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Nutrient Flux in a Landscape: Effects of Coastal Land Use and Terrestrial Community Mosaic on Nutrient Transport to Coastal Waters

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ABSTRACT: Long-term interdisciplinary studies of the Rhode River estuary and its watershed in the mid-Atlantic coastal plain of North America have measured fluxes of nitrogen and phosphorus fractions through the hydrologically-linked ecosystems of this landscape. These ecosystems are upland forest, cropland, and pasture; streamside riparian forests; floodplain swamps; tidal brackish marshes and mudflats; and an estuarine embayment. Croplands discharged far more nitrogen per hectare in runoff than did forests and pastures. However, riparian deciduous hardwood forest bordering the cropland removed over 80 percent of the nitrate and total phosphorus in overland flows and about 85 percent of the nitrate in shallow groundwater drainage from cropland. Nevertheless, nutrient discharges from riparian forests downslope from croplands still exceeded discharges from pastures and other forests. The atomic ratio of nitrogen to phosphorus discharged from the watersheds into the estuary was about 9 for total nutrients and 6 for inorganic nutrient fractions. Such a low N:P ratio would promote nitrogen rather than phosphorus limitation of phytoplankton growth in the estuary. Estuarine tidal marshes trapped particulate nutrients and released dissolved nutrients. Subtidal mudflats in the upper estuary trapped particulate P, released dissolved phosphate, and consumed nitrate. This resulted in a decrease in the ratio of dissolved inorganic N:P in the estuary. However, the upper estuary was a major sink for total phosphorus due to sediment accretion in the subtidal area. Bulk precipitation accounted for 31 percent of the total nongaseous nitrogen influx to the landscape, while farming accounted for 69 percent. Forty-six percent of the total non-gaseous nitrogen influx was removed as farm products, 53 percent either accumulated in the watershed or was lost in gaseous forms, and 1 percent entered the Rhode River. Of the total phosphorus influx to the landscape, 7 percent was from bulk precipitation and 93 percent was from farming. Forty-five percent of the total phosphorus influx was removed as farm products, 48 percent accumulated in the watershed, and 7 percent entered the Rhode River. These nitrogen and phosphorus discharges into the Rhode River, although a small fraction of total loadings to the watershed, were large enough to cause seriously overenriched conditions in the upper estuary.

Introduction

The landscape of the mid-Atlantic coastal plain of North America is a mosaic of different hydrologically-linked ecosystems. Agricultural uplands are major sources of nutrient discharges from coastal plain watersheds (Correll 1983, 1987; Jordan et al. 1986a). Upland forests also release nutrients, but at much lower rates than agricultural lands (Correll 1983; Weller et al. 1986). In contrast, other ecosystems such as riparian forests (Correll and Weller 1989), flood plain forests, freshwater swamps (Brinson et al. 1984; Yarbro et al. 1984), and tidal marshes (Correll 1981; Jordan et al. 1983; Jordan and Correll 1985; Jordan et al. 1986b) act as nutrient sinks. Whether these ecosystems trap or release nutrients may depend on how much nutrient they receive from uphill ecosystems. For example, riparian forests are often located downhill of agricultural lands in the coastal plain. Typically the concentration of nitrate in agricultural drainage waters is dramatically reduced as it moves through these riparian forests and before it reaches the adjacent stream channel (Lowrance et al. 1984a; Jacobs and Gilliam 1985b; Cooper et al. 1986; Correll and Weller 1989).

Hydrologically-linked ecosystems interact through the flux of water-borne sediments and nutrients. Nutrients discharged from many upland ecosystems pass through lowlands and a continuum of freshwater and brackish wetlands on their way to estuaries and the sea. Understanding the dynamics of such nutrient flows requires knowledge

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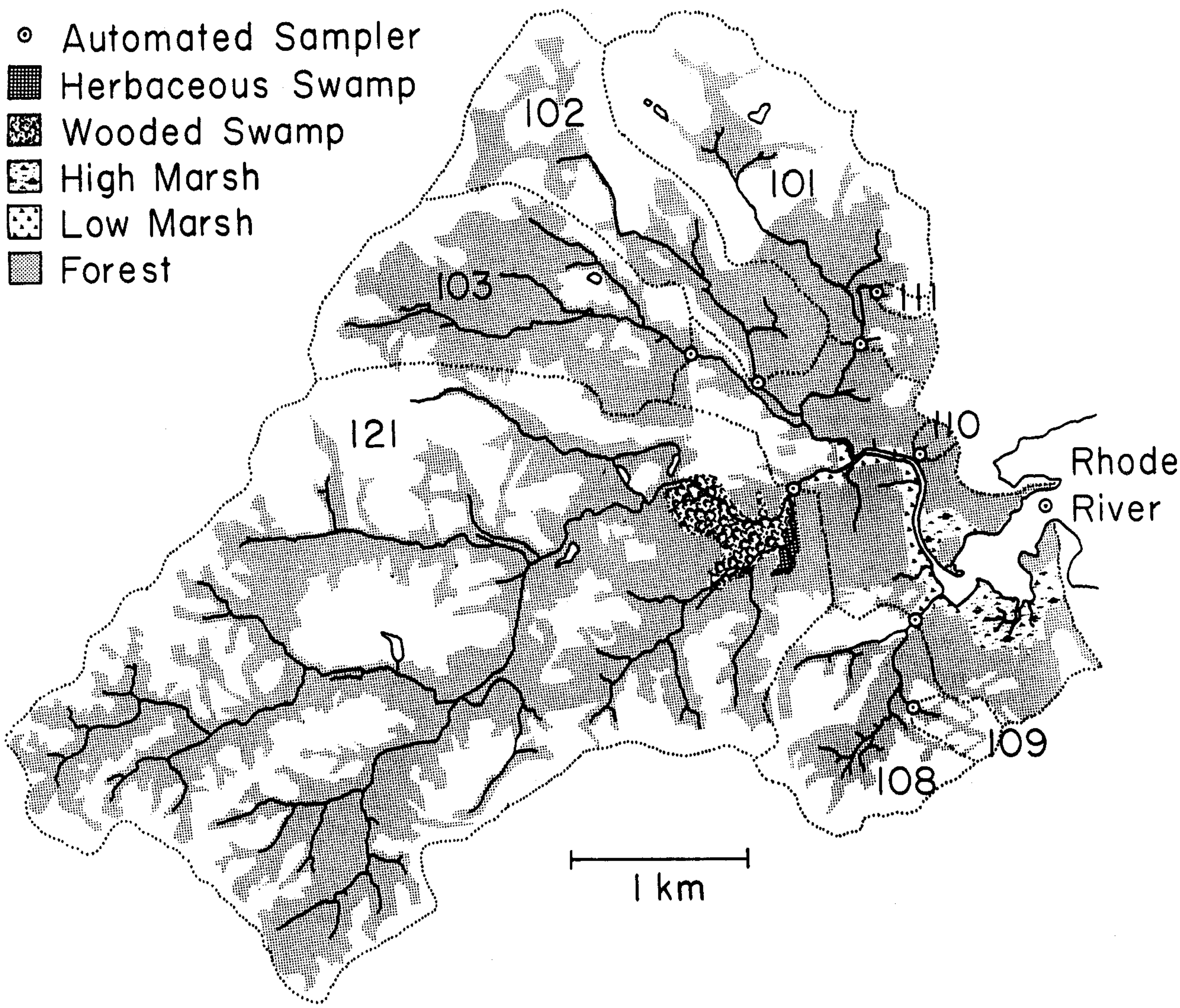

Fig. 1. The upper Rhode River and eight subwatersheds where nutrient fluxes were measured. Dotted lines are watershed boundaries (from Jordan et al. 1986a).

of the effects of land use on nutrient discharge and of the effects of uphill ecosystems on downhill ecosystems.

There have been many studies of nutrient cycling and flow through specific ecosystems, but few studies of nutrient flows through landscapes containing several different kinds of ecosystems. In this we provide a synthesis of our long-term studies of nitrogen and phosphorus flux through a complex coastal landscape containing many different hydrologically-linked ecosystems.

Site Description

The study site is the Rhode River estuary and its watershed, located east of Washington, D.C. on the western shore of Chesapeake Bay (38°51′N, 75°36′W). We studied eight subwatersheds comprising 2,286 ha which drain into a tidal creek at the head of the Rhode River (Fig. 1). Overall, the studied watersheds were 62% forest, 23% croplands, 12% pasture, and 3% freshwater forested swamp (Correll 1977), but land use differed from subwatershed to subwatershed (Table 1). The soils are rich in nutrients and consist of fine sandy loams of sedimentary origin (Correll 1983). An impervious clay aquiclude forms a continuous layer just above sea level, creating perched local aquifers within each subwatershed (Chirlin and Schaffner 1977). The forests are deciduous and mostly of the tulip poplar association (Brush et al. 1980). The croplands are predominantly in corn production.

The upper part of the Rhode River consists of 23 ha of shallow (less than 1 m deep) tidal mudflats and creeks bordered by 22 ha of high tidal marshes

TABLE 1. Land uses for the eight Rhode River study subwatersheds (Fig. 1; Jordan et al. 1986a).

Watershed	Area (ha)	Land Use Percentages		
		Crops	Pastures	Forests
#101	226	15.6	27.2	57.2
#102	192	23.8	21.6	54.6
#103	254	6.6	16.5	77.0
#108	150	26.6	20.2	53.2
#109	16.3	65.6	0	34.4
#110	6.3	0	0	100.0
#111	6.1	0	73.3	26.7
#121	1,229	28.9	8.9	62.3

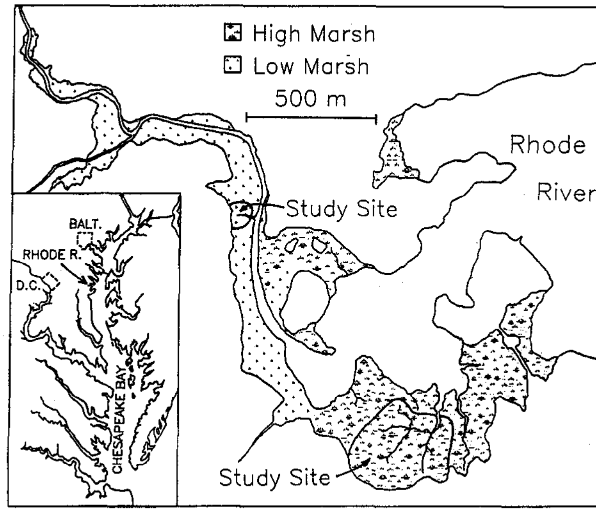

Fig. 2. The upper estuarine area of the Rhode River subestuary including high and low brackish tidal marshes and subtidal mudflat. Study sites refer to marsh areas where data were taken. Inset shows the location of the Rhode River on Chesapeake Bay (38°51′N, 76°32′W; from Jordan et al. 1983).

and 13 ha of low tidal marshes (Fig. 2). The mean tidal amplitude in the Rhode River is 30 cm, but water level can fluctuate considerably more due to weather conditions such as winds and pressure differentials. The mudflat area is half exposed by 2% of low tides and almost fully exposed by 0.6% of low tides (Jordan et al. 1986b). The mudflats are therefore essentially subtidal. The high marsh is 42 cm above mean low water, is flooded by 20% of high tides, and is vegetated by *Spartina patens, Distichlis spicata, Iva frutescens, Spartina cynosuroides,* and *Scirpus olneyi.* The low marsh is 30 cm above mean low water, is flooded by 46% of high tides, and is vegetated primarily by *Typha angustifolia* (Jordan et al. 1986b). Salinity in these ecosystems range from 0‰ to 18‰. The Rhode River is a 485 ha tributary to Chesapeake Bay. Mean depth is 2 m and maximum depth 5 m. Salinity at the junction with Chesapeake Bay ranges from 5‰ to 20‰ (Pierce et al. 1986).

Methods

Natural drainage divides separate the watershed into a series of subwatersheds (Fig. 1). These subwatersheds were isolated from deeper aquifers by a clay aquiclude. Water samples and flow measurements for eight subwatersheds were taken continuously by automated sampling stations (Correll 1977, 1981). The stations for seven of the subwatersheds employed V-notch weirs. The eighth (number 121) was tidally influenced, so a tidal flume, tide gauge, and electromagnetic current meter were used for flux measurements.

To estimate fluxes among estuarine ecosystems we constructed flumes at the mouths of two tidal creeks, one draining a low marsh and one draining a high tidal marsh (Fig. 2). These stations were used to take tidal flux measurements for flooding tides and receding tides (Jordan et al. 1983; Jordan and Correll 1991). A similar sampling station located on pilings in a constricted channel between the headwaters and the main basin of the tidal Rhode River (Fig. 2) measured tidal flux in and out of the upper estuarine area (Correll 1981). The sampling stations automatically collected water samples in volumes proportional to the flows. The tidally-influenced stations collected separate ebb and flood samples. The automated volume-integrated samples were composited for weekly time periods. Samples for nutrient analysis were preserved with 1–3 ml l^{-1} 15 N sulfuric acid. Volume-proportional samples were also taken manually in some cases for the separate analysis of particulate and dissolved nutrient fractions (Jordan et al. 1983). The analytical techniques we used are described by Correll (1981), Jordan et al. (1983), and Jordan et al. (1986b). Bulk precipitation was sampled and analyzed as described by Correll and Ford (1982).

The role of riparian forests in altering nutrient flux from uplands of different land uses was studied with transects of samplers along the pathways of overland storm flow and groundwater flow (Correll et al. 1984). Overland flow was sampled with polyethylene pit traps (Peterjohn and Correll 1984). We measured water table slopes and sampled groundwater by using wells made of perforated polyvinyl chloride pipe placed in holes bored with a bucket auger. Holes were bored either to the top of the clay aquiclude or to a 4 m depth, whichever came first. The pipes were inserted into the holes and clay was used to seal around the pipe at the soil surface. Both overland flow samplers and groundwater wells were cleaned and pumped dry prior to sampling (Peterjohn and Correll 1984).

Samples were analyzed as described by Peterjohn

TABLE 2. Annual nutrient discharges for three different watersheds dominated by the indicated land uses (Correll 1983). Discharges are in kg ha^{-1} of nitrogen or phosphorus per year. Numbers in parentheses refer to subwatersheds listed in Table 1.

Parameter	Cropland (#109)	Pasture (#111)	Forest (#110)
Total-nitrogen	13.8	5.95	2.74
Dissolved ammonium	0.45	0.51	0.15
Nitrate	6.35	3.20	0.36
Total-phosphorus	4.16	0.68	0.63
Orthophosphate	1.20	0.32	0.15
Atomic ratio of total-nitrogen : total-phosphorus	1.50	3.95	1.96

and Correll (1984, 1986) and by Correll and Weller (1989). Changes in groundwater concentration were corrected for the effects of evapotranspiration and infiltration of rain in the forest (Peterjohn and Correll 1986). The relative volumes of overland and groundwater flows were estimated by graphical and analysis of hydrographs measured at the weirs (Peterjohn and Correll 1984). Interpretation of the hydrology was simplified by the presence of a shallow clay aquiclude. The role of vegetative assimilation and long-term storage of nutrients in riparian forest biomass was measured by tree population surveys, incremental coring, nutrient analysis of cores, and allometric equations for the biomass (Peterjohn and Correll 1984; Correll and Weller 1989).

Results

Variability in Watershed Discharges

We have observed large interannual and interwatershed variations in nutrient discharges from the Rhode River subwatersheds. Since the subwatersheds are both small and contiguous, the interwatershed differences seem to be primarily due to differences in land use and topography. Data from three small watersheds with similar basin slopes (Correll 1983) best illustrate this point (Table 2). The watershed dominated by row crops discharged much higher amounts of all nutrient fractions than did the completely forested watershed. A pastureland watershed had intermediate discharges (Correll 1983). Most notably, the cropland watershed discharged 17.6 times as much nitrate and 8 times as much phosphate as the forested watershed.

TABLE 4. Interannual and seasonal variations in total-phosphorus discharge from watershed 101 over a three-year period (kg P ha^{-1}; Correll et al. 1977).

Year	Winter	Spring	Summer	Fall	Total Year
1974	31	221	33.5	91.6	377
1975	73	591	298	486	1,447
1976	381	131	139	109	761
Mean	162	314	157	229	862

When all of the subwatersheds under study were used in regression analyses to predict nutrient discharges from land use composition, both nitrogen and phosphorus discharges increased significantly as percent cropland increased, but did not vary significantly with percent pasture (Jordan et al. 1986a). The land use regression model explained 90% of the variability in N discharge by the watersheds, and 73% of the variability in P discharge. Thus the importance of land use composition in controlling nutrient discharges is apparent, even for mixed land-use watersheds.

Discharges from a given watershed also had very large temporal variation. Within a year, discharges from temperate watersheds are highly seasonal because of fluctuations in temperature and evapotranspiration (Correll and Ford 1982; Correll 1983). However, discharges vary greatly among years for the same watersheds (Table 3), mostly due to interannual differences in rainfall. For example, annual nitrate discharges varied 3.5-fold and spring seasonal discharge varied 6.8-fold during a period of only 4.5 years (Correll and Ford 1982). In another case the discharge of total P from a single subwatershed (#101, Table 1) varied during a three-year period by 9-fold in the summer season and 4-fold on an annual basis (Table 4; Correll et al. 1977).

Effects of Riparian Forest on Cropland Discharges

Direct measurements from watersheds dominated by cropland (Table 2) and regression analyses of land-use composition versus nutrient discharge

TABLE 3. Interannual variations in nitrogen discharges from the combined Rhode River study subwatersheds from 1974 to 1978 (kg N ha^{-1}; Correll and Ford 1982).

Parameter	Spring Season		Total Year	
	Mean	Extremes	Mean	Extremes
Total-nitrogen	1.03	0.32–2.19	2.20	1.11–3.47
Dissolved ammonium	0.081	0.026–0.176	0.178	0.097–0.275
Nitrate	0.364	0.095–0.647	0.916	0.379–1.33

TABLE 5. Effects of a riparian forest on suspended particulates and nutrient concentrations (mg l^{-1}) in overland flows from a cropland moving through the forest to a first-order stream (Peterjohn and Correll 1984).

Location	Season	Total Suspended Particles	Nitrate-Nitrogen	Ammonium-Nitrogen		Organic-Nitrogen		Total-Phosphorus	
				Particulate	Dissolved	Particulate	Dissolved	Particulate	Dissolved
Entering riparian forest	Spring	8,840	3.73	0.73	3.63	27.7	1.47	3.22	0.26
	Summer	11,500	10.50	0.52	1.17	32.1	2.72	11.9	0.13
	Fall	3,830	1.57	0.30	0.90	16.8	0.78	3.29	0.13
	Winter	1,760	1.99	0.05	0.25	1.3	2.04	0.86	0.32
	Year	6,480	4.45	0.40	1.49	19.5	1.75	4.82	0.21
Leaving riparian forest	Spring	372	0.74	0.08	0.40	2.5	1.18	0.45	0.25
	Summer	524	1.03	0.11	0.18	3.5	0.71	1.04	0.18
	Fall	(no overland flows occurred)							
	Winter	360	1.05	0.08	0.18	2.0	0.08	—	—
	Year	419	0.94	0.09	0.41	2.7	0.66	0.74	0.22

indicate that croplands are the largest sources of nutrients in Rhode River watershed discharges. Further analyses of the internal nutrient processing within watershed 109 confirm and extend this conclusion. Watershed 109 is composed of 10.4 ha of uplands in corn production and 5.9 ha of deciduous hardwood forest, most of which is found along the first-order stream channel draining the watershed. Extensive studies of the nutrient dynamics of this riparian forest indicate that the majority of the nutrients and sediments in both overland flows and shallow groundwater from the cropland are removed within the forest before they reach the stream channel (Tables 5 and 6). Over 90% of annual suspended sediment loads and about 80% of the nitrate in overland flows were removed in transit (Peterjohn and Correll 1984). Nitrate removal from groundwater averaged about 85% over a three-year period and ranged from 84% to 87% (Correll and Weller 1989). Seasonally, nitrate removal from groundwater was least efficient (81%) in the winter and most efficient in the fall (97%; Table 6). Nitrate removal in the spring varied from 88% to 92%.

TABLE 6. Effects of a riparian forest on nitrate flux in groundwater from a cropland through the forest to a first-order stream. Input flux includes precipitation; data have been corrected for the effects of evapotranspiration using a chloride balance. Fluxes are in keq N 5.9 ha^{-1} forest (Correll and Weller 1989).

Year	Spring	Summer	Fall	Winter	Complete Year
Year one					
Input	4.60	3.28	0.77	14.97	23.6
Output	0.57	0.39	0.04	2.02	3.0
Year two					
Input	13.64	4.04	1.50	6.91	26.1
Output	1.04	0.91	0.05	2.11	4.1
Year three					
Input	1.89	0.48	0.96	3.31	6.6
Output	0.36	0.04	0.01	0.59	1.0
Three-year					
Mean input	5.03	2.60	1.08	8.40	18.8
Mean output	0.66	0.45	0.03	1.57	2.7

We hypothesize that denitrification is the most important mechanism for the nitrate loss, especially from groundwater (Correll and Weller 1989). The nitrate removed from cropland drainage waters was not simply converted to dissolved, reduced forms of nitrogen (Table 5; Peterjohn and Correll 1984). Direct measurements of nitrogen assimilation and storage in the woody biomass of riparian forest trees indicated that storage in biomass could account for 25%, at most, of the nitrogen removed by the forest from the cropland discharges (Correll and Weller 1989). In addition, direct in situ chamber measurements of nitrous-oxide releases at the soil surface indicated much higher rates of denitrification in the area of the riparian forest where the groundwater nitrate loss occurred (Correll 1991).

In addition to removing high proportions of nutrients and sediments in cropland discharges, these riparian forests affect the hydrology of the landscape. Riparian forests have high rates of evapotranspiration relative to other land uses. Evapotranspiration rates were 107 cm yr^{-1} and 118 cm yr^{-1} for the two years analyzed (Peterjohn and Correll 1986). This high rate of evapotranspiration is a significant factor in the hydrology of the system at the landscape level since riparian forests occur on all watersheds and occupy a significant proportion of the total watershed.

Another functional effect of riparian forests on groundwater is to increase pH. Agricultural groundwater entering the forest had annual averages of pH 4.56 and 4.46 during two study years, while the pH leaving the forest was 5.46 and 5.50,

TABLE 7. Annual nutrient fluxes (g m^{-2} yr^{-1} nitrogen or phosphorus) into (+) or out of (−) the upper Rhode River, an area including 29 ha of high marsh, 17 ha of low marsh, and 32 ha of mudflat. Fluxes of particulate and dissolved forms are combined (Jordan et al. 1983).

Nutrient	Land Runoff	Precipitation on Upper Rhode River	Tidal Exchange with Lower Rhode River	Retention
Total-phosphorus	0.695	0.051	0.751	1.50
Total-phosphate	0.281	0.012	−0.090	0.20
Total-organic phosphorus	0.414	0.040	0.841	1.29
Total-nitrogen	4.08	1.2	10.1	15.3
Total-ammonium	0.30	0.27	−0.288	0.279
Nitrate + nitrite	0.59	0.43	0.021	1.04
Total-organic nitrogen	3.19	0.47	10.3	14.0

respectively (Peterjohn and Correll 1986). Such a pH change has important implications to the control of belowground nutrient processes since the rates of these processes are often pH-dependent and hydronium ions are sometimes reactants.

Nutrient Flux Within the Upper Estuary

Nutrients and sediments are delivered from the watershed to the upper estuary, which includes high and low tidal marshes and a shallow subtidal mudflat (Fig. 2). These three ecosystems influence transport and transformation of nutrients in important and unique ways.

In general, the marshes trap particulate nutrients and release dissolved nutrients (Jordan et al. 1983). However, the high marsh exports particulate organic C. The high and low marshes differ in other ways as well. For example, on an areal basis, the high marsh exports much more dissolved organic N and exports much less dissolved phosphate than the low marsh. Also, the low marsh imports more particulate matter than the high marsh, possibly because of the longer submergence time of the low marsh. For both marshes, higher tides lead to greater submergence and more trapping of particulate matter (Jordan et al. 1983; Jordan and Correll 1991). Particulate nutrients trapped in the marshes can be converted to dissolved nutrients and be released into interstitidal water which seeps from creek banks at low tide. However, seepage of interstitial water from creek banks of the low marsh accounts for less than half of the export of dissolved nutrients (Jordan and Correll 1985).

The mudflat traps particulate matter at an even higher rate than the marshes (Jordan et al. 1986b). Once deposited, particulate P is converted to dissolved phosphate and released from the sediments

TABLE 8. Annual nutrient fluxes: precipitation inputs and tidal exchanges by marshes (g m^{-2} yr^{-1} nitrogen or phosphorus). Fluxes of particulate and dissolved forms are combined. Positive tidal exchanges are net inputs to marshes, and negative exchanges are net outputs (Jordan et al. 1983).

Nutrient	Precipitation	Tidal Exchange	
		High Marsh	Low Marsh
Total-phosphorus	0.051	0.57	−0.54
Total-phosphate	0.012	0.35	−1.7
Total-organic phosphorus	0.040	0.22	1.2
Total-nitrogen	1.2	−2.9	0.91
Total-ammonium	0.27	−0.15	−1.3
Nitrite + nitrite	0.43	−0.070	0.35
Total-organic nitrogen	0.47	−2.6	1.8

of the mudflat resulting in a marked increase in the dissolved phosphate concentration in the water column of the upper estuary (Jordan et al. 1991). The mudflat consumes almost all of the nitrate discharged from the local watershed and perhaps some nitrate originating from Chesapeake Bay as well (Jordan et al. 1991). The consumption of nitrate and the production of phosphate greatly reduces the ratio of dissolved inorganic N:P in the upper Rhode River (Jordan et al. 1991).

By combining data from automated samplers and measurements of atmospheric precipitation inputs, we can compare the net nutrient fluxes in and out of the upper estuary as a whole (Table 7). These comparisons are for the total nutrient fluxes of combined particulate and dissolved fractions. Watershed discharge was the greatest source of nitrate and phosphate input to the upper estuary while tidal exchange from the lower estuary was the greatest source of organic N and organic P. Tidal exchange resulted in outputs of phosphate and ammonium from the upper to the lower estuary. Precipitation was an important source of N, but a trivial source of P. By adding the fluxes of N and P in and out of the upper estuary we can calculate net retention, the amount of nutrient accumulating in the system (plus the amount lost to the atmosphere

TABLE 9. Net retention of nutrients (kg yr^{-1} of nitrogen or phosphorus) in the different ecosystems of the upper Rhode River (Fig. 2). Retention of nitrogen includes conversion to gaseous forms as well as accretion. Negative retentions indicate net release (Jordan et al. 1983).

Nutrient	High marsh (29 ha)	Low marsh (17 ha)	Mudflat (32 ha)
Total-phosphorus	180	−84	1,070
Phosphate	104	−291	345
Organic phosphorus	75.4	287	728
Total-nitrogen	−490	352	12,000
Ammonium	35.4	−172	355
Nitrate + nitrite	104	131	577
Organic nitrogen	−629	391	11,100

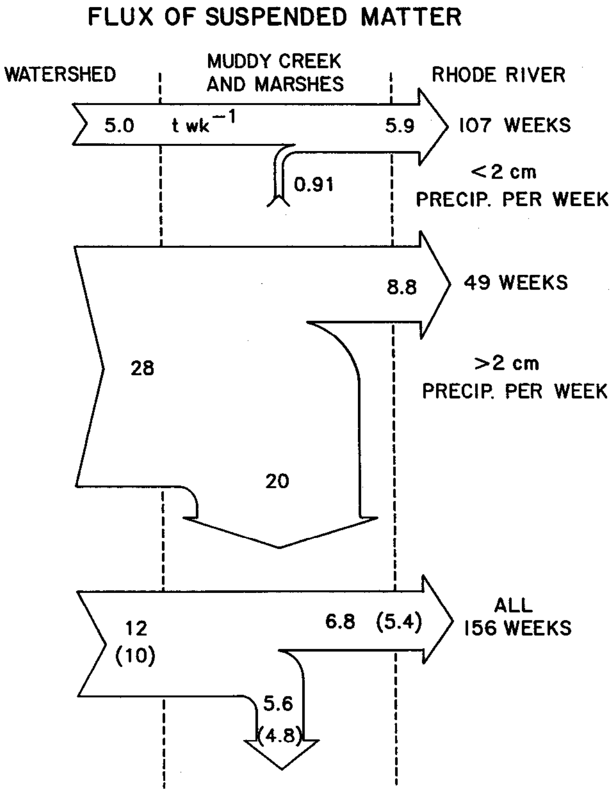

Fig. 3. Average flux of suspended sediments (tonnes/week) during weeks with low and high precipitation (from Jordan et al. 1986b). Numbers in parentheses are for mineral matter. Downward arrows represent net retention of sediment, upward arrows represent net release.

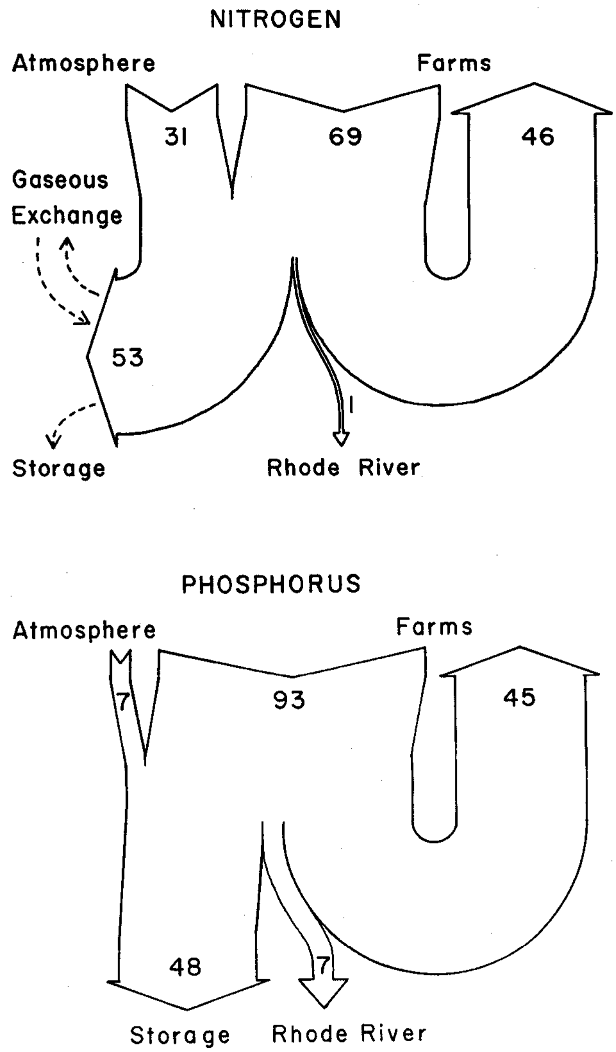

Fig. 4. Annual nitrogen and phosphorus fluxes into and out from the entire Rhode River landscape as percentages of the total input (from Jordan et al. 1986a).

in the case of N). In general, the upper estuary acted as a sink for nutrients, retaining most of the ammonia and phosphate entering the system and all of the other nutrient forms entering.

Precipitation was an important source of ammonium and nitrate to the marshes, but a minor source of other nutrients compared to tidal exchange (Table 8). Tidal exchange indicates that N is produced by the high marsh and consumed by the low marsh. Tidal exchange measurements by Jordan et al. (1983) suggested that the low marsh exports P, but more recent measurements (Jordan and Correll 1991) indicate that over the long term the low marsh is a sink for P as would be expected for a system that accretes sediment. Comparing net retention of nutrients by the marshes and by the mudflat (Table 9), we find that the mudflat retains far more nutrients and that the nutrient retention by the upper Rhode River as whole is largely a reflection of retention by the mudflat.

Most of the phosphorus and a significant fraction of the nitrogen flux from the watershed is in particulate form (Jordan et al. 1986b). Since particulate fluxes from the watershed are storm-related they are extremely erratic. They depend not only upon the frequency and size of rainfall events, but upon rainfall intensity and the vegetational cover on croplands at the time of the storms. Of the 1,900 tonnes of sediment delivered from the watershed during a three-year period, 72% were delivered during the 31% of the weeks in which over 2 cm of precipitation occurred (Fig. 3; Jordan et al. 1986b). Furthermore, 980 tonnes or 51% of the total sediments delivered were retained in the mudflat during those weeks with over 2 cm of precipitation. During the weeks with less precipitation, 97 tonnes or 5% of the total sediment delivered from the watershed were actually resuspended and exchanged further down the Rhode River from the mudflat (Fig. 3; Jordan et al. 1986b).

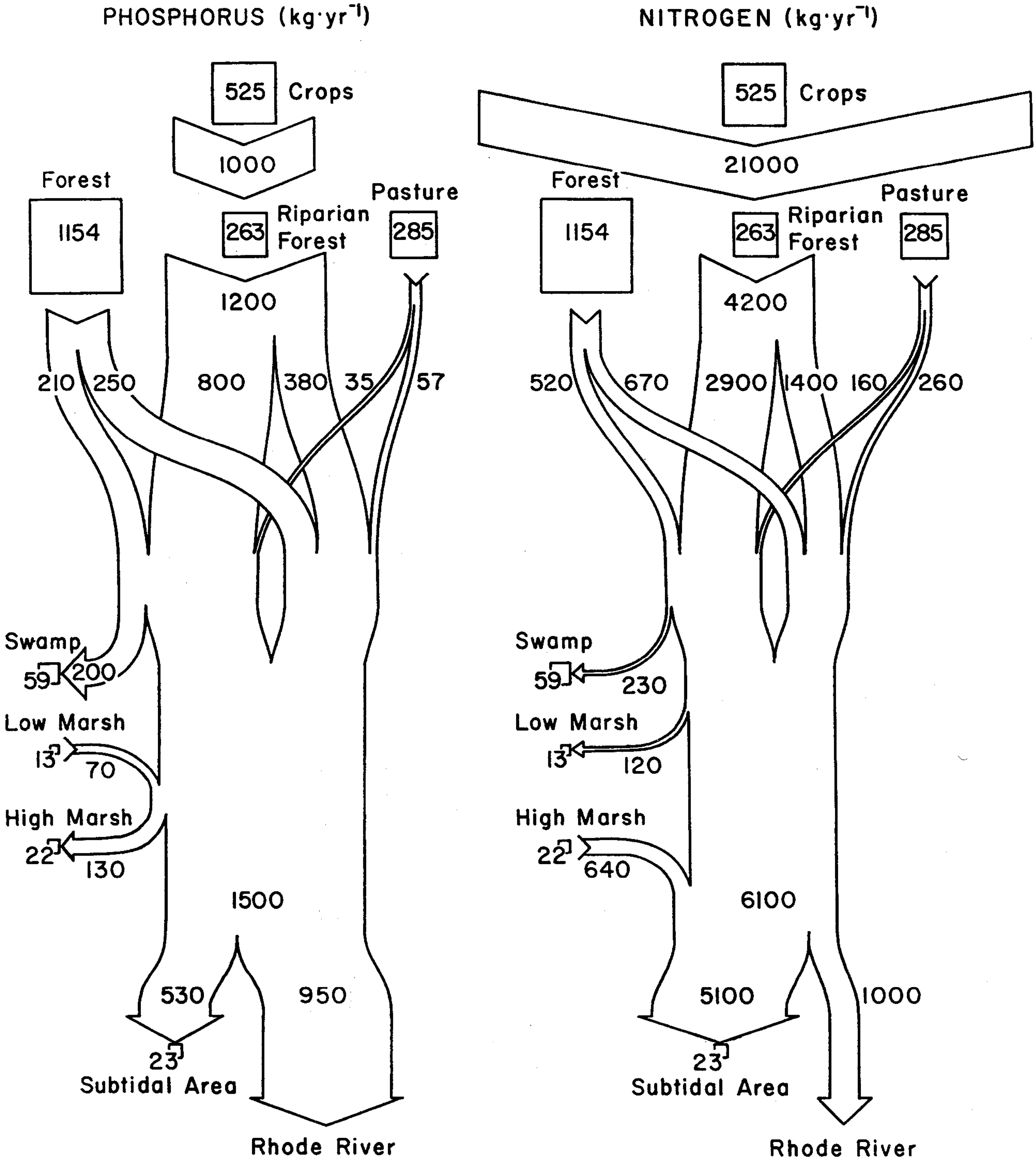

Fig. 5. Net annual nitrogen and phosphorus fluxes (kg yr⁻¹ of nitrogen or phosphorus) through the component ecosystems of the Rhode River landscape (Jordan et al. 1986a). Arrows indicate watershed discharges from upland systems, net uptake by the freshwater swamp, and net tidal exchanges by the marshes and subtidal area. Widths of arrows are proportional to the fluxes given by the numbers in arrows. Numbers in boxes give the area of each ecosystem type (ha). Watershed fluxes are split according to whether they went through the freshwater swamp or directly into tidal waters. Nitrogen and phosphorus exchanges with the atmosphere, inputs as fertilizer or feed, and removals in harvest are not shown.

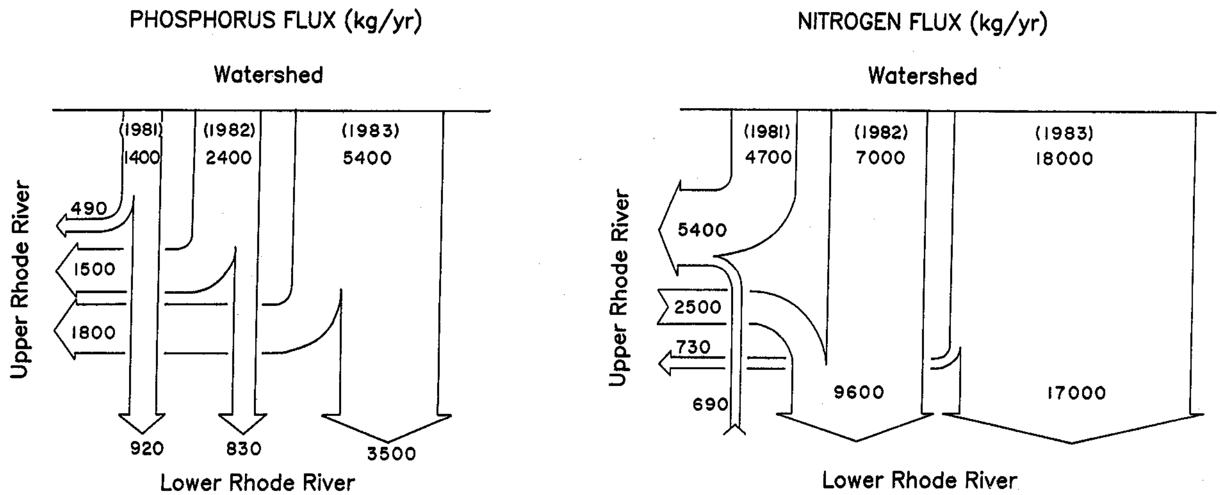

Fig. 6. Variability of annual phosphorus (left) and nitrogen (right) fluxes into and out of the upper Rhode River estuary.

Overall Landscape Synthesis

To gain an overall perspective of the complex nutrient dynamics of this landscape, we constructed flow diagrams at several hierarchical levels. First, we consider annual fluxes of total nitrogen and total phosphorus for the upper Rhode River and its watershed (Fig. 4; Jordan et al. 1986a). For nitrogen, 31% enters the system as precipitation and 69% as farm chemicals. Farm product exports account for 46% of the outputs, gaseous exchanges to the atmosphere and storage account for 53%, and flux to the Rhode River tidal basin is only 1% of the total system inputs. For phosphorus, farm chemicals account for 93% of the inputs and precipitation is 7%. Farm product exports account for 45% of the outputs, storage 48%, and flux to the tidal basin 7%.

Second, we split the landscape into its component ecosystems and estimated the net discharge or uptake of nutrients from each type of ecosystem (Fig. 5; Jordan et al. 1986a). Croplands discharge the most N although they cover less area than the forests. Most of the N discharged from croplands was taken up by adjacent riparian forests, but these riparian forests still discharged more N than forests and pastures. About half of the watershed drains directly into the upper estuary and half drains through a freshwater swamp which acts as a sink for both N and P. Tidal marshes had relatively little effect on the total N and P flow through the tidal headwaters compared to the subtidal area which was an important nutrient sink.

The data for the tidal headwaters depicted in Fig. 5 were taken in 1981, a relatively dry year. When we compared this part of the system for three years we found that the efficiency of retention by this part of the landscape varied (Fig. 6a, b). Thus phosphorus retention was 35%, 62%, and 33% in 1981, 1982, and 1983, respectively. For nitrogen, the variation was even more pronounced, ranging from 115% to −36% to 4% in 1981, 1982, and 1983, respectively.

Passage through the landscape changes the molar ratios of nitrogen to phosphorus (Fig. 7; Jordan et al. 1986a), affecting the quality of plant nutrients delivered to downstream systems. This ratio is very high for cropland discharges, but is dramatically lowered by passage through the riparian forest ecosystem. By the time the waters are discharged into tidal waters the overall flux has a ratio of about 9 for total nutrients and about 6 for inorganic nutrient fractions.

Discussion

The Rhode River landscape is a fairly typical Atlantic coastal plain watershed/estuarine system. It is dominated by forests and agriculture in the uplands. The uplands drain into a wetland continuum consisting of riparian forests on low-order streams, flood-plain forests on higher order streams, freshwater marshes, and brackish marshes. The Rhode River watershed lies totally within the inner coastal plain and therefore has relatively high topographic relief compared with outer coastal plain systems. The soils of the Rhode River watershed, like most soils of the inner coastal plain, are nutrient-rich, fine silty loams rather than the nutrient-deficient, sandy soils of the outer coastal areas. Also, the soils have low moisture infiltration rates, high moisture capacity, and high erodibility when compared to other soils. The dominant forest communities both in the uplands and lowlands

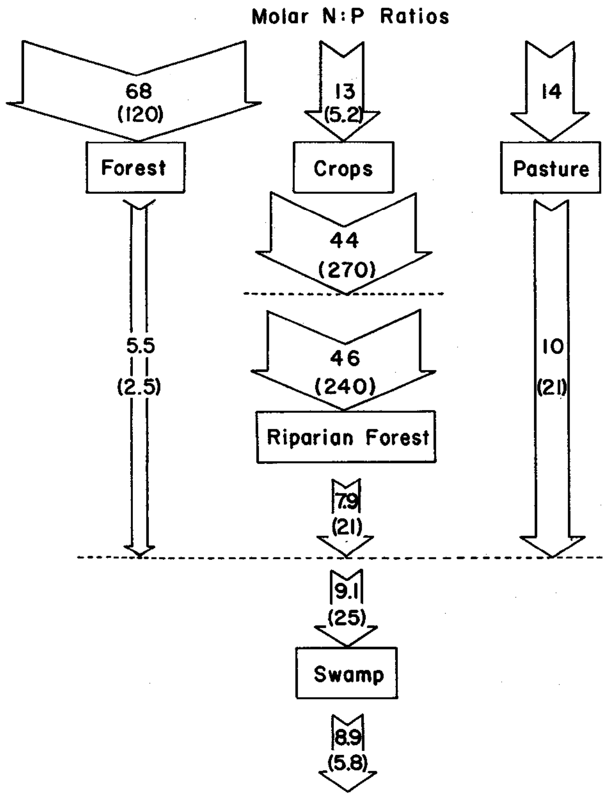

Fig. 7. Molar nitrogen : phosphorus ratios of nutrients entering and leaving ecosystems of the Rhode River landscape and of nutrients discharged to the upper estuary (from Jordan et al. 1986a). Nutrients entering a system include inputs from precipitation and farming as well as from upstream systems. Widths of arrows are proportional to ratios of total nutrients given by numbers without parentheses. Ratios of inorganic nutrients are given in parentheses.

are deciduous, hardwood forests. These features of the Rhode River system must be kept in mind when generalizing our findings to other systems.

We have consistently stressed the importance of interannual variation in summarizing our findings. Differences in nutrient dynamics between habitats or land uses have been documented, but interannual differences for the same system are equally important and infrequently documented. If one does not have multiyear data sets, it is very dangerous to reach sweeping conclusions, especially for relatively small differences (see also Likens 1989). For example, if one compared a cropland discharge during a dry year with that from a forest or pastureland during a wet year one might incorrectly argue that they are the same. Likewise, one could select a wet versus a dry year to evaluate the nutrient retention effects of the upper estuary and reach widely different conclusions. Because we have simultaneous multiyear data sets, we have been able to reach a number of important conclusions.

It is clear that in any given weather regimen croplands are the largest source of watershed nutrient discharge per surface area. This is true for both phosphorus and nitrogen and for both overland storm flows and groundwater. Furthermore, since the study watersheds had been in these land uses for many years, our results are not influenced by transitory impacts such as clearcutting a forest and then either maintaining the land fallow (Bormann et al. 1968) or allowing forest regrowth (Pierce et al. 1972). The higher discharge of phosphorus from cropland probably is related primarily to greater rates of sheet erosion and to the higher surface soil pH due to liming. Others have found, as we did, that nutrient discharge from watersheds increases as the percentage of cropland increases (Omernik 1979). However, our forests discharge less nitrogen and more phosphorus than most forests reviewed by Beaulac and Reckhow (1982), probably because of the unusually high soil phosphorus concentrations in this inner coastal plain landscape.

It is also convincing that riparian forests have a major influence on nutrient fluxes from our croplands to stream channels. This is most evident in the case of nitrate in groundwater (Table 6). However, it is apparent that these riparian forests also play a significant role in trapping nitrate and suspended sediments from overland storm flows, which are very important in this landscape (Table 5). Similar riparian forest effects have also been documented in coastal plain sites in North Carolina (Jacobs and Gilliam 1985a, b; Cooper et al. 1986) and in the inner coastal plain of Georgia (Lowrance et al. 1984a, b). However, one should not assume that these results are universal. Certainly an important factor influencing the function of these systems is the prevalence of aquicludes or confining layers near the soil surface (Lowrance et al. 1984b; Peterjohn and Correll 1984; Jacobs and Gilliam 1985a; Peterjohn and Correll 1986). Such confining layers prevent significant infiltration to deeper strata and assure extensive contact between shallow groundwater and roots of riparian vegetation.

We conceptualize the belowground nutrient dynamics of these coastal plain riparian forests as electron donor-receptor controlled (Fig. 8). Organic matter released from the riparian trees serves as an electron donor source. As groundwater moves through the riparian zone, first dissolved oxygen is used in respiration, then nitrate in denitrification, and finally sulfate is reduced (Correll and Weller 1989).

We found that the 59-ha, forested, floodplain swamp (Mill Swamp, Fig. 1) through which over half of the watershed drainage passes, was a sink for 17 kg N ha^{-1} yr^{-1} and 3.8 kg P ha^{-1} yr^{-1} (Jordan et al. 1986a). Similarly, Yarbro et al. (1984) found

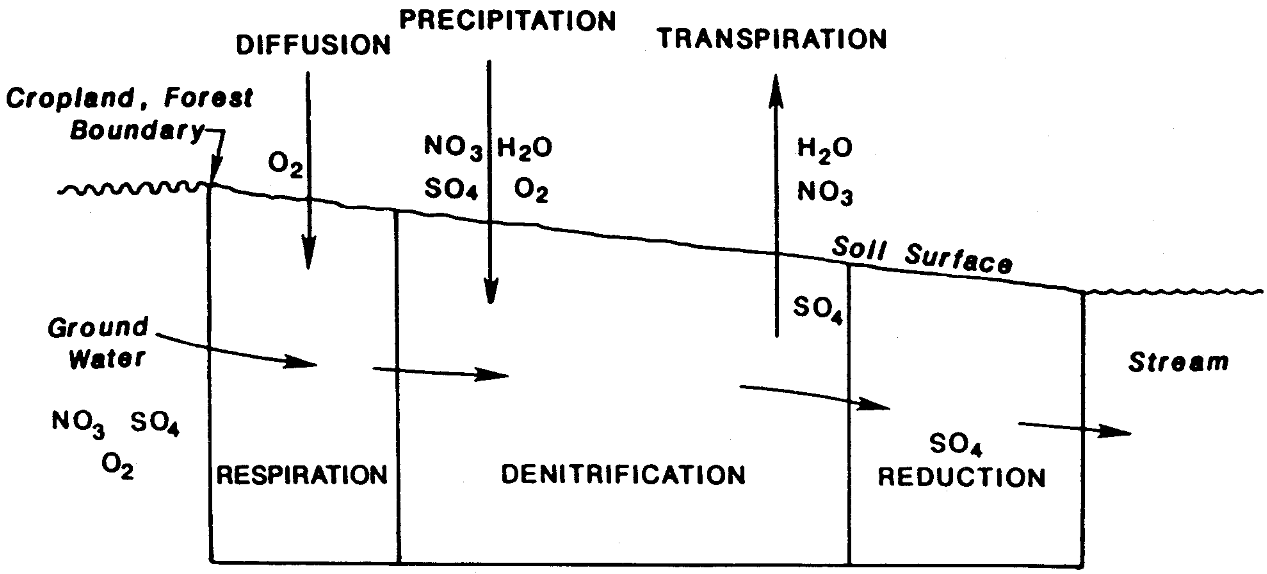

Fig. 8. Conceptual model of belowground processes affecting groundwater nutrients in riparian forests (from Correll and Weller 1989).

that a swamp in North Carolina retained 13 kg N ha^{-1} yr^{-1} and 3.1 kg P ha^{-1} yr^{-1}. However, that swamp mainly retained dissolved ammonium and phosphate and ours retained nitrate and particulate phosphorus. Mitsch et al. (1979) found that a swamp in southern Illinois trapped primarily particulate phosphorus, and Brinson et al. (1984) found that a swamp in North Carolina could act as a nitrate sink.

Within the upper estuary it is apparent that the subtidal mudflats had the largest effect on nutrient and sediment trapping and recycling (Tables 8 and 9). While the tidal marshes play a role, especially in trapping particulates and releasing dissolved nutrients, these fluxes cancel in terms of total nutrient flux and their net rates are lower than those of the mudflats. Tidal marshes typically export dissolved nutrients, but may either import or export particulate nutrients (Nixon 1980; Jordan et al. 1983). The marshes of the Rhode River have accreted sediment at about the rate of sea-level rise over the past 150 years and have thus avoided submergence (Jordan et al. 1986b). The Rhode River mudflat has accreted at about twice the rate of sea-level rise and has therefore become shallower (Jordan et al. 1986b). Some tidal marsh systems receiving less sediment input than the Rhode River marshes have not accreted in pace with sea-level rise and have been subject to erosion and submergence (Baumann et al. 1984; Stevenson et al. 1985). In our system, sediment accretion can account for the amount of phosphorus retained (Jordan et al. 1983; Jordan and Correll 1991).

Despite the beneficial large retentions of nutrients in different ecosystems, especially the extensive riparian forests of the Rhode River landscape, approximately 7% of the phosphorus and 1% of the nitrogen inputs to the system are exported to the estuary (Fig. 4). Although small, these percentages represent major inputs to the already over-enriched Rhode River estuary. It also receives major nitrogen exchanges from the Chesapeake Bay (Table 7) and is near its assimilation capacity. It is therefore timely to assess how to reduce both nitrogen and phosphorus loadings to this estuary and to the Chesapeake Bay. Clearly, the structural characteristics of the landscape, such as the distribution of riparian forests adjacent to croplands and the extent of wetlands, are important in influencing nutrient throughput. The lessons learned from analysis of nutrient flow in the Rhode River watershed and estuary will be relevant to a large number of other tributary subestuaries of the Chesapeake and of other systems in the Atlantic coastal plain of North America.

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