Nitrate Contamination of Groundwater under Irrigated Coastal Plain Soils

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ABSTRACT

To develop best management practices (BMP) for agricultural land to protect groundwater, data is needed on the leaching of N from irrigated coastal plain soils treated with poultry manure. This study was conducted to determine the vertical and seasonal patterns of NO_3 leaching under such soils. Four commercially farmed corn (*Zea mays* L.) fields were studied, two receiving only fertilizer N (240 to 360 kg N ha^{-1} over a 2-yr period) and two with a continuing history of poultry manure applications (25–29 Mg ha^{-1} over 2 yr). In each field, a transect of four monitoring wells was installed 4 to 8 m deep (1 m below the seasonally low water table). Three additional wells were installed in forestland adjacent to three of the fields. Groundwater and soils (to 1.5-m depth) were periodically sampled for analysis of NO_3-N. Under the unmanured field, groundwater NO_3-N concentrations averaged 15.1 mg L^{-1} during August through November 1986, while the corresponding figure for the manured fields was not significantly different at 18.3 mg L^{-1}. Two months after spreading manure in November and December, as much as 104 mg NO_3-N was measured in the groundwater under the manured fields. From December 1986 through September 1987 the groundwater under the manured fields had significantly higher NO_3-N concentrations than did that under the unmanured fields (43.7 vs. 18.1 mg L^{-1}, respectively). Only for one well site with a buried A horizon did high Cl to NO_3-N ratios and low NO_3-N concentrations indicate rapid denitrification. The forestland groundwater always contained <1 mg NO_3-N L^{-1}, and high Cl to NO_3-N ratios, suggesting that NO_3 in the cropland groundwater was lost after entering the forested areas, and that forests may therefore protect waterways from subsurface N contamination.

NITRATE CONTAMINATION of the Columbia Aquifer, a shallow unconfined aquifer of Maryland's Coastal Plain, is of concern because of potential adverse effects on human and animal health, and because of its potential to contribute to eutrophication of the Chesapeake Bay.

Several factors combine to make the NO_3 contamination of this aquifer important to water quality in the Chesapeake Bay. First, the groundwater of the Columbia aquifer feeds into major tributaries of the Chesapeake Bay. Nitrogen is the nutrient most responsible for eutrophication of the brackish waters of the lower bay and its tributaries (Taft, 1982). Secondly, although Maryland normally has rainfall adequate for production of agronomic crops, the amount of irrigated cropland has been increasing dramatically in the past 15 yr. In 1975, the eastern shore of Maryland had 7500 ha of irrigated land, mostly in horticultural crops. This figure had increased to 13 950 by 1980 and 20 450 by 1985. In 1985, 47% of the irrigated land was devoted to corn and soybean [*Glycine max* (L.) Merr.]. Thirdly, NO_3-N was found to be the most important contaminant in the unconfined aquifers under the Delmarva Peninsula (Bachman, 1984). Irrigated corn, grown on light textured soils, may have a particularly great potential for NO_3-N pollution. Farmers consider that the higher yield potentials of irrigated land justify higher rates of N fertilization. Typically, farmers apply 200 to 250 kg N ha^{-1} for irrigated corn and 120 to 150 kg N ha^{-1} for rainfed corn on these light-textured soils.

An additional factor that may enhance the potential for groundwater contamination is the widespread application of poultry manure to irrigated land to supply N and dispose of the manure. The average rate of application by Delmarva farmers is >13 Mg ha^{-1} of manure containing 24 kg N Mg^{-1}. This equates to approximately 300 kg N ha^{-1}. In some cases this amount of manure is applied twice a year to a given field. Also, commercial fertilizer N is often applied in addition to manure.

These fertilization practices, along with irrigation of these droughty, light-textured soils, which have high permeabilities and leaching potentials, offer a very high potential for groundwater contamination with NO_3. In order to develop BMP for Coastal Plain croplands, data is needed on the fate of NO_3-N as a result of the irrigation, fertilization, and manure application practices common on these sandy soils. This study was initiated to: (i) characterize the depth and seasonal pattern of NO_3-N leaching under center-pivot irrigated coastal plain soils, (ii) compare NO_3-N leaching under fields treated with poultry manure and commercial fertilizer, and (iii) compare NO_3-N in groundwater and in the soil profile under center-pivot irrigation to that under adjacent forestland.

MATERIAL AND METHODS

Cultural Practices

Four commercially operated fields were investigated in this study. All fields were planted to corn in 1986 and irrigated by center-pivot sprinkle systems using surface water sources. Irrigation was scheduled by the individual farmers on the basis of perceived crop water stress, plus, in the case of Field S, on tensiometer readings of -70 kPa or less. The irrigated area in each field was 50 ha, but total field sizes ranged from 65 to 85 ha. Water inputs by precipitation and irrigation during the study period are shown in Table 1. The

Table 1. Water inputs as precipitation and irrigation to the study fields in 1986–1987.

Field code	Precipitation† 1986	Precipitation† 1987‡	Irrigation 1986	Irrigation 1987‡	Total, Jan. 1986–Sept. 1987
	mm				
F	901	655	311	280	2147
T	913	652	230	152	1947
S	950	626	257	196	2029
D	887	676	101	254	1918

† Precipitation based on distance weighted mean of three nearest recording stations.

‡ 1 Jan.–30 Sept. only, for 1987.

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fields were located on land mapped as Sassafras (Typic Hapludults) and associated soils. These soils had slopes ranging from 0 to 4%, and were formed in sandy Coastal Plain sediments with strata ranging in texture from very fine sands to gravelly coarse sands. The fields were located in southern Caroline and northern Dorchester counties, Maryland (Fig. 1).

Table 2. Nitrogen applications to the study fields in 1986–1987.†

Field code	Fertilizer-N Spring 1986	Fertilizer-N Spring 1987	Manure-N Spring 1986	Manure-N Fall 1986	Manure-N Spring 1987	Total-N
	kg N ha^{-1}					
F	107	100	430	270	–	906
T	107	–	430	–	160	697
S	240	–	–	–	–	240
D	240	120	–	–	–	360

† Based on 24 kg N Mg^{-1} average poultry manure analysis.

Application of fertilizers, manures, and irrigation and cultural practices were those typically employed by each individual farmer (Table 2). Tillage consisted of chisel-plowing in spring; corn was planted at a population density of approximately 60 000 plants ha^{-1}. In 1986 all four fields were planted to corn. In 1987 Fields F and D remained in corn and Fields T and S were planted to soybean.

Fields F and T received 107 kg N ha^{-1} as planting and side-dress fertilizer plus 18 Mg ha^{-1} of poultry manure in the spring of 1986. An additional 7 Mg ha^{-1} manure was spread in Field T in mid-October 1986. A large amount of poultry manure was stockpiled in an 80 m long pile along an unpaved farm lane that paralleled the row of monitoring wells. This manure pile was approximately 20 m from two of the monitoring wells in Field F from early December 1986 until the manure was spread over the field in mid-March 1987, at 11 Mg ha^{-1}. Fields S and D received between 225 to 240 kg N ha^{-1} as fertilizer in 1986 (including NH_3 metered into the irrigation water in Field S). These fields had not received any poultry manure for at least 6 yr. Fields F and D received

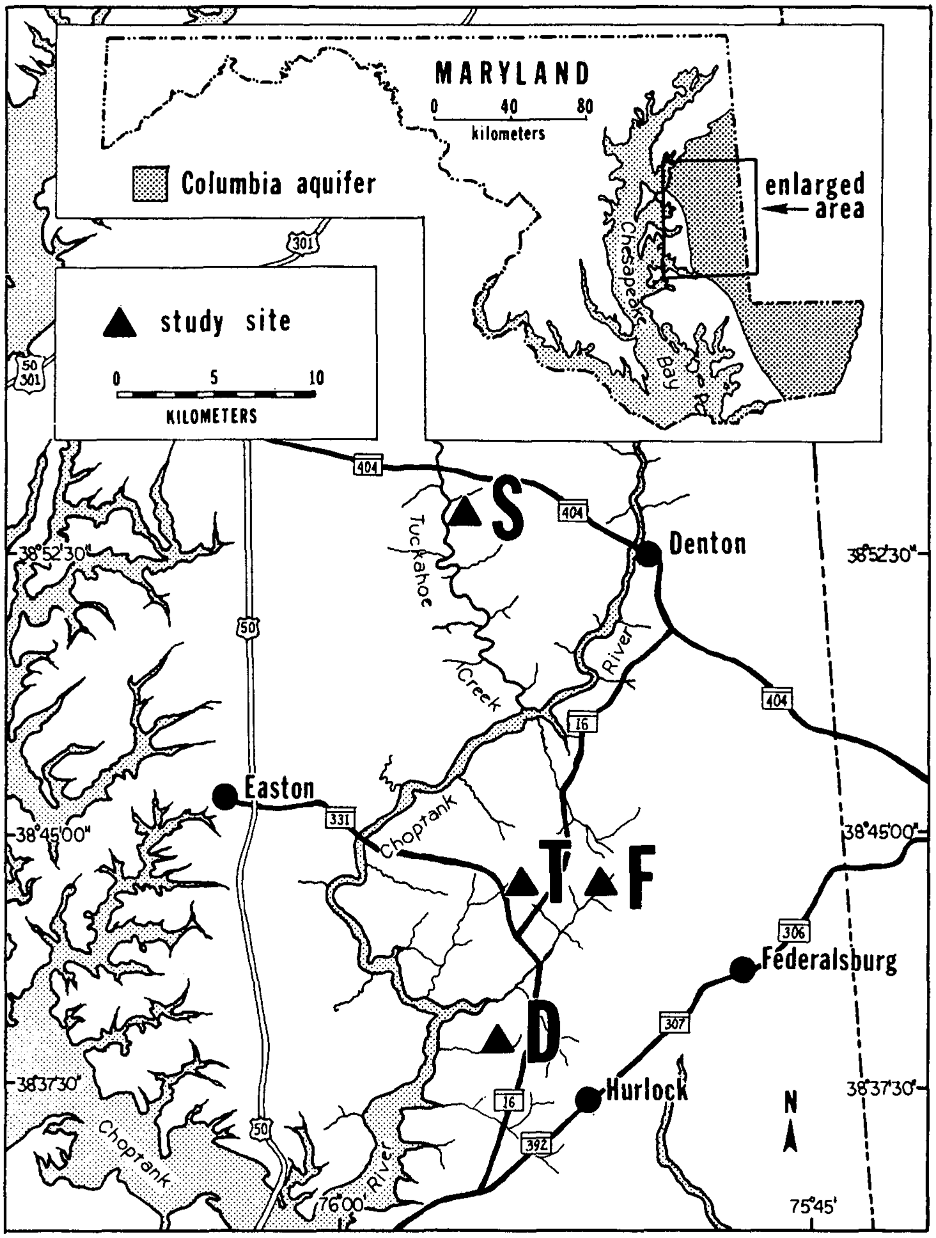

Fig. 1. Location of the four study sites and the Columbia aquifer in Maryland.

a topdressing of N during June 1987 at rates of 100 and 120 kg N ha^{-1}, respectively.

Sampling

Nitrates in the soil and groundwater under four commercial crop fields were monitored from August 1986 through September 1987. Nineteen monitoring wells were installed in May and June of 1986. In each field four wells were installed 80 to 100 m apart in a transect along a radius of the irrigated circle, running down slope. A typical installation is shown in Fig. 2. Each well was coded with the letter of the field and a number, 1 (at the lowest elevation) to 4 (at the highest elevation). An additional well (no. 5) was installed in forestland approximately 100 m from adjacent cropland near Fields S, T, and F.

The wells varied from 4.4 to 7.5 m deep so that each extended at least 1 m below the seasonally low water table (see Table 3). Each well consisted of a PVC riser 1.5 m long and a slotted screen below. The screen and riser were 0.05-m i.d. PVC and the screen had 0.5-mm openings. When installed, each well was surrounded by a 0.05-m thick layer of coarse, washed sand and sealed to a depth of 0.20 to 0.50 m with bentonite. Each riser protruded approximately 0.30 m above the ground level and was sealed with a threaded cap fitted with a rubber O-ring.

Soil samples were collected within a radius of 6 m of each well in August and October 1986, and March and June 1987. These samples were collected to a depth of 1.5 m in five 0.30-m intervals. Each soil sample was a composite of six 0.02- by 0.30-m cores taken with a sleeved JMC 0-contam-

Table 3. Groundwater characteristics under four fields sampled 20–25 Sept. 1987.

Well no.	Water table†	Well depth	Vegetation	Temperature	pH	Eh	Organic C	NO_3-N	Cl^-
	m			C°		mV	mg L^{-1}		
				Manured fields					
T1	1.89	6.00	Soybean R6	14	4.4	35	6.17	0.35	66.9
T2	2.81	5.95	Soybean R6	13	3.5	405	1.16	23.28	33.4
T3	3.45	5.99	Soybean R6	13	3.8	440	1.62	30.23	35.4
T4	3.50	5.97	Soybean R6	13	3.7	445	1.29	32.19	45.6
F1	2.30	4.50	Corn stubble	13	4.0	480	0.49	25.09	32.4
F2	2.29	4.45	Corn stubble	12	4.6	450	0.62	25.32	29.5
F3	2.20	4.51	Corn stubble	13	3.5	450	0.57	34.14	52.8
F4	2.51	4.42	Corn stubble	13	5.3	399	–	17.30	21.7
Means‡					3.8	438	0.96*	26.78*	35.8
				Unmanured fields					
S1	3.66	7.46	Soybean R5	13	3.9	490	0.41	22.25	30.0
S2	4.59	7.49	Soybean R5	14	4.5	470	0.26	16.84	33.9
S3	5.18	7.30	Soybean R5	14	4.3	500	0.42	9.38	14.6
S4	5.38	7.50	Soybean R5	12	4.3	500	0.12	11.81	23.6
D1	2.18	6.05	Corn stubble	14	4.7	512	0.16	18.88	129.4
D2	3.22	6.02	Corn stubble	14	4.4	508	0.13	14.30	58.8
D3	3.13	6.05	Corn stubble	14	3.8	494	0.24	16.9	78.9
D4	3.20	5.98	Corn stubble	14	4.5	455	0.19	11.77	105.1
Means					4.2	491	0.24*	15.27*	59.3
				Forested sites					
T5	4.47	7.09	Hardwoods	12	3.8	448	0.60	0.18	10.2
F5	2.68	4.48	Pines	12	3.6	452	1.14	0.17	5.7
S5	3.85	7.37	Hardwoods	14	3.5	512	0.95	0.09	4.4
Means					3.6	471	0.90	0.15	6.8

* Indicates significant difference ($P < 0.05$) by unpaired *T* test.

† Depth below land surface.

‡ Means of manured fields do not include values for Well T1.

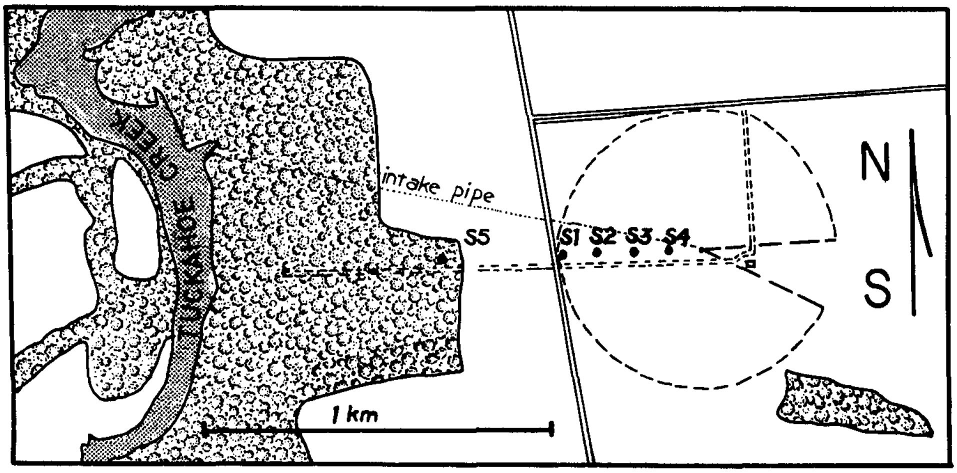

Fig. 2. Typical layout of a field study site. The site shown is Field S with associated Wells S1 through S5. White areas are land in row crops. Circular dashed line represents the irrigated area. In this case a segment was unirrigated because of the location of the farm house. Forestland is indicated by the tree pattern.

ination probe (Clements Assoc., Newton, IA). The soil was chilled on ice during transport to the laboratory. These samples were then rapidly fan-dried at room temperature, ground in a hammer mill, and sieved (<2 mm). Nitrate-N (2 *M* KCl extractable) in the soil samples was determined by Cd reduction and auto analyzer techniques (Technicon Industrial Systems, 1973).

The water table depth was measured by an electrical resistance meter with a calibrated cable; groundwater samples were obtained at each well at approximately monthly intervals from August 1986 through September 1987. Each well was pumped repeatedly, and the temperature and pH of the water measured, so that at least four well-volumes were removed and the temperature and pH of successive volumes had stabilized before a sample of the entire water column was obtained with a ball-valve tube bailer. This was emptied into a clean plastic 10-L container from which a 120-mL subsample was obtained in a screw-top polyethylene container. Water samples were kept on ice on the way to the laboratory and then frozen until analyzed. Storage time was typically 5 to 10 d. Nitrate-N (NO_2-N), Cl, NH_4-N, SO_4-S, and PO_4-P in filtered (<0.2 m) water samples were determined by ion chromatography (USEPA, 1983) at the Wye Research and Education Center Water Quality Laboratory.

A platinum electrode with a calomel reference was used to determine the Eh of the groundwater in situ during the September 1987 sampling. The reported Eh values are mV indicated plus 242 mV to correct for the reference electrode potential (Jackson, 1974). Total organic C was determined on the March and September 1987 samples after filtering ($<0.2\ \mu M$) using a carbon analyzer. Soil bulk density and gravimetric moisture content at each sampling depth were determined using undisturbed cores collected during the May 1987 sampling.

RESULTS AND DISCUSSION

Concentrations of phosphate-P, ammonium-N, and NO_3-N in the groundwater samples were negligible, each being <0.1 mg L^{-1} in most cases (data not shown). However, the concentration of NO_3-N in the groundwater under all four fields exceeded the USEPA drinking water standard of 10 mg L^{-1} in almost every case (Table 4). During the period from August to November, the average NO_3-N concentration was 18.3 mg L^{-1} from groundwater under the manured fields (F and T) and 15.1 mg L^{-1} for the unmanured fields (S and D). Although the manured fields had slightly higher levels of groundwater NO_3-N on each sampling date than did the unmanured fields, the difference was not statistically significant during this period (Fig. 3). This indicates a fairly short residence time for these groundwaters as little residual NO_3-N from the previous years' manuring was evident.

The groundwater NO_3-N under the unmanured fields (S and D) showed little change from August to February, despite the onset of rains in September following one of the driest summers on record. In addition, Field D had very similar groundwater NO_3-N concentrations to those in Field S. Field D, however, experienced an irrigation equipment-related water shortage during pollination leading to a crop failure, while moisture was maintained near field capacity in Field S, where an excellent yield was produced (approximately 10 000 kg ha^{-1} of grain). These data suggest that crop uptake did not play a dominant role in determining the N balance in these fields.

The seasonal patterns of groundwater NO_3-N concentrations were similar under the two manured fields until the December, and especially February, sampling dates. In February, the effects of the fall spread or stockpiled manure became apparent with highly elevated concentrations of NO_3-N in the groundwater. Nitrate-N concentration under Field T, on which manure was spread in October, did not increase dramatically until between the December and February sam-

Table 4. Concentrations of NO_3-N in groundwater from August 1986 to May 1987.

Well no.	Vegetation	Aug.	Sept.	Oct.	Nov.	Dec.	Feb.	Mar.	May
		mg L^{-1}							
				Manured fields					
T1	Corn/wheat (*Triticum aestivum* L.)	<0.1	1.8	1.6†	2.0	2.3	<0.1	<0.1	0.5
T2	Corn/wheat	18.0	16.1	19.8†	19.6	36.0	64.4	62.7	65.7
T3	Corn/wheat	18.6	18.3	25.5†	23.3	29.5	28.4	51.6	70.6
T4	Corn/wheat	25.9	23.6	25.0†	24.8	25.4	55.1	83.4	54.2
F1	Corn/corn	14.1	13.7	18.8	9.4	17.1	21.1	18.5	29.6
F2	Corn/corn	19.5	11.6	15.7	13.3	35.1§	104.1§	94.9	80.9
F3	Corn/corn	16.3	10.9	18.6	13.2	40.1§	74.0§	–‡	59.1
F4	Corn/corn	–‡	18.3	23.6	19.7	34.5§	16.9§	18.6	15.9
				Unmanured fields					
S1	Corn/barley (*Hordeum vulgare* L.)	20.4	18.1	20.7	17.0	16.4	19.0	22.1	24.3
S2	Corn/barley	19.9	17.1	25.0	17.4	14.0	21.1	25.8	17.7
S3	Corn/barley	12.3	13.1	12.5	11.9	14.9	9.3	14.5	11.3
S4	Corn/barley	13.7	12.2	13.4	11.7	9.5	14.0	17.0	11.1
D1	Corn/corn	17.7	13.7	20.9	14.6	15.1	16.5	36.3	23.2
D2	Corn/corn	14.6	11.6	13.3	13.4	22.0	21.5	22.6	19.1
D3	Corn/corn	15.1	10.9	19.3	12.2	10.7	21.0	24.4	28.3
D4	Corn/corn	7.3	18.3	–‡	9.8	9.6	22.6	28.5	38.0
				Forested sites					
T5	Forest	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
F5	Forest	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
S5	Forest	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

† 7 Mg ha^{-1} poultry manure spread on Field T in mid-October.

‡ Data not available.

§ Poultry manure was stockpiled within 20 m of Wells F2 and F3 from December–March.

pling dates. By February as much as 64.4 mg NO_3-N L^{-1} were measured in the groundwater under that field. In Field F, manure was stockpiled in the open field approximately 20 m from Wells F2 and F3 from early December to mid-March, at which time the manure was spread evenly across the field at 11 Mg ha^{-1}. The effects of this stockpiled manure upon groundwater NO_3-N concentrations could be seen in February groundwater samples from Wells F2 and F3 (Table 4). Samples from these wells contained 104.1 and 74.0 mg L^{-1} NO_3-N, respectively. Even excluding these data affected by manure stockpiling, from December 1986 through September 1987, the difference in groundwater NO_3-N between manured (S and D) and unmanured (F and T) fields (43.7 and 18.1 mg L^{-1} NO_3-N, respectively) was statistically significant if Well T1 is not included in the comparison (Fig. 3).

Well T1 was an important exception to the above trends. This well was located near the bottom of the slope where the water table was generally within 1 to 2 m of the soil surface and a fibric Ab horizon was located beneath 1.0 m of spoil material excavated during the construction of an irrigation pond. The existence of this organic-rich horizon in a waterlogged environment is very conducive to denitrification and it is hypothesized that this process was responsible for the consistently low NO_3-N concentrations (<0.1 to 2.3 mg L^{-1}) found in this particular well (Table 4). Well T1 was also the only well to have >0.1 mg L^{-1} NH_4-N, with values ranging from 0.45 to 2.0 mg L^{-1}.

This high NH_4-N and low NO_3-N can be attributed to denitrification and the inhibition of nitrification by the anaerobic conditions in this profile. The high chloride levels (Table 5) in Well T1 groundwater indicate that leaching was taking place at least as rapidly at this well site as at the others. Water from Well T1 had 6 to 10 mg L^{-1} total organic C compared to <2 mg L^{-1} in water from all other wells (Table 3). The Eh of this water was much lower (35 mV) than that of water from the other wells (400 to 500 mV). Other well sites (F1 to F3) had similarly high water tables, but none of the others had significant amounts of organic matter below the water table and none had consistently lower groundwater NO_3-N concentrations than the better drained sites in the same field. Thus, among the well sites studied, denitrification appeared to be very ef-

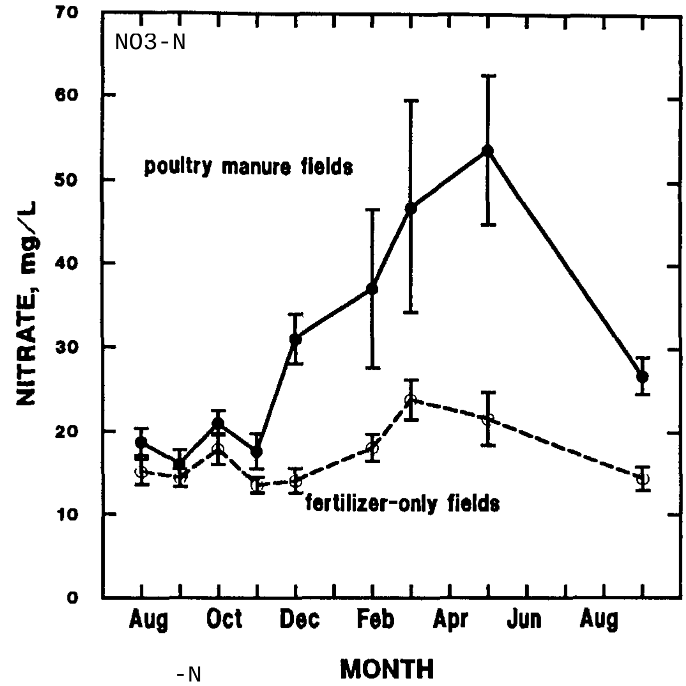

Fig. 3. Nitrate -N concentration in groundwater as affected by use of poultry manure on irrigated cropland. Data from Well T1 and that affected by manure stockpiled near wells has not been included. Error bars are standard errors.

Table 5. Concentrations of Chloride (Cl^-) in groundwater from August 1986 to May 1987.†

Well no.	Vegetation	Aug.	Oct.	Nov.	Dec.	Feb.	Mar.	May
		mg L^{-1}						
				Manured fields				
T1	Corn/wheat	52.2	57.3	94.9	61.7	60.4	61.3	58.6
T2	Corn/wheat	30.5	35.4	30.7	32.6	40.8	37.9	38.7
T3	Corn/wheat	26.3	32.3	28.9	27.6	20.0	39.3	43.7
T4	Corn/wheat	36.9	40.6	35.2	33.9	37.7	49.1	35.8
F1	Corn/corn	16.2	18.1	11.1	21.2	24.6	24.5	40.0
F2	Corn/corn	30.7	19.9	19.1	48.5	68.2	60.4	55.0
F3	Corn/corn	30.4	27.5	19.9	50.7	55.6	–‡	45.7
F4	Corn/corn	–‡	67.4	59.7	47.1	25.5	30.8	16.5
				Unmanured fields				
S1	Corn/barley	24.5	25.6	22.0	19.0	22.1	25.0	28.2
S2	Corn/barley	21.2	24.6	21.3	18.0	26.9	27.2	22.7
S3	Corn/barley	19.8	20.3	16.8	23.8	20.4	32.1	25.0
S4	Corn/barley	26.4	4.5	19.2	15.3	30.9	35.8	27.4
D1	Corn/corn	31.7	36.7	31.0	34.7	216.6	208.2	204.4
D2	Corn/corn	29.8	29.6	28.4	170.1	179.4	147.7	161.7
D3	Corn/corn	32.5	33.3	27.9	28.4	97.0	127.3	120.5
D4	Corn/corn	18.8	22.2	17.9	17.0	121.4	179.9	172.9
				Forest sites				
T5	Forest	–‡	9.3	9.8	9.1	7.4	10.5	6.5
T5	Forest	5.2	4.5	6.4	5.8	5.6	5.4	6.3
S5	Forest	5.9	6.8	3.6	4.0	4.1	3.2	3.5

† Field D was fertilized with 115 kg ha^{-1} K as KCl in November 1986; Field S received 108 kg ha^{-1} KCl in May 1986 and 1987; Field T received 61 kg ha^{-1} K as KCl in May 1986 and 1987; and Field F received 61 kg ha^{-1} K as KCl in May 1986 and 1987.

‡ Data not available.

Table 6. Nitrate-N in the upper 1.5 m of soil from August 1986 to May 1987.

Site (well no.)	Soil depth	Month of sampling†			
		Aug. 1986	Oct. 1986	Mar. 1987	June 1987
	m	$mg\ kg^{-1}$			
Manured fields					
T(2-3)	0–0.3	20.7 ± 1.6	9.63 ± 0.7	0.87 ± 0.05	<0.002
T(2-3)	0.3–0.6	14.1 ± 2.0	15.1 ± 3.9	1.83 ± 0.12	0.83 ± 0.12
T(2-3)	0.6–0.9	9.7 ± 0.9	13.0 ± 1.5	3.63 ± 0.22	1.97 ± 0.32
T(2-3)	0.9–1.2	5.6 ± 0.1	11.1 ± 0.9	5.63 ± 0.12	2.57 ± 0.41
T(2-3)	1.2–1.5	5.9 ± 0.4	6.6 ± 1.3	8.70 ± 0.02	3.93 ± 0.62
F(1-4)	0–0.3	12.9 ± 2.5	11.2 ± 1.3	1.73 ± 0.31	20.8 ± 0.60
F(1-4)	0.3–0.6	5.3 ± 0.1	8.7 ± 1.5	2.10 ± 0.29	5.95 ± 0.60
F(1-4	0.6–0.9	2.6 ± 0.3	5.0 ± 0.7	3.30 ± 0.54	3.63 ± 0.32
F(1-4)	0.9–1.2	2.9 ± 0.1	3.7 ± 0.2	6.70	4.12 ± 0.27
F(1-4)	1.2–1.5	2.4 ± 0.1	3.4 ± 0.1	–‡	9.70
Unmanured fields					
S(1-4)	0–0.3	4.7 ± 0.9	11.7 ± 1.9	1.26 ± 0.08	3.10 ± 0.72
S(1-4)	0.3–0.6	9.4 ± 1.8	6.5 ± 0.6	0.73 ± 0.11	0.13 ± 0.03
S(1-4)	0.6–0.9	8.1 ± 1.2	4.6 ± 0.7	1.00 ± 0.12	0.09 ± 0.01
S(1-4)	0.9–1.2	5.3 ± 0.5	3.6 ± 0.6	1.60 ± 0.18	0.56 ± 0.14
S(1-4)	1.2–1.5	4.1 ± 0.4	3.2 ± 0.4	3.65 ± 0.52	–‡
D(1-4)	0–0.3	26.5 ± 2.1	17.8 ± 0.6	1.70 ± 0.19	8.48 ± 0.64
D(1-4)	0.3–0.6	1.13 ± 0.07	8.6 ± 0.91	1.47 ± 0.09	3.05 ± 0.32
D(1-4)	0.6–0.9	0.65 ± 0.14	1.3 ± 0.30	2.38 ± 0.48	1.95 ± 0.37
D(1-4)	0.9–1.2	1.10 ± 0.13	1.1 ± 0.21	3.50 ± 0.39	1.90 ± 0.28
D(1-4)	1.2–1.5	1.93 ± 0.08	2.3 ± 0.20	4.73 ± 0.27	2.83 ± 0.17
Forested sites					
T,F,S-5	0–0.3	1.13 ± 0.08	1.33 ± 0.10	0.45 ± 0.07	0.10 ± 0.03
T,F,S-5	0.3–0.6	0.97 ± 0.08	1.23 ± 0.08	0.33 ± 0.07	<0.01
T,F,S-5	0.6–0.9	0.90 ± 0.04	1.10 ± 0.07	0.43 ± 0.09	0.28 ± 0.07
T,F,S-5	0.9–1.2	0.77 ± 0.05	1.2	0.70 ± 0.01	–‡
T,F,S-5	1.2–1.5	0.50	–‡	0.80 ± 0.02	–‡

† Means of three or four locations at each site ± SE.
‡ Data not available.

Table 7. Seasonal changes in total amount of NO_3-N in the soil profiles of fields with or without poultry manure.†

Field	Profile depth	Manure applied	Month sampled			
			Aug.	Oct.	Mar.	June
			$kg\ ha^{-1}$			
T	(0–1.5 m)	Yes	268a‡	266a	99b	44c
F	(0–1.2 m)	Yes	114b	137a	66c	166a
S	(0–1.5 m)	No	151a	142a	39b	23b
D	(0–1.5 m)	No	150a	149a	66b	87b

† Means of four well sites, except for Field T that included three well sites.
‡ Means in a row followed by same letter are not different at the 0.05 level of significance by Duncan's multiple range test, with well sites as replications within a field.

fective in preventing NO_3-N contamination of groundwater by leaching only where a large C source was located deep enough in the soil profile to be in a severely anaerobic environment.

The NO_3-N in the soil profiles (Table 6) corroborates many of the above trends in the groundwater and highlights the magnitude of N losses. In the upper 0.60 m, NO_3-N levels were highest in the fall of 1986, suggesting that much N was left over that the crop did not use—especially in Field D, where the crop of corn failed due to insufficient irrigation. The downward movement of this excess NO_3-N is readily apparent from the data. The total NO_3-N present in the soil profiles was calculated from data on the soil bulk density (mean bulk density = 1.58 Mg m^{-3}) and NO_3-N concentration of the soil. This data (Table 7) shows that from 71 to 167 kg NO_3-N ha^{-1} were lost from these fields between October and March. These NO_3-N losses were undoubtedly a result of N transformations as well as leaching, though the greater losses near the surface of the soil combined with increases in NO_3-N at the lower depths suggest that leaching was the dominant process over winter.

Another important observation was that on all sampling dates, groundwater from all wells located in forested land had concentrations of NO_3-N below the limit of detection (<0.1 mg L^{-1}). The location of the forestland wells was such that groundwater would flow to them from the cropland. Although the actual groundwater flow was not determined, the piezometric surfaces suggested flow in this direction. The question then arises: What happened to the NO_3-N in the groundwater as it moved from the cropland, that predominates in each watershed, to the forestland? Concentrations of chloride (Table 5) were much lower under forestland in all cases but one, indicating that dilution effects may explain some of the NO_3-N reduction between cropland and forestland. The main sources of Cl on the cropland were KCl fertilizer and, especially in the case of Field D, slightly brackish irrigation water taken from tidal rivers. However, the difference for NO_3-N between cropland and forestland groundwaters was at least 150-fold, whereas that for chloride was <10-fold (from 20 to 95 under cropland vs. 4 to 10 mg Cl L^{-1} under forestland).

Also, the groundwater chloride to NO_3-N ratio was more than an order of magnitude greater under the forest. For example, in September 1987 this ratio was 45.3 for the forest vs. 1.3 and 3.9 for the manured and unmanured fields, respectively. This was inspite of the fact that no chloride (other than rainfall) was applied to the forests as it was to the cropland. Thus, it is likely that some mechanism is acting to lower NO_3-N concentrations in groundwater that is not acting equally to reduce chlorides in groundwater. Two possible mechanisms are NO_3-N uptake by the forest trees and denitrification of the NO_3-N after it reaches the groundwater. Plant uptake is unlikely to be the mechanism responsible for several reasons. First, many of the forest groundwater samples came from 5 to 6 m below the surface, too deep for efficient NO_3-N uptake. Second, NO_3-N concentrations were just as low when the trees were dormant in December and February as during the summer and fall. Uptake by trees would result in a definite seasonal peak in winter and early spring.

Since NO_3-N reached high concentrations in the groundwater under the crop fields, but was very low under the forest, it may be hypothesized that it was lost by denitrification in the groundwater environment itself. Such denitrification has been reported in the literature, but under rather different circumstances. For example, work in Germany has shown that sulfide in groundwater can provide the needed energy source for certain denitrifiers (Bottercher et al., 1985). However, the sulfide and sulfate levels were very low in our study. Sulfate-S ranged from 1 to 22 mg L^{-1}, but the variation was unrelated to NO_3-N levels (data not shown). Other studies (e.g., Lowrance et al., 1984; Gambrell et al., 1975) have reported substantial denitrification in very shallow groundwater of certain riparian forests and poorly drained soils. These waters, however, had much higher levels of dissolved organic C (5 to 130 mg L^{-1}) than those in the present study (except Well T1), due to the proximity of the O and A horizons to the shallow groundwater.

Recent work by Parkin and Meisinger (1989) supports the concept that denitrification activity is closely related to organic C supply. Both the numbers of denitrifying organisms and denitrification enzyme activity were undetectable below the 2-m depth in the vadose zone in their study on a Maryland Coastal Plain soil. However, they did not measure denitrification below the water table and a small increase in denitrifiers just above the water table leaves open the possibility of significant denitrification in the groundwater itself. The biochemistry of denitrification indicates that, for most heterotrophs, approximately 1 mol of organic C is needed to provide the energy for the reduction of 1 mol of NO_3-N (Tiedje et al., 1984). However, in a continuous flow system such as the groundwater in our study area, it is conceivable that organic C concentrations could be much lower than that of NO_3-N if C, not N, was limiting the rate of denitrification. Under this scenario, as the high-NO_3, low-C groundwater passes under the forest, NO_3-N additions decline dramatically, while C additions increase. This increased C input would not be reflected in increased organic C concentrations until enough of the NO_3-N was denitrified to reduce the NO_3-N substrate to a level where N, not C, was rate-limiting. As the groundwater passes this point under the forest, the C concentration would begin to increase and the NO_3-N concentration would be very low. Our data is not in conflict with this hypothesis, but a series of wells in a transect from the cropland–forest boundary to a considerable distance (10 to 100 m) into the forest would be necessary to test the model.

Finally, it should be noted that the Eh values in both the cropland and forestland groundwater in our study are far too high (+500 mV) to allow denitrification, at least under equilibrium conditions. However, it is recognized that chemical equilibrium may not exist in dynamic soil and groundwater systems. Recent studies by Lowrance (1987), using the acetylene blocking technique, suggest that denitrification occurred in a similar Coastal Plain aquifer, albeit at very low rates. Thus, a plausible case may be made that the dramatic reduction in NO_3-N between groundwater under cropland and that under forest may be a result of a combination of dilution and denitrification.

CONCLUSIONS

The data reported here suggest that N application rates typical for commercial irrigated corn on Maryland's sandy Coastal Plain soils can result in NO_3-N concentrations in the groundwater under these fields in the range of 10 to 20 mg L^{-1} throughout the year. Typical rates of poultry manure application resulted in significantly higher NO_3-N concentrations in groundwater under irrigated sandy soils, the difference being largely attributable to the greater total N loading on the fields receiving poultry manure. Maryland has recently instituted a manure testing program (Bandel, 1989) designed to inform farmers of the actual N content of their manure so as to discourage environmentally harmful rates of manure and insurance applications of fertilizers where they are not needed. This study highlights the need for such a program.

Nonetheless, NO_3-N concentrations in groundwater under forest vegetation did not appear to be affected by the N applied to cropland, even where cropland was the dominant land use representing 65 to 80% of the watershed land area. A more detailed study will be required to provide quantitative estimates of the roles of dilution, denitrification, or other processes on this phenomenon. In any case, our study suggests that forests may protect surface waters from eutrophication caused by groundwater N, even if the forest is not on a riparian site with shallow groundwater.

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