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LONG-TERM NITROGEN DEPOSITION ON THE RHODE RIVER WATERSHED

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Abstract: We have continuously measured, on an event basis, bulk precipitation fluxes of nitrate for 21 years, ammonium for 17 years, and total nitrogen for 18 of those years. The long-term, volume-weighted mean concentrations of nitrate, ammonium, and organic nitrogen were 502, 289, and 333 ug N per liter, respectively. Fluxes of nitrate have increased over the last 20 years and have varied from 3.26 kg N ha^{-1} yr^{-1} in 1974 to 8.86 kg N ha^{-1} yr^{-1} in 1989, and averaged 5.56 kg N ha^{-1} yr^{-1}. Ammonium fluxes increased as well, with a minimum of 1.72 kg N ha^{-1} yr^{-1} in 1980 and a maximum of 4.44 kg N ha^{-1} yr^{-1} in 1991, and averaged 3.18 kg N ha^{-1} yr^{-1}. Organic nitrogen was more variable and, if anything, declined. It varied from a low of 1.79 kg N ha^{-1} yr^{-1} in 1990 to a maximum of 6.73 kg N ha^{-1} yr^{-1} in 1978 and averaged 3.62 kg N ha^{-1} yr^{-1}. Fluxes of nitrate, ammonium, and organic nitrogen all peaked in the spring. Fluxes of nitrate and organic nitrogen were lowest in the fall, while ammonium flux was lowest in the winter. The sum of overland storm and groundwater fluxes of all three fractions of nitrogen from cropland-dominated, pasture-dominated, and forested watersheds all peaked in the spring and were lowest in the fall. Watershed discharge fluxes of organic nitrogen were 87%, 21%, and 41% of bulk precipitation fluxes, respectively, for cropland, pasture, and forest. Watershed discharges of inorganic nitrogen were 51%, 9%, and 3% of precipitation fluxes, respectively, for cropland, pasture, and forest.

INTRODUCTION

Atmospheric deposition of nitrate, ammonium, and organic nitrogen has been an often overlooked component of the nitrogen budget of ecosystems. Atmospheric deposition is composed of both wet deposition in rainwater and dry deposition. The dry component consists of sedimenting particles, and aerosols and molecules trapped from the air by impaction on surfaces of plants, soil, water, etc. This dry deposition is difficult to measure and few accurate data exist for the Chesapeake Bay region. However, the techniques for measuring wet deposition and bulk precipitation are well established and are relatively easy. The main difference between the sampling techniques for wet and bulk precipitation is that the wet-only collector is closed between rainstorms, while the bulk sampler is open all of the time. Thus, the bulk collector samples both wet deposition in rainwater and sedimenting dry particulates between storms. In our experience there are few significant differences in the chemical, composition of samples taken by the two methods side by side (Jordan et al. in press).

In the Chesapeake Bay region, acidic atmospheric deposition has deleterious effects on watersheds and freshwater ecosystems (Correll and Ford 1982, Correll et al. 1984, Weller et al. 1986, Correll et al. 1987, Baker et al. 1991). In addition, enrichment of precipitation with nitrate and ammonium contributes to eutrophication of tidal waters (Correll and Ford 1982, Jordan et al. 1983, Correll 1987, Fisher and Oppenheimer 1991) and possibly the coastal ocean (Pearl 1985, 1993, Fanning, 1989).

Our measurements of wet and bulk deposition at the Rhode River site on the western shore of the Bay near Annapolis, Maryland, from 1973 to the present are the longest set of data for the Chesapeake Bay region. Here we report detailed results for the volume and nitrogen content of bulk precipitation. For further data on other components and statistical trend analyses, see Jordan et al. (in press). We also compare these nitrogen input fluxes with long-term discharge fluxes from

Rhode River subwatersheds with different land uses (Correll 1977, 1981, Correll et al. 1992). This study is part of an overall long-term airshed/watershed/estuary study of the Rhode River, a tributary system of Chesapeake Bay (Jordan et al. 1991a, 1991b, Correll et al. 1992).

METHODS

Precipitation volume was measured with a Belfort weight-recording rain gauge and with a standard weather-bureau manual rain gauge. Bulk precipitation samples for chemical analysis were collected with a 28 cm diameter polyethylene funnel on a polyethylene bottle mounted on a 13 m high tower near the rain gauges. After each event or combination of events of more than 5 mm of precipitation, samples were collected and the sampler was cleaned. Nine hundred and thirty seven samples were collected. Samples were stored at 4° C until analysis and analyses, for ammonium and TKN were made within 5 days, nitrate within 2 weeks, or else the samples were frozen.

Three watersheds, drained by small first-order streams, were sampled (Correll 1977). One (no. 110) was a mature deciduous forest that had never been clearcut and another (no. 109) was two-thirds row crops and one-third riparian forest and had been in agricultural use since at least 1846 (Vaithiyanathan and Correll 1992). The third (no. 111) was a pasture used for beef cattle grazing. Watershed discharges were measured with sharp-crested V-notch weirs and volume-integrated samples representative of the chemical composition of the discharge were taken for laboratory analysis of nutrient composition (Correll 1977, 1981). Aliquots of streamwater were pumped from the stream channel when a fixed increment of flow had occurred. These aliquots were composited for one-week intervals in plastic bottles with sulfuric acid preservative. The watersheds are all underlain by the Marlboro clay, an impervious aquiclude near sea level, and the weir foundations extend down to this layer. Thus, both overland storm flows and shallow groundwater originating within the watershed are forced to flow through the weir.

Analytical techniques for nitrate were changed over time, but whenever techniques were changed a series of samples were analyzed by both the old and new techniques to test comparability. Triplicate analyses were routinely performed on about 10% of the samples to assess analytical precision. Nitrate was initially analyzed by colorimetry after cadmium amalgam reduction to nitrite (APHA 1976), and later with a Dionex ion chromatograph and a Technicon auto-analyzer (method no. 696-82W). Ammonium was analyzed by the hypochlorite oxidation technique (American Public Health Association 1976). Total Kjeldahl nitrogen was digested according to Martin (1972), and the resultant ammonium was distilled and analyzed by Nesslerization (American Public Health Association 1976). The concentration of total organic nitrogen was calculated as the difference between TKN and ammonium. The concentration of total nitrogen was calculated as the sum of TKN and nitrate.

RESULTS

Annual Bulk Precipitation

The annual volume of rainfall from 1974 through 1993 averaged 111.7 cm (table 1), somewhat above the long-term mean of 108.6 cm for the vicinity of the Rhode River between 1817 and 1977 (Higman and Correll 1982). Years in which rainfall was more than 20% below the long-term mean were 1977, 1980, and 1986. Years when rainfall was more than 20% above the mean were 1975, 1979, and 1989. None exceeded the extremes in the 160 - year record.

Volume-weighted annual nitrate concentrations averaged 502 ug N l^{-1} (table 1) and increased over the 20-year period (figure 1). Nitrate concentrations were more than 20% below the 20-year mean in 1974, 1975, and 1979 and were more than 20% above the mean in 1978, 1986, and 1989. Rates of nitrate deposition in bulk precipitation averaged 5.56 kg N ha^{-1} yr^{-1} and peaked at 8.86 kg N ha^{-1} yr^{-1} in 1989 (table 1, figure 2). Volume-weighted annual ammonium concentrations averaged 289 ug N l^{-1} (table 1) and also increased over the 16-year period (figure 1). Ammonium concentrations were more than 20% below the 16 year mean in 1979, 1980, and 1982 and were more than 20% above the mean in 1986, 1991, and 1992. Rates of ammonium deposition in bulk precipitation averaged 3.18 kg N ha^{-1} yr^{-1} and peaked at 4.44 kg N ha^{-1} yr^{-1} in 1991 (figure 2). The mean for organic nitrogen deposition for the 13 complete years measured was 3.62 kg N ha^{-1} yr^{-1} (table 1). Organic nitrogen deposition was much more variable than nitrate or ammonium ranging from a low of 1.79 kg N $ha^{-1}yr^{-1}$ in 1990 to a high of 7.63 kg N $ha^{-1}yr^{-1}$ in 1991 (figure 2). Total nitrogen deposition for the 17 years measured averaged 11.8 kg N ha^{-1} yr^{-1} (table 1).

Table 1. Volume-weighted annual mean bulk precipitation data for the Rhode River site.

Year	Volume (cm)	Nitrate (ug N/l)	(kg N/ha)	Ammonium (ug N/l)	(kg N/ha)	Organic N (kg N/ha)	Total N (kg N/ha)
1974	106.1	308	3.26				7.97
1975	133.3	295	3.93				9.34
1976	119.2	410	4.89				10.4
1977	82.4	447	3.69				9.34
1978	119.7	633	7.58	264	3.16	6.73	17.5
1979	164.5	375	6.17	174	2.87	3.81	12.9
1980	85.9	498	4.27	200	1.72	2.89	8.88
1981	90.9	491	4.46	316	2.87	5.22	12.6
1982	114.1	455	5.19	224	2.56	2.40	10.1
1983	130.1	578	7.52	257	3.34	4.07	14.9
1984	126.5	494	6.25	338	4.28	3.13	13.7
1985	96.6	563	5.44	289	2.79	1.95	10.2
1986	86.5	614	5.32	358	3.10	2.34	10.8
1987	112.6	524	5.90	292	3.29		
1988	98.0	530	5.19	278	2.72		
1989	146.6	604	8.86	242	3.55		
1990	110.0	503	5.53	341	3.75	1.79	11.1
1991	105.0	590	6.19	423	4.44	7.63	18.3
1992	106.7	561	5.99	363	3.87	2.45	12.3
1993	98.6	573	5.65	262	2.58	2.61	10.8
Mean	111.7	502	5.56	289	3.18	3.62	11.8

Seasonal Bulk Precipitation

Mean winter (December-February) precipitation for the 21 years of our study was 25.9 cm, higher than the 24.6 cm 160 -year mean volume for winter precipitation (Higman and Correll 1982). Years during this study in which precipitation was over 30% below this long-term mean were 1977, 1980, and 1981, while 1978, 1979, 1984, 1987, and 1994 were more than 30% above this mean (table 2). The winter of 1979 exceeded the maximum volume recorded during the 160 years prior to 1978 (Higman and Correll 1982). Winter nitrate concentrations for the 21 seasons of our study averaged 512 ug N l^{-1} (table 2). Years in which nitrate concentrations were more than 30% below the mean were 1974, 1975, 1979, and 1987, while concentrations were more than 30% above the mean in 1978 and 1989. In winter nitrate depositon averaged 1.29 kg N ha^{-1}season^{-1}, peaking in 1978 at 3.06 kg N ha^{-1}season^{-1}. Winter ammonium concentrations and deposition rates were lower than for the other seasons. For 17 winters ammonium concentrations averaged 197 ug N ha^{-1} season^{-1} (table 2). Concentrations were more than 30% below this mean in 1978, 1979, and 1980, while in 1986, 1989, and 1990 concentrations were more than 30% above the mean. Mean ammonium depositon rates were 0.484 kg N ha^{-1}season^{-1} and peaked in 1994 at 0.627 kg N ha^{-1} season^{-1}. Organic nitrogen and total nitrogen deposition rates averaged 0.365 and 2.07 kg N ha^{-1} season^{-1}, respectively (table 2).

During the 21 spring seasons of our study precipitation volume averaged 28.4 cm (table 2), slightly above the long-term average of 28.0 cm (Higman and Correll 1982). In 1973, 1977, 1985, 1986, and 1987, precipitation was more than 30% below the long-term mean, while in 1978, 1983, 1984, and 1989 it was more than 30% above the long-term mean. Mean spring nitrate concentrations, at 569 ug N l-1, were the highest of any season (table 2). Spring nitrate concentrations were more than 30% below the mean in 1973, 1974, and 1975, while in 1986 and 1987 they were more than 30% above the mean (figure 3). Spring deposition of nitrate averaged 1.54 kg N ha^{-1} season^{-1} with peaks in 1984 and 1989 of 2.77 and 2.78 kg N ha^{-1}season^{-1}, respectively. Spring ammonium concentrations averaged the highest of any season at 419 ug N l^{-1} (table 2). In 1978, 1979, 1980, 1983, and 1993 spring ammonium concentrations were more than 30% below the average, while they were more than 30% above the mean in 1986, 1987, and 1991 (Fig. 4). Ammonium

Table 2. Volume-weighted mean seasonal bulk precipitation for the Rhode River site.

Winter	Volume	Nitrate		Ammonium		Organic N	Total N
	(cm)	(ug N/l)	(kg N/ha)	(ug N/l)	(kg N/ha)	(kg N/ha)	(kg N/ha)
1974	30.4	313	0.950				1.56
1975	26.8	340	0.910				1.47
1976	28.9	535	1.54				2.46
1977	11.5	456	0.525				0.817
1978	41.8	732	3.06	132	0.552	0.719	4.33
1979	49.6	326	1.61	117	0.579	0.447	2.64
1980	12.9	461	0.593	132	0.170	0.263	1.03
1981	13.9	458	0.636	212	0.294	0.175	1.11
1982	25.2	610	1.54	207	0.522	0.354	2.41
1983	26.1	646	1.69	220	0.574	0.790	3.05
1984	34.4	494	1.70	144	0.495	0.234	2.43
1985	17.9	596	1.07	219	0.391	0.0781	1.54
1986	19.2	584	1.12	274	0.525	0.236	1.88
1987	39.2	347	1.36	152	0.596	0.265	2.22
1988	27.0	451	1.22	197	0.531		
1989	17.7	842	1.49	322	0.571		
1990	18.2	562	1.02	267	0.485	0.0612	1.57
1991	23.3	473	1.10	226	0.528	0.490	2.12
1992	20.3	520	1.06	180	0.366	0.215	1.64
1993	24.4	527	1.29	172	0.418	0.529	2.23
1994	34.4	471	1.62	182	0.627	0.623	2.87
Mean	25.9	512	1.29	197	0.484	0.365	2.07
Spring							
1973	14.8	388	0.576				1.21
1974	31.7	298	0.946				3.36
1975	32.6	362	1.18				3.08
1976	20.0	533	1.06				2.63
1977	18.4	576	1.06				3.23
1978	40.0	506	2.02	206	0.823	2.88	5.73
1979	27.9	435	1.22	251	0.701	1.04	2.96
1980	30.6	515	1.57	211	0.646	1.27	3.49
1981	28.4	518	1.47	457	1.30	3.29	6.06
1982	23.6	528	1.24	326	0.768	0.720	2.73
1983	48.7	444	2.16	276	1.34	1.18	4.68
1984	40.9	677	2.77	539	2.21	1.54	6.52
1985	19.4	536	1.04	474	0.918	0.941	2.90
1986	10.8	128	1.21	697	0.749	0.597	2.56
1987	19.1	956	1.82	548	1.04	1.46	4.33
1988	22.9	616	1.41	479	1.10		
1989	43.5	639	2.78	311	1.35		
1990	34.1	420	1.43	414	1.41	0.892	3.73
1991	30.5	630	1.92	743	2.27	5.70	9.89
1992	24.2	738	1.78	528	1.28	0.475	3.53
1993	34.5	503	1.74	243	0.839	0.893	3.47
Mean	28.4	569	1.54	419	1.17	1.63	4.00

Table 2. (continued)

Summer	Volume	Nitrate		Ammonium		Organic N	Total N
	(cm)	(ug N/1	(kg N/ha)	(ug N/l)	(kg N/ha)	(kg N/ha)	(kg N/ha)
1973	24.8	438	1.09				1.89
1974	23.9	350	0.834				2.02
1975	38.9	264	1.03				3.03
1976	38.0	316	1.20				3.31
1977	23.4	508	1.19				3.30
1978	21.8	538	1.17	506	1.10	1.32	4.72
1979	39.3	538	2.11	272	1.07	1.37	4.19
1980	19.9	641	1.28	280	0.558	1.28	2.77
1981	30.0	449	1.35	258	0.773	1.26	3.39
1982	37.8	430	1.62	255	0.964	1.26	3.45
1983	24.4	716	1.75	408	0.995	1.26	4.34
1984	27.9	452	1.26	381	1.06	1.26	3.15
1985	20.2	492	0.993	435	0.877	1.23	2.46
1986	34.6	463	1.60	288	0.995	1.23	3.39
1987	25.0	574	1.43	313	0.782		
1988	22.0	630	1.39	340	0.749		
1989	52.5	539	2.83	174	0.913		
1990	41.4	602	2.49	358	1.48	0.263	4.61
1991	26.7	767	2.04	367	0.980	0.158	4.12
1992	31.2	467	1.46	364	1.14	0.310	3.37
1993	11.0	897	0.987	407	0.448	0.404	1.80
Mean	29.3	527	1.48	338	0.931	0.971	3.30
Fall							
1973	18.1	183	0.330				0.701
1974	20.1	266	0.534				1.03
1975	35.0	231	0.807				1.76
1976	32.4	335	1.08				2.02
1977	29.0	313	0.910	127	0.369	0.452	1.99
1978	16.2	820	1.33	423	0.684	0.449	2.69
1979	47.7	257	1.23	109	0.519	0.446	3.06
1980	22.5	368	0.827	153	0.343	0.435	1.59
1981	18.6	542	1.01	270	0.502	0.414	2.00
1982	27.6	284	0.783	111	0.307	0.383	1.55
1983	31.0	623	1.93	138	0.427	0.339	2.86
1984	23.3	221	0.515	222	0.516	0.279	1.56
1985	39.2	599	2.35	153	0.601	0.180	3.29
1986	22.0	628	1.38	377	0.831	0.177	2.93
1987	29.4	435	1.28	293	0.862		
1988	26.1	452	1.18	132	0.345		
1989	32.9	534	1.76	217	0.714	0.186	3.31
1990	16.3	358	0.585	228	0.372	0.182	1.17
1991	24.5	460	1.12	270	0.661	0.189	2.13
1992	31.0	545	1.69	352	1.09	0.197	3.76
1993	28.7	572	1.64	305	0.875	0.117	3.34
Mean	27.2	430	1.16	228	0.590	0.295	2.25

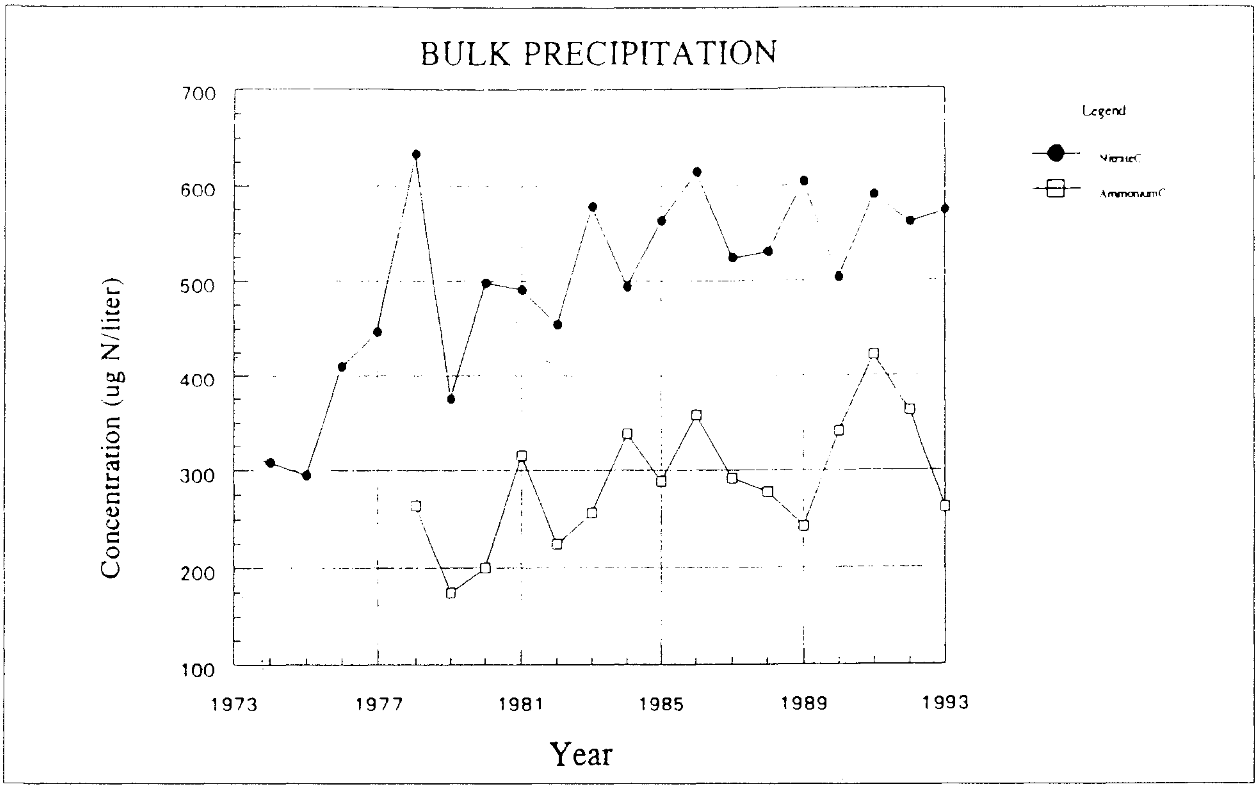

Figure 1. Long-term variations in annual volume-weighted mean nitrate and ammonium concentrations in bulk precipitation at the Rhode River, site. Solid points are nitrate means.

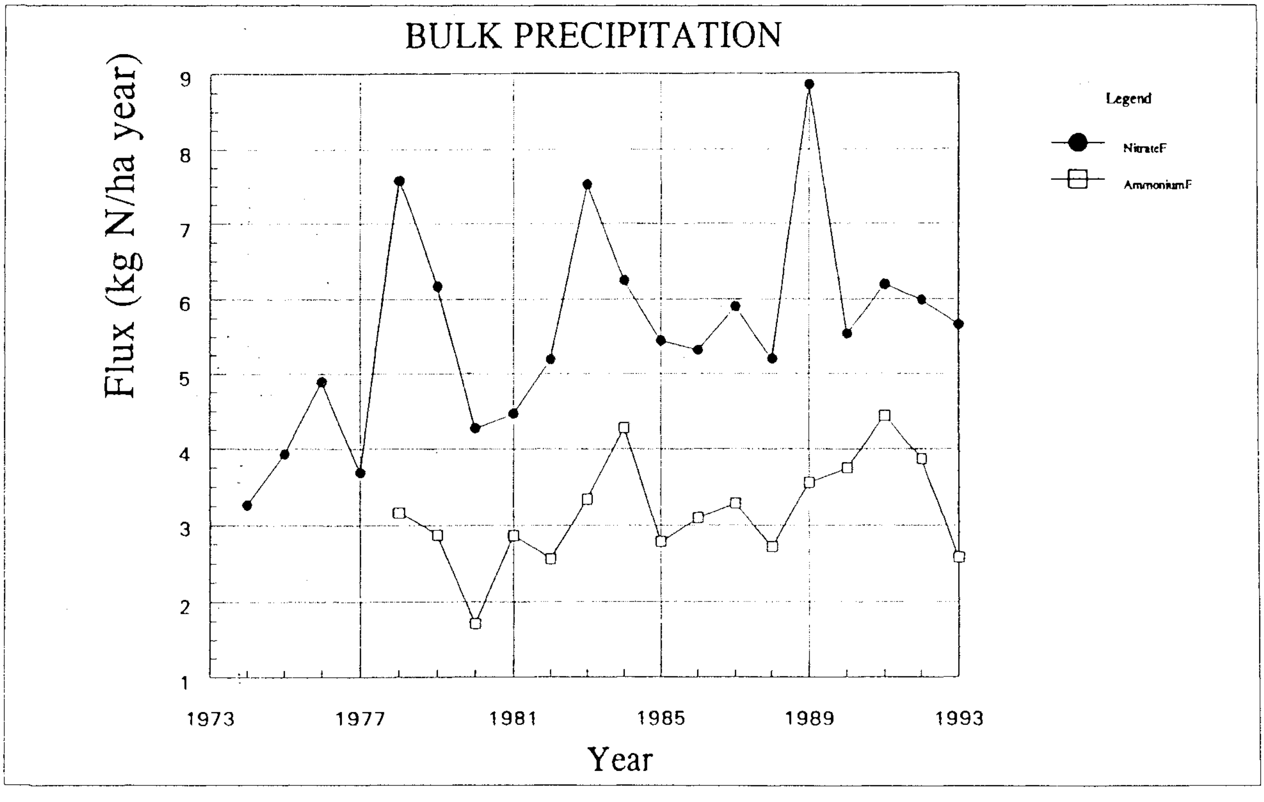

Figure 2. Long-term variations in annual atmospheric deposition of nitrate and ammonium in bulk precipitation at the Rhode River, site. Solid points are nitrate means.

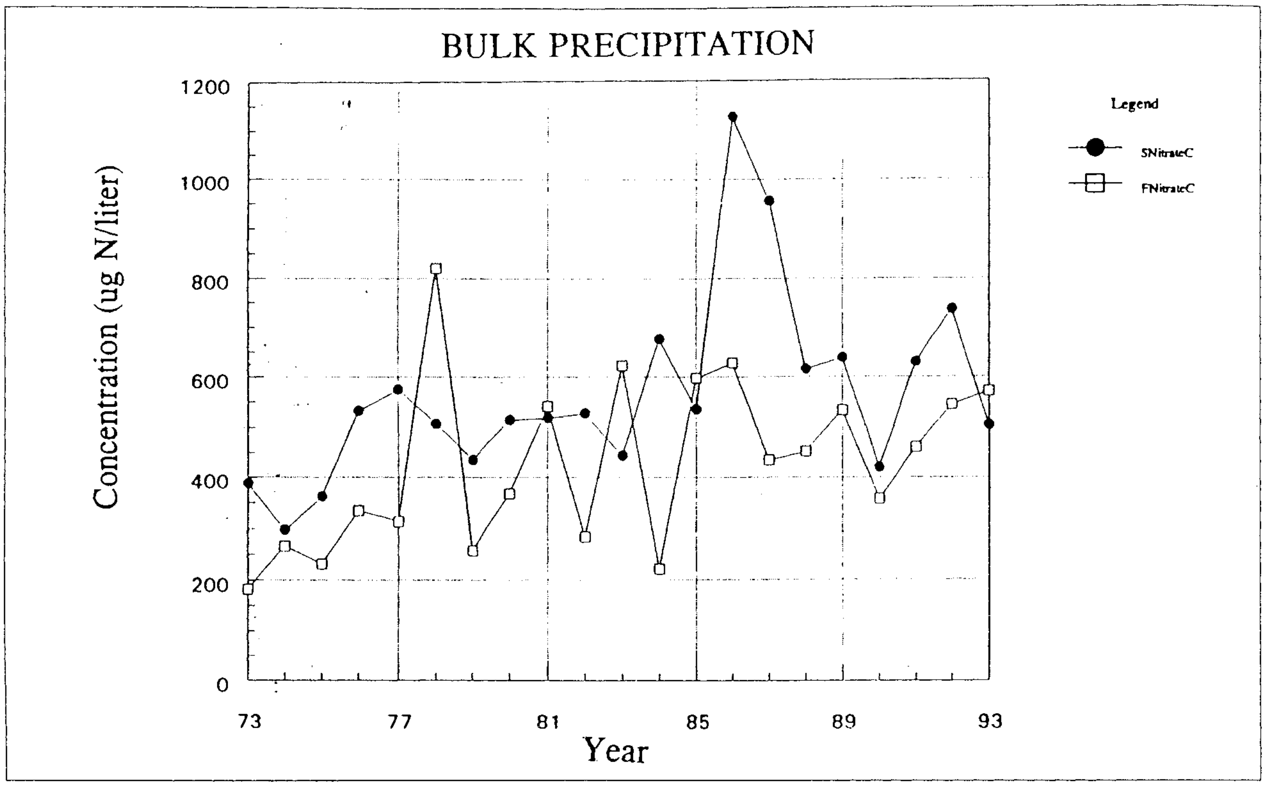

Figure 3. Interannual variations in annual volume-weighted nitrate concentrations in bulk precipitation at the Rhode River site. Solid points are spring means and open squares are fall means.

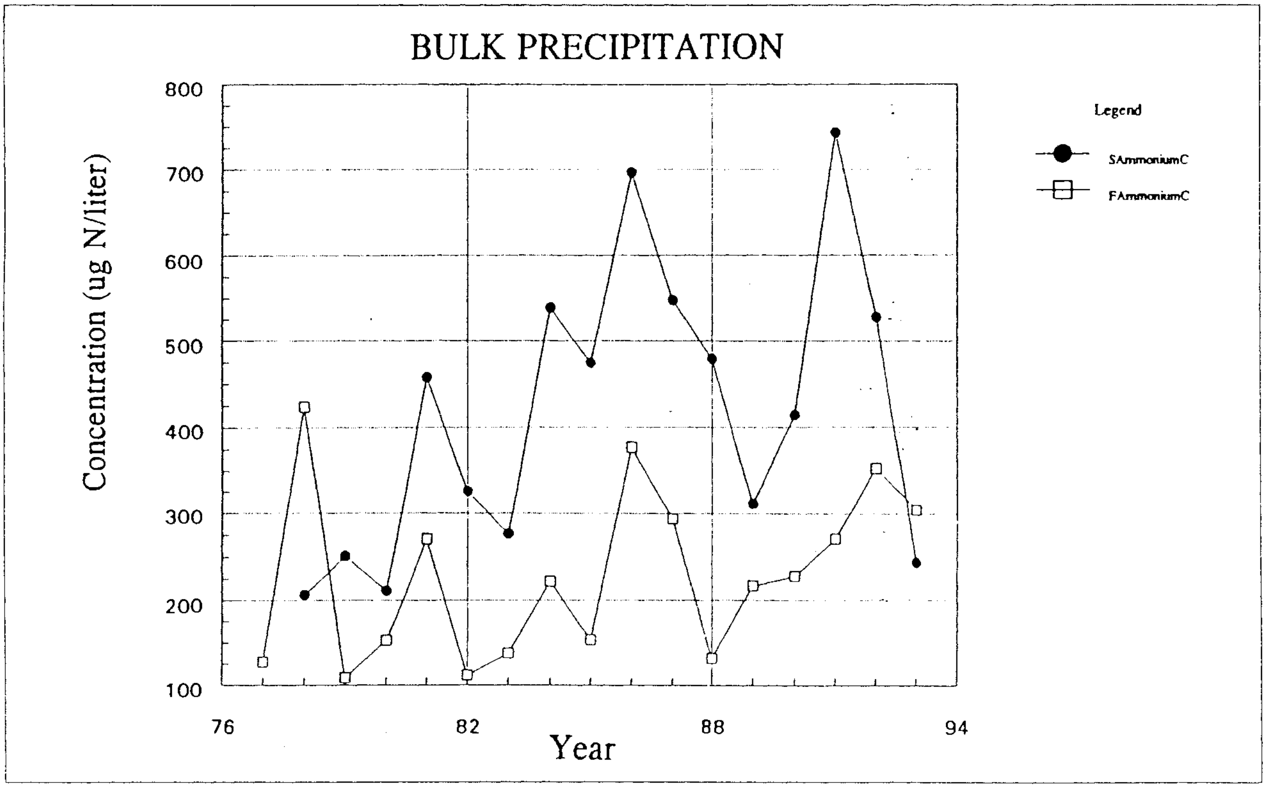

Figure 4. Interannual variations in volume-weighted ammonium concentrations in bulk precipitation at the Rhode River site. Solid points are spring means and open squares are fall means.

depositon in spring averaged 1.17 kg N ha^{-1} season^{-1} with peaks in 1984 and 1991 of 2.21 and 2.27 kg N ha^{-1} season^{-1}, respectively. Depositon of organic nitrogen and total nitrogen also was highest in the spring and averaged 1.63 and 4.00 kg N ha^{-1} season^{-1}, respectively (table 2).

During the 21 summer seasons of our study, the volume of precipitation averaged 29.3 cm (table 2), somewhat below the 160-year of 31.4 cm (Higman and Correll 1982). In 1978, 1980, 1985, and 1993, precipitation was more than 30% below the long-term mean, while in 1989 and 1990 it was over 30% above the mean. Summer nitrate concentrations averaged 527 ug N l^{-1}. Summer nitrate concentrations were more than 30% below the mean in 1974, 1975, and 1976, but were more than 30% above the mean in 1983, 1991, and 1993 (table 2). Nitrate deposition in summer averaged 1.48 kg ha^{-1} season^{-1}, with a peak of 2.83 kg N ha^{-1} season^{-1} in 1989. Summer ammonium concentrations averaged 338 ug N l^{-1}. In 1989 , ammonium concentration was more than 30% below the mean, while in 1978 it was more than 30% above the mean. Summer deposition of organic nitrogen and total nitrogen averaged 0.971 and 3.30 kg N ha^{-1} season^{-1}, respectively (table 2).

Fall precipitation had a mean volume of 27.2 cm during the 21 falls of our study, considerably higher than the 160-year of 24.5 cm (Higman and Correll 1982). Precipitation in the fall was over 30% below the long-term mean in 1978 and 1990, but more than 30% above this mean in 1975, 1976, 1979, 1985, and 1989 (table 2). Mean fall nitrate concentrations and deposition rates were lower than for any of the other seasons. Nitrate concentrations were more than 30% below the mean of 430 ug N l^{-1} in 1973, 1974, 1975, 1979, 1982, and 1984, while concentrations were more than 30% above this mean in 1978, 1983, 1985, 1986, and 1993 (figure 3). Nitrate deposition in the fall averaged 1.16 kg N ha^{-1} season^{-1}, but ranged from 0.330 to 2.35 kg N ha^{-1} season^{-1} in 1973 and 1985, respectively. Fall ammonium concentrations were over 30% below the average of 228 ug N l^{-1} in 1977, 1979, 1980, 1982, 1983, 1985, and 1988, but were more than 30% above this mean in 1978, 1986, 1992, and 1993 (figure 3). Ammonium deposition in the fall averaged 0.590 kg N ha^{-1} season^{-1} and ranged from 0.31 to 1.09 kg N ha^{-1} season^{-1} in 1982 and 1992, respectively. Fall deposition of organic nitrogen and total nitrogen averaged 0.295 and 2.25 kg N ha^{-1} season^{-1}, respectively.

Comparisons of Bulk Precipitation Deposition with Watershed Discharges

At the Rhode River site, precipitation inputs to the watershed as bulk precipitation usually exceeded watershed outputs in overland stormflow and groundwater for nitrate, ammonium, and organic nitrogen (table 3). The cropland-dominated watershed had by far the highest discharges per area for all nitrogen fractions, but these fluxes only exceeded bulk precipitation input fluxes for nitrate in the spring for organic nitrogen in the winter and summer. Average annual nitrogen discharge from the cropland-dominated watershed was still less than precipitation input despite the large input of fertilizer nitrogen (Peterjohn and Correll 1984) to the croplands.

Forest area yield discharges were lowest in all seasons for nitrate, in the winter and fall for ammonium, and in the winter for organic nitrogen (table 3). Annual discharges of nitrate from forest were only 21% of those from pasture and 3.5% of those from cropland. Annual discharges of ammonium from forest slightly exceeded those from pasture, but were only 30% of those from the cropland-dominated watershed. In the spring and summer, ammonium discharges from forest were 29% and 6% above those from pasture, respectively, but only 42% and 18% of those from cropland, respectively. Forest discharges of organic nitrogen were relatively high compared to those of inorganic nitrogen, but did not exceed bulk precipitation fluxes for any season (table 3). Forest annual discharges of organic nitrogen were only 41% of the input flux in bulk precipitation.

Pasture discharges of nitrate and organic nitrogen per area were intermediate between those for the cropland-dominated watershed and for forest, but were lowest of the three land use categories for ammonium and total nitrogen (table 3).

DISCUSSION

In general, the rate of deposition of nitrogen in bulk precipitation is higher than watershed nitrogen discharges per hectare (table 3). This might lead one to conclude that atmospheric wet depositon falling directly on the surface waters of the estuary are larger than nonpoint sources of nitrogen in land discharges. However, one must remember that the watershed has more surface area than the estuary. For example, the Rhode River watershed has six times the surface area of the Rhode River (Correll 1977, Jordan et al. 1991a).

Table 3. Comparison of long-term mean Rhode River watershed bulk precipitaion nitrogen inputs with nitrogen discharges from three land use categories. All values are in kg of nitrogen per hectare. Measurements spanned 16 complete years for the cropland and forest watersheds and 14 years for the pasture watershed.

A. Nitrate Season	Precipitation Inputs	Watershed Outputs Cropland	 Pasture	 Forest
Winter	1.29	1.28	0.324	0.0281
Spring	1.54	1.98	0.310	0.0948
Summer	1.48	0.569	0.0259	0.0133
Fall	1.16	0.127	0.0111	0.00469
Total for Year	5.56	3.90	0.649	0.138
B. Ammonium				
Winter	0.484	0.112	0.0531	0.0284
Spring	1.17	0.205	0.0675	0.0870
Summer	0.931	0.163	0.0282	0.0298
Fall	0.590	0.0288	0.0129	0.0098
Total for Year	3.18	0.524	0.154	0.157
C. Organic-N				
Winter	0.365	0.490	0.243	0.176
Spring	1.63	1.25	0.360	0.681
Summer	0.971	1.20	0.126	0.364
Fall	0.295	0.147	0.0603	0.216
Total for Year	3.62	3.16	0.763	1.47
D. Total-N				
Winter	2.07	1.88	0.620	0.233
Spring	4.00	3.44	0.738	0.863
Summer	3.30	1.94	0.180	0.407
Fall	2.25	0.304	0.0843	0.230
Total for Year	11.8	7.58	1.57	1.77

The watershed of Chesapeake Bay is almost 15 times larger than the combined surface area of the Bay and its tidal tributaries (Correll 1987).

Even when one takes the relative areas of the watershed into account, however, in most years the Rhode River receives more inorganic nitrogen in bulk precipitation falling directly on the tidal waters than it receives in watershed discharges (Correll and Ford 1982). However, Chesapeake Bay has proportionally more watershed than does Rhode River. The importance of atmospheric deposition as a source of nitrogen for the watershed of the Bay was emphasized by Fisher and Oppenheimer (1991) in an analysis that included two key assumptions. First, it was assumed that atmospheric dry deposition of nitrogen was equal to wet deposition. Because there were essentially no measurements of dry deposition in the region, this might be a fair assumption. Second, it was assumed that nitrogen deposited on forested watershed areas was not retained very effectively. This was not so for the coastal plain forest we studied (e.g., Weller et al. 1986 and table 3), but may be a better assumption for some areas of the watershed that are within the Appalachian Plateau physiographic province. For example, the Fernow Experimental Forest in the Appalachian Plateau on the upper Potomac River watershed in West Virginia was much less effective at retaining nitrogen than was the forest we studied. Over a 13-year period ending in 1990, precipitation at the Fernow forest averaged 149.4 cm and contained

Table 4. Comparison of Rhode River bulk precipitation composition with Ooher long-term wet deposition study sites on or adjacent to the Chesapeake Bay watershed. Volume-weighted mean annual nitrate and ammonium concentrations (ug N l^{-1}).

Collection Site	Years Included	Nitrate	Ammonium
Rhode River, MD	1974-1993	502	289
Fernow Exp. Forest, WV	1978-1990	366	156
Tunkhannock, PA	1979-1987	365	187
Ithaca, NY	1977-1987	417	230
Penn. State Univ., PA	1977-1987	41	245
Univ. Virginia, VA	1977-1987	356	200
Lewes, DE	1979-1987	283	186

156 ug l^{-1} of ammonium nitrogen and 366 ug l^{-1} of nitrate nitrogen. Stream discharge from the control forested watershed contained an average of 87 ug l^{-1} of ammonium nitrogen and 771 ug l^{-1} of nitrate nitrogen (Adams et al. 1994). If the only effect of the watershed were to evaporate and transpire water vapor, leaving the nutrient salts behind, the mean stream concentration of ammonium and nitrate nitrogen would have been 336 ug l^{-1} and 791 ug l^{-1}, respectively, in that stream discharge averaged 69.3 cm per year. This suggests that this forest was retaining only 74% of the ammonium and 3% of the nitrate from the wet precipitation, assuming that there was no dry deposition. For comparison, nitrate retention calculated in a similar manner for the Rhode River forest was 97.5% (table 3).

Wet deposition varies spatially throughout the Chesapeake watershed. The wet deposition at the Fernow Experimental Forest was about the same as our measurements at the Rhode River site. The volume of precipitation was 34% higher at Fernow and the nitrate content was 37% lower than at Rhode River. The Utility Acid Precipitation Study Program (American Public Health Association 1989) reported long-term (1979-87) means of 365 and 187 ug N l^{-1} for nitrate and ammonium, respectively, at Tunkhannock in north-eastern Pennyslvania. The U.S. Deptartment of Energy (1089) has reported wet deposition from 1977 through 1987 for Ithacy, New York (just north of the boundary of the Bay's watershed), Pennsylvania State University, and the University of Virginia Data from 1979 through 1987 were also reported from Lewes, Delaware (just east of the boundary of the lower Bay watershed) (U.S. Department of Engery 1989). Nitrate concentrations from these four sites ranged from 283 ug N l^{-1} at Lewes to 441 ug N l^{-1} at Pennsylvania State University. Ammonium concentrations ranged from 186 ug N l^{-1} at Lewes to 245 ug N l^{-1} at PA State University. Our long-term means for nitrate and ammonium of 502 ug N l^{-1} and 289 ug N l^{-1} are somewhat higher than the six other sites (table 4).

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REFERENCES

Adams, M.B., J.N. Kochenderfer, F. Wood, T.R. Angradi, and P. Edwards. 1994. Forty Years of Hydrometeorological Data from the Fernow Experimental Forest, West Virginia. U.S. Forest Service Report No. NE-184, Radnor, PA. 24 pp.

APHA (American Public Health Association). 1976. Standard Methods for the Examination of Water and Wastewater, 14th ed. APHA, Washington, D.C.

Baker, L.A., A.T. Herlihy, P.R. Kaufmann, and J.M. Eilers. 1991. Acidic lakes and streams in the United States: The role of acidic deposition. Science 252:1151-1154.

Correll, D.L. 1977. An overview of the Rhode River watershed program. In: Correll, D.L., ed. Watershed Research in Eastern North America. Washington, DC: Smithsonian Institute Press, 105-120.

Correll, D.L. 1981. Nutrient mass balances for the watershed, headwaters intertidal zone, and basin of the Rhode River estuary. Limn. Oceanogr. 26:1142-1149.

Correll, D.L. and D. Ford. 1982. Comparison of precipitation and land runoff as sources of estuarine nitrogen. Estuar. Coast. Shelf Sci. 15:45-56.

Correll, D.L., N.M. Goff, and W.T. Peterjohn. 1984. Ion balances between precipitation inputs and Rhode River watershed discharges. Bricker, O.P., ed. Geological Aspects of Acid Deposition. Stoneham, Butterworth Press, 77-111.

Correll, D.L. 1987. Nutrients in Chesapeake Bay. In: Majumdar, S.K., L.W. Hall Jr., and H.M. Austin, eds. Contaminant Problems and Management of Living Chesapeake Bay Resources. Philadelphia, PA Acad. Sci. 298-320.

Correll, D.L., J.J. Miklas, A.H. Hines, and J.J. Schafer. 1987. Chemical and biological trends accociated with acidic atmospheric deposition in the Rhode River watershed and estuary. Water Air Soil Pollut. 35:63-86.

Correll, D.L., T.E. Jordan, and D.E. Weller. 1992. Nutrient flux in a landscape: Effects of coastal land use and terrestrial community mosaic on nutrient transport to coastal waters. Estuaries 15:431-442.

Fanning, K.A. 1989. Influence of atmospheric pollution on nutrient limitation in the ocean. Nature 339:460-463.

Fisher, D.C. and M. Oppenheimer. 1991. Atmospheric nitrogen deposition and the Chesapeake Bay estuary. Ambio 20:102-108.

Higman, D. and D.L. Correll. 1982. Seasonal and yearly variation in meteorological parameters at the Chesapeake Bay Center for Environmental Studies. In: Correll, D.L., ed. Environmental Data Summary of the Rhode River Ecosystem, Sect. A: Long-Term Physical and Chemical Data. Edgewater, MD, Smith. Environ. Res. Center 1-159.

Jordan, T.E., D.L. Correll, and D.F. Whigham. 1983. Nutrient flux in the Rhode River: Tidal exchange of nutrients by brackish marshes. Est. Coast. Shelf Sci. 17:651-667.

Jordan, T.E., D.L. Correll, J. Miklas, and D.E. Weller. 1991b. Nutrients and chlorophyll at the interface of a watershed and an estuary. Limn. Oceanogr. 36:251-267.

Jordan, T.E., D.L. Correll, J. Miklas, and D.E. Weller. 1991a. Long-term trends in estuarine nutrients and chlorophyll, and short-term effects of variation in watershed discharge. Mar. Ecol. Prog. Ser. 75:121-132.

Jordan, T.E., D.L. Correll, D.E. Weller, and N.M. Goff. In Press. Temporal variation in precipitation chemistry on the shore of Chesapeake Bay. Water Air Soil Pollut.

Martin, D.F. 1972. Marine Chemistry, Vol. 1. New York, Dekker.

Pearl, H.W. 1985. Enhancement of marine primary production by nitrogen-enriched acid rain. Nature 315:747-749.

Paerl, H.W. 1993. Emerging role of atmospheric nitrogen deposition in coastal eutrophication: Biogeochemical and trophic perspectives. Can. J. Fish. Aquat. Sci. 50:2254-2269.

Peterjohn, W.T. and D.L. Correll. 1984. Nutrient dynamics in an agricultural watershed: Observations on the role of a riparian forest. Ecology 65:1466-1475.

MAP3S Network Summary Data Reports. U.S. Dept. Energy, Pacific Northwest Laboratory. Richland, WA.

Utility Acid Precipitation Study Program. Summary Reports. Washington, DC.

Vaithiyanathan, P. and D.L. Correll. 1992. The Rhode River watershed: Phosphorus distribution and export in forest and agricultural soils. J. Environ. Qual. 21:280-288.

Weller, D.E., W.T. Peterjohn, N.M. Goff, and D.L. Correll. 1986. Ion and acid budgets for a forested Atlantic coastal plain watershed and their implications for the impacts of acid deposition. In: Correll, D.L., ed. Watershed Research Perspectives. Washington, DC, Smithsonian Press, 392-421.

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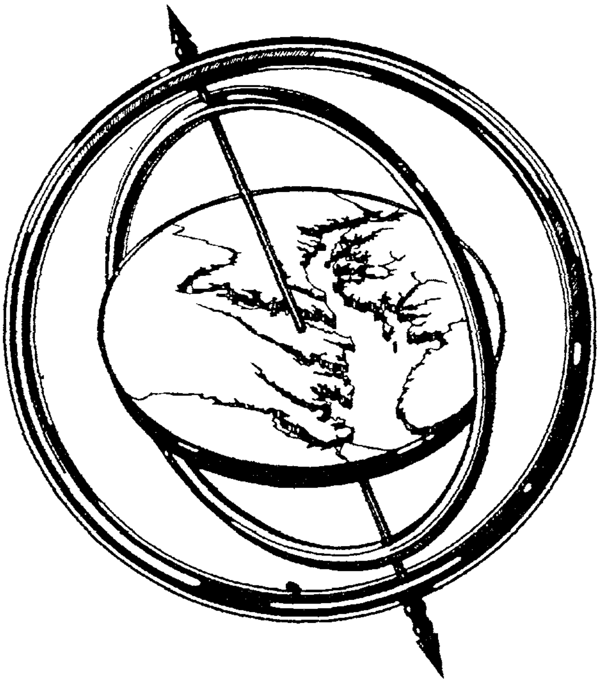

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