentrations in tiles A and C were only 11 and 10 mg N l^{-1}. Soil sampling indicated that during this time most of the fertilizer still remained in the NH_4^+ form (Fig. 4). By May 10, more than half of the fertilizer had nitrified and there was nearly 90 kg of NO_3^- N ha^{-1} in field 2 (individual field data not shown). Rainfall of 130 mm occurred during the week of May 19 and this high soil NO_3^- pool caused by nitrification of the NH_4^+ fertilizer resulted in the largest one day loss of N from the watershed.

Soil inorganic N pools remained high throughout the 1995 growing season (Fig. 4). The hot, dry period in June and July of 1995 limited N uptake by the seed corn crop and over the entire watershed, nearly 100 kg of N ha^{-1} remained in the upper 50 cm in October. Total NO_3^- export for the three tiles was 1.2 and 1.9 Mg N for the water year 1995 and 1996, respectively. Although there was 140 mm more rainfall during the 1996 water year than 1995 and subsequently more tile flow, the higher N export in 1996 was probably because of the high inorganic N pool remaining in the soil after the poor growing season. Drury et al. (1996) also found the greatest loss of NO_3^- in tile drainage to occur after a dry growing season which limited maize yields and N uptake. For all three tiles, the total N export increased for the 1996 water year compared with 1995, although percent increases varied (Table 2). The difference in increase in annual N exported for each tile can be explained by reviewing tile locations and timing of fertilizer application to the watershed.

Field 1, where tile B was located, was fertilized in June 1995. Concentrations of NO_3^- in tile B rarely exceeded 10 mg N l^{-1} during the 1995 water year. However during the spring of 1996, concentrations were routinely more than 15 mg N l^{-1}. Because of residual fertilizer in field 1, tile B experienced an increase in N export of 126% during the water year 1996 compared with 1995 with only a 49% increase in flow. Flow for tiles A and C increased 98 and 72% for the 1996 water year compared with 1995, but the percent increase in N export for the two water years was different (tile A increased 130% whereas tile C increased only 24%). Flow weighted mean concentrations of NO_3–N also support the hypothesis that tile C drained a greater percentage of field 2 than tile A (Table 2). These differences in annual N export patterns between the tiles suggest that timing of N application and area drained had a large influence on total N export of each tile.

During the 1995 and 1996 water years, the total amount of N leached through the three tile systems was 3.1 Mg. Based on a 40 ha watershed, this total represented 29 and 48 kg N ha^{-1} leached during the 1995 and 1996 water years, respectively. However, during extremely heavy rainfall events, tile flow rates were related to the persistence of detention storage in low-lying areas in the field. Low-lying areas in the field were approximately 50% of the watershed size and appeared to dominate tile flow and water chemistry until surface water was drained. Therefore, the effective area of influence of tile drainage may be considered elastic, ranging between 20 and 40 ha depending on the intensity of rainfall and soil moisture status before the rain event.

Assuming that soil organic matter content remains constant over the duration of a crop rotation, a simplified N budget approach was used to balance watershed inputs and outputs (Barry et al., 1993). Based on an average effective drainage area of 30 ha for the watershed, 38 and 64 kg N ha^{-1} leached during the 1995 and 1996 water years, respectively. Also using this average drainage area, the fertilizer input to the watershed was 4.1 Mg N and the mineralization estimate for the 2 years was 6.6 Mg N (net annual mineralization rates of 88 and 133 kg N ha^{-1} were used for 1994 and 1995, respectively) for a total N input of 10.7 Mg N. Harvested grain removed 3.5 Mg N from the watershed for a total amount remaining of 7.2 Mg N. When subtracting grain N accumulation and leaching losses from total N inputs, this simple N budget approach could not account for 4.1 Mg N. Although whole shoot N accumulation can account for a portion of this missing N, it was assumed that net mineralization estimates account for the majority of N released from crop residue. Based on 3.1 Mg N of cumulative tile export, leaching losses represented 43% of the N remaining in the field after harvest, and 76% of N applied as fertilizer.

Patni et al. (1996) found N loss to range from 10 to 39 kg N ha^{-1} yr^{-1} under conventional tillage on maize fields in Ontario (7 to 30% of applied fertilizer), with loss primarily a function of precipitation amount during the dormant season. In 2 years with tile flow (nondrought years) Logan et al. (1994) measured tile drainage loss of NO_3^- under conventional maize and soybeans of 14 to 86 kg N ha^{-1} yr^{-1}, respectively. The present estimates of 38 and 64 kg N ha^{-1} were in this same range, and also demonstrated that precipitation dynamics in combination with soil inorganic N status control leaching losses.

The watershed N budget for inputs and outputs was nearly balanced for soybean production in 1994. Although the soybean crop was efficient at using N as it became available and depleted soil inorganic N pools, tile N export during the 1995 water year was enhanced by leaching of fertilizer N applied in February to field 2. During the 1996 water year, N export in tile drainage increased because of higher annual tile flow combined with a large amount of soil inorganic N remaining after harvest for the previous year. Therefore, during the 1995 and 1996 water years, nearly all N leaching was attributed to factors associated with seed corn production.

In May of both years, rainfall exceeded infiltration rates and ponded water remained in the fields for five consecutive days in 1995 and 12 consecutive days in 1996. Soil temperatures were above 10°C and substantial denitrification of N fertilizer and/or residual N may have occurred when fields were flooded, thus, decreasing the overall soil inorganic N pool. Torbert et al. (1992) found that when Drummer soil was flooded for more than 5 days nearly 50% of the N fertilizer applied was lost through denitrification. Soil inorganic N was not measured in the spring of 1996, and it is likely that a substantial portion of the missing 4.1 Mg N was denitrified especially during the extended flooding in May of 1996.

In general, for maize, crop uptake can account for 50% of the N input and the remaining 50% can be divided approximately between leaching and denitrification (Allison, 1966). However, N fertilizer recovery can increase when the subsequent soybean crop absorbs either residual fertilizer or mineralized N from maize residue. In contrast, maize inbreds utilize less N compared with hybrids, and lower N fertilizer recovery is expected when producing seed corn. Because of inherent lower N accumulation by inbreds and an unfavorable growing season in 1995, overall grain N accumulation for the 1994 and 1995 growing seasons was only 33% of the total N input with leaching losses representing 29%. The balance of 38% may have remained in the soil (either as residual N or N in crop residue) or denitrified. Although field denitrification rates were not measured in this experiment, with an assumed 50% reduction, then 2.1 Mg N (68 kg N ha^{-1}) was lost from denitrification during the experimental period.

Flow weighed mean concentrations of NO_3^- in tiles were similar in magnitude and in seasonal pattern to NO_3^- concentrations in the Embarras River. When averaging all three tiles together, monthly NO_3^- concentrations exceeded the EPA drinking water standard of 10 mg l^{-1} a total of two of 10 months and eight of 10 months for the 1995 and 1996 water years, respectively. During months that tile NO_3^- concentrations were above the EPA standard, weekly grab samples from the Embarras River were also consistently above the standard. From January through July of 1996, the river NO_3^- concentration exceeded the EPA standard 22 out of 30 weeks with a high of 15.1 mg N l^{-1} in June. The standard was surpassed only three times during that same time period in 1995. When tile flow ceased throughout the Camargo watershed each year, river NO_3^- concentrations quickly fell below 2 mg N l^{-1}. These data suggest that agricultural runoff primarily transported through tile lines greatly influenced the concentration of NO_3^- in the river. In addition, the poor growing season of 1995 apparently resulted in high inorganic N pools throughout the Camargo watershed which provided the source of N in the river during the winter and spring of 1996 (David et al., 1997).

The Embarras River is impounded to form a reservoir (Lake Charleston) for the drinking water supply of Charleston, IL, which is located 35 km downstream of Camargo. The watershed below Camargo continues to be dominated by row-crop agricultural land use. It is apparent that nonpoint source pollution of N from agricultural production is creating high NO_3^- pollution in waters draining to Lake Charleston. N fertilizer coupled with N added to the soil solution from mineralization of organic matter can create high inorganic N pools after harvest, especially after a poor growing season. In a maize/soybean crop rotation, best management practices should ensure that an appropriate N credit is assessed to the soybean crop to reduce the N fertilizer rate for the following year. In addition, when seed corn is being produced in a maize/soybean rotation, N fertilizer rate should be reduced further because of the inherent lack of N uptake by maize inbreds as compared with hybrids. Although seed corn harvest removed a small amount of N from the watershed in 1995 and high inorganic N pools existed after harvest, the percentage of residual N leached was similar to the average (41%) for the entire Camargo watershed during those two water years (David et al., 1997).

4. Conclusions

In general, all three tiles responded similarly to precipitation events producing similar flow hydrographs, although the magnitude of flow and total NO_3^- export were different because of source areas drained. N export was closely associated with high flow events, whereby the majority of NO_3^- was leached from the watershed during saturated soil conditions in the spring before crop planting. Tile drainage water N concentration was highly dependent on the amount and form of inorganic N in the soil. Inorganic N pools were greater after maize production than soybean production and were substantially higher after a poor maize growing season in 1995. Although tile N export was higher after maize production, the timing of N fertilizer application also influenced N export. It was suspected that high inorganic N pools from nitrification of $(NH_4)_2SO_4$ before crop uptake was responsible for tile NO_3^- concentrations of 49 mg N l^{-1} in May of 1995, which produced the largest one day loss of N from the watershed during the experimental period. Differences in annual N export for each tile were the result of a combination of factors including; timing and area of N fertilization, amount and distribution of precipitation, crop uptake of soil derived N, and inorganic N pools remaining after harvest.

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