Marine Biology 35, 359-373 (1976)


# Flows of Materials between Poorly Flooded Tidal Marshes and an Estuary*

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Abstract

Flows of particulate carbon, nitrogen, phosphorus, chlorophyll *a*, crude fiber, carbohydrate, and adenosine tri-phosphate; and of dissolved nitrogen and phosphorus between a marsh and the Patuxent estuary, Maryland, USA, were measured over a 2-year period. Virtually no carbon was exchanged, while net flows of nitrogen and phosphorus were from the marsh to the estuary, principally in dissolved forms.

## Introduction

Previous studies of the Patuxent River estuary suggested that there was substantial production of a copepod, *Eurytemora affinis*, and insufficient primary production to supply the requirements for energy of that species (Heinle and Flemer, 1975). The upper portion of the Patuxent River estuary is bordered by 19.1 $km^2$ of tidal marshes with an annual areal production of 1,000 to 1,500 g $m^{-2}$ $year^{-1}$ of ash-free dry weight (Heinle et al., 1974). With a probable carbon content of 45% (Keefe and Boynton, 1973), this production represents a large potential source of carbon to the adjacent estuary.

There are several sources of detritus in estuaries. Most of the European work (e.g. Fenchel, 1972) has been on detritus derived from submerged rooted plants. Allochthonous material of upland origin is the largest single source of carbon in the upper Chesapeake Bay (Biggs and Flemer, 1972). In most North American mid-Atlantic estuaries, fringing salt marshes are a major source of detritus. Teal (1962) calculated that 45% of the annual production of a Georgia salt marsh was exported to the adjacent estuary. There was some export of detritus throughout the year, with greatest amounts in the fall (de la Cruz, 1965). The relative importance of marshes and primary production in open waters has been assessed in North Carolina marshes (Williams, 1966; Williams and Murdoch, 1969), where the marshes occupy 5.9% of the estuarine area but provide 22.9% of the total net primary production. In the same estuaries, benthic organisms were suspected to be the major consumers of primary production (Williams *et al.*, 1968). Mangrove swamps also contribute to detrital food webs (Odum, 1970).

Tidal marshes have also been suggested as sinks, or at least buffers, in the nutrient cycles of estuaries, particularly phosphorus (Ho *et al.*, 1970; Pomeroy *et al.*, 1972), and have been known to retain added nutrients (Valiela *et al.*, 1973; Sullivan and Daiber, 1974). Axelrad (1974) measured exchanges between marshes and an estuary at two sites having mean high water salinities of 7 and 12‰. He found evidence for fixation of molecular nitrogen on the marsh and tidal import of particulate nitrogen and phosphorus to the marsh. There was export of dissolved inorganic and organic phosphorus, ammonia, and organic nitrogen from the marsh.

In order to better understand the role of tidal marshes of low salinity and low tidal amplitude in estuarine ecosystems, we have estimated the flows of particulate carbon, and dissolved and particulate nutrients between the estuary and the surrounding marshes over a 2-year period. Particulate material is

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defined by us as that retained by a Whatman® 2 µm GF/C filter (see Paerl, 1974).

The salinity of the upper Patuxent River estuary in Maryland ranges from freshwater at Hills Bridge to 5 to 14‰ at Hallowing Point, varying seasonally (Heinle and Flemer, 1975, their Fig. 1). The bordering marshes in the more saline areas typically have dense stands of the giant cordgrass *Spartina cynosuroides* along their outer margins and along creek banks, forming low levees that somewhat isolate back portions of the marshes. Vegetation behind the *S. cynosuroides* is generally dominated by the three-square *Scirpus Olneyi* or the cattail *Typha* sp. Muskrats, *Ondatra zibethica macrodon*, are common on most marshes in the area.

Marshes in freshwater have no levees and are generally wetter. Bordering vegetation is usually *Peltandra* sp. or *Pontederia* sp., more succulent forms. Species with dense root mats, *Zizania aquatica* and *Phragmites communis*, occur on higher parts of these marshes.

For a more complete description of the estuary see Herman *et al.*, (1968), and references cited therein, and Heinle and Flemer (1975).

## Materials and Methods

### *Study Area*

A privately owned marsh, Gotts' marsh, fringing the upper Patuxent estuary was selected as a study site (Fig. 1). The marsh is located 2 km south of Lower Marlboro, Maryland, on the east shore of the Patuxent estuary. A key feature of the marsh was the presence of a relatively narrow (6 m at the mouth) tidal slough, Middle Creek, with no apparent upland source of water. A bridge was constructed near the mouth of the creek to enable the taking of samples without disturbing bottom sediments by boat traffic during low water levels. The total extent of Gotts' marsh was estimated to be 1.27 km$^2$. The area drained by the tidal slough (Fig. 1) is about 0.33 km$^2$. The dominant vegetation on the marsh was typical of low-salinity Patuxent marshes (Fig. 1). Dominant species were *Spartina cynosuroides, Scirpus Olneyi, Typha angustifolia, T. latifolia, Pontederia cordata*, and *Peltandra virginica*. Annual tidal amplitude is about 1.3 m. Salinity in the adjacent estuary ranges from 0 to (rarely) 9‰, and is usually below 5‰ (Herman *et al.*, 1968; Heinle and Flemer, 1975). The marsh has an abundant population of muskrats, *Ondatra zibethica madrodon*. There have been minor modifications of the marsh; a dredged pond, shown as a wide place just below Station 7 in the slough (Fig. 1), and an associated weir for control of the water level in the upper part of the marsh.

Marshes on the upper part of the Patuxent at Jug Bay (Station 4 of Heinle and Flemer, 1975) are somewhat different in their character. Tidal creeks are broad and shallow, and the borders of the marshes are vegetated by *Peltandra* sp., *Pontederia* sp., and lack levees (Heinle *et al.*, 1974). Species with dense root mats, such as *Zizania aquatica* and *Phragmites communis*, occur on these marshes but generally not adjacent to open water.

### *Measurement of Exchange of Water and Sampling*

Water samples were pumped hourly except at slack tide from about 10 cm below the surface and 10 cm above the bottom from the center of Middle Creek with a Teel® No. 1P646 battery-operated submersible pump and collected in polyethylene carboys. When the tide heights were less than 0.5 m only a single sample was collected. Sampling was done over 13 h on each date except once when samples were collected for 25 h. Unless specified otherwise, all unfiltered samples, the filtrate, and GF/C glass-fiber filters used in all of the chemical analyses were frozen over dry ice and returned to the laboratory. Samples obtained from the polyethylene carboys were shaken well before aliquots were removed.

Exchanges of water were estimated by measuring current velocities at one to four points in Middle Creek under the bridge we constructed near the mouth (Fig. 1). The number of measurements, usually 4, decreased with decreasing tidal height. The current meter described by Byrne and Boon (1973), calibrated periodically in a hydraulic flume, was used to estimate velocities. Individual measurements of velocity were multiplied by the cross sectional area represented by each respective sampling point to estimate volumes of flow, which were then summed to obtain total flow.

During most of the first year's study of fluxes we did not possess a working current meter. Flows of those sampling dates were estimated from data obtained from several intensive samplings during the summer of 1973 by a graphical method relating tide height (from a tide staff or recording gauge) and change in tide height per hour to volume flow (see "Results" for details).

### *Analytical Methods and Exchange of Materials*

Samples of chlorophyll *a* were collected on Whatman® GF/C filters and the chlorophyll *a* was estimated fluorometrically with a Turner fluorometer (Yentsch and Menzel, 1963; Holm-Hansen *et al.*, 1965) as modified by Flemer *et al.* (1970).



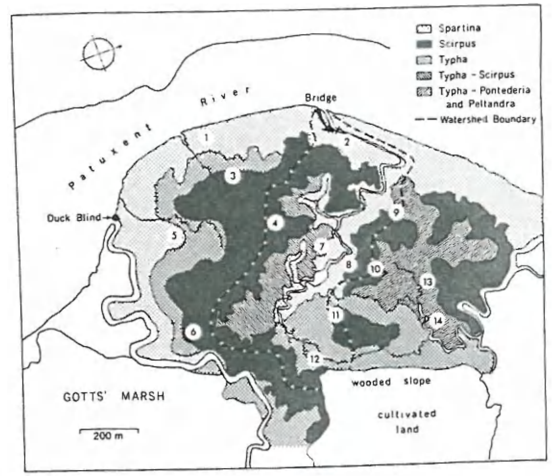


Fig. 1. Vegetation map of Gotts' marsh. Approximate boundary of the watershed of Middle Creek is shown as dashed line. Station numbers refer to sites where biomass was sampled by Heinle *et al.* (1974). Water samples were collected from the bridge near the mouth of Middle Creek. Distribution of dominant vegetation (*Spartina cynosuroides, Scirpus Olneyi, Typha angustifolia* and *T. latifolia, Pontederia cordata, Peltandra virginica*) is shown

Seston, or total suspended material, was determined on tared GF/C filters after drying to a constant weight over silica gel.

Particulate carbon was determined by the method of Menzel and Vaccaro (1964) using a Beckman Model IR 215 infrared analyzer and a Coleman CHO analyzer. Particulate nitrogen was determined with a Coleman Model 29A nitrogen analyzer equipped with a Model 29 combustion tube and syringe. Particulate carbohydrate and crude fiber analyses followed the procedure of Strickland and Parsons (1968).

Total phosphorus was determined with the oxidation method of Menzel and Corwin (1965). The same method was used to oxidize dissolved organic phosphorus materials after passing the same through a GF/C filter. Dissolved inorganic reactive phosphorus was determined with the composite reagent method (Strickland and Parsons, 1968).

Ammonia nitrogen determination followed the procedure of Solórzano (1969). Nitrate and nitrite nitrogen were analyzed by the method of Strickland and Parsons (1965). Soluble organic nitrogen was determined by difference between the inorganic forms and total dissolved nitrogen measured by a modification of the ultraviolet-light oxidation technique of Strickland and Parsons (1968). A half-strength seawater solution was used as the solvent for the blanks, ammonium sulfate and pyridine standards. The seawater solution was made according to Strickland's and Parson's (1968) nitrate method, then diluted by one-half with double-distilled, deionized water. This solution was used to dilute river-water samples and to add salts to facilitate the ultraviolet oxidation, since incomplete oxidation occurred in the absence of salt. We diluted 20 ml of river-water sample to 100 ml with half-strength seawater. Two drops of 30% hydrogen peroxide were added to the sample in a quartz tube, the sample capped, and irradiated 7 cm from a 1,200 W Hanovia-Englehardt 189A lamp for 3 h. Strickland and Parsons' (1968) procedure was followed for the remainder of the analysis.

Samples from 25 ml of water were collected on 0.45 um Millipore® filters for analysis of adenosine tri-phosphate (ATP). Extraction was done immediately in the field according to the method described in Strickland and Parsons (1968). As the waters sampled were of low salinity, we added 0.014 M $MgSO_4$ to the tris buffer after Ferguson and Murdoch (1975), as higher extractions were obtained when salt was added.

Dissolved organic carbon was analyzed with a Dohrmann Model DC-50 organic carbon analyzer. This instrument was found to be relatively insensitive to the concentrations of dissolved organic carbon we encountered.

Analytical errors experienced in our laboratory range from less than 1 to 5% (1 standard deviation) of mean concentrations for the nitrogen fractions, and from 3 to 18% of mean concentrations for the phosphorus fractions.

Actual exchanges of materials on each sampling date were initially calculated by multiplying the averaged (surface and bottom at the beginning and end of an interval) concentrations of the materials by the estimated volume of flow for each hourly interval. Total exchanges per tidal cycle were determined from the differences of quantities or materials entering and leaving the marsh. As differences in volumes exchanged on ebb and flood tides occurred, due to differences in beginning and ending tide heights, we calculated net monthly exchanges of materials by multiplying the total monthly tidal volume of the marsh as estimated from the 24 sampling trips by the time and volume-weighted mean concentration of each variable on flood and ebb tides (see "Results" for further details). Since the time and volume-weighted mean concentrations of the variables measured reflect any errors that might have occurred in estimating or measuring volumes of flow, the first year's data, except for March and June, should be viewed with some caution as flows were estimated from later data rather than measured.

The areal extent of all marsh types was measured by polar planimetry of photographic prints made from negatives kindly provided to us by the National Aeronautics and Space Administration, Langley, Virginia.

## Results

Flows were estimated monthly from July, 1972 to June, 1974 with the exception of January and February, 1974, when no samples were taken in January and two in February (Table 1). The extra sampling in February was an attempt to sample during a predicted abnormally high tide. The tide (7 February) was not unusually high. During the first year's sampling there were generally residual flows out of the marsh while there were usually residual flows into the marsh during the 1973-1974 sampling. Residuals, a net difference in volumes of flow on flood and ebb tides, can occur in two ways: as a result of a difference in tide level at the beginning and end of sampling, and as a consequence of a source of water (rainfall or groundwater) within the system. Because of the mixed semidiurnal tides and strong meteorological influence in Chesapeake Bay, we found predictions of tide height to be relatively inaccurate. Beginning and ending tide heights during our study were seldom the same. As a consequence, there were usually residuals due to differences in tide height. The averages of beginning and ending tide heights for all 24 sampling dates were nearly alike however, 0.643 and 0.650 m, respectively (Table 1), so for the entire study the net residual due to differences in tide heights should be near zero. The tidal volume of Middle Creek ranged from 2,000 to about 10,000 $m^3$ when high tides were below mean high water (about 1 m on our relative scale). We found tidal volumes up to 27,000 $m^3$ when high tides exceeded 1 m (Table 1). The total net residual flow during the cycles sampled was 36,686 $m^3$ out of the marsh. Rainfall (measured at Solomons, Maryland, about 40 km south of the study site) converted to volume, accounted for 19,381 $m^3$, leaving 17,302 $m^3$ unaccounted for (Table 1). This volume, spread evenly over the study period, amounts to a flow of 55.5 $m^3/h^{-1}$, a flow that would be barely perceptible at low tide. Hourly flows were frequently from 1,000 to 6,000 $m^3$ at higher tide levels. The 55.5 $m^3/h^{-1}$ could easily be achieved by groundwater seepage along the landward margin of the marsh. Large residuals occurred at times in the absence of rainfall or differences in tide height. On August 15, 1972 and January 17, 1973, for example, there were virtually no differences between beginning and ending tide heights and no rainfall during the preceding day. On both occasions, the estimated residual out of the marsh was about 4,000 $m^3$. Had we measured rainfall at the study site discrepancies of this sort might have been explained.

Velocity measurements were made only during March and June in the first year's sampling. To estimate mass flows on dates when no velocity measurements were



Table 1. Tide height and volumes exchanged between Middle Creek and Patuxent estuary. Precipitation volumes were calculated from rainfall at Solomons, Maryland, and a marsh surface area of 328,604 $m^2$. Negative signs indicate residual flows out of marsh and positive signs residual flows into marsh

| Date | Observed tide height (m) | | | | Volume flow ($m^3$) | | | Volume ($m^3$) |
|---|---|---|---|---|---|---|---|---|
| | Begin | End | High | Low | Ebb | Flood | Residual | Precipitation (Prec. day ÷ 2) |
| 1972 | | | | | | | | |
| 18 July | 0.91 | 0.97 | 1.02 | 0.42 | 10,255 | 9,620 | - 635 | 458 |
| 15 Aug. | 0.92 | 0.91 | 0.92 | 0.40 | 9,150 | 4,800 | - 4,350 | 0[c] |
| 12 Sept. | 0.94 | 0.84 | 0.94 | 0.35 | 13,700 | 4,040 | - 9,680 | 0 |
| 17,18 Oct.[a] | 0.70 | 0.17 | 0.85 | 0.17 | 12,430 | 4,490 | - 7,940 | 0 |
| 21 Nov. | 0.24 | 0.51 | 0.87 | 0.22 | 9,915 | 4,670 | - 5,245 | 7,095 |
| 20 Dec. | 0.21 | 0.44 | 0.87 | 0.14 | 5,705 | 4,310 | - 1,395 | 99 |
| 1973 | | | | | | | | |
| 17 Jan. | 0.38 | 0.37 | 0.95 | 0.32 | 10,550 | 7,050 | - 3,500 | 0 |
| 27 Feb. | 0.46 | 0.61 | 0.76 | 0.46 | 5,100 | 3,700 | - 1,400 | 168[c] |
| 22 Mar. | 0.93 | 0.76 | 0.87 | 0.46 | 9,300 | 4,100 | - 5,200 | 2,713 |
| 25 Apr. | 1.06 | 1.01 | 1.13 | 0.66 | 24,350 | 17,110 | - 7,240 | 710 |
| 24 May | 0.88 | 0.97 | 1.15 | 0.61 | 18,790 | 19,600 | + 800 | 0 |
| 19 June | 0.99 | 0.83 | 0.99 | 0.43 | 14,370 | 3,500 | -10,870 | 4,507 |
| 12 July | 0.50 | 0.43 | 0.75 | 0.39 | 5,510 | 3,085 | - 2,425 | 0[c] |
| 14 Aug. | 0.60 | 0.75 | 1.07 | 0.49 | 13,940 | 19,124 | + 5,184 | 877 |
| 12 Sept. | 0.70 | 0.61 | 0.89 | 0.46 | 9,976 | 6,038 | - 3,938 | 0 |
| 24 Oct. | 0.52 | 0.62 | 0.97 | 0.39 | 6,283 | 7,729 | + 1,446 | 0 |
| 20 Nov. | 0.85 | 0.91 | 0.91 | 0.46 | 4,230 | 6,482 | + 2,252 | 0 |
| 31 Dec. | 0.98 | 1.22 | 1.22 | 0.54 | 13,161 | 27,317 | +14,156 | 0[c] |
| 1974 | | | | | | | | |
| 7 Feb.[b] | 0.33 | 0.36 | 1.03 | 0.33 | 9,635 | 13,976 | + 4,341 | 2,754 |
| 21 Feb.[b] | 0.57 | 0.64 | 0.93 | 0.30 | 4,545 | 6,188 | + 1,643 | 0 |
| 19 Mar. | 0.20 | 0.27 | 0.73 | 0.20 | 2,199 | 2,806 | + 607 | 0 |
| 17 Apr. | 0.28 | 0.30 | 0.78 | 0.28 | 2,494 | 3,376 | + 882 | 0 |
| 16 May | 0.48 | 0.27 | 0.80 | 0.27 | 3,325 | 1,936 | - 1,389 | 0[c] |
| 6 June | 0.89 | 0.84 | 0.92 | 0.49 | 11,111 | 8,324 | - 2,787 | 0[c] |
| Total | | | | | 230,024 | 193,351 | -36,683 | 19,381 |
| Average | 0.643 | 0.650; difference between net residual flow and rainfall volume = 17.302 | | | | | | |

[a]24 h (two-tidal cycles).

[b]Note no sample during January, two during February.

[c]Rainfall occurred during preceding 5 days.

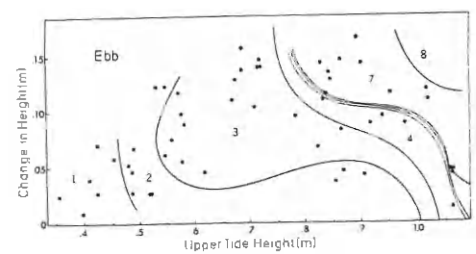


Fig. 2. Flow characteristics of Middle Creek at ebb tide. 1: 0 to 500; 2: 500 to 1,000; 3: 1,000 to 2,000; 4: 2,000 to 3,000; 5: 3,000 to 4,000; 6: 4,000 to 5,000; 7: 5,000 to 6,000; and 8: 6,000 to 7,000 $m^3$ of water per h

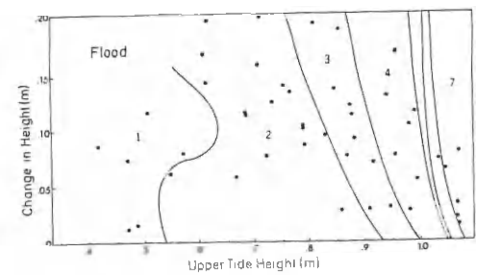


Fig. 3. Flow characteristics of Middle Creek at flood tide. Volumes marked as in Fig. 2

made we constructed two figures plotting volume flow ($m^3$ $h^{-1}$) against two independent variables: change in tide height, and upper tide height during hourly intervals. The flow characteristics during ebb tide (Fig. 2) are somewhat different than during flood tide (Fig. 3). During ebb tide, large volume flows occurred at lower tide heights and with less change in height than during flood tide. This was generally a consequence of the fact that on most occasions there was a net flow (residual) out of the marsh. The hourly tide staff, or recording tide gauge, readings were used to estimate volume flow for each 1-h interval from Figs. 1 and 2 on those dates when no velocities were measured. The tidal volume of the marsh appears to range between 4,000 and 27,000 $m^3$ based on estimated volumes of exchange (Table 1).

We observed that the general surface of the marsh was flooded only when tides exceeded 1 m on our relative scale. This occurred on only 6 of our sampling dates (Table 1). On these dates, tidal exchanges were larger than those observed on other dates sampled (Table 1). Examination of continuous tide records from July 18 to August 15, 1972 and October 11, 1972 to January 9, 1973 revealed that 1 m was exceeded on 100 of 228 tidal cycles. This proportion was not significantly different from one-half (chi-square = 3.439, 1 degree of freedom) suggesting that 1 m is near mean, or at least median high water. Confidence limits cannot be precisely placed on the residual flows, but ± 1,000 $m^3$ for lower tides and ± 4,000 $m^3$ for higher tides appear to be reasonable estimates.

While the coincidence of average beginning and ending tides allows the assumption that all of the residual flow over the 2-year period was due to rainfall and groundwater, the occurrence of high residuals on individual sampling dates, coupled with seasonal changes in mean concentrations of the various parameters, introduces a variable bias into the calculation of fluxes by summing measured fluxes from the individual dates. We, therefore, used a different approach than that used by other workers (see "Discussion"). The time and volume-weighted mean concentrations (Table 2) were calculated by dividing the masses of the various parameters exchanged by the appropriate ebb or flood volumes (Table 1). We assumed that the total volume-flow measured during the 25 tidal cycles sampled (Table 1) multiplied by 2.24 (56 tidal cycles per month ÷ 25 tidal cycles measured) provided the best estimates of total monthly flows. The volumes were 433,106 and 515,254 $m^3$ for flood and ebb tides, respectively. The above volumes were multiplied by the mean concentrations (Table 2) to estimate monthly fluxes of materials (Table 3).

Two major features are apparent in Table 3; the total amount of materials exchanged between marsh and estuary was small relative to standing crops or production of the marsh (Heinle *et al.*, 1974), and there was no consistent seasonal pattern of exchange during the 2 years. The annual flux of particulate carbon was only 7.29 g $m^{-2}$, less than 1% of the annual production (Heinle *et al.*, 1974). Approximately 34% of the flux of particulate carbon were carbohydrates (assuming 50% carbon). Net annual flows of all parameters except chlorophyll *a* were from the marsh to the estuary. There are slight discrepancies in the net fluxes of total phosphorus and nitrogen and the sums of their components. These were the result of analytical variation and rounding errors in calculation and are not large. Multiplication of the flux of ATP by 250 (Hamilton and Holm-Hansen, 1967) provides an estimate of 200 kg $year^{-1}$ of living carbon leaving the marsh, only 0.61 g $m^2$ $year^{-1}$. This estimate must be viewed with extreme caution because of problems with our analyses, and should be considered a minimal value.

Flows of particulate and dissolved phosphorus were about equal in magnitude and amounted to 0.138 and 0.190 g $m^{-2}$ $year^{-1}$, respectively, from the marsh to the estuary. The magnitudes of the monthly flows of the two fractions of phosphorus were never large, and showed no noticeable agreement with each other, or with the other parameters we measured.

Only 1,140 kg of the 1,367 kg net flow of total dissolved nitrogen were accounted for by the sum of the 4 fractions measured, one of which (dissolved organic nitrogen) was determined by difference among the hourly samples. Incomplete sampling and loss of some samples probably caused this, in addition to the rounding and analytical errors mentioned above. The greatest amount of nitrogen leaving the marsh was in the dissolved rather than particulate form, and about half of the dissolved fraction was organic nitrogen. The contribution of total dissolved nitrogen amounts to 4.14 g $m^{-2}$ $year^{-1}$.

While the net flow of dissolved nitrogen was generally out of the marsh, inorganic nitrogen, particularly nitrate and ammonia, was taken up during May, June, and July. During these months, however, a large amount of dissolved organic nitrogen was usually lost from the



Table 2. Time and volume-weighted mean concentrations of particulate and dissolved chemical concentrations on ebb (E) and flood (F) tides in Middle Creek. PC: Particulate carbon; PN: particulate nitrogen; PP: particulate phosphorus; TP: total phosphorus; TDP: total dissolved phosphorus; CHO: carbohydrate; Chl. *a*: chlorophyll *a*; ATP: adenosine tri-phosphate; TDN: total dissolved nitrogen, DON: dissolved organic nitrogen. Dashes: no data

| Date | Tide | Concentration ($g \cdot m^3$) PC | PN | PP | TP | TDP | CHO | Crude fiber | Seston | Chl. *a* | TDN | $NO_2$ | $NO_3$ | $NH_3$ | DON | ATP ($mg \cdot m^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1972 | | | | | | | | | | | | | | | | |
| July | E | 2.9 | 0.37 | - | - | - | 2.33 | 0.037 | - | - | - | - | - | - | - | 1.5 |
| | F | 3.3 | 0.41 | - | - | - | 2.16 | 0.026 | - | - | - | - | - | - | - | 1.9 |
| Aug. | E | 3.0 | 0.43 | 0.08 | 0.15 | 0.07 | 2.25 | 0.040 | - | 0.033 | 0.45 | 0.005 | 0.093 | - | - | 1.3 |
| | F | 1.4 | 0.38 | 0.09 | 0.13 | 0.04 | 2.72 | 0.017 | - | 0.037 | 0.41 | 0.004 | 0.113 | - | - | 2.0 |
| Sept. | E | 2.1 | 0.29 | 0.07 | 0.10 | 0.03 | 1.71 | 0.036 | - | 0.022 | 0.42 | 0.002 | 0.005 | 0.082 | 0.33 | 1.7 |
| | F | 3.2 | 0.36 | 0.09 | 0.12 | 0.03 | 2.44 | 0.017 | - | 0.032 | 0.41 | 0.002 | 0.002 | 0.049 | 0.35 | 1.0 |
| Oct. | E | 2.8 | 0.37 | 0.05 | 0.14 | 0.09 | 2.37 | 0.042 | - | 0.022 | 0.44 | 0.004 | 0.062 | 0.083 | 0.29 | - |
| | F | 3.4 | 0.44 | 0.05 | 0.15 | 0.10 | 2.43 | 0.052 | - | 0.034 | 0.45 | 0.004 | 0.079 | 0.061 | 0.31 | - |
| Nov. | E | 3.5 | 0.30 | 0.14 | 0.22 | 0.06 | 0.90 | 0.028 | - | 0.004 | 0.34 | 0.009 | 0.452 | 0.290 | 0.20 | 0.6 |
| | F | 3.4 | 0.35 | 0.19 | 0.25 | 0.06 | 0.80 | 0.026 | - | 0.005 | 1.03 | 0.007 | 0.450 | 0.239 | 0.39 | 0.2 |
| Dec. | E | 3.4 | 0.30 | 0.18 | 0.27 | 0.09 | 1.68 | 0.030 | 72.1 | 0.002 | - | - | - | - | - | 0.2 |
| | F | 3.2 | 0.25 | 0.19 | 0.28 | 0.03 | 1.58 | 0.026 | 74.2 | 0.003 | - | - | - | - | - | 0.2 |
| 1973 | | | | | | | | | | | | | | | | |
| Jan. | E | 3.0 | 0.25 | 0.14 | 0.22 | 0.08 | 2.15 | 0.049 | 245.3 | 0.002 | 1.61 | 0.013 | 0.649 | 0.511 | 0.44 | 0.4 |
| | F | 3.5 | 0.27 | 0.23 | 0.33 | 0.10 | 2.21 | 0.056 | 61.4 | 0.002 | 1.49 | 0.013 | 0.651 | 0.569 | 0.26 | 0.2 |
| Feb. | E | 2.5 | 0.32 | 0.17 | 0.29 | 0.12 | 0.96 | 0.048 | 63.3 | 0.002 | 2.14 | 0.013 | 0.986 | 0.462 | 0.68 | 0.7 |
| | F | 3.2 | 0.31 | 0.20 | 0.31 | 0.11 | 1.13 | 0.055 | 63.3 | 0.003 | 1.86 | 0.013 | 1.004 | 0.449 | 0.39 | 1.1 |
| Mar. | E | 3.1 | 0.31 | 0.18 | 0.23 | 0.05 | 1.69 | 0.050 | 70.2 | 0.006 | 1.52 | 0.024 | 0.637 | 0.211 | 0.64 | 0.4 |
| | F | 1.9 | 0.25 | 0.16 | 0.25 | 0.09 | 1.33 | 0.036 | 71.3 | 0.005 | 1.67 | 0.026 | 0.712 | 0.280 | 0.65 | 0.4 |
| Apr. | E | 8.8 | 0.87 | 0.31 | 0.44 | 0.13 | 2.86 | 0.085 | 193.2 | 0.025 | 0.77 | 0.019 | 0.618 | 0.098 | 0.03 | 1.3 |
| | F | 4.5 | 0.50 | 0.19 | 0.33 | 0.14 | 1.83 | 0.057 | 64.3 | 0.017 | 0.65 | 0.022 | 0.630 | 0.104 | 0.10 | 1.3 |
| May | E | 2.9 | 0.40 | 0.14 | 0.17 | 0.03 | 1.61 | 0.039 | 49.5 | 0.040 | 0.95 | 0.010 | 0.194 | 0.099 | 0.63 | 2.4 |
| | F | 3.4 | 0.50 | 0.18 | 0.22 | 0.04 | 1.44 | 0.035 | 68.8 | 0.040 | 1.05 | 0.012 | 0.244 | 0.210 | 0.59 | 2.4 |
| June | E | 3.9 | 0.50 | 0.16 | 0.22 | 0.06 | 1.70 | 0.056 | 63.1 | 0.030 | 0.58 | 0.017 | 0.184 | 0.147 | 0.23 | 2.2 |
| | F | 5.1 | 0.79 | 0.17 | 0.25 | 0.08 | 3.44 | 0.076 | 56.3 | 0.066 | 0.75 | 0.009 | 0.297 | 0.212 | 0.24 | 5.5 |
| July | E | 4.7 | 0.34 | 0.23 | 0.37 | 0.14 | 2.07 | - | 92.8 | 0.024 | 0.90 | 0.045 | 0.371 | 0.214 | 0.27 | 1.4 |
| | F | 4.0 | 0.46 | 0.24 | 0.36 | 0.12 | 2.45 | - | 98.1 | 0.026 | 0.92 | 0.054 | 0.461 | 0.255 | 0.15 | 1.4 |
| Aug. | E | 7.8 | 0.77 | 0.13 | 0.31 | 0.13 | 2.12 | 0.065 | 122.6 | 0.025 | 0.42 | 0.003 | 0.010 | 0.130 | 0.28 | 3.9 |
| | F | 7.0 | 0.69 | 0.19 | 0.30 | 0.11 | 2.04 | 0.055 | 148.1 | 0.025 | 0.51 | 0.003 | 0.007 | 0.218 | 0.28 | 3.0 |
| Sept. | E | 4.8 | 0.57 | 0.16 | 0.20 | 0.04 | 2.37 | - | 71.8 | 0.037 | 0.78 | 0.003 | 0.008 | 0.044 | 0.73 | 1.7 |
| | F | 4.7 | 0.52 | 0.15 | 0.19 | 0.04 | 2.63 | - | 65.7 | 0.040 | 0.70 | 0.002 | 0.008 | 0.033 | 0.65 | 2.2 |
| Oct. | E | 3.8 | 0.50 | - | - | - | 2.33 | 0.045 | 63.0 | 0.042 | - | - | - | - | - | 2.8 |
| | F | 5.0 | 0.74 | - | - | - | 2.70 | 0.045 | 84.9 | 0.056 | - | - | - | - | - | 4.0 |
| Nov. | E | 2.7 | 0.28 | 0.11 | 0.14 | 0.03 | 1.44 | - | 56.6 | 0.018 | 1.38 | 0.016 | 0.479 | 0.453 | 0.33 | 0.1 |
| | F | 3.3 | 0.34 | 0.13 | 0.17 | 0.04 | 1.23 | - | 58.7 | 0.020 | 0.80 | 0.014 | 0.459 | 0.527 | - | 0.1 |
| Dec. | E | 6.0 | 0.43 | 0.22 | 0.27 | 0.05 | 2.37 | 0.080 | 105.5 | 0.014 | 1.33 | 0.022 | 0.574 | 0.317 | 0.42 | - |
| | F | 9.9 | 0.77 | 0.29 | 0.41 | 0.12 | 2.76 | 0.114 | 236.5 | 0.018 | 0.87 | 0.018 | 0.428 | 0.352 | 0.07 | - |
| 1974 | | | | | | | | | | | | | | | | |
| Feb. | E | 6.7 | 0.86 | 0.28 | 0.30 | 0.02 | 2.19 | - | 118.7 | 0.003 | 1.79 | 0.018 | 0.671 | 0.363 | 0.72 | 0.7 |
| | F | 6.5 | 1.10 | 0.32 | 0.34 | 0.02 | 2.16 | - | 168.1 | 0.004 | 1.72 | 0.019 | 0.735 | 0.445 | 0.52 | 0.5 |
| Feb. | E | 2.8 | 0.32 | 0.15 | 0.20 | 0.05 | 1.11 | 0.054 | 51.2 | 0.002 | 1.51 | 0.013 | 0.678 | 0.141 | 0.38 | 0.4 |
| | F | 4.0 | 0.67 | 0.27 | 0.33 | 0.06 | 1.39 | 0.063 | 104.2 | 0.003 | 1.42 | 0.013 | 0.720 | 0.460 | 0.22 | 0.9 |
| Mar. | E | 2.2 | 0.60 | 0.18 | 0.25 | 0.07 | 1.26 | - | 59.3 | 0.003 | 2.16 | 0.031 | 1.044 | 0.667 | 0.42 | 0.5 |
| | F | 4.7 | 0.63 | 0.26 | 0.33 | 0.07 | 2.11 | - | 111.4 | 0.004 | 2.01 | 0.032 | 0.965 | 0.610 | 0.41 | 0.5 |
| Apr. | E | 4.3 | 0.35 | 0.11 | 0.25 | 0.14 | 1.11 | 0.034 | 48.8 | 0.004 | 1.49 | 0.019 | 0.674 | 0.353 | 0.49 | 0.8 |
| | F | 4.8 | 0.70 | 0.12 | 0.25 | 0.13 | 1.10 | 0.035 | 69.3 | 0.005 | 1.63 | 0.019 | 0.678 | 0.347 | 0.59 | 0.8 |
| May | E | 7.6 | 0.88 | 0.24 | 0.35 | 0.11 | 4.20 | - | 82.0 | 0.131 | 0.94 | 0.012 | 0.047 | 0.091 | 0.79 | 13.0 |
| | F | 6.0 | 0.92 | 0.19 | 0.26 | 0.07 | 2.70 | - | 73.9 | 0.177 | 0.96 | 0.021 | 0.185 | 0.066 | 0.68 | 12.8 |
| June | E | 4.7 | 0.75 | 0.15 | 0.23 | 0.08 | 2.06 | 0.052 | 74.1 | 0.067 | 1.05 | 0.024 | 0.359 | 0.113 | 0.65 | 6.1 |
| | F | 5.1 | 0.78 | 0.19 | 0.24 | 0.05 | 2.59 | 0.059 | 92.1 | 0.096 | 0.94 | 0.034 | 0.333 | 0.141 | 0.43 | 6.6 |

Table 3. Net monthly fluxes of materials from Gotts' marsh calculated from mean concentrations (Table 2) and estimated monthly tidal volumes (515,254 $m^3$ ebb, and 433,106 $m^3$ flood). All values are in kg per month. Net flows out of marsh are indicated by minus and net flows into marsh by plus signs. Cf: Crude fiber, other abbreviations as in Table 2

| Date | PC | PN | PP | TP | TDP | CHO | Cf | Seston | Chl. a | TDN | $NO_2$ | $NO_3$ | $NH_3$ | DON | ATP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1972 | | | | | | | | | | | | | | | |
| July | + 195 | - 13.0 | - | - | - | - 522 | - [illegible] | - | - | - | - | - | - | - | -0.082 |
| Aug. | - 73 | - 57.0 | - [illegible] | - 20.99 | -13.75 | - 281 | - 4.[illegible] | - | - 0.979 | - [illegible] | -0.314 | + 1.0[illegible] | - | - | -0.113 |
| Sept. | + 394 | + [illegible] | + 2.91 | - [illegible] | - 2.47 | + 176 | - 2.50 | - | + 1.523 | - [illegible] | -0.[illegible] | - 1.71 | - 21.03 | - 13.4 | -0.441 |
| Oct. | + 29 | [illegible] | - 4.10 | - 7.17 | - 1.06 | - 169 | - 0.[illegible] | - | + 3.[illegible]0 | - 31.3 | -0.329 | - 2.27 | - 13.44 | - 15.2 | - |
| Nov. | - [illegible] | - 3.0 | +10.15 | - [illegible] | +15.21 | - 118 | - 2.17 | - | - [illegible].104 | - 12.[illegible] | -1.[illegible] | + 17.93 | - 0.76 | + 65.8 | -0.022 |
| Dec. | + 366 | - 40.2 | -10.46 | + 17.35 | - [illegible] | - 122 | + 4.[illegible] | - 5,010 | + 0.273 | - | - | - | - | - | -0.0[illegible] |
| 1973 | | | | | | | | | | | | | | | |
| Jan. | - 30 | - 11.3 | +27.47 | + 20.57 | + [illegible].09 | - 121 | - 1.00 | +[illegible] | - [illegible].165 | -124.3 | +1.060 | + 52.45 | - 16.85 | -114.1 | -0.312 |
| Feb. | + [illegible] | - [illegible].5 | - 0.97 | - 15.1[illegible] | -14.19 | - 6 | - 0.91 | - [illegible] | + 0.2[illegible] | -207.1 | -1.0[illegible] | - 23.2[illegible] | - 43.57 | -131.5 | +0.11[illegible] |
| Mar. | - 774 | + [illegible] | -23.45 | - 10.23 | +11.22 | - 595 | -10.17 | - 5,290 | - 0.976 | - 7.9 | -1.105 | - 10.[illegible] | + 11.01 | - 40.3 | -0.033 |
| Apr. | -2,335 | -221.7 | -72.44 | + [illegible].71 | - 6.35 | - 651 | -70.[illegible] | -71,700 | - 5.518 | - 23.6 | -0.261 | - 40.57 | - 5.45 | + 27.9 | -0.107 |
| May | - 21 | + [illegible] | + 5.32 | + 7.59 | + 1.46 | - [illegible] | - 4.93 | + [illegible] | - 3.[illegible] | - 14.7 | +0.044 | + 5.72 | + 39.94 | - 69.1 | -0.197 |
| June | + 200 | + 94.6 | - 8.81 | - 5.0[illegible] | + 1.7[illegible] | + 214 | + 4.0[illegible] | -10,710 | +13.127 | + 25.0 | -1.561 | + 31.[illegible] | + 16.[illegible] | - 14.[illegible] | +1.248 |
| July | - 690 | + [illegible]4.0 | -14.56 | - 24.72 | -20.16 | - 6 | - | - 9,660 | - 1.115 | - 55.2 | +0.202 | + 5.50 | + 0.18 | - 74.1 | -0.115 |
| Aug. | - 3[illegible]7 | - 97.0 | -10.4[illegible] | - [illegible] | -19.74 | - 2[illegible] | - 3.27 | + 970 | - 2.053 | + 4.5 | -0.246 | - 2.12 | + 27.[illegible] | - 23.0 | -0.710 |
| Sept. | - 437 | - 63.5 | -17.4[illegible] | - 20.76 | - 3.23 | - 32 | - | - [illegible] | - 1.740 | - 92.7 | -0.480 | - 0.[illegible] | - 9.38 | - 94.6 | +0.077 |
| Oct. | + 207 | + 62.3 | - | - | - | - 3[illegible] | - 4.00 | + 4,230 | + 2.632 | - | - | - | - | - | +0.289 |
| Nov. | + 3[illegible] | + 3.0 | - 0.1[illegible] | + 1.49 | + 1.[illegible] | - 201 | - | - 3,[illegible] | - 0.[illegible]13 | -[illegible] | -2.[illegible] | - 48.01 | - 5.1[illegible] | - | -0.008 |
| Dec. | +1,1[illegible] | +111.9 | +12.24 | + [illegible] | +26.21 | [illegible]5 | + [illegible].15 | +[illegible] | + [illegible] | -309.5 | -1.[illegible] | -110.39 | - 10.[illegible] | -186.1 | - |
| 1974 | | | | | | | | | | | | | | | |
| Feb. | - 637 | + 33.3 | - 5.[illegible]8 | - 7.22 | - 1.[illegible] | - 147 | - | +11,[illegible] | + [illegible] | -132.3 | -1.04[illegible] | - 2[illegible].41 | + 5.63 | -145.3 | -0.144 |
| Feb. | + 2[illegible] | +125.3 | +39.65 | + 33.[illegible] | + 0.23 | + 30 | - 0.53 | +14,75[illegible] | + 0.269 | -163.0 | -1.068 | - 37.50 | - 28.00 | -100.5 | +0.18[illegible] |
| Mar. | + 302 | - 36.3 | +19.[illegible] | + 11.11 | - 5.75 | + 265 | - | +17,[illegible] | + 0.1[illegible] | -242.4 | -2.114 | -119.58 | - 79.48 | 38.[illegible] | -0.341 |
| Apr. | - 137 | +122.2 | - 4.71 | - 25.53 | -15.[illegible] | - [illegible] | - [illegible] | + 4,670 | ± 0.101 | - [illegible].7 | -1.561 | - 53.61 | - 31.59 | + 23.6 | -0.066 |
| May | - 371 | - 54.9 | -41.37 | - 67.73 | -26.16 | - 995 | - | -10,635 | +1[illegible].162 | - 66.5 | +2.012 | + 55.20 | - 18.31 | -112.6 | -1.205 |
| June | - 213 | - 4[illegible].6 | + 5.00 | - 14.56 | +19.56 | + 61 | - 1.[illegible] | + 1,71[illegible] | + [illegible] | -133.3 | +2.[illegible]00 | - 11.28 | + 2.05 | -140.1 | -0.285 |
| Net fluxes per year[a] | -2,397 | - 83.1 | -4[illegible] | -109.[illegible] | -62.38 | -1,[illegible]41 | -23.76 | -45,[illegible] | +11.060 | -1,3[illegible] | -3.391 | -305.4 | -128.99 | -696.1 | -0.801 |

[a] Sums of monthly fluxes divided by 2.

marsh. The net annual flows of all fractions were from the marsh to the estuary, in fairly large amounts, suggesting that the Patuxent marshes may be a major source of nitrogen for the Patuxent River estuary. Total dissolved nitrogen had a net monthly flow from the estuary to the marsh only during June and August, 1973.

Concentrations of nutrients, particularly the forms of nitrogen, frequently changed with changes in the height of tide or the direction of tidal flow. Interpretation of changes of concentrations with changes in tide height allows estimates of direction of fluxes that are somewhat independent of those in Table 3; in fact, substantial conclusions have been drawn from such interpretation in the literature (Gardner, 1975). Six distinct patterns were observed for the abundant forms of nitrogen — ammonia, nitrate, and dissolved organic nitrogen (DON). Nitrite usually followed the pattern shown by nitrate. Five of the patterns are shown in Figs. 4-6. The lack of strict seasonal consistency of the observed patterns (Table 4) suggests that simple and logical explanations such as those of Gardner (1975) are not yet possible. The observed patterns do generally agree with the directions of fluxes shown in Table 3, and thus reinforce those data.

Pattern 1 (Fig. 4) was the most common, and occurred on 7 of 21 occasions (Table 4). In Pattern 1, ammonia decreased with ebb tides and increased with flood tides, nitrate decreased with ebb tides and rose abruptly to high constant values with flood tides, while DON was present in higher concentrations during ebb tides and lower concentrations during flood tides (Fig. 4). On 5 of the 7 occasions when Pattern 1 was observed, total dissolved phosphorus (TDP) varied inversely with ammonia and nitrate (Table 4). Pattern 1 suggests



Table 4. Seasonal occurrence of patterns of nutrient concentration with change in tide height. Patterns 1-5: as in Figs. 4-6; Pattern 6: $NH_3$ as in Patterns 2 or 3, DON as in Pattern 1. Pattern 7 was like Pattern 4, but ammonia was more constant and concentration of nitrate was much higher. TDP: total dissolved phosphorus; chl a: chlorophyll a. –: Dissolved nitrogen not measured

| Month | Pattern no. | Remarks |
|---|---|---|
| 1972 | | |
| July | - | - |
| Aug. | 1 | Only $NO_3$ measured, TDP and chl a inverse |
| Sept. | 5 | TDP like $NH_3$ and $NO_3$ |
| Oct. | 3 | TDP like $NH_3$, chl a high on flood, low on ebb |
| Nov. | 6 | TDP like $NO_3$ |
| Dec. | - | - |
| 1973 | | |
| Jan. | 1 | Weak pattern |
| Feb. | 7 | TDP like $NH_3$ and $NO_3$ |
| Mar. | 1 | TDP inverse to $NH_3$ and $NO_3$ |
| Apr. | 6 | Weak pattern; TDP like $NO_3$ |
| May | 1 | TDP inverse to $NH_3$ and $NO_3$ |
| June | 1 | TDP and chl a inverse to $NH_3$ and $NO_3$ |
| July | 1 | TDP and chl a inverse to $NH_3$ and $NO_3$ |
| Aug. | 4 | TDP and chl a constant |
| Sept. | 3 | TDP relatively constant; chl a like $NH_3$ |
| Oct. | - | - |
| Nov. | 2 | TDP inverse to $NO_3$ |
| Dec. | 2 | TDP like $NH_3$; chl a inverse |
| 1974 | | |
| Feb. 7 | 4 | TDP and chl a constant |
| Feb. 21 | 2 | TDP like $NO_3$ |
| Mar. | 1 | TDP relatively constant; chl a inverse to $NH_3$ and $NO_3$ |
| Apr. | 3 | TDP and chl a like $NH_3$ |
| May | 5 | TDP inverse to $NO_3$; chl a like $NO_3$ |
| June | 2 | TDP like DON |

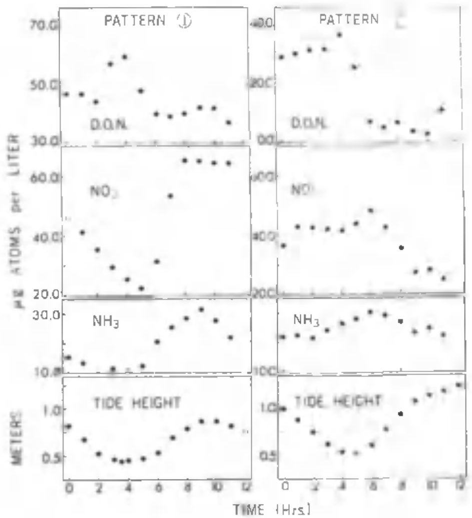


Fig. 4. Concentration Patterns 1 and 2. Mean concentrations for hourly intervals (two-point moving averages) are shown with upper tide height during the interval. D.O.N.: Dissolved organic nitrogen

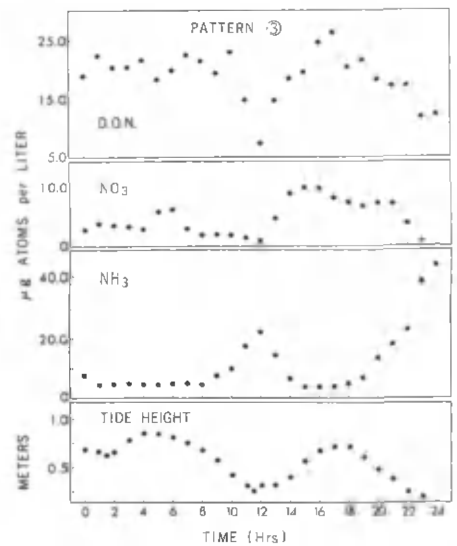


Fig. 5. Concentration Pattern 3. Concentrations and tide height as in Fig. 4

that ammonia and nitrate were being taken up by the marsh and that DON and TDP were flowing from the marsh to the estuary. Except for March, 1973 (TDP) and March, 1974 ($NH_3$ and $NO_3$), the fluxes shown in Table 3 are in general agreement with Pattern 1.

Ammonia and nitrate varied somewhat inversely with tide height in Pattern 2 (Fig. 4), which occurred 4 times. High concentrations of DON occurred during ebb tides and lower concentrations during flood tides. The concentration of TDP showed three different variations within Pattern 2 (Table 4). Pattern 2 suggests that all three forms of nitrogen were flowing from the marsh to the estuary and agrees with the fluxes in Table 3 except for ammonia during June, 1974.

The third most common pattern (Pattern 3, Fig. 5), was observed on 3 of 21 dates when nitrogen was measured (Table 4). Ammonia varied inversely with tide height while nitrate and DON varied more or less directly with tide height. On 2 of the 3 dates, TDP followed the pattern of $NH_3$ and was relatively constant on one date. Pattern 3 suggests that ammonia was flowing from the marsh to the estuary in small amounts, since high concentrations occurred only on low tides when volumes exchanged were low, while nitrate was flowing from the estuary to the marsh. Little exchange of DON is suggested by Pattern 3. The fluxes in Table 3 agree with Pattern 3 for ammonia on all but one date (September, 1973) but are the opposite for nitrate on all but one date (October, 1972).

Pattern 4 (Fig. 6) occurred twice. Ammonia varied inconsistently with tide height, the concentration of nitrate was nearly constant, and DON was higher on ebb tides than on flood tides. The concentration of TDP was relatively constant on both dates (Table 4). This pattern suggests fluxes of DON from the marsh to the estuary and lesser exchanges of the other forms. The data in Table 3 are consistent with Pattern 4.

Another pattern was observed twice, Pattern 5 (Fig. 6). Ammonia varied inversely with tide height, while nitrate was lower on flood tides. The concentration of DON was slightly higher on flood tides than on ebb tides. This pattern suggests that ammonia and nitrate were flowing from the marsh to the estuary, while DON was flowing from the estuary to the marsh. The data in Table 3 are consistent except for nitrate during September, 1972, which showed a slight net flow out of the marsh.

A sixth pattern was observed twice, in November, 1972 and April, 1973. It was the only pattern that showed higher concentrations of DON on flood tides than on ebb tides. Ammonia was higher on low tides, like Pattern 3, while nitrate increased with tide height. This pattern suggests flows of DON into the marsh and occurred on the only two dates when this was observed (Table 3). There was a net outward flow of ammonia on both dates, as suggested by the pattern of concentrations, but nitrate also flowed outward, in contradiction to the patterns (Table 3).

A seventh pattern was observed only once, in February, 1973. It was similar to Pattern 4, but the concentration of ammonia was more constant and nitrate was higher (about 70 µg-at $l^{-1}$). The data in Table 3 are consistent with this pattern.

There were about 3.39 $km^2$ of marshes scoured by ice during the winter of 1972-1973 (Fig. 7). Virtually all of the annual standing crop of 1,000 to 1,500 g $m^{-2}$ dry weight (Heinle *et al.*, 1974) was removed to the estuary during January through March. The annual contribution of particulate carbon from this source is 1,525 metric tons (assuming 45% carbon). Table 5 shows the estimated amounts of phosphorus, nitrogen and carbon entering the upper Patuxent estuary from stable and scoured marshes and sewage treatment plants. While most of the organic carbon contributed from treatment plants was respired in the upper river [we estimated previously (Heinle *et al.*, 1974) that only 760 to 1,230 metric tons of particulate carbon enter the study area from upland sources], the phosphorus and nitrogen probably are carried to the estuary.

The marshes contributed a minor portion of the total phosphorus entering the system, particularly in consideration of upland non-point sources excluded from Table 5, and appeared to absorb no phosphorus. The data in Table 5 suggest that about 20% of the accounted nitrogen budget was contributed by the marshes. Note that upland non-point sources of nitrogen are likely to be large and the fluxes were estimated from less data than those on phosphorus and carbon (Table 3), and might therefore be less reliable. The percentages used to calculate flows of particulate phosphorus and nitrogen in Table 5 were within the range of those reported for live and dead *Spartina alterniflora* by Keefe and Boynton (1973), and overlapped the range reported by Valiela and Teal (1974) for

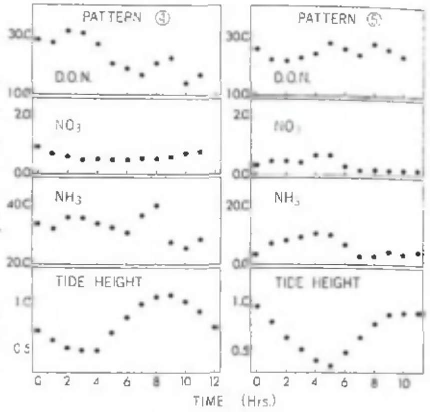


Fig. 6. Concentration Patterns 4 and 5. Concentrations and tide height as in Fig. 4

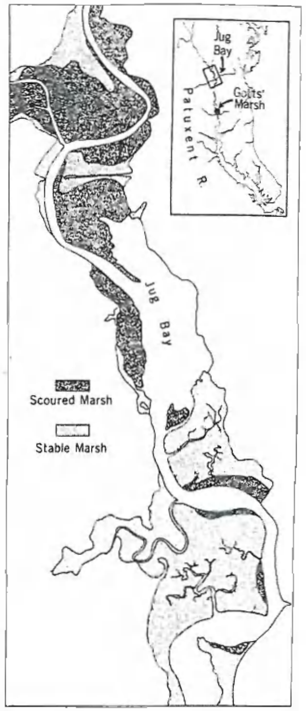


Fig. 7. Marshes in vicinity of Jug Bay that were extensively scoured by ice. Inset shows locations of Jug Bay and Gotts' marsh on Patuxent estuary



Table 5. Amounts of materials entering Patuxent estuary from marshes and other sources. All values in metric tons per year

| Component | Stable marshes | Scoured marshes | Sewage-treatment plants |
|---|---|---|---|
| Total phosphorus (as P) | 5.2 | 3.4-6.4[a] | 570.5[c] |
| Total nitrogen (as N) | 69.3 | 21.2-42.4[a] | 458.1[c] |
| Particulate carbon | 114.6 | 1,907[b] | 8,727[d] (combined particulate and dissolved) |
| Dissolved organic carbon | 110 (approximate) | - | - |

[a] Calculated from a phosphorus content of 0.08 to 0.15% of dry weight and a nitrogen content of 0.5 to 1.0% of dry weight (see text)

[b] Calculated from a production of 1,250 g $m^{-2}$ $year^{-1}$ and a carbon content of dry weight.

[c] Calculated from Table 7-3 of Anonymous (1974).

[d] Calculated from an estimated sewage flow of 8.7 x $10^3$ $m^3$ $day^{-1}$, a content of gross organic matter of 55 mg $\ell^{-1}$ (Weinberger *et al.*, 1966), and a presumed carbon content of 50%. In reality, only 760 to 1,230 metric tons enter our study area from upland sources including treatment plants.

living *S. alterniflora*, *S. patens*, and *Distichlis spicata*. The data from Gotts' marsh (Table 3) suggest that an additional amount of nitrogen in the dissolved form could be contributed to the estuary from the scoured marshes.

## Discussion

Our data (Table 3) suggest that fluxes of detritus from stable marshes subjected to modest amounts of tidal flooding are slight, amounting to less than 1% of the maximum areal standing crops. The stable marshes in the Patuxent are those having a zone of *Spartina cynosuroides* along creek and river banks. These results are in sharp contrast to results from marshes exposed to greater flooding (Teal, 1962; de la Cruz, 1965; Heald, 1969), where 20 to 45% of the annual production of marsh plants is exported as detritus. Teal (1962) summed the other known losses of net production in a Georgia marsh and assumed that the remaining quantity is exported. Export of suspended and floating particulate organic matter from a Georgia marsh was measured by de la Cruz (1965). He estimated an export of 21% of monthly production during the summer. Taking the liberty of assuming that the six tidal cycles studied by de la Cruz lead to an annual average, we calculated that 19 to 29% of the annual net production reaches the estuary, i.e., 292 g $m^{-2}$.

The concentrations of particulate organic matter were always 2 or 3 times higher on ebb tides during the studies of de la Cruz (1965), in contrast to our results (Table 2). Assuming that detritus is 45 to 50% carbon, the absolute range of concentrations that we encountered (Table 2) was within that found by de la Cruz (1965). The methods used by de la Cruz to measure flow of water in and out of his study creek were not described. He appears to have assumed equal volumes of ebb and flood in reaching his conclusions.

The asymmetry in tidal flow that we observed (Figs. 2 and 3) was not unusual for tidal marshes (Boon, 1975). There were no large net differences in volumes exchanged from the marsh studied by Boon to the adjacent estuary.

The estimates of volumes of water exchanged between the marsh and the estuary are undoubtedly less precise for the first year of our study (Table 1). The fact that the flows of some forms, particularly nitrogen, showed similar patterns in both years, and that the patterns of concentration (Figs. 4-6; Table 4) reinforce the estimates of flows (Table 3) suggests that serious error did not occur.

Heald (1969) estimated flux of detritus from a Florida mangrove swamp. His qualified estimate was 370 g $m^{-2}$ $year^{-1}$ of detritus from a production of 880 g $m^{-2}$ $year^{-1}$. Heald actually measured production of dead plant material, not areal standing crops. His is thus a much better estimate of actual net annual production than ours (Heinle *et al.*, 1974), or that of Teal (1962), or de la Cruz (1965) [see Keefe (1972) for a discussion of the relative merits of estimates of production based on areal standing crops]. The method that Heald (1969) used to calculate export appears not to have included estimates of net flow outward due to freshwater runoff. If this is true, his estimated export of detritus is lower than the real value as concentrations of detritus are higher on ebb tides. If evaporation from the mangroves exceeded freshwater flow, his estimates of export may be too high.

The relatively poor tidal flooding of Gotts' marsh may account for the low amounts of particulate carbon exported to the estuary. The Georgia marshes have a tidal amplitude of 2 to 3 m. The Patuxent marshes rarely experience an amplitude of 1 m, even during spring tides. The relative tide level at which the general surface of Gotts' marsh begins to flood, 1 m, appears to represent about mean high water or slightly below. Both the seasonal and quantitative aspects of our study may be biased by the fact that our highest fluxes out of the marsh, and the occasions when a large flux into the marsh was indicated, all occurred on tidal cycles that approached or exceeded 1 m on our relative scale.

In the Patuxent, most of the detritus reaching the estuary from the marshes has its origin in marshes without levees that are scoured by ice during most winters. Most of these marshes are in the Jug Bay area (Fig. 7). Old residents on the river indicate that the Jug Bay marshes are of recent (within the last 70 years) origin, and resulted from the deposition of silt around a railroad causeway (now abandoned) constructed around 1895. The marsh at Iron Pot Landing, at the confluence of the Western Branch with the estuary just above Jug Bay (Fig. 7), was extensively scoured also. We were unable to determine the age of the latter marsh. If the low marshes in the upper Patuxent maintain their profile they presumably will continue to be a source of detritus for the estuary. There are plant species on these marshes that have dense root mats



and could presumably form levees. The fact that the recently formed Jug Bay marshes comprised much of the scoured area suggests they have not yet developed a stable surface. The marshes scoured by ice contributed over half of the particulate carbon entering the upper Patuxent, suggesting that the carbon budget for the upper Patuxent may vary considerably from year to year depending on the severity of the winters.

The concentrations of phosphorus we observed (Table 2) were generally higher than those that Pomeroy *et al.* (1965) suggested would drive the absorption equilibrium between the water and sediments toward the sediments (assuming that most of the dissolved phosphorus was phosphate). Our data suggest no exchange of this sort, so the sediments in the study area may be saturated with phosphorus most of the time. In the shallow marsh and estuarine system modeled by Pomeroy *et al.* (1972), phosphate concentrations tended toward 0.1 mg-at $m^{-3}$, while the lowest concentrations of total dissolved phosphorus we observed were 0.62 mg-at $m^{-3}$ (0.31 g $m^{-3}$, Table 2) in February, 1974. The high concentrations are not surprising in the light of the large contribution of phosphorus from sewage-treatment plants (Table 5).

Pomeroy *et al.* (1969) suggested that phosphorus was transported from deep reduced-sediments by marsh plants and exported to an estuary in detrital form. One might thus expect, in a balanced system, that input of phosphorus to the marsh might be either a dissolved phosphorus, that would absorb to oxidized surface sediments in the marsh, or phosphorus already adsorbed to sediment particles which might settle on the marsh. Our studies do not suggest export of phosphorus as detritus, as the flux of particulate phosphorus does not agree well with that of particulate carbon in either magnitude or direction (Table 3). However, the net annual flux of particulate phosphorus from Gotts' marsh (Table 3) was 0.34 g $m^{-2}$ $year^{-1}$. If the summer standing crops have a phosphorus content of from 0.08 to 0.15% of dry weight (Keefe and Boynton, 1973; Heinle *et al.*, 1974; Valiela and Teal, 1974) and the dry-weight biomass of the marsh plants is 1,000 to 1,500 g $m^{-2}$ (Heinle *et al.*, 1974), the standing crop of phosphorus in the marsh plants would range from 0.8 to 2.25 g $m^{-2}$. The flux we estimated (0.34 g $m^{-2}$ $year^{-1}$) thus represents 15 to 43% of the standing crop. Addition of the dissolved phosphorus (Table 3) increases these values, as 0.19 g $m^{-2}$ $year^{-1}$ enter the estuary in this form (Table 3).

The studies of Valiela *et al.* (1973) suggest that salt marshes are capable of absorbing substantial quantities of nutrients applied during the growing season. Van Raalte *et al.* (1974) found that when free nitrogenous nutrients are present, nitrogen fixation within a marsh is suppressed. Increases of standing crops of marsh vegetation were observed by Valiela and Teal (1974) following fertilization with nitrogen, but not with phosphorus. Production of *Spartina* spp. marshes at higher salinities thus appears to be limited by nutrients, particularly nitrogen, and these marshes have fairly high assimilative capacity for nitrogen applied to the surface, especially short-*Spartina* spp. high marshes. By contrast, Gotts' marsh showed no indication of nutrient limitation as standing crops were equally high on all parts of the marsh (Heinle *et al.*, 1974). The flux of nitrogen from the marsh as total dissolved nitrogen was 1,367 kg $year^{-1}$, an amount equivalent to 4.1 g $m^{-2}$. If the standing crop of marsh vegetation (Heinle *et al.*, 1974) had a nitrogen content of 0.5 to 1.0% of dry weight (Keefe and Boynton, 1973; Heinle *et al.*, 1974; Valiela and Teal, 1974), there was 5.0 to 22.5 g $m^{-2}$ of nitrogen in the dry weight biomass of 1,000 to 1,500 g $m^{-2}$. The flux was thus between 18 and 82% of the range of estimates of nitrogen content of the vegetation. Van Raalte *et al.* (1974) estimated that 1.2 g $m^{-2}$ of nitrogen were fixed in unfertilized parts of a *Spartina* spp. marsh, an amount nearly sufficient to account for the standing crops of 1.5 g $m^{-2}$ of nitrogen observed by Valiela and Teal (1974) on the same marsh. Corell (1976) calculated that about 2.5 g $m^{-2}$ $year^{-1}$ of nitrogen fell in rainfall on a watershed in Chesapeake Bay. The watershed he studied was within the airshed of a major metropolitan area, Washington, D.C., while Gotts' marsh lies south of the prevailing airshed of Washington, D.C.

Our data (Table 3) do suggest some utilization of inorganic nitrogen by Gotts' marsh during May, June, July, and August, but with concurrent flow of larger amounts of dissolved organic nitrogen from the marsh to the estuary. While growth of vegetation is greatest in spring and early summer, decomposition of vegetation appears to be more evenly distributed in time. Heinle *et al.* (1974) found that the quantity of dead standing vegetation decreased substantially between late June and late July in Gotts' marsh.

Gardner (1975) described enrichment of marsh runoff with ammonia from interstitial water during low tides. His work, done on a *Spartina* spp. marsh during June, July, and August, showed changes in concentrations of ammonia similar to those we observed in Patterns 2 (Fig. 4) and 3 (Fig. 5), suggesting fluxes of ammonia to the estuary. Pattern 3 occurred most commonly during the early spring and late fall while Pattern 2 was observed more often in the winter (Table 4), in contrast to Gardner's results. The concentrations of dissolved phosphorus were often inversely related to the concentrations of ammonia in our study (Table 4), also in contrast to the results of Gardner. Our data suggest flows of ammonia from the estuary to the marsh during June through August. Poor tidal flooding and poor drainage of our study area may account for these differences. Where analytical errors are relatively large, as with our measurements of phosphorus, or where the mean concentrations of measured variables differed little, as with many variables during some months (Table 2), little credence can be given the estimates of direction or magnitude of monthly fluxes (Table 3). In general, these are the variables that showed very small net fluxes and no consistent seasonal patterns. The possibility also remains that major exchanges of materials during unusual storms were not measured, a fault common to all work of this sort that we are aware of.

Our results differ considerably from other work, virtually all of which was done on high-salinity salt marshes. Stable marshes on the Patuxent contribute very little detritus to the estuarine ecosystem, but do exchange phosphorus and nitrogen, both of which were exported to the estuary during the 2 years of our study. Nutrient loading of the Patuxent by treated sewage (Table 5) may have changed the ecosystem to such an extent that "normal" relationships are no longer apparent; however, production estimates of a similar marsh that is not heavily loaded, the upper part of Parker Creek marsh (Heinle *et al.*, 1974), indicate that nutrients do not greatly limit the standing crops of vegetation, mainly *Typha* sp., as standing crops were only slightly lower than those in the Patuxent marshes. At higher salinities in the same marsh, particularly within the *Spartina patens-Distichlis spicata* association, standing crops were lower than in the *Typha* sp. community. Studies of unperturbed low-salinity marshes, or of the Patuxent marshes after proposed reductions in the nitrogen additions (Anonymous, 1974), might help determine the role of low-salinity marshes in undisturbed estuarine ecosystems.

*Acknowledgements.* The following individuals provided valuable assistance in collecting and analyzing samples: Captains G. Cox and R. Younger of the research vessels; L. Beaven, M. Cole, R. Huff, E. Hughes, J. Lawson, R. Murtagh, S. Sulkin, J. Ustach, and R. Ziesel. Aerial photographs of the Patuxent marshes were taken on request by the National Aeronautics and Space Administration during a cooperative study with our laboratory. Financial support was received from the Office of Water Resources Research through Projects B-016 Md. and B-019 Md., and from the National Science Foundation (RANN) through the University of Maryland.

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Date of final manuscript acceptance: January 12, 1976. Communicated by M.R. Tripp, Newark