Bly Creek ecosystem study – nitrogen exchange within a euhaline salt marsh basin of North Inlet, South Carolina*

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ABSTRACT: Nitrogen exchange within the Bly Creek basin (North Inlet, South Carolina, USA) was studied during 34 tidal cycles between 20 June 1983 and 19 June 1984. Estimates of tidally mediated transport were made along with annual estimates of nitrogen input to the basin via streamwater, groundwater, and rainwater. Within the basin, effects of the vegetated marsh, oyster reef community, and the tidal creek on material transport were assessed. There was a small, but statistically insignificant ($\alpha = 0.05$) NH_4^+ export from the basin through the tidal creek of 433 kg N yr^{-1} (0.65 g N m^{-2} yr^{-1}); inputs into the basin via streamwater, groundwater, and rain totalled 78 kg NH_4^+-N yr^{-1}. The NH_4^+ mass balance suggests the basin is not a source or a sink for this constituent to the surrounding estuary. However, since the vegetated marsh surface imports ca 1500 kg NH_4^+-N yr^{-1}, the tidal creek subsystem must act as a source. It is suggested that remobilization of NH_4^+ within the tidal creek water column and/or benthic community produces the ammonium necessary to satisfy the input of this constituent to the vegetated marsh. There was also a small, insignificant import of nitrate + nitrite into the basin through the tidal creek of 158 kg N yr^{-1} (0.23 g N m^{-2} yr^{-1}). The vegetated marsh is capable of removing all the nitrate + nitrite potentially imported into this system via tidal water, streamwater, groundwater, and rain. There was a significant ($\alpha = 0.05$) dissolved organic nitrogen (DON) export from the basin of 7782 kg N yr^{-1} or 11.7 g N m^{-2} yr^{-1}, whereas there was a statistically insignificant import of particulate nitrogen (PN) (1541 kg N yr^{-1} or 2.3 g N m^{-2} yr^{-1}). The vegetated marsh within the basin appears to be the main source of DON material to the basin as a significant amount of DON was exported both during tidal inundation and via runoff during tidal exposure. Due to the lack of statistical significance in the tidally mediated PN flux, it is difficult to state whether the basin is a source or sink for this constituent. However, a negative association between tidally mediated PN flux and maximum tidal height suggests that the marsh surface is important in removing PN during high tide conditions.

INTRODUCTION

To test the 'Outwelling Hypothesis' (Odum 1968, Nixon 1980) nitrogen transport studies have been conducted in many marsh-estuarine systems (Axelrad 1974, Heinle & Flemer 1976, Valiela et al. 1978, Woodwell et al. 1979, Dame et al. 1986). The results from these research efforts suggest that NH_4^+, DON, and PN are generally exported through tidal creeks into the

adjacent water body while nitrate is imported. Since initial speculation by Teal (1962), the vegetated marsh surface has been considered to be the source of the materials outwelled through tidal creeks. Denitrification and N_2-fixation rates in salt marsh sediments have been used to explain import and export of nitrate and ammonium respectively (Nixon 1980), whereas the source of exported dissolved organic material (DOC in particular) has been attributed to leaching from live and dead *Spartina* (Gallagher et al. 1976, Turner 1978, Pakulski 1986) or diffusion from marsh sediments (Pomeroy et al. 1977). Correspondingly, the source of

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the outwelled PN was assumed to be associated with marsh macrophyte productivity (Valiela et al. 1978). However, a flume study on a mesohaline marsh in Virginia (Wolaver et al. 1983, Wolaver & Zieman 1984) showed that this subsystem is a sink for particulate nitrogen, NH_4^+, and DON, and a small source for nitrate. The results from the research discussed above suggest that there is no clear understanding of which subsystems (vegetated marsh, tidal creek, invertebrate community, etc.) within the marsh-estuarine system are controlling nitrogen flux magnitude and direction or what specific mechanisms are involved.

To address this problem, the 'Bly Creek Ecosystem Study' evaluated material processing in a salt marsh-estuarine system by estimating contemporaneously (1) the major fluxes into and out of the system (tidally mediated exchange, streamwater, groundwater, and rain) and (2) the contribution of the major subsystems (vegetated marsh, oyster reef, and tidal creek) to material transport. In this article we will discuss the tidally mediated transport of nitrogen and evaluate the aqueous nitrogen mass balances for the Bly Creek basin, North Inlet, South Carolina, USA. These results will be then integrated with those from flume studies which were conducted on the vegetated marsh (Wolaver et al. 1985, Whiting et al. unpubl.) and oyster reef community (Dame et al. 1985, Dame et al. unpubl.).

METHODS

To study nitrogen exchange between the Bly Creek basin and the adjacent water body, material flux measurements were made at a transect across the only tidal creek within the system. The Bly Creek transect (BCT) was 53 m wide with a mean depth of 1.33 m at mean tide height and was located near the midpoint of the Bly Creek basin (Fig. 1). The vegetation within the basin is dominated by the various growth forms of *Spartina alterniflora*. The area of the basin is 660 000 m^2 of which 532 000 m^2 are covered by vegetated salt marsh, and 128 000 m^2 by tidal creek channels including 1000 m^2 of oyster reef community.

Nitrogen concentration and velocity measurements were made at the BCT during 34 complete tidal cycles, every 11.8 d, between 20 June 1983 and 19 June 1984. This sampling schedule was chosen to obtain a representative range of lunar and diel periods over each season. Water samples were taken at one station in the middle of the BCT. One station was chosen following a detailed analysis of flows across the channel during a 2 tidal cycle calibration sampling (Kjerfve & Wolaver 1988). These samples were collected at 2 depths (near bottom and mid water-column depth) once every hour for a full tidal cycle beginning at low tide. All water

samples were placed immediately on ice in the field and were returned to the chemistry laboratory for processing within 2 h of collection. Initially, a 3 ml aliquot was removed and stored (frozen) for total nitrogen (TN) determination. The rest of the sample was then filtered through a Whatman 4.7 cm GF/F filter with a 3 ml subsample frozen for total dissolved nitrogen (TDN) analysis. Two other aliquots were removed from the filtered sample and preserved in phenol or mercuric chloride for ammonium and nitrate analyses, respectively. TN and TDN were determined by digesting the appropriate filtered and unfiltered samples via the alkaline persulfate technique (Glibert et al. 1977). In the digestion all the reduced forms of nitrogen were oxidized to nitrate. Subsequently, the NH_4^+ and nitrate sample were analyzed using an Autoanalyzer II system [ammonium, Berthelot reaction (O'Brian & Fiore 1962), Technicon industrial method (154-71W); nitrate + nitrite, Griess reaction, Technicon industrial method (158-71W/A)]. Particulate nitrogen (PN) and dissolved organic nitrogen (DON) were calculated as follows:

$$PN = TN - TDN$$
$$DON = TDN - NH_4^+ - (NO_3^- + NO_2^-)$$

Water velocities were measured at the same station and times as the collection of water samples but with a depth increment of 0.5 m from the tidal creek bottom to the water surface. These measurements were made with current crosses (Kjerfve 1982), with flow directions estimated using a surface streamer and compass. Instantaneous water discharge estimates through the BCT were made by decomposing the velocity vectors into an along-channel u-flow component (positive for ebb) and an across-channel v-flow component (positive toward the northern bank; Kjerfve et al. 1981, Kjerfve & Wolaver 1988). A cubic spline was fitted to each individual vertical u-component velocity profile and 11 equidistant velocity values were interpolated. Each velocity was cross multiplied by the transect width and time-varying depth; the resulting product was summed over the total cross section to yield instantaneous discharge.

Instantaneous mass fluxes (IMF) were calculated by first spline-fitting the nitrogen concentration values similarly to the velocities. Then 11 interpolated nitrogen values were cross multiplied with the appropriate velocity, station width, and water depth, and summed over the cross section. IMF values for each sample period were then integrated over time to obtain the net flux per tidal cycle. This integration was accomplished by fitting the following sine-cosine model to the IMF values.

$$IMF(t) = \sum_{r=1}^{5} \alpha_r \sin(2\pi t/P_r) + \sum_{r=1}^{5} \beta_r \cos(2\pi t/P_r) + \varepsilon$$
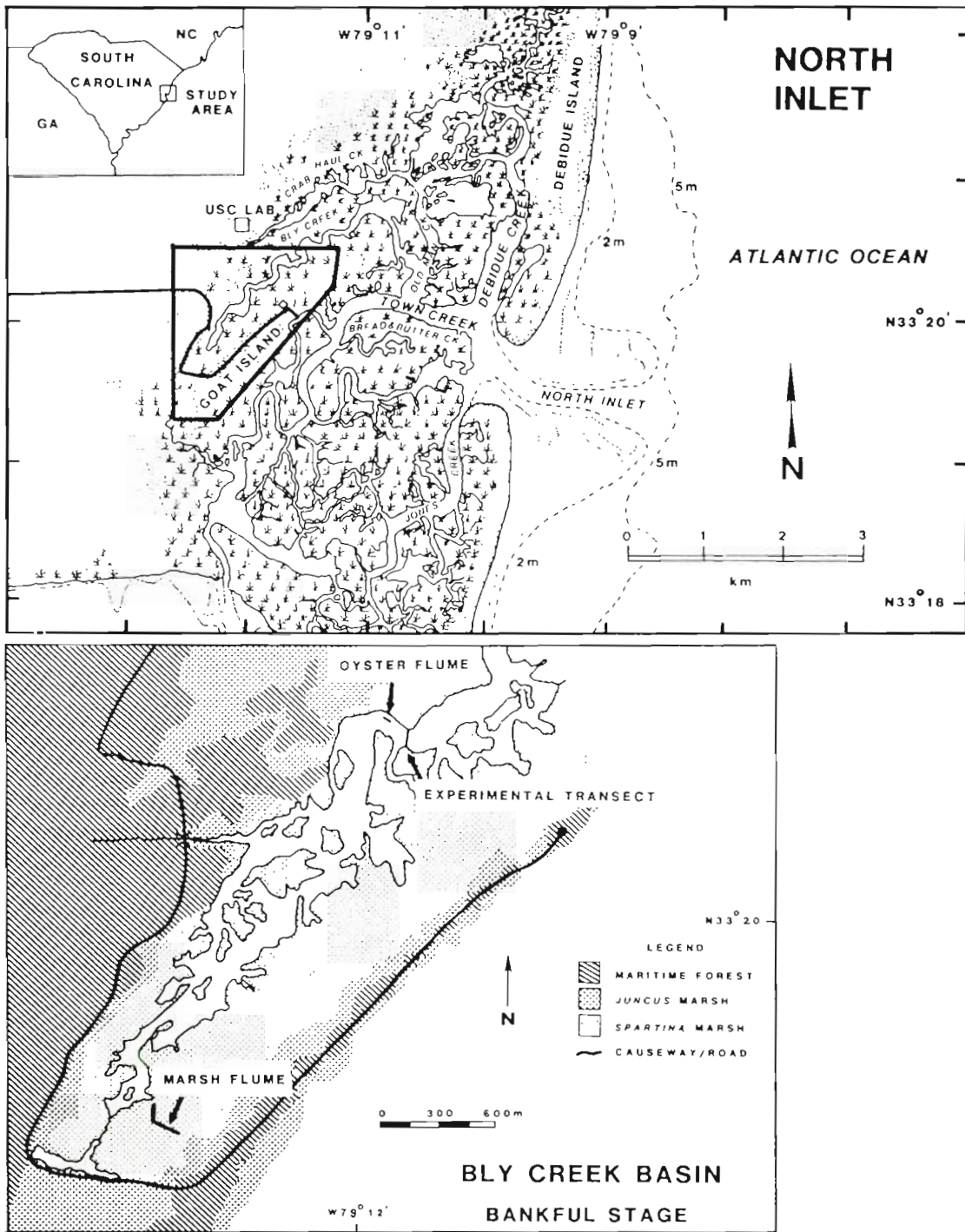
Fig. 1. Study site in South Carolina, USA

In fitting the model, periodicities of major tidal constituents (K1, M2, M4, M6) were selected with the corresponding periods $P_1 = 24.86$ h, $P_2 = 12.42$ h, $P_3 = 6.21$ h, $P_4 = 3.11$ h, and $P_5 = 4.14$ h. In addition, t = time (h) from an arbitrary starting time; $\alpha_1 \ldots \alpha_5$, $\beta_1 \ldots \beta_5$ = unknown parameters; ε = a random error term. The model is similar to that used by Chrzanowski et al. (1982), Whiting et al. (1985), and Wolaver et al. (1985).

To estimate the seasonal and annual exchange of material through the BCT a set of 24 parameters (Table 1) were measured for each tidal cycle throughout the sampling year. We estimated the annual flux for the

Table 1   Predictor variables used in stepwise regression analysis

Variable name	Description
TIDE	Maximum tidal height
L1 TIDE	Maximum tidal height on previous cycle
L2 TIDE	Maximum tidal height on second previous cycle
RAIN	Rainfall on current cycle
L1 RAIN	Rainfall on previous cycle
L2 RAIN	Rainfall on second previous cycle
R13	Sum of rainfall (> 1.27 cm event^{-1}) during tidal exposure over preceding 8 cycles
R14	Sum of rainfall (> 0.25 cm event^{-1}) over preceding 8 cycles
BIO	Biomass of live *Spartina* at creekside
DERBIO	Derivative of BIO with respect to time
FRESWTR	Freshwater flow during current cycle
L1 FRESH	Freshwater flow during previous cycle
L2 FRESH	Freshwater flow during second previous cycle
AWTMP	Water temperature $- 18.47$[a]
WTMP2	Square of water temperature
LIGHT	Proportion of tidal cycle in daylight
LIGHT2	Square of LIGHT
ALTWT	AWTMP $\times$ (LIGHT $- 0.5$)[b]
AWIND	Average wind speed $- 8.76$[c]
AWNDWT	AWIND $\times$ AWTMP
AXWIND	Maximum wind speed
AIRTMP	Air temperature less water temperature
L100WT	Water temperature for the 100th previous cycle
L100WT2	Square of L100WT

[a] 18.47 = average of water temperatures for sampled cycles
[b] (LIGHT $- 0.5$) = average of a variable LIGHT for sampled cycles
[c] 8.76 = average of average wind speeds for the sample cycles

period between 19 June 1983 and 18 June 1984. During this time, there were 707 tidal cycles of which we sampled 34. To obtain monthly and annual flux estimates an initial stepwise regression was performed. This regression was used to select a smaller set (<24) of predictor variables to be used in modelling the net flux/ cycle for each constituent. This subset of predictor variables was further refined by running all possible regressions and selecting the model that produced the minimum value of Mallows' Cp statistic (Mallows 1973). This model was used to form the regression estimate of the net flux on a monthly and an annual basis. The standard errors associated with the annual net flux estimates take into account the variability in net flux/ cycle estimates as well as the error in estimating the annual net flux from the 34 sampled cycles.

Annual nitrogen inputs into the Bly Creek basin via streamwater, groundwater, and rain were also estimated. Streamwater discharge measurements were made using a Parshall flume (1950) for the blackwater stream which enters the basin. In addition, nutrient concentrations in the streamwater were obtained by sampling 1 storm event per month. The storms were sampled once every 2 h for 2 d. Since there was little variability in nutrient concentration throughout the period of an individual storm, the mean nutrient concentration per storm was multiplied by the monthly streamwater discharge to estimate the monthly nutrient input into the basin. The annual nutrient streamwater flux was obtained by summing monthly fluxes.

Groundwater flow within the basin was evaluated using a piezometric grid: 108 piezometers were inserted into the sediment of the Bly Creek basin at various depths and at specified stations along 3 transects. This configuration allowed for an evaluation of the direction and magnitude of groundwater movement throughout the basin. Water flow estimates were made by solving Darcy's equation using gradients in water table between the forested upland and the tidal creek and a transmissivity of 30 m^2 (Williams 1981). Nutrient concentrations were also measured in each of the piezometers every 2 mo throughout the sampling year. Groundwater flow was coupled with monthly mean nutrient content to estimate the monthly and eventual annual nitrogen flux into the tidal creek. Rainwater input to the Bly Creek basin was measured by the use of a weighing type recording rain gauge located 800 m west of the basin. Rainwater nitrogen concentrations were extracted from data collected on a separate project (conducted within a mile of the basin) whose duration overlapped the Bly Creek study. Water samples were taken for nitrogen analysis after each rain storm throughout the study period. Monthly nitrogen mean concentrations were crossed multiplied with monthly rainfall amount to estimate monthly nitrogen inputs into the basin via rainwater. Annual inputs were calculated summing the monthly fluxes.

RESULTS AND DISCUSSION

The most important aspect of any study of material flux through a tidal creek is the water budget due to its strong influence on material transport. The Bly Creek basin was chosen for this study since (1) it is confined on 3 sides by land and has only 1 tidal creek through which tidal water can flow into and out of the basin, and (2) the freshwater inputs to the basin could be estimated. In addition, the basin is shallow so at times it is nearly drained at low tide. This should ensure that water storage due to residual tidal flow, wind-drift, and estuarine storage/emptying (caused by the dynamic coupling to the coastal ocean) is minimal. The estimate of water flux through the tidal creek indicates there

Table 2. Summary of annual fluxes (kg N yr^{-1}; +: export; −: import)

	H$_2$O (m^3 yr^{-1})	NH$_4^+$	NO$_3^-$ + NO$_2^-$	DON	PN
Tidal creek	1.15 × 10^7	433	−158.0	7780	−1540
(SE)	(8.01 × 10^6)	(830)	(124)	(2460)	(3670)
Streamwater	−7.7 × 10^5	−6.6	−5.2	−892	0.0
Groundwater	−1.2 × 10^5	−60.3	−3.2	−152	0.0
Rainwater	−7.9 × 10^5	−11.3	−10.5	−189	0.0
Net basin budget	9.0 × 10^6	354	−177	6550	−1540
Vegetated salt marsh					
Nitrogen flux during tidal inundation		−1500	−330	3140	−1730
Nitrogen export via runoff and seepage during tidal exposure		112	11	1660	1170
Oyster reef community		125	1	−127	−222

was a small, though insignificant, export out of the basin of 1.15 × 10^7 m^3 yr^{-1} (α = 0.05, SE = 8.01 × 10^6). On a per tidal cycle basis, this water export represents 2.4 % of the tidal prism at basinful stage or 8.1 % of the mean tidal prism.

In this study, we attempted to account for all the fluxes (except evapotranspiration) which may cause an imbalance of water flow at the transect. These include streamflow, groundwater flow, rainfall, storage effects, and sheetflow. The latter refers to water transport over the vegetated marsh and occurs when tidal water height is greater than bankful. Eiser & Kjerfve (1986), after producing a detailed topographic map of the basin, showed that water storage in the basin at MLW (0.86 m above creek bottom at the BCT) was 2500 m^3. The storage of tidal water within the basin during the sampling year was estimated by calculating the average difference between successive low tides for the 34 samplings. This value was only 0.01 m per tide, suggesting that storage effects in this system were negligible, as expected. Eiser & Kjerfve (1986) also showed that sheetflow during a reasonably high tide was unimportant, but suggested that sheetflow could be important for high spring tides. An insignificant association between maximum high tide and the estimated import or export of water at the BCT suggests that this process has a negligible effect on net water transport. Finally, only 13 % of the estimated water export from the basin can be accounted for by water inputs via streamwater, groundwater, and rain (Table 2). It is suggested that the point estimate of water export from this basin is due to sampling error since all the fluxes which account for this export were shown to be relatively insignificant.

Mean tidal NH$_4^+$ concentrations varied seasonally between 1.0 and 10.4 μM N with higher values observed during late summer and early fall (Fig. 2A). The net NH$_4^+$ flux data (Fig. 2B) suggest that there was an import to the basin during late summer and early fall and a general export from the basin throughout the rest

of the year. The annual flux estimate indicated that the basin exported a statistically insignificant (α = 0.05) 433 kg N (SE = 830 kg N) or 0.65 g N m^{-2} yr^{-1}. This
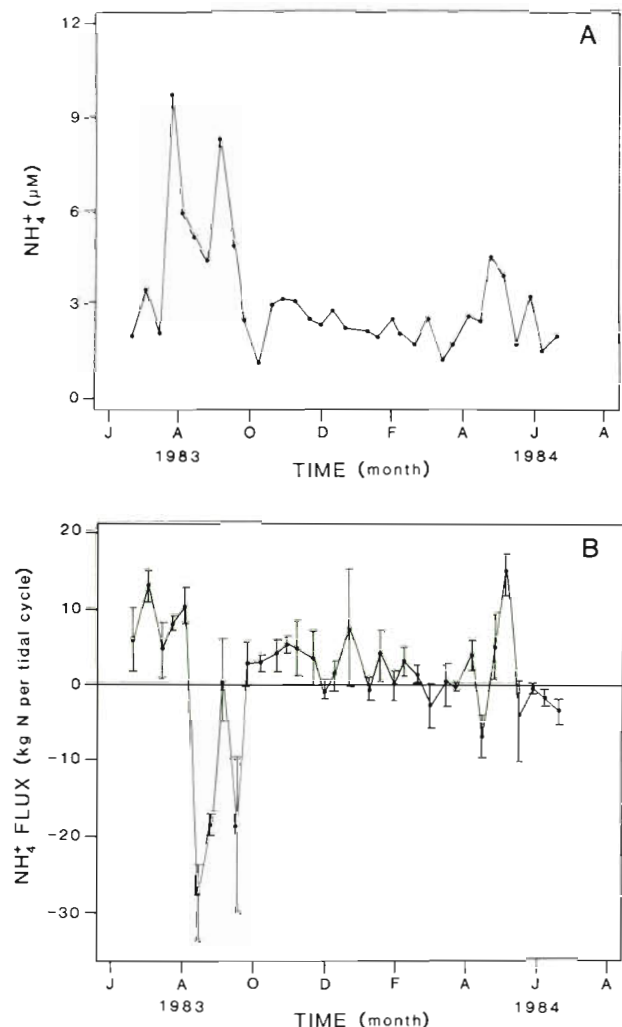

Fig. 2. (A) Mean tidal NH$_4^+$ concentrations and (B) net NH$_4^+$ flux as a function of time of year (export +, import −)

export value is in the lower range observed for the North Inlet system (Whiting et al. 1987) and other marsh-estuarine systems (Nixon 1980).

To determine the ammonium aqueous mass balance for the Bly Creek basin it is necessary to compare the tidally mediated export of this constituent from the basin with the inputs via streamwater, groundwater, and rain. The flux estimates in Table 2 suggest that inputs into the basin via streamwater, groundwater, and rain account for only a small percentage of the potential export from the basin through the tidal creek. However, it is difficult to state whether the basin is a source for NH_4^+ because the tidally mediated export is not statistically significant ($\alpha = 0.05$).

Even though the Bly Creek system may not act as a sink or source for ammonium on an annual basis, there appears to be an active movement of ammonium within the basin. A study conducted to evaluate the nutrient processing role of the vegetated marsh surface (Whiting et al. unpubl.) suggests that this subsystem was a sink for ammonium throughout the year (ca 1500 kg NH_4^+-N yr^{-1}; Table 2), especially during late summer and early fall. Since the flux estimates at the transect did not indicate a large import to the basin, there must be a source within the basin to supply the large input of NH_4^+ to the vegetated marsh. The results from a nutrient exchange study on a oyster reef community within the basin (Dame et al. unpubl) did not show a large source of ammonium from this subsystem (Table 2). This would suggest the tidal creek water column and/or benthic community as the source of NH_4^+ within the basin. Results from a number of recent studies (Agosta 1985, Jordan & Correll 1985) indicate that seepage from creekbanks during low tide may contribute significant amounts of dissolved nutrients to the tidal creek. The advective movement of interstitial water from the creek bottom (Whiting & Childers unpubl.) coupled with diffusion are possibly other major sources of nutrients (in this case, NH_4^+) to the creek water.

Mean tidal nitrate + nitrite ($NO_3^- + NO_2^-$) values varied from 0.1 to 2.1 μMN (Fig. 3A). High $NO_3^- + NO_2^-$ values were observed during August, September, and December and during spring. The $NO_3^- + NO_2^-$ flux values (Fig. 3B) show a mixed trend with respect to transport direction: imports were observed during the spring, late summer, and early fall, and exports dominated the remainder of the year. On an annual basis there was a statistically insignificant ($\alpha = 0.05$) $NO_3^- + NO_2^-$ import into the basin of 158 kg N (SE = 124 kg N) or 0.23 g N m^{-2} yr^{-1}. This value is lower than most of the observed imports of this constituent into other marsh-estuarine system (Nixon 1980).

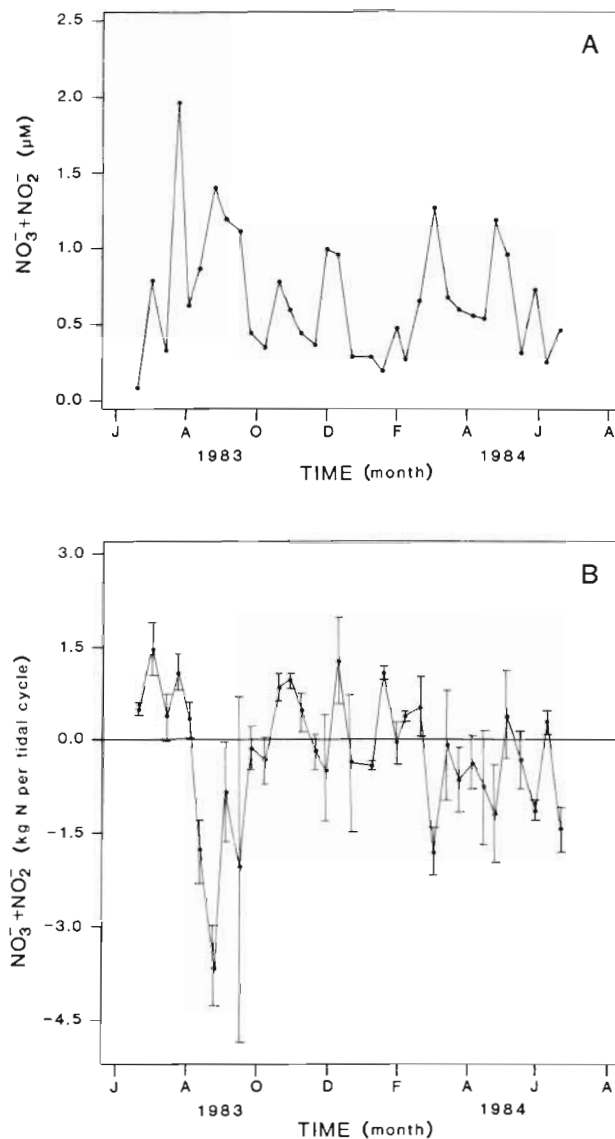The aqueous $NO_3^- + NO_2^-$ mass balance for the Bly Creek basin suggests this system is a sink for this

Fig. 3. (A) Mean tidal $NO_3^- + NO_2^-$ (NN) concentrations, and (B) NN flux as a function of time of year (export +, import −)

constituent (Table 2). However, since the tidally mediated flux is not statistically significant, this assertion cannot be made with confidence. Within the basin, the vegetated marsh is capable of removing all the $NO_3^- + NO_2^-$ that was potentially imported into the basin via tidal exchange, streamwater, rainwater, and groundwater (Table 2). The results from the flume study on the oyster reef community show this subsystem contributes little to the cycling of $NO_3^- + NO_2^-$ within the basin (Dame et al. unpubl.).

Even though the vegetated marsh may remove all the $NO_3^- + NO_2^-$ which is potentially imported into the basin, the tidal creek is not a passive conduit for this constituent. The dynamic activity of $NO_3^- + NO_2^-$ processing within the tidal creek is illustrated by its

trend of concentration with time throughout the tidal cycle. Of 34 tidal cycles, 14 showed a maximum NO_3^- + NO_2^- concentration at maximum flood and ebb discharge. This NO_3^- + NO_2^- concentration trend with time over a tidal cycle suggests that this constituent is possibly produced during periods of maximum water flow and turbulence. A positive association between water velocity and benthic respiration has been observed in a Maryland estuary (Boynton et al. 1981). It is suggested that NO_3^- + NO_2^- is produced in the water column by the oxidation of NH_4^+ via nitrification. The NO_3^- + NO_2^- produced via this process is potentially removed from the tidal water within the tidal creek or as the water floods over the marsh surface. Nitrification within the tidal creek water was also suggested by Wolaver et al. (1984) as a possible source of NO_3^- + NO_2^- in another tidal creek in North Inlet.

Mean tidal DON concentrations varied between 11.2 and 34.7 μM N (Fig. 4A). The highest DON values were observed from March to July, which corresponds with the periods of streamflow for the small blackwater stream entering the basin. The relationship between DON concentration and tidal water salinity (Fig. 4B) supports this assertion since there is a negative association between these 2 variables when all the points which lie in the vicinity of 36 ppt salinity are omitted. DON concentrations within the blackwater stream reach 118 μM N during high flow conditions. However, there is another source of DON within the basin because high values of this constituent are also found at near seawater salinity. The source of this material could be either groundwater, export from the vegetated marsh during tidal inundation, runoff from the marsh during tidal exposure, or infiltration and commensurate seepage from the creek banks along the major tidal creeks. The net DON flux trend (Fig. 4C) suggests that DON was exported throughout the year. Annually there was a statistically significant (α = 0.05) DON export from the basin of 7780 kg N (SE = 2460 kg N yr^{-1}). This annual export on an areal basis (11.7 g N m^{-2} yr^{-1}) is slightly greater than the range observed for other marsh-estuarine systems (Nixon 1980).

The DON mass balance for the Bly Creek basin (Table 2) suggests that the sum of the inputs into the basin via streamwater, groundwater, and rain are not enough to account for the export of this constituent from the basin. This suggests that there must be a DON source within the basin. The flume study on the vegetated marsh shows that this subsystem acted as a DON source with a statistically significant export during tidal inundation (3140 kg N yr^{-1}). If the value for DON export from the marsh via runoff and seepage during tidal exposure (1660 kg N yr^{-1}) is added to this, the total DON export from the marsh into the tidal creek will be even higher. The nutrient exchange study
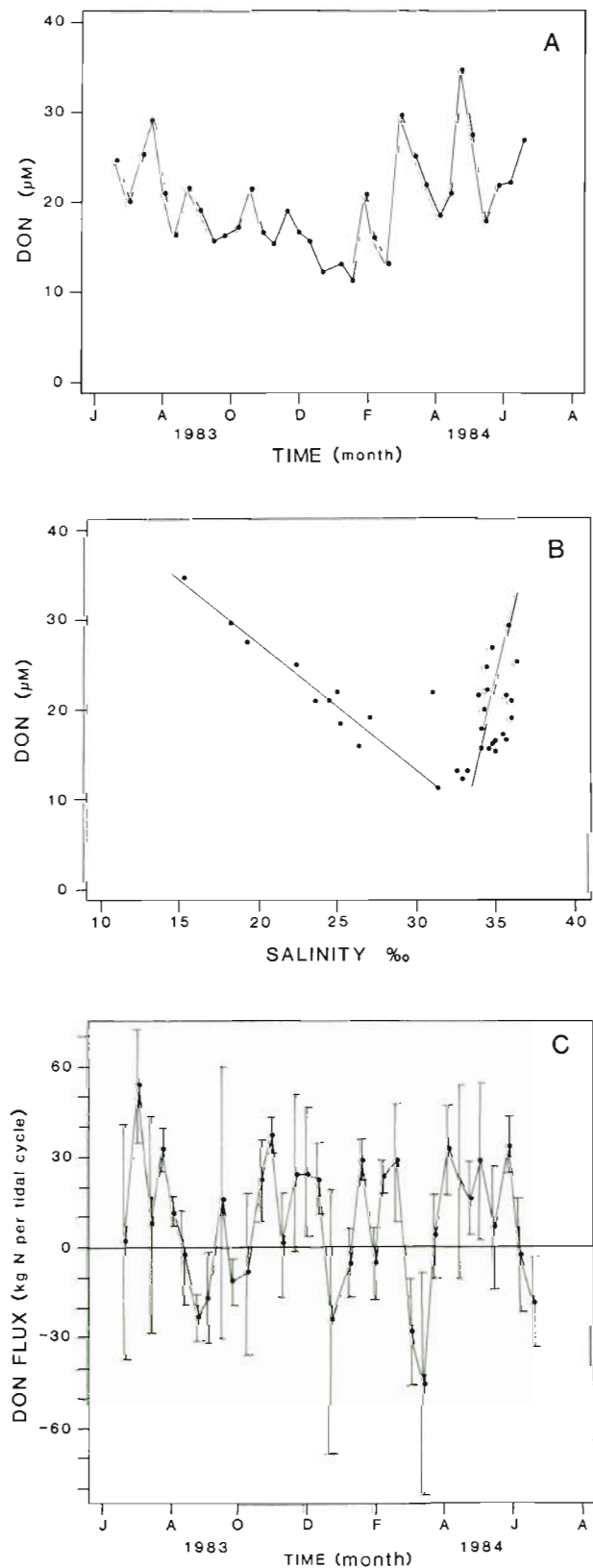

Fig. 4. (A) Mean tidal dissolved organic nitrogen (DON) concentrations as a function of time of year, and (B) tidal water salinity. (C) DON flux as a function of year (export +, import −)

on the oyster reef community suggests that this subsystem imported 127 kg N yr^{-1}. This analysis indicates that the vegetated marsh could account for most of the DON exported from the basin.

Mean tidal particulate nitrogen (PN) concentrations varied seasonally between 3.7 and 35.2 μM N (Fig. 5A), with higher values observed during spring and summer. The highest values of PN were found just after a major storm passed through North Inlet (3.4 cm rain during low tide conditions). The similarity in trend of PN values and water temperature suggest that PN loads in the tidal water were caused by increased bioturbation and resuspension during the warmer months. The PN net flux data (Fig. 5B) indicate that during most of the year there was no net trend in flux direction through the tidal creek. However, during late summer and early fall when the tidal water had its highest PN load there was a net import into the basin. The annual flux estimate suggests that a statistically insignificant (α = 0.05) 1540 kg N (SE = 3670 kg N yr^{-1}) was imported into the Bly Creek basin. The magnitude of the PN flux on an areal basis (2.3 g N m^{-2} yr^{-1}) is in the range of those found for other marsh-estuarine systems (Nixon 1980).

The Bly Creek basin is neither a sink nor a source for PN to the surrounding estuary since the nontidal inputs to the basin are negligible and the tidally mediated input to the basin is statistically insignificant (Table 2). Within the basin the vegetated marsh (Whiting et al. unpubl.) removed a statistically insignificant amount of PN and the oyster reef community removed only 233 kg N yr^{-1} (Dame et al. unpubl.). However, a graph of PN flux through the tidal creek and maximum tidal height (Fig. 5C) suggests that when high tides were observed within the basin and a large percentage of the vegetated marsh was inundated there was an input of PN through the tidal creek. Therefore, it is proposed that the vegetated marsh can affect the PN transport direction and magnitude when high tide conditions prevail.

Marsh-estuarine systems along the eastern coast of the USA have been shown to export NH_4^+, DON, and PN, and import NO_3^-. These results led Nixon (1980) to suggest that marshes import dissolved oxidized nitrogen and export reduced dissolved and particulate forms. The Bly Creek Ecosystem Study supports these trends, with the obvious exception that this system potentially imported PN. Even though the tidal creek has not been seen as a passive conduit, the vegetated marsh has long been thought to be the site which controlled the trends discussed above.

Significant rates of denitrification and N_2-fixation within the vegetated marsh have led to the assumption that these processes were responsible for the import of NO_3^- and export of NH_4^+ found in most of the nitrogen exchange studies in tidal creeks (Nixon 1980). How-
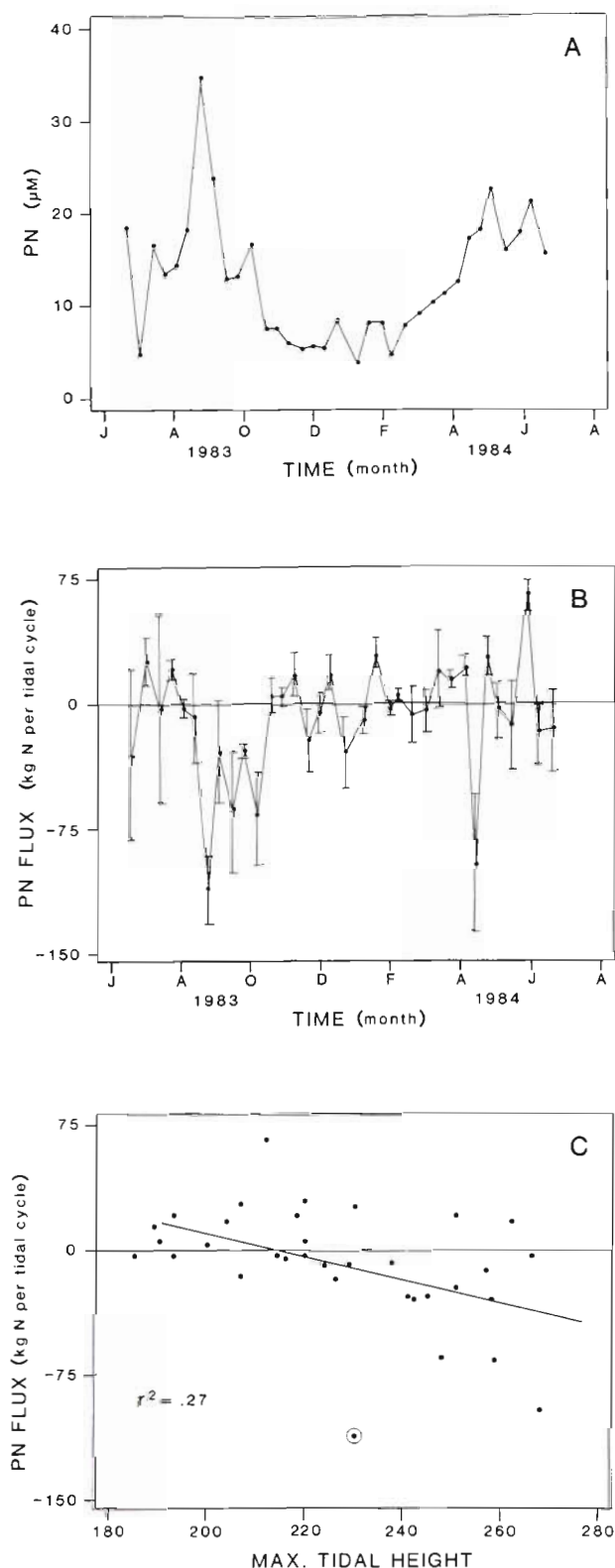

Fig. 5. (A) Mean tidal particulate nitrogen (PN) concentrations, and (B) PN flux as a function of time of year (export +, import −). (C) Net PN flux as a function of maximum tidal height (export +, import −; circled data point omitted from regression analysis)

ever, flume studies on vegetated marshes in both mesohaline and euhaline (Bly Creek study site) systems suggest that this subsystem is a sink for NH_4^+. The NH_4^+ flux data from the Bly Creek study indicate that the tidal creek subsystem produced the NH_4^+ which was both potentially exported from the basin and removed as tidal water resided on the marsh surface. It is hypothesized that the tidal creek water column coupled to the benthic substrate is heterotrophic with a net remobilization of NH_4^+. NH_4^+ may be produced by (1) heterotrophic utilization of particulates and/or dissolved organics, and/or (2) phytoplanktonic excretion. This study does support the contention that the vegetated marsh is the sink for the $NO_3^- + NO_2^-$ imported in this and possibly other tidal creek systems. The vegetated marsh within the Bly Creek basin was capable of removing all the $NO_3^- + NO_2^-$ that was potentially imported into the basin via the tidal creek, streamwater, groundwater, and rain. However, the tidal creek was shown not to be an inactive conduit for this constituent. It is hypothesized that active cycling of NO_3^- occurs within the tidal creek water column, with NO_3^- formed via nitrification.

The origin of outwelled dissolved organics has been attributed to processes occurring on the vegetated marsh surface such as leaching from live and dead *Spartina* (Turner 1978, Pakulski 1986) or diffusion from marsh sediments (Pomeroy et al. 1977). Correspondingly, the source of the outwelled PN was assumed to be associated with marsh macrophyte productivity (Valiela et al. 1978). This study supports the assertion that the vegetated marsh may be an important source of DON which is outwelled in this system (Whiting et al. unpubl.) and possibly other marsh-estuarine systems. In addition, it appears that a significant percentage of the DON exported from this basin entered the basin via the blackwater stream. This DON had its source in litter decomposition within the maritime forest (Wolaver & Williams 1986). The Bly Creek PN flux data suggest that the vegetated marsh has a strong effect on the flux direction and magnitude of this constituent through the tidal creek during high tide conditions. It appears that normally there was a PN export through the tidal creek, especially if the maximum tidal height was lower than 230 cm (Fig. 5C). This can be explained by asymmetries in velocity and discharge magnitude as a function of time over a tidal cycle. In this system maximum water velocity and discharge were always observed on the ebbing tide. In addition, maximum flood and ebb water velocity and discharge occurred just before and just after high slack tide. The observed asymmetry in magnitude and timing of maximum water velocity and discharge suggests that there should normally be an export of particulates through the tidal creek (Boon 1975). However, the effect of the

marsh surface on removing particulate material from the tidal water was strong enough to counter this trend when a large percentage of the marsh was inundated.

In summary, the Bly Creek Ecosystem Study showed that the movement of nitrogen through the Bly Creek basin is quite complicated and may be controlled by chemical, physical, hydrodynamic (asymmetries in tidal velocity and discharge), and biological processes. Evidence suggests that the tidal creek subsystem is where reduced particulate and dissolved organic species are processed. These materials enter the tidal creek from either the adjacent marsh or are transported into the basin through the tidal creek. The by-products of decomposition, especially NH_4^+, are released into the tidal creek water column with the possible production of nitrate via nitrification. Most of this material is then transported back onto the vegetated marsh surface on the flood tide where it is utilized.

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