NUTRIENT FLUX IN A LANDSCAPE:
THE RHODE RIVER WATERSHED AND RECEIVING WATERS

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Abstract--We present here a synthesis of our studies of nitrogen and phosphorus flux through a watershed and its receiving waters during a one year period (March 1981 to March 1982). The 2286 ha watershed consists of 62% forest, 23% cropland, 12% pasture, and 3% freshwater swamp. It drains into the tidal headwaters of the Rhode River, a subestuary of Chesapeake Bay. The 58 ha tidal headwaters consist of 40% subtidal mudflats and creeks, and 60% tidal marsh. We used automated sampling stations to monitor nutrient fluxes between the headwaters and the Rhode River, and nutrient fluxes from eight subwatersheds of differing land use compositions.

Croplands discharged far more nitrogen per hectare in runoff than did forests and pastures. Most of the nitrogen released by the croplands was absorbed by adjacent riparian forests. However, nutrient discharges from these riparian forests still exceeded discharges from pastures and other forests. The ratio of nitrogen to phosphorus leaving all forests was so low that nitrogen rather than phosphorus could limit phytoplankton growth in the receiving waters.

The freshwater swamp was a minor sink for nutrients. The tidal headwaters were a major sink for phosphorus due to sediment accretion in the subtidal area. The headwaters were also a sink for nitrogen in the year of this study, but were a source in other years.

Of the total non-gaseous nitrogen influx to the landscape, 31% was from bulk precipitation and 69% was from farming. Forty-six percent of the total non-gaseous nitrogen influx was removed as farm products, 53% either accumulated in the system or was lost in gaseous forms, and 1% entered the Rhode River. Of the total phosphorus influx to the landscape, 7% was from bulk precipation and 93% was from farming. Forty-five percent of the total phosphorus influx was removed as farm products, 48% accumulated in the system, and 7% entered the Rhode River.

INTRODUCTION

Hydrologically linked ecosystems interact through the flow of water-borne nutrients. Nutrients discharged from uplands pass through lowlands and through a series of aquatic ecosystems on their way to the sea. Understanding the dynamics of such nutrient flows requires knowledge of the effect of land use on nutrient discharge and of the effects of uphill ecosystems on downhill ecosystems.

Agricultural lands are sources of nutrient discharges from watersheds (Biggar and Correy, 1969; Omernik, 1976). Forests also release nutrients, but at lower rates than agricultural lands (Cooper, 1969; Likens and Bormann, 1974). In contrast, riparian forests (Peterjohn and Correll, 1984), flood plain forests, freshwater swamps (Brinson, 1984; Yarbro et al., 1984), and tidal marshes (Valiela et al., 1976) can act as nutrient sinks. Whether these systems do trap nutrients may depend on how much nutrient they receive from uphill systems. For example, riparian forests receiving nutrient influxes from adjacent croplands can retain much of the nutrients they receive (Peterjohn and Correll, 1984; Lowrance et al., 1984).

There have been many studies of nutrient flow through specific ecosystems, but few studies of nutrient flows through landscapes containing several ecosystems. In this paper we present a synthesis of our studies of nitrogen and phosphorus flux through a complex landscape containing many different hydrologically linked ecosystems.

STUDY SITE

The Rhode River estuary is located east of Washington, DC on the western shore of Chesapeake Bay. We studied the watershed which drains into a tidal creek at the head of the Rhode River estuary (Fig. 1). The 2286 ha watershed consists of 62% forest, 23% croplands, 12% pasture, and 3% freshwater swamp (Correll, 1977). The soils are fine sandy loams (Kirby and Mathews, 1973). The forests are deciduous and mostly of the tulip poplar association described by Brush (1980). The land we catagorized as cropland consists of 53% corn fields, 19% tobacco fields, and 28% residential land plus roads (Correll, 1977). The pastures are grazed primarily by beef cattle (Miklas et.

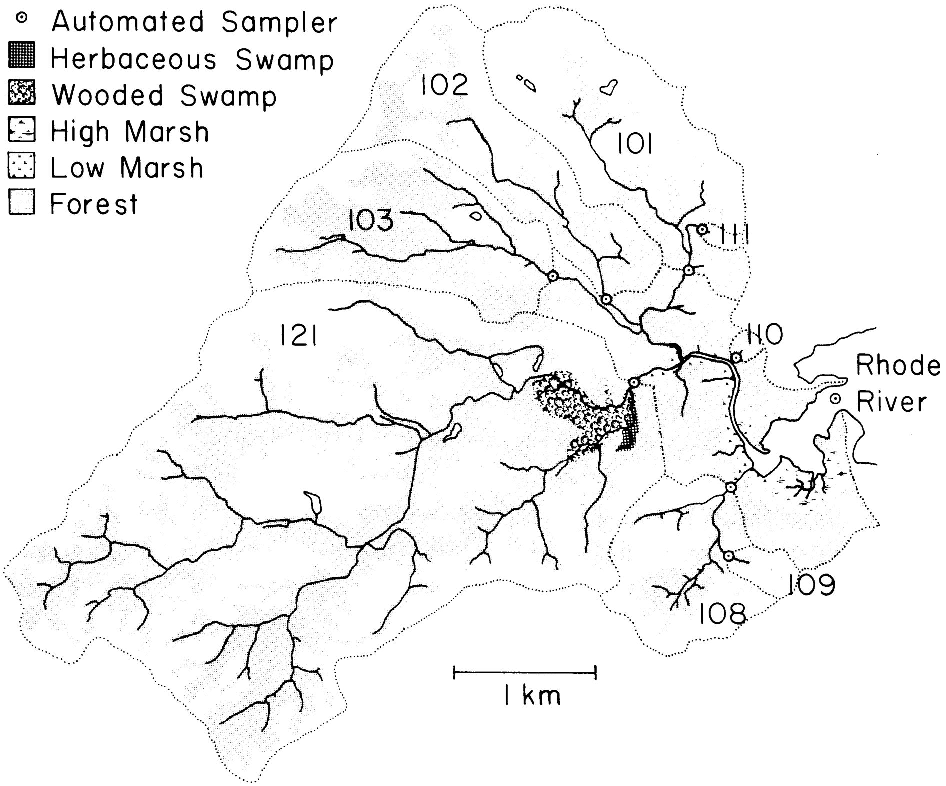

Fig. 1. The eight numbered subwatersheds and tidal headwaters where we measured nutrient fluxes. Dotted lines are watershed boundaries.

al., 1977). The freshwater swamp, Mill Swamp, includes wooded areas of the river birch-sycamore association (Brush, 1980) and an area covered by herbaceous plants and suffrutescent shrubs (Whigham et al., these proceedings).

The tidal creek at the head of the Rhode River estuary, includes 23 ha of subtidal mudflats and creeks and is bordered by 13 ha of tidal low marsh and 22 ha of tidal high marsh. The low marsh is about 30 cm above mean low water and is vegetated primarily by _Typha angustifolia_. The high marsh is about 42 cm above mean low water and is vegetated by _Spartina patens_ and many other species (Jordan et al., 1983). The mean tidal amplitude is 30 cm, but water level can fluctuate just as much due to weather conditions. The salinity in the estuarine headwaters ranges from 0 to 16 ppt.

METHODS

The watershed's aquifers are isolated from deeper aquifers by an underlying layer of clay, the Marlboro Clay (Chirlin and Schaffner, 1977). Natural drainage divides separate the watershed into several subwatersheds (Fig. 1). We monitored discharges of water and nutrients from eight of these subwatersheds totaling 2057 ha. Water samples and flow measurements were taken continuously by automated sampling stations (Correll, 1977 and 1981). The stations for seven of the subwatersheds employed V-notch weirs for flux measurements. The eighth subwatershed (number 121) was tidally influenced, so a tidal flume, a tide gauge, and an electromagnetic current meter were used for flux measurements. A similar sampling station located in a constricted channel between the headwaters and the rest of the Rhode River (Fig. 1) measured tidal flux in and out of the headwaters (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 volume-integrated samples were composited for weekly time periods. Samples for nutrient analysis were preserved with 1-3 ml per liter 15 N sulfuric acid. The analytical techniques we used are described by Correll (1981). Nutrient discharges from 229 ha of unmonitored watersheds were estimated from data on the monitored watersheds. Bulk precipitation was sampled and analyzed as described by Correll and Ford (1982). The study period ran from March 1981 to March 1982.

RESULTS

The subwatersheds differ in their percentages of forest, pasture and cropland (Table 1, Fig. 2). We regressed the annual nutrient discharges per hectare against the percentages of cropland and pasture (Table 1 and 2, Fig. 2). Both nitrogen and phosphorus discharges increased significantly as percent cropland increased, but did not vary significantly with percent pasture (Table 2). We used the regression equations to predict nutrient inputs to the freshwater swamp located at the bottom of watershed 121 (Fig. 1), then subtracted the measured discharge from watershed 121 to estimate the net nutrient exchanges in the swamp.

Extrapolating the regression suggests that pure cropland should discharge 7.53 kg N ha^{-1} yr^{-1}, but our previous studies of a small watershed containing mostly corn fields (watershed 109, Fig. 1,2) indicated that the corn fields discharged 39 kg N ha^{-1} yr^{-1} (Peterjohn and Correll, 1984). The discrepancy exists because the riparian forest between the corn fields and the stream retains most of the nitrogen it receives from the corn fields. Therefore, a watershed containing both cropland and riparian forest discharges less nitrogen than does the cropland itself. In contrast, extrapolating the regression assumes incorrectly that discharges from a watershed with both cropland and forest will equal the sum of discharges from the cropland and discharges from the forest. Therefore, to estimate nutrient discharges by the croplands

Table 1. Land uses and nutrient discharges for eight Rhode River subwatersheds.

Watershed	Area	Land use percentages			Discharge (kg ha^{-1} yr^{-1})	
	(ha)	Crops	Pastures	Forests	Nitrogen	Phosphorus
101	225.9	15.6	27.2	57.2	1.97	0.61
102	191.7	23.8	21.6	54.6	3.41	0.89
103	253.8	6.6	16.5	77.0	1.89	0.72
108	150.4	26.6	20.2	53.2	3.10	1.16
109	16.3	65.6	0	34.4	4.89	1.29
110	6.3	0.9	0	99.1	0.42	0.10
111	6.1	0	73.3	26.7	1.02	0.17
121	1228.8	28.9	8.9	62.3	2.17	0.69

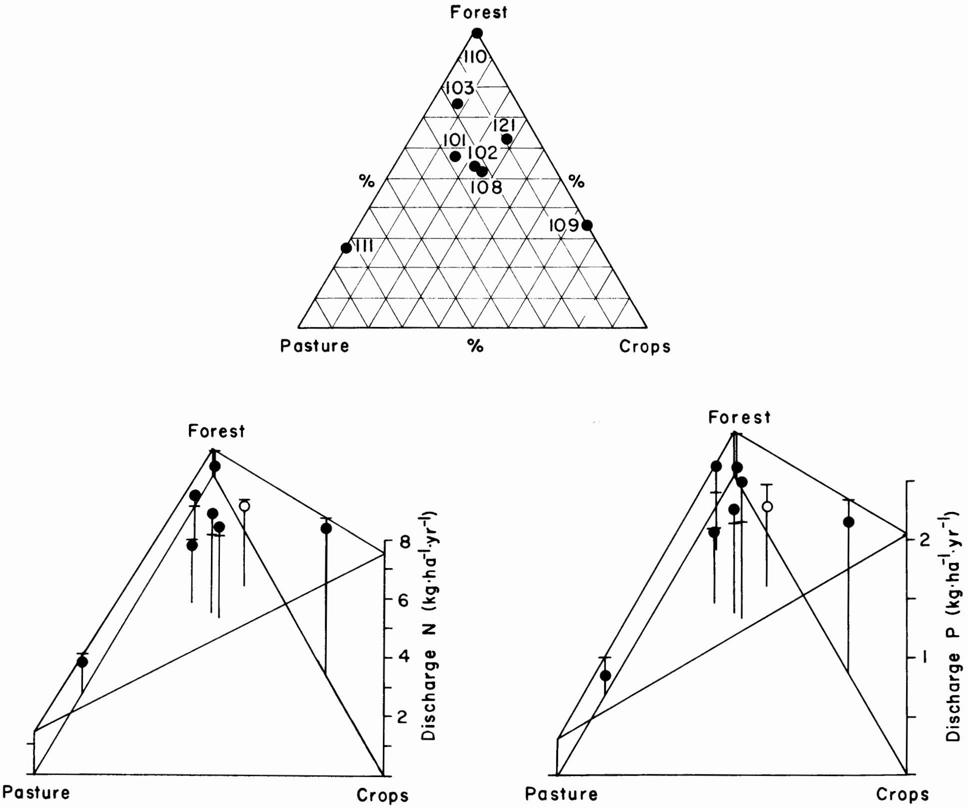

Fig. 2. Upper triangle: land use composition of eight numbered subwatersheds. Corners of triangles are 100% of indicated land use. Lower triangles: total nitrogen and phosphorus discharge plotted against land use percentages. Points represent measured discharges. Plane through points was fit by linear regression. Horizontal dashes indicate discharges predicted by the regression. Watershed 121 (open circle) was not used in the regression.

Table 2. Summary statistics for regression models.

Discharge kg N or P ha^{-1} yr^{-1} = A + B(fraction crop) + C(fraction pasture)

	Nitrogen			Phosphorus		
Parameter	Parameter Estimate	Standard Error	p^*	Parameter Estimate	Standard Error	p^*
A	0.98	0.47	0.108	0.39	0.23	0.161
B	6.55	1.20	0.005	1.66	0.58	0.045
C	0.51	1.11	0.672	-0.07	0.54	0.900
Model:	F = 17.6,	p = 0.010,	r^2 = 0.898	F = 5.46,	p = 0.072,	r^2 = 0.732

* for null hypothesis that parameter = 0

in our entire watershed, we have assumed that discharges from the corn fields of watershed 109 are representative of discharges by all of the croplands. We estimated the discharges from riparian forests bordering the croplands in our watershed from the regression equations assuming a 2:1 ratio of cropland to riparian forest as in watershed 109.

Data from Correll et al. (1984) suggests that the riparian forest bordering the pasture of watershed 111 (Fig. 1 and 2) does not absorb much of the nutrient input it receives from the pasture. Therefore, we felt it was reasonable to extrapolate the regressions (Fig. 2) to estimate the nutrient discharges from pure pasture. We also estimated discharges from pure forest by extrapolation. The discharges from watershed 110 (Fig. 1 and 2) which is nearly pure forest were lower than we would expect from extrapolation (Fig. 2), but we attribute this to the fact that most of the forest of watershed 110 is older than most of the forests in our watershed (Roberts, 1979).

We calculated nutrient fluxes in the tidal headwaters from our measurements of tidal exchanges between the headwaters and the Rhode River, and from our measurements of nutrient discharges from the watershed into the headwaters. We subtracted nutrient exchanges by the marshes (Jordan et al.,

1983) from net exchanges by the tidal headwaters to estimate nutrient exchanges by the subtidal areas. Figure 3 presents all of the measurements and estimates of between-ecosystem nutrient fluxes in a single flow diagram.

Croplands discharge by far the most nitrogen of any ecosystem in our watershed despite the fact that they cover less area than forests (Fig. 3). Most of the nitrogen leaving the croplands is intercepted by riparian forests. Nevertheless, these riparian forests discharge more nitrogen and phosphorus than other forests or pastures. Pastures, partly due to their small area, contribute very little to the total discharges of either nitrogen or phosphorus from the watershed.

The freshwater swamp acted as a sink for phosphorus and, to a lesser extent, for nitrogen (Fig. 3). Much of the phosphorus retained was trapped during a week when a severe storm caused high sediment discharges by the watershed. Thus, the trapping of phosphorus was probably the result of trapping sediment.

The tidal marshes had very little effect on the net flow of nutrients through the tidal headwaters (Fig. 3). In addition, the net effects of the low and high marshes were opposite and tended to cancel each other. In contrast, the subtidal area trapped large amounts of nutrients (Fig. 3). As with the freshwater swamp, much of the phosphorus trapping followed a severe storm. Net nitrogen flux in the subtidal area varied from year to year. In some years the subtidal area was a source rather than a sink for nitrogen (unpublished data). However, the trapping of phosphorus occurred consistently from year-to-year.

We calculated the total inflows of nutrients to each ecosystem by adding the inputs from bulk precipitation (13.7 kg N ha^{-1} yr^{-1}, 0.449 kg P ha^{-1} yr^{-1}), inputs from upstream parts of the watershed, and inputs from farming. We calculated the total outflows by adding nutrient discharge downstream and nutrient removals by farming. Farming inputs to pastures were 52 kg N ha^{-1} yr^{-1} and 10 kg P ha^{-1} yr^{-1} and outputs were 31 kg N ha^{-1} yr^{-1} and 4.5 kg P ha^{-1} yr^{-1} (Correll et al., 1977; Miklas et al., 1977). Farming exchanges for cropland were assumed equal to those for the corn fields of watershed 109, with inputs of 105 kg N ha^{-1} yr^{-1} and 20 kg P ha^{-1} yr^{-1}, and outputs of 71 kg N ha^{-1} yr^{-1} and 10 kg P ha^{-1} yr^{-1} (Peterjohn and Correll, 1984). In the case of the tidal marshes, nutrients entering with the flood tide were considered

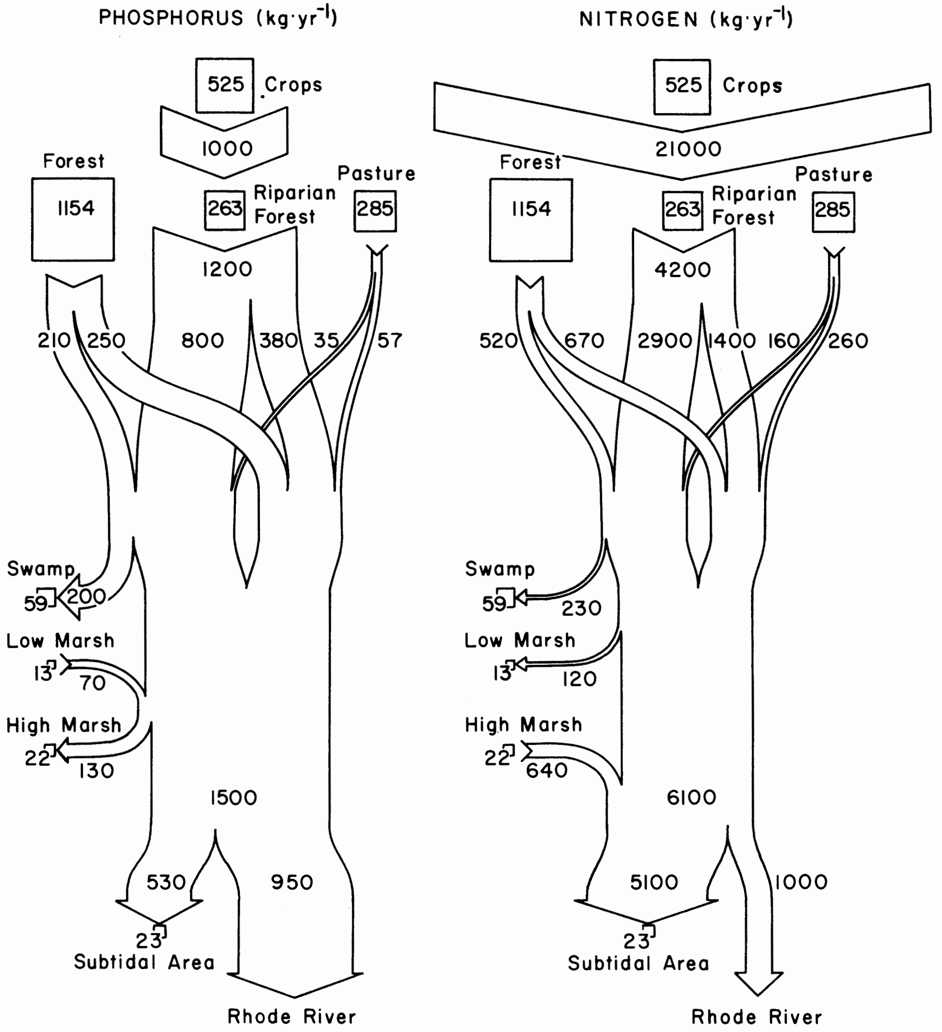

Fig. 3. Net total nitrogen and phosphorus fluxes, kg yr^{-1}, indicated by numbers in arrows. Numbers in boxes are areas in hectares of each ecosystem type. Watershed fluxes are split according to whether they go through the swamp or directly to tidal waters. Fluxes in tidal waters are net tidal exchanges.

part of the inflow, and nutrients leaving with the ebb tide part of the outflow. Our measurements of nitrogen flow refer only to non-gaseous forms.

Inflows of nutrients generally exceed outflows in most of the ecosystems we studied (Fig. 4). This is especially marked for non-gaseous nitrogen flows in the forests. However, phosphorus inflows to the forests are about equal to outflows. In contrast to forests, croplands are more retentive of phosphorus than of nitrogen. In the freshwater swamp and pastures, nitrogen retention is roughly proportional to phosphorus retention. The low and high tidal marshes behaved oppositely to each other, with one retaining a given nutrient while the other released it.

Differences in nitrogen and phosphorus flows result in differences in the N:P ratios of nutrients entering and leaving an ecosystem. For example, the molar N:P ratio of nutrients entering the forests is greater than 40 but the N:P ratio of nutrients discharged from the forests is less than 10 (Fig. 5). In contrast, the trend for croplands is exactly opposite, with the discharged nutrients having a higher N:P ratio. However, the relatively nitrogen rich discharge from croplands enters riparian forest where much of the nitrogen is

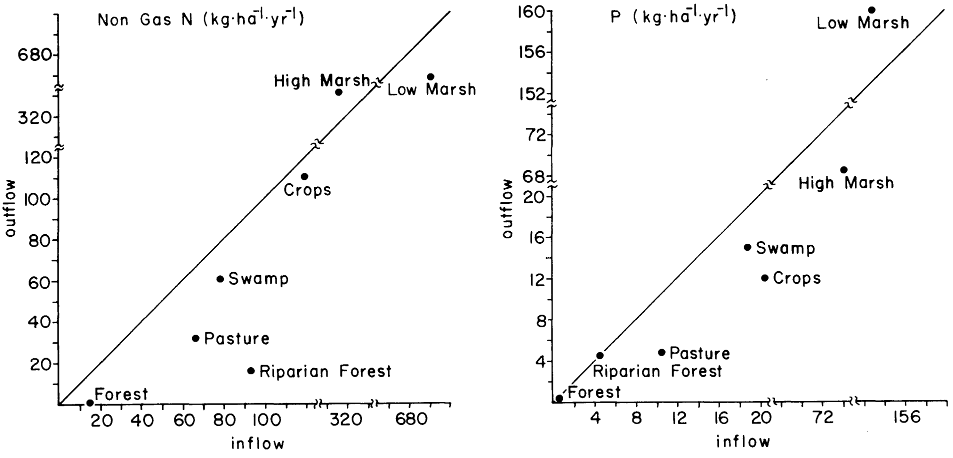

Fig. 4. Total outflow versus total inflow of non-gaseous nitrogen and phosphorus for various ecosystems. The line of equality is shown. Riparian forest refers to forest between croplands and streams.

retained. Consequently, the discharge from the riparian forests is relatively nitrogen poor. By the time the nutrients leave the watershed and enter the tidal waters the N:P ratio has dropped to 10 or less (Fig. 5). At such a low ratio, nitrogen rather than phosphorus would potentially limit phytoplankton growth (Redfield, 1958). The trends are even more pronounced for the N:P ratios of inorganic nutrients, those most readily available for plant growth (Fig. 5).

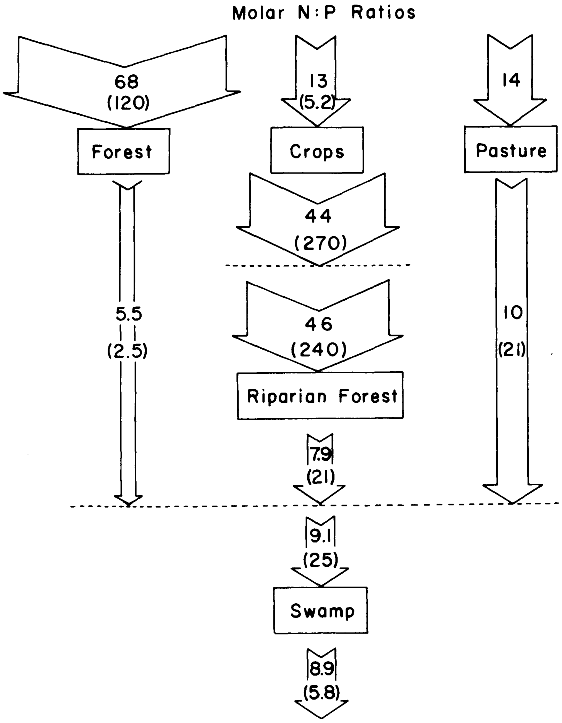

Fig. 5. Molar N:P ratios of nutrients entering ecosystems and of nutrients discharged to the watershed. Nutrients entering a system include inputs from precipitation and from farming as well as from upstream systems. Widths of arrows are proportional to ratios for total nutrients shown without parentheses. Ratios for inorganic nutrients are in parentheses. Most of the discharge from forests, riparian forests, and pastures flows directly to tidal waters without passing through the swamp.

Examining nutrient flux through the entire landscape of watershed plus tidal headwaters, we find that farming provides the largest input of nitrogen and phosphorus (Fig. 6). Bulk precipitation provides less than one tenth of the total input of phosphorus but about a third of the total input of nitrogen. Harvesting of farm products removes slightly less than half of the total inputs of nitrogen and phosphorus. Most of the rest of the inputs accumulate in the landscape or are lost as gaseous forms. Only 1% of the nitrogen and 7% of the phosphorus entering the landscape is discharged to the Rhode River.

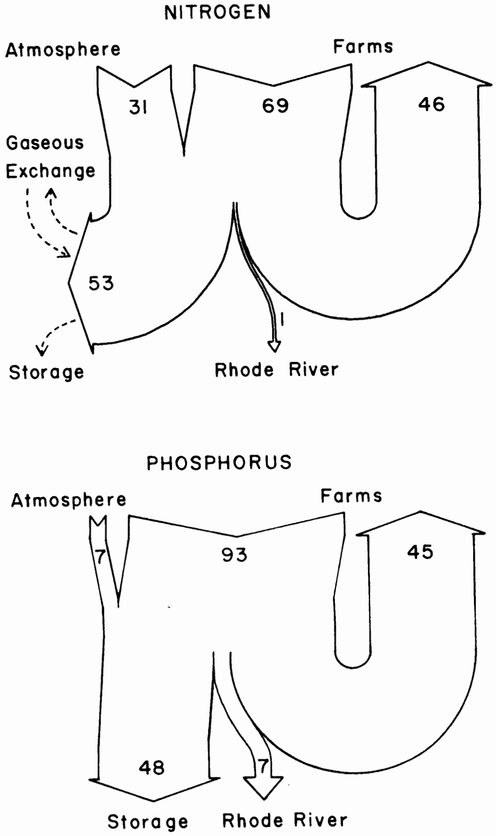

Fig. 6. Non-gaseous nitrogen and phosphorus fluxes through the entire landscape as percentages of the total input.

DISCUSSION

Since our automated stations sample discharges from areas containing more than one type of ecosystem, we had to deduce the behavior of individual ecosystems. Comparing our results to results of studies of single ecosystems, we find both similarities and differences. For example, our multiple regression models indicate that our forests discharge less nitrogen and more phosphorus than do most forests reviewed by Beaulac and Reckhow (1982). Thus, the N:P ratio of nutrients discharged from our forests is relatively low.

Nutrient release by forests is generally thought to be related to age or amount of disturbance. Young or highly disturbed forests release the most nutrients, old forests release less, and intermediate aged forests release the least (Bormann and Likens, 1979). Watershed 110 (Fig. 1), which consists almost entirely of very old forest (Roberts, 1979), discharged much less nitrogen and phosphorus than the average forest in our regression model (Fig. 2). Soil type may also influence phosphorus discharge. Dillon and Kirchner (1975) found that watersheds with soils of sedimentary origin, like ours, discharged more phosphorus than those with soils of igneous origin. Our forests discharge less nitrogen and phosphorus than they receive in precipitation as do most forests (Likens et al., 1977).

Nutrient releases from forests are generally less than releases from croplands. Others have found, as we did, that nutrient discharge from watersheds increases as the percentage of cropland increases (Fig. 2; Likens and Bormann, 1974; Omernik, 1976). However, the amounts of nutrients released by croplands differ greatly even among lands with the same crop. This is partly due to the variety of farming methods. For example, nutrient budgets have been published for corn fields with farming inputs ranging from 0 to 448 kg N ha^{-1} yr^{-1} and 0 to 81 kg P ha^{-1} yr^{-1}, and watershed discharges ranging from 1 to 72 kg N ha^{-1} yr^{-1} and 0.02 to 19 kg P ha^{-1} yr^{-1} (Beaulac and Reckhow, 1982). The nutrient budgets for the corn field we studied fit within these broad ranges. Frissel (1977) reviewed data from many kinds of arable land and found that, when farming inputs of nitrogen were less than 150 kg N ha^{-1} yr^{-1}, farming outputs were about 66% of the inputs. In comparison, our corn field returned 68% of the nitrogen investment.

Our regression models indicated that pastures release nutrients at rates more like those of forests than those of croplands (Fig. 2). Similarly, Beaulac and Reckhow (1982) found that pastures exhibited a wide range of nutrient discharges overlapping the range of discharges from forests. However, nitrogen discharge from our pastures is lower than that from most pastures (Beaulac and Reckhow, 1982). This may represent a real difference or it may be an error due to extrapolating our regression model. As we have mentioned, such an extrapolation would underestimate nitrogen discharge by croplands because riparian forests retain most of the nitrogen the croplands release. An earlier study suggested that the riparian forests adjacent to our pastures trap little or no nitrogen (Correll et al., 1984), but further research is needed to confirm this.

Riparian forests bordering croplands are major nitrogen sinks, but it is not clear if they are phosphorus sinks as well. In our watershed 109, measurements of phosphorus concentration in surface and ground water along transects from the corn fields into the riparian forest suggest that the riparian forest traps most of the phosphorus it receives in surface runoff but releases phosphorus in ground water (Peterjohn and Correll, 1984). Discharge of phosphorus from the whole watershed measured at a weir was about equal to the estimated discharge from the corn fields (Peterjohn and Correll, 1984) suggesting that, overall, the riparian forest traps very little phosphorus. Our estimates of between-ecosystem nutrient fluxes (Fig. 3) reflect the weir data although we are uncertain whether the riparian forests are phosphorus sinks. Others have found that riparian forests near croplands are sinks for both nitrogen and phosphorus (Lowrance et al., 1984; Yeats and Sheridan, 1983; Cooper et al., these proceedings).

We found that the fresh water swamp was a sink for 17 kg N ha^{-1} yr^{-1} and 3.8 kg P ha^{-1} yr^{-1}. Similarly, Yarbro et al. (1984) found 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 ammonia and phosphate while 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. Although several studies have shown swamps to be nutrient sinks, Elder et al. (1985) found that a flood plain in Florida was a source of nitrogen, phosphorus and particulate detritus.

The tidal marshes in our landscape were not very important in net nutrient fluxes (Fig. 3). This is due to their small areas and the fact that the marshes import particulate nutrients and export dissolved nutrients, resulting in little net flux (Jordan et al., 1983). Tidal marshes typically export dissolved nutrients, but may either import or export particulate nutrients (Nixon, 1980; Jordan et al., 1983).

The subtidal area was an important sink for phosphorus and nitrogen in the year of this study (Fig. 3). In other years, however, it was a source of nitrogen (unpublished data), so it may not be an important long-term nitrogen sink. The subtidal area is a long-term sink for sediment though (Jordan, Pierce and Correll, in prep.), and accretion of sediment can account for the amount of phosphorus trapped (Jordan et al., 1983).

In conclusion, croplands were the dominant nutrient sources in our landscape although they cover only 23% of the area. Most of the nitrogen released by croplands is retained by adjacent riparian forests. Therefore, the ratio of nitrogen to phosphorus discharged by these riparian forests was relatively low (<10). The N:P ratio of nutrients discharged by other forests was similarly low. As a result, nitrogen rather than phosphorus could limit phytoplankton growth in the receiving waters. Sediment accretion in the subtidal area of the receiving waters was the major sink for phosphorus.

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DISCUSSION: Jordan Paper

Question (Gilliam): How did you obtain your nutrient budgets coming off your agricultural lands? How did you calculate your agricultural land inputs?

Answer: For the cropland and the pastureland we used surveys of the farmers to determine how much nutrients were added in the fertilizer and how much were removed in farm products. For the discharge from croplands we relied on measurements from one particular watershed. There we measured the discharge from the cornfields using surface water collectors and a series of wells arranged in transects from the cornfields into the riparian forest.

Question (Gilliam): How did you get your water flow from the series of wells? How do you know how much went that way?

Answer: We looked at the hydrographs from the stream weir at the bottom of the watershed. You can separate out surface water flow from groundwater flow using a graphical method.

Question (Gilliam): I assume that your losses of phosphorus from the field are as dissolved phosphate?

Answer: Most of the phosphorus moving through that system really is associated with sediment. Some of this gets stopped by the riparian zone so there is some trapping.

Quesion (Gilliam): Did I misinterpret your data? I thought you said you get very little phosphorus trapped there and much of the nitrogen was trapped.

Answer (Peterjohn): We had quite a bit of trapping of sediment and particulate-associated phosphorus in the surface runoff. However, some dissolved phosphorus is lost in subsurface discharge.

Comment (Jordan): So maybe what you are seeing is a trapping of particulate phosphorus in the riparian zone followed by a slow conversion of some of the phosphorus to dissolved forms which eventually make their way out past the weir.

Comment (Gilliam): I think this is a surprise, Dave. I am just trying to figure out why your observations are so different from ours in North Carolina.

Comment (Correll): The groundwater in the riparian zone quite often goes anoxic in the summer, and I think that has a lot to do with this question. When it is anoxic or alternately anoxic at times you do get more phosphorus released in the groundwater.

Question (Alaback): You said the input of nutrients for the forest came primarily from the atmosphere. I was wondering why, or did you have data on weathering and inputs from soil? Is that an important property?

Answer: It may be quite important. Your saying that there could be weathering going on in the forest's soils, and we think that is happening. This is just of a semantic problem. I don't think that is an input because the material is already there. But, yes that may be an important source of nitrogen for the plant life.

Question (Meisinger): You were a little concerned about being able to measure groundwater flux going directly into the tidal marshes. I am surprised to see your marshes play such a small role. Do you have some idea of how much groundwater is flowing into those marshes directly?

Answer: We think there is a negligible amount of groundwater directly entering the marshes. When you get to the marshes you are in a brackish water area. If you look at the salinity of the water entering the marsh with the flooding tide vs ebbing from the marsh there is no change in salinity. So there is very little direct entry of groundwater into the marshes. What they are receiving is nutrients from tidal water and ultimately from the watershed.

WATERSHED RESEARCH PERSPECTIVES

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