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Influences of flood and ebb tides on nutrient fluxes and chlorophyll on an intertidal flat

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ABSTRACT: Intertidal estuarine sediment processes produce organics and nutrients and are influenced by river outflow and tidal cycles. Hence the sediments act as a source or sink of nutrients into or out of the water column. In most studies, a chamber incubation approach is used to study fluxes of nutrients into and out of the sediment; the chamber isolates the sediments from the hydrodynamics occurring in the overlying water column. Therefore, field data over an entire intertidal flat are lacking. Here, we present a unique case in which an intertidal flat is semi-enclosed, usually inundated for 12 to 14 h during a tidal cycle, and hence can be treated like an incubation chamber during this period of submergence. The intertidal flat on Sturgeon Bank, British Columbia, was directly exposed to domestic sewage effluents from the Iona Sewage Treatment Plant between 1967 and 1989. Since 1989, the sewage effluent has been diverted and discharged into deep water in the Strait of Georgia. The objective of the present study was to determine the effects of tidal cycles on the flux of nutrients from the sediment into the water column. We expanded the spatial scale of our study site by treating the semi-enclosed tidal flat as a large natural incubation chamber during the 12 to 14 h period of submergence. Water samples at 10 stations covering Sturgeon Bank were taken during late flood tides and middle ebb tides, 12 to 13 h later. Salinity, temperature, chl *a*, nutrients (NH_4, NO_3 and PO_4), suspended load, and particulate carbon (PC) and nitrogen (PN) at the surface were measured or analyzed. Based on nearly 2 yr observation between 1994 and 1995, we found that water coming onto Sturgeon Bank was a mixture of different origins since salinity was not correlated with temperature or any other variables except for particulate C/N. Chl *a* was higher during flood tides than during ebb tides, indicating a loss of chl *a* from the water column, likely due to feeding by benthic organisms. Ammonium concentrations were almost always higher during ebb tides than flood tides, indicating a release of NH_4 from the sediment. Therefore, the intertidal flat of Sturgeon Bank appears to be a sink for chl *a* and a source of NH_4 to the Strait of Georgia. Particulate C/N ratios were always higher than 7, indicating a predominantly terrestrial origin of particulate organics. Particulate C/N ratios were also found to be higher during ebb tides than flood tides, indicating preferential utilization of PN when organic matter was deposited onto the sediment. Our study has shown that it is possible to treat an intertidal flat as an incubation chamber and follow fluxes of nutrients and particulates into and out of the water column during flood and ebb tides. With this approach, we concluded from NH_4 concentrations and fluxes that the intertidal flat at Sturgeon Bank showed no signs of eutrophication due to previous sewage effluent contamination.

KEY WORDS: Pelagic-benthic coupling · Nutrient source · Chl *a* sink · Intertidal flat · Tidal cycle · Sturgeon Bank

INTRODUCTION

Processes in estuarine sediment regulate the flow of nutrients from terrestrial sources to the ocean and influence the overall productivity of estuarine ecosystems (Nixon 1981). In general, 25% of the nitrogen used in primary productivity in the water column is supplied by nitrogen fluxes from the sediments (Fisher et al. 1982, Kemp & Boynton 1984). On the other hand, between $\frac{1}{4}$ and $\frac{1}{2}$ of the allochthonous carbon inputs plus autochthonous primary productivity are oxidized by the sediments (Nixon & Pilson 1983). Due to the increase in human pollution, estuarine sediments also

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represent a primary repository for anthropogenic chemicals entering the marine environment (Means et al. 1989, cf. Demuth et al. 1993).

The study sites were on Sturgeon Bank, which is an intertidal flat located west of Vancouver (see Fig. 1). Its landward margin is fringed by a 1 km wide brackish marsh, and the sedimentary flat is 5 km wide and extends into the Strait of Georgia. To the south, the Steveston Jetty separates Sturgeon Bank from the Main Arm (South Arm) of the Fraser River, and the Iona Jetty (6 km long) divides Sturgeon Bank into 2 flats of which the southern part is larger than the northern part. The Middle Arm of the Fraser River discharges directly onto the intertidal flat, while the river discharge or the riverine plume from the Main Arm invades the flat with tidal flows and through the jetty openings. Tidal cycles in the Strait of Georgia are mainly semi-diurnal (LeBlond 1983). Tidal ranges are between 2 and 5 m due to the change in height of the lower low water during spring and neap tides. During flood tides, seawater inundates the flat and dams the river flow of both the Main and Middle Arms of the Fraser River. During ebb tides, the river flow increases and the flat is exposed. The Fraser River discharge is minimal in winter, starts to increase in April, reaches a maximum in June and then gradually decreases until September. The flat consists mostly of sandy sediments (Luternauer & Murray 1973).

Between 1962 and 1988, the Iona Sewage Treatment Plant on Iona Island discharged primary treated sewage (estimated 23 000 kg suspended solids d^{-1}) into a ditch along the south side of the Iona Jetty. The initial intention was to discharge sewage effluent during flood tides so that the effluent could retreat into the Strait of Georgia with ebb tides and be further diluted with seawater in the Strait. However, depending on wind conditions and the phases of the (spring vs neap) tidal cycle every 2 wk, the effluent frequently spilled onto the intertidal flat and solids settled onto the sediment. Part of the intertidal ecosystem was heavily contaminated during this period. Early studies have shown that heavy metals (especially Hg) were very high near the outfall and decreased as one moved further away (McGreer 1979, Thomas & Bendell-Young 1998). Diversity of benthic fauna was very low at sites near the outfall and increased with the distance from the outfall (Otte & Levings 1975).

Beginning in 1989, the primary treated sewage was diverted directly into the deep water (approximately 100 m deep) in the Strait of Georgia, through 2 large pipes. This diversion has largely reduced direct effluent pollution of the intertidal flat and allowed the intertidal ecosystem to recover from earlier contamination. This diversion offered a unique opportunity to study the recovery process. This study was part of a larger project initiated in 1994 under the Fraser River Action Plan and involved multi-disciplinary studies on topics including heavy metals in sediments (Thomas & Bendell-Young 1998), sediment nutrient dynamics (Yin et al. unpubl. data), benthic algal biomass (Yin et al. unpubl. manuscript), benthic primary productivity (Ross 1998), and dynamics of important invertebrates such as *Macoma* sp. and *Corophium* sp. (Arvai 1997) and shore bird feeding (Sewell 1996).

Most studies have focused on the processes in subtidal estuarine sediments that are constantly under water as opposed to processes in intertidal sediments (Nixon 1981). Estuarine intertidal flats are an important interface between terrestrial river discharge and marine waters and often form part of estuarine deltas. Estuarine intertidal sediments receive large amounts of sediment-bound nutrients and organic detritus from the river and act like a platform for processing these sediment-bound organics or nutrients that pass through it. Therefore, intertidal sediments may represent a source or sink of a nutrient into or out of the water column during tidal cycles. The processes involved in the uptake or release of nutrients from the sediment are complex and will depend on the location, depth within the water column and tidal phases (Wolaver & Zieman 1983). Whether the sediment acts as a sink or source is also nutrient-specific and seasonally dependent (Watson et al. 1993).

In most studies, observations are obtained with the chamber incubation method which does not match the scale of intertidal flats. In this study, we treated a semi-enclosed intertidal flat like an incubation chamber and sampled the water column between flood and ebb tides over the entire flat for salinity, nutrients, particulate carbon (PC) and nitrogen (PN). The objectives of the present work were to: (1) examine whether the intertidal flat is a source or sink of nutrients for the Strait of Georgia, (2) to determine what regulates nutrients and chl in the exchange between the water and the flat, and (3) assess the effects of tidal cycles on nutrients and chl *a* on the flat and in the water column of the Strait of Georgia.

MATERIALS AND METHODS

The area of Sturgeon Bank between the north and south jetties (Fig. 1) forms an enclosed flat that opens to the tidal waters of the Strait of Georgia. This area of Sturgeon Bank serves as a natural incubator: water fills the area during a flood tide, incubates over 12 to 14 h and leaves during the following ebb tide. Our sampling strategy was based on this concept. Due to the semi-diurnal nature of the tides in this area, there is sometimes a higher low water (HLW) phase of the tidal cycle during the 12 to 14 h. The HLW is usually about 3 m in the Tidal Water Table, and, at this water level, the flat is still inundated by tidal water. The less strong ebb and flood periods are excluded when we refer to flood and ebb tides in our results.

Stations, sampling time and sampling protocol. Ten sampling stations were selected (Fig. 1; W1 to W10). Five stations (W1 to W5) were constantly under water at the 10 m depth contour offshore. The other 5 near-shore stations (W6 to W10) were in the middle of the intertidal flat; they were covered by water during high tides and exposed to the air during low tides. The near-shore stations were ~3 m at higher high water. The water was sampled during the late stage of a flood tide and during the middle stage of the following ebb tide. Therefore, changes in water parameter values during this time period provided information on the interaction between the overlying water and sediment. The sampling frequency was bi-weekly in spring and summer, and monthly or longer in fall and winter. Sampling always took place during spring tides.

A water analyzer was used *in situ* to measure salinity and temperature. At each station, surface water was collected with a plastic bucket. All water samples were stored in 1 l polyethylene bottles and transported to the laboratory in coolers for the analyses of chl *a*, PC and PN a few hours later. Subsamples for nutrients (NO_3, NH_4 and PO_4) were immediately filtered via a syringe and Swinex filter holder into acid-cleaned bottles through 25 mm GF/F filters which were pre-combusted at 480°C for 4 h. These nutrient samples were frozen within 4 h and kept for later analysis.

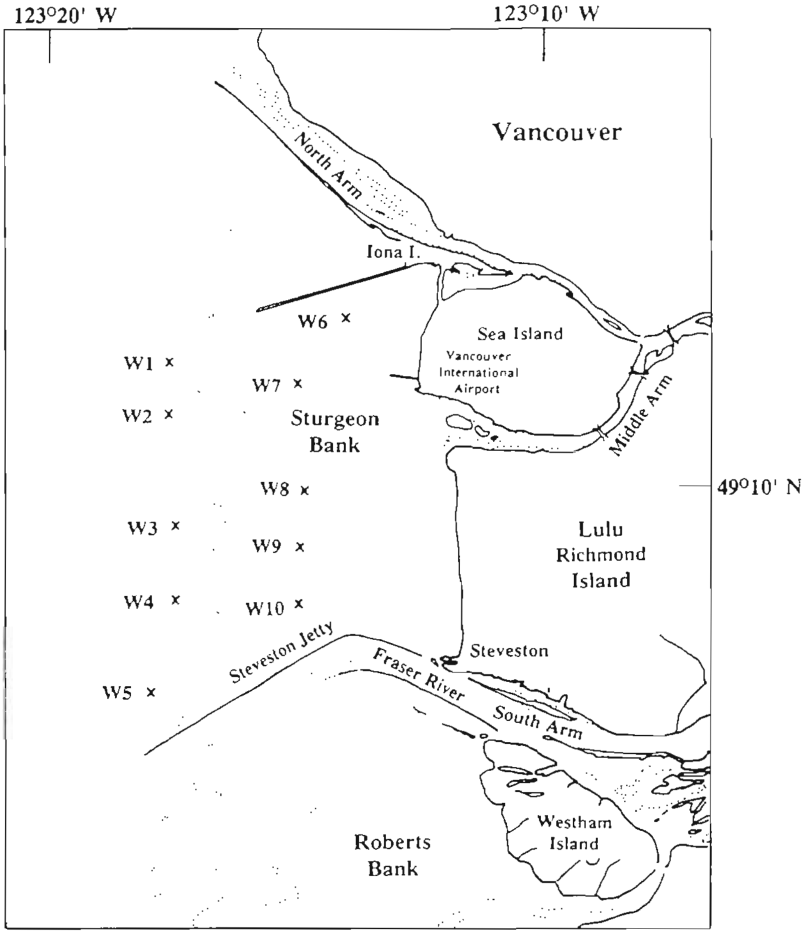

Fig. 1. Map of Sturgeon Bank and Roberts Bank. Dotted line on the right indicates the edge of the marsh and on the left the lowest (LLW) tidal line. The hovercraft positioning uses GPS which is accurate to within 25 or 50 m depending on weather

Analytical methods. Samples for chl *a* (200 to 300 ml) were filtered onto Whatman GF/F filters. Filters were placed into 10 ml of 90% acetone and sonicated (in the dark) for 10 min in ice-cold water. After sonication, chl *a* was extracted in the cold and dark for 24 h in 90% acetone, and analyzed by *in vitro* fluorometry (Parsons et al. 1984) using a Turner Designs® Model 10 fluorometer.

Samples for suspended loads were collected on pre-combusted GF/F filters, dried for 24 h at <60°C and weighed. The average weight of 10 GF/F filters was subtracted from each sediment-containing filter in order to obtain the amount of suspended load on a filter. Samples for PC and PN (usually 400 ml) were collected on combusted (460°C for 4 h) Whatman® GF/F filters and stored frozen in a desiccator. The filters were dried for 24 h at <60°C and analyzed with a Carlo Erba Model NA 1500 NCS elemental analyzer, using the dry combustion method described by Sharp (1974).

All nutrients were determined using a Technicon AutoAnalyzer® II. No correction was made for salinity effects since salinity effects on nutrient analysis were tested and were found to be small (Collos et al. 1992). Nitrate (plus nitrite) and ammonium were determined following the procedures of Wood et al. (1967) and Slawyk & MacIsaac (1972), respectively. Phosphate was analyzed according to Hager et al. (1968).

RESULTS

Salinity was lower during ebb tides than during flood tides (Fig. 2), indicating more freshwater outflow from the Fraser River during ebb tides. This was consistent with other studies where the freshwater outflow is dammed during flood tides and released during ebb tides (LeBlond 1983, Geyer & Farmer 1989). Salinity of

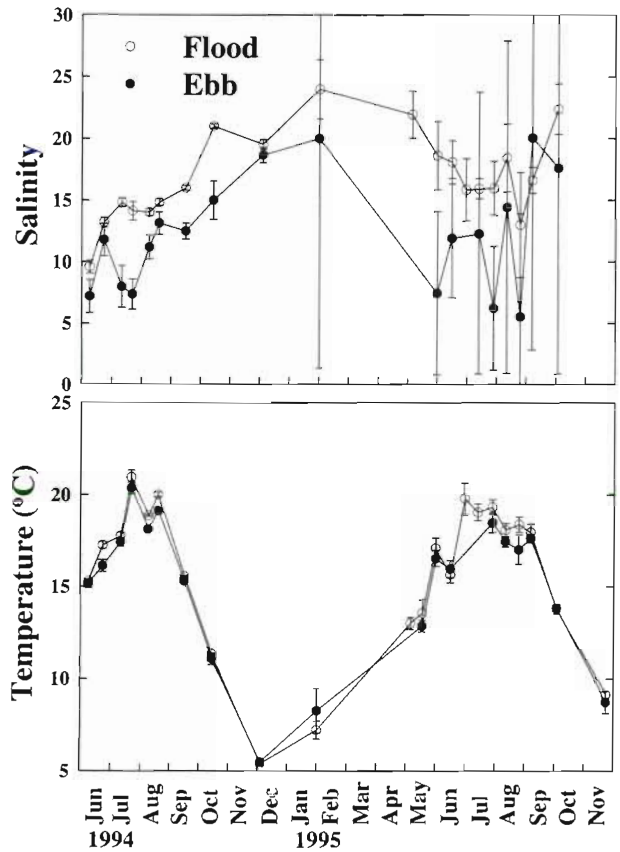

Fig. 2. Time series of salinity and temperature in the water column (average of the 10 stations) during tidal floods and ebbs for 1994 and 1995. Error bars = ±1 SE (n = 10)

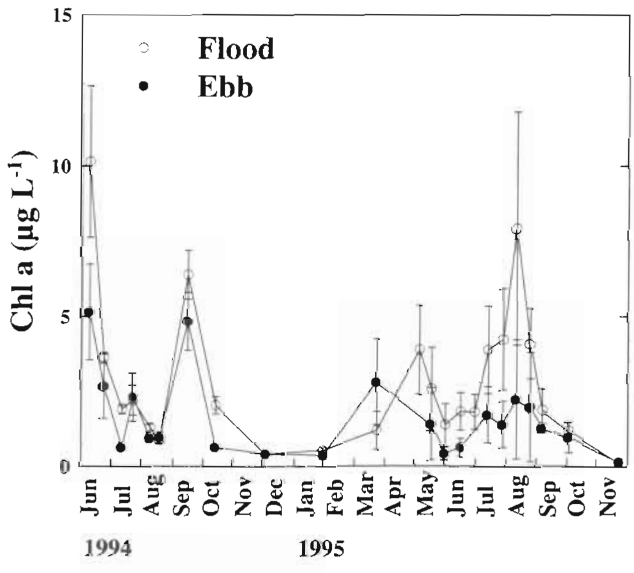

Fig. 3. Time series of chl *a* in the water column (average of the 10 stations) during tidal floods and ebbs for 1994 and 1995. Error bars = ±1 SE (n = 10)

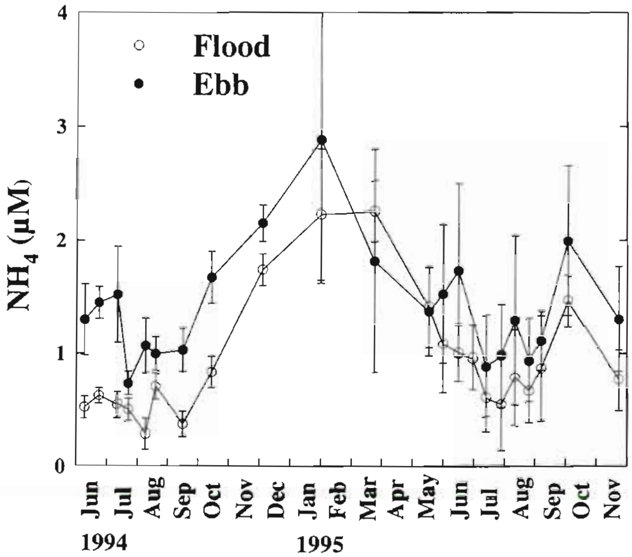

Fig. 4. Time series of NH_4 in the water column (average of the 10 stations) during tidal floods and ebbs for 1994 and 1995. Error bars = ±1 SE (n = 10)

the surface water during flood and ebb tides was low (around 10) in June and July and high (near 20) in December and January (Fig. 2). This reflected the maximum freshwater outflow from the Fraser River in June and the minimum in winter. The temperature of the surface water showed obvious seasonality, being highest in July and August (around 20°C) and decreasing to the lowest value in December (5°C) (Fig. 2). However, variations in temperature among the 10 stations were small, and the differences were also small between flood and ebb tides, although temperature was usually higher during flood tides than during ebb tides.

Chl *a* during ebb tides was lower than during flood tides over most of the sampling period (Fig. 3). This indicated that the water column lost chl *a*, possibly to the sediment. The loss appeared to be higher when chl *a* in the flood tide water was high (Fig. 3). There were temporal fluctuations in chl *a* over the 2 yr. The spring bloom is commonly observed during late March and early April in the Strait of Georgia (Parsons et al. 1969, Yin et al. 1996, 1997a). However, chl *a* in March (22 March) 1995 was low and increased in May (4 May) (Fig. 3). This indicated that the spring bloom was developing during the April period. There was a chl *a* peak of 10 μg l^{-1} in June 1994 in the flood tide water, which was high for the Strait of Georgia. This peak did not occur in 1995. High chl *a* (6 μg l^{-1}) observed in September 1994 occurred in August 1995 (Fig. 3).

Ammonium concentrations were high in winter and low in summer (Fig. 4), although NH_4 was rarely depleted. NH_4 concentrations were higher during ebb tides than during flood tides except for 2 occasions (22 to 23 March and 16 to 17 May 1995, Fig. 4). This indicated that NH_4 was released into the water column.

Temporal variation of NO_3 concentrations was strong, with low concentrations from June to September (<3 µM) 1994 and dramatically higher concentrations during October 1994 to March 1995. When NO_3 concentrations were low (Fig. 5), NO_3 was higher during ebb tides than during flood tides, indicating a release of NO_3 into the water column from the sediment. However, when NO_3 was high (as in winter), NO_3 was lower during ebb tides than during flood tides, indicating the loss of NO_3 from the water column to the sediment. High NO_3 in late March (22 March) 1995 was consistent with low chl *a* for the same day. This might be due to a continuation of the winter conditions since the spring bloom had not consumed NO_3 (Yin et al. 1997a) or might be due to wind mixing, as was observed in the Strait of Georgia (Yin et al. 1997b).

The temporal fluctuations in PO_4 concentrations were similar to NO_3. However, PO_4 concentrations were not consistently higher or lower between flood and ebb tides (Fig. 6). This is possibly due to the complicated adsorption or desorption of PO_4 from sediments during the period of high freshwater influence. Previous observations indicated that when water samples were filtered (as was the case in this study), a considerable amount of sediment-bound PO_4 was removed by filtering out the sediment particles (Harrison et al. unpubl.).

Suspended load showed little temporal variation during flood tides over 2 yr, but showed 2 peaks in the outgoing ebb water in July and August 1994 and June 1995 (Fig. 7A). Fluctuations in PC (Fig. 7B) and PN (Fig. 7C) were similar to suspended load. PC ranged from 30 µM in winter to a peak of 120 µM in August 1994, while PN was as low as 2 µM in winter, but was higher in late spring and summer. PC/PN ratios were mostly higher than 6.7 (Fig. 7D).

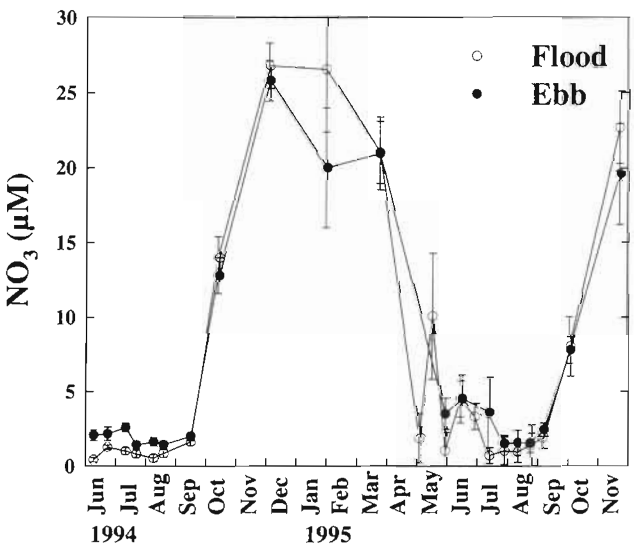

Fig. 5. Time series of NO_3 in the water column (average of the 10 stations) during tidal floods and ebbs for 1994 and 1995. Error bars = ±1 SE (n = 10)

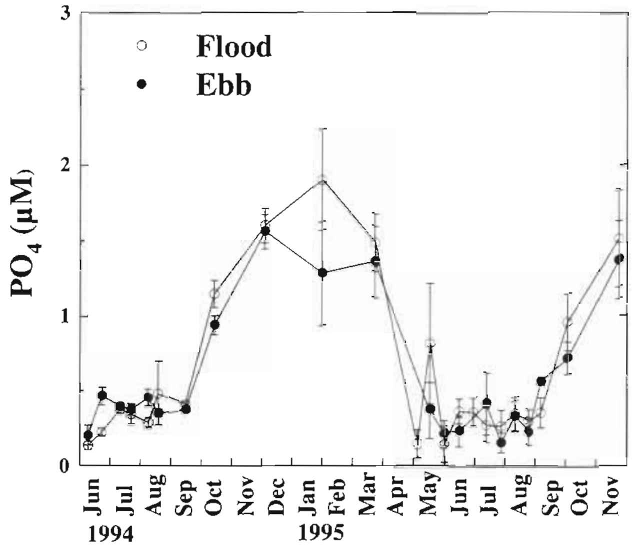

Fig. 6. Time series of PO_4 in the water column (average of the 10 stations) during tidal floods and ebbs for 1994 and 1995. Error bars = ±1 SE (n = 10)

DISCUSSION

Water masses on Sturgeon Bank

A freshwater influence was dominant over Sturgeon Bank based on the range of temporal fluctuations in salinity. However, water masses on Sturgeon Bank did not appear to have any particular spatial pattern. There were no large differences in salinity among stations for either year except for Stn W7 which is near the channel of the Fraser River Middle Arm and Stn W10 which might be influenced by freshwater passing through the openings in the Steveston Jetty (Fig. 8). The analysis of salinity-temperature diagrams also indicates different sources of water masses coming onto and leaving the tidal flat, since the correlation between salinity and temperature at 10 stations for flood or ebb tides was not significant for most tidal cycles (Fig. 9). Such a mosaic of water masses on Sturgeon Bank is not unexpected. Our previous studies have shown that the water masses near the Fraser River estuary are complex due to the presence of the riverine plume, estuarine plume and deep seawater (Yin et al. 1995a). The dynamics can be further complicated by tidal cycles and winds (Feeney 1995, Yin

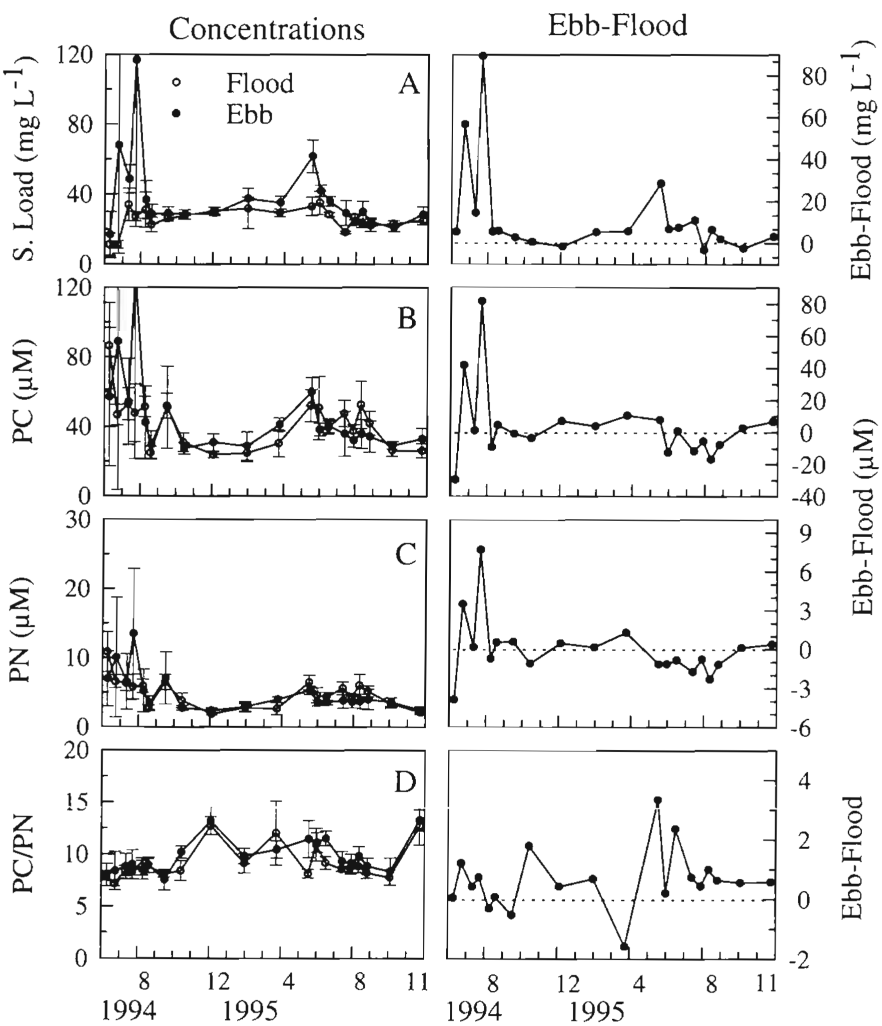

Fig. 7. Time series of concentrations (average of the 10 stations) (left panels) and fluxes (right panels) of: (A) suspended loads, (B) PC, (C) PN, and (D) PC/PN atomic ratios in the water column during tidal floods and ebbs for 1994 and 1995. For concentrations, error bars = ±1 SE (n = 10). Flux is the difference between measurements made during ebb and flood tides (ebb minus flood); values above 0 (above the dashed line) indicate a flux out of the sediment, and those below 0 show a flux into the sediment

et al. 1995b,c, Amos et al. 1997). Because of the interacting dynamics, other variables did not appear to be correlated with salinity during most tidal cycles (Fig. 9). Even suspended load, which should be related with freshwater, was not correlated with salinity. In spite of no long-term spatial pattern for salinity, chl *a* was the highest at Stn W3 during flood tides and at Stn W6 during ebb tides (Fig. 8). The highest NH_4 at Stn W10 in 1995 might be related to the lowest salinity water which was freshly discharged from the river (Fig. 8).

Nutrient flux

Whether estuarine sediment is a sink or source of nutrients for the water column (Nixon 1981) remains an important question for the estuarine ecosystem, particularly with increasing anthropogenic input of nutrients to estuarine environments. The seasonal pattern of nutrient flux is crucial in order to understand this question. One important finding in this study was that NH_4 was released into the water column between a flood tide and its following ebb tide. This release of NH_4 always occurred except on 2 occasions (Fig. 10). The potential sources of NH_4 to Sturgeon Bank are freshwater from the river, flood water, direct excretion by benthic animals, interstitial water which contains nutrients from mineralization and infaunal activities, and excretion by zooplankton and other animals that come with the flood tide waters. It has been demonstrated on a mudflat in France that benthic feeding activity increased when flood tide water swept over the sediment and, as a result, NH_4 was excreted and

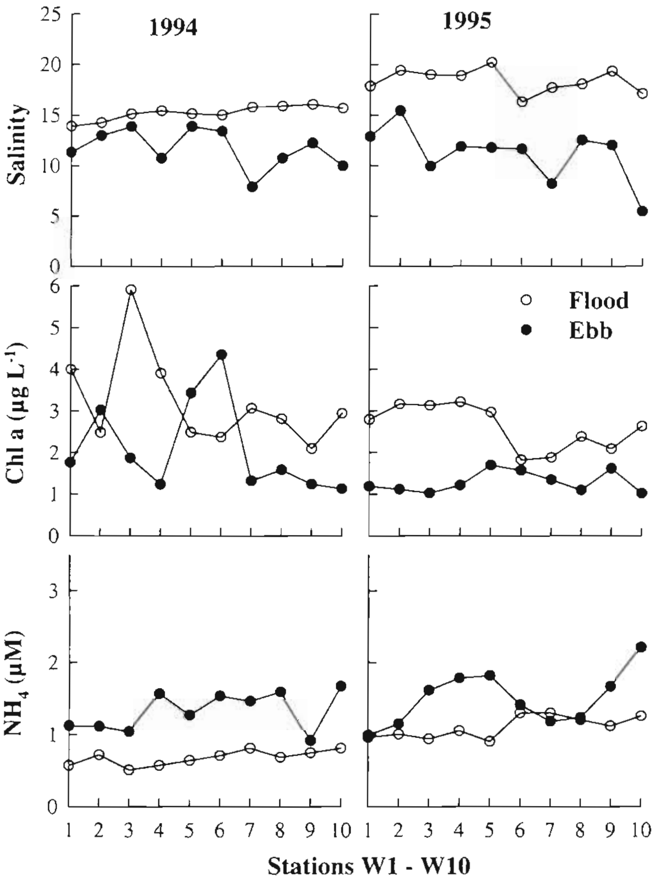

Fig. 8. Yearly average of salinity, chl *a* and NH_4 at each station in the water column during tidal floods and ebbs for 1994 and 1995

released into the water (Rybarczyk et al. 1993). The activities of benthic macrofauna were also observed to result in enhanced fluxes of nutrients out of the sediment (Watson et al. 1993).

In the current study, chl *a* in flood tide waters was apparently lost from the water column in most months of 1994 and 1995 (Fig. 10). The possible mechanisms by which chl *a* can decrease in the water column are sedimentation, and feeding by benthic and pelagic animals. Sedimentation should result in a correlation between chl *a* and suspended loads, or between their fluxes, which was not the usual case for the former (Fig. 11) and not significant for the latter (Table 1). Therefore, animal feeding was likely responsible for this loss of chl *a* and, therefore, may have contributed to the observed NH_4 flux. However, there was no significant correlation between fluxes of chl *a* and NH_4. This lack of correlation suggests that other processes are also operating, such as the flux of NH_4 out of the sediment due to much higher concentrations in the interstitial water. The release of NH_4 into the overlying water probably occurs more rapidly when water is sweeping over the sediment surface. NH_4 concentrations in the pore water on Sturgeon and Roberts Banks to the south of the Steveston Jetty were found to range from 200 to 1000 µM in the top 1 cm of sediment (Yin et al. unpubl. data), much higher than in the water column. After the initial release of NH_4 into the water column, the exchange between sediment and the water column is dependent on the gradient of NH_4 at the water-sediment interface. The flux of NO_3 not only supported the observation of the exchange in NH_4, but also indicates the exchange of NO_3 at the water-sediment interface at the same time. In fact, the nutrient concentrations that we measured during the late stage of the flood tide might have contained NH_4 and NO_3 from this exchange process as well as from the initial release; our values would thus be an underestimate of fluxes of NH_4 and NO_3 from the sediments on this bank.

Nutrient sources

The almost constant flux of NH_4 into the water column raises the question of the source of nitrogen. The estimate of NH_4 flux (out of the sediment) using the time-weighted averaging method (instead of an average over the number of sampling points over time) was 1.25 mM m^{-2} d^{-1}. However, based on the measured PN data, the PN flux averaged with the time-weighted method was estimated to be only 0.38 mM m^{-2} d^{-1} (into the sediment). This was not sufficient to support the NH_4 flux. On the other hand, the daily chl *a* flux was estimated to be 2.87 mg chl *a* m^{-2} d^{-1} (into the sediment). This value represents 12.06 mM m^{-2} d^{-1} of PN using the regression equation obtained for the Strait of Georgia (Yin et al. 1996). The estimated flux of NH_4 was only about 10% of this chl *a*-PN flux. One plausible explanation for this discrepancy between the 2 estimates is that PN contained a large portion of detritus of terrestrial origin. PN (including chl *a*) could settle onto the sediment and be resuspended during the period between a flood tide and the next ebb tide. Assuming benthic feeding selectively utilized chl *a*, the resuspended PN contained even more detritus of terrestrial origin. This is suggested by higher C/N ratios during ebb tides than flood tides (Fig. 7). In addition, it is interesting to note that a significant correlation between chl *a* and PN occurred more frequently during flood tides than during ebb tides (12 vs 6 times) (Fig. 11). The notion of resuspension of detritus was supported by a highly significant correlation between fluxes of suspended load, PC and PN (Fig. 7, Table 1). It explains the small flux of PN compared to the large flux of chl *a*, although there was a weak correlation between the 2 fluxes (Table 1).

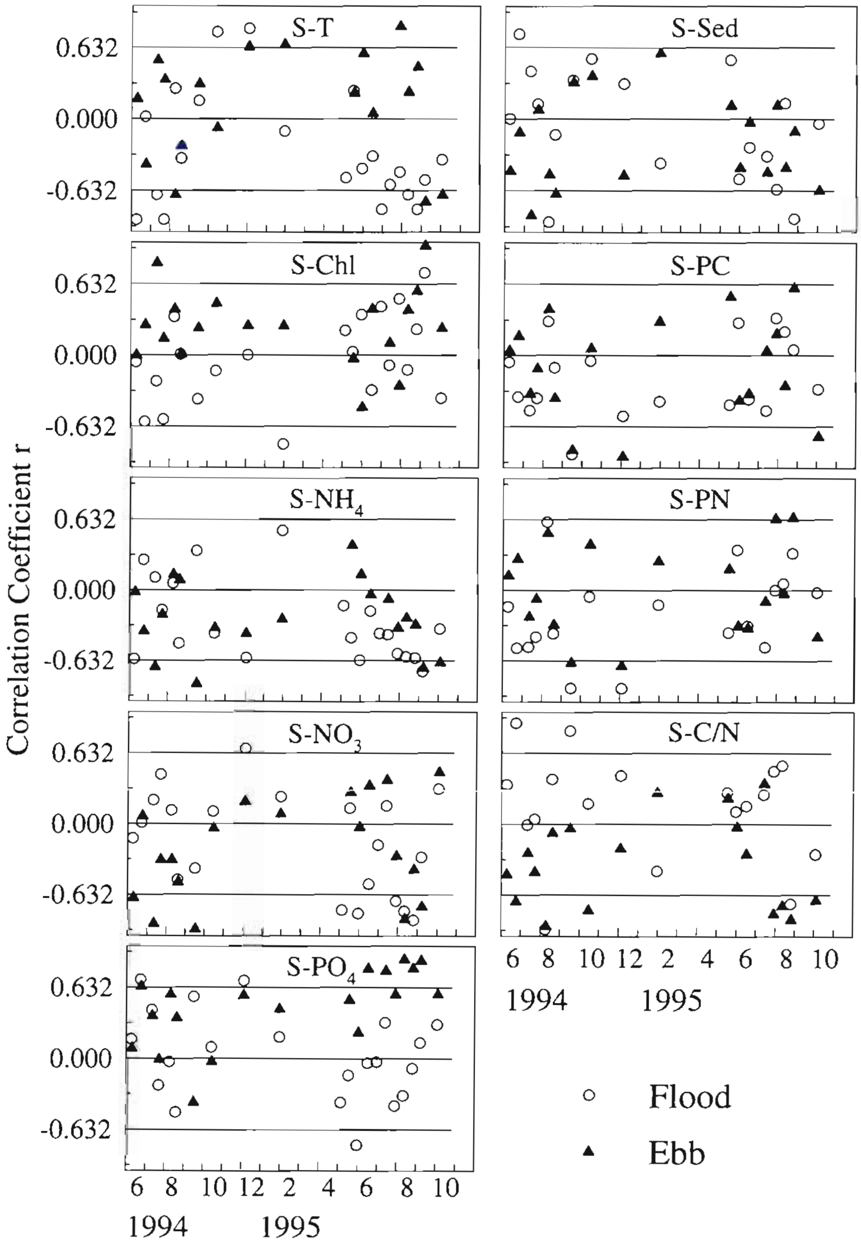

Fig. 9. Correlation between salinity (S) and other variables, including temperature (T), chl *a*, NH_4, NO_3, PO_4, suspended load (Sed), PC, PN, and PC/PN (C/N) ratios during 1994 and 1995. Each point represents a correlation coefficient r among 10 stations during a flood tide or an ebb tide. The 2 horizontal lines at −0.632 and 0.632 are critical values for r; points above 0.632 or below −0.632 are significant at $p < 0.05$ (Zar 1984)

Effects of tidal cycles on the exchange of nutrients between the water column and sediment were evident for Sturgeon Bank. When flood tide water comes onto the flat, chl *a* and other particulate organic matter are ingested by benthic animals. Some portion of the organics may be deposited onto the sediment, whereas another portion may be resuspended. Particulate organic matter not only comes from the Strait of Georgia, but also comes from the riverine plume originating from the Main Arm and Middle Arm of the Fraser River. When organics are deposited onto the sediment, they will be subjected to bacterial decomposition. Buried organics are decomposed and dissolved in the interstitial water. The exchange of dissolved constituents is subject to the gradient of a particular constituent at the sediment-water interface. Earlier studies showed that the intertidal flat was rich in organic matter before sewage effluent was diverted (Otte & Lev-

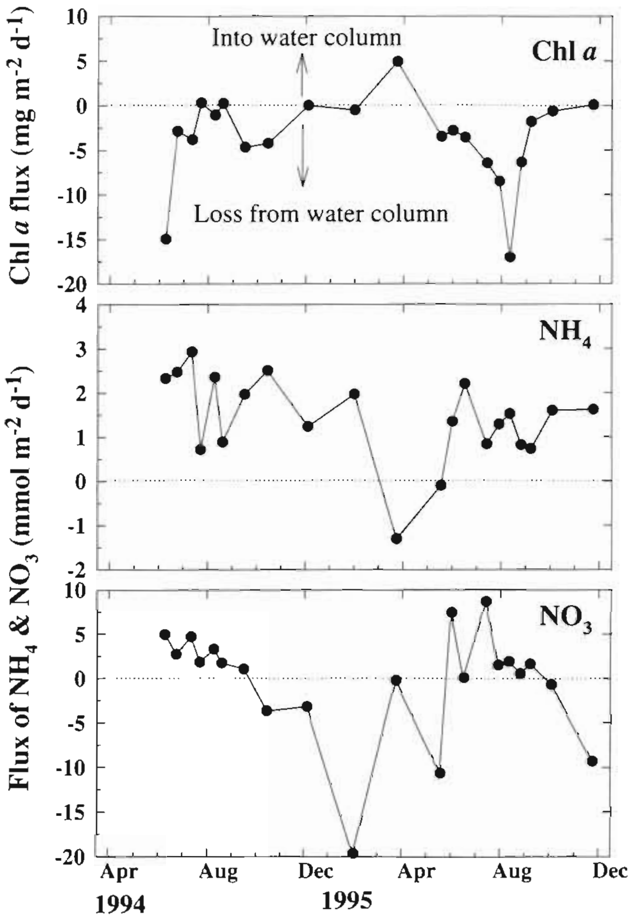

Fig. 10. Time series of fluxes of chl *a*, NH_4 and NO_3 in the water column during tidal floods and ebbs for 1994 and 1995

ings 1975). Presumably, there must have been a large flux of NH_4 out of the sediment right after the diversion of sewage effluent. A few years later, in 1994, our data on fluxes of nitrogen (PN, NO_3 and NH_4) did not show an internal source of nitrogen from this organic contamination. Sturgeon Bank cannot be considered a eutrophied flat when the flux of NH_4 is compared with other systems (Table 2). The NH_4 flux from the sediment to the water column on Sturgeon Bank was higher than one observed from deep water sediments (Blackburn et al. 1996), and within the range of the York River, Virginia (Rizzo 1990), a subtidal area of Mobile Bay, Alabama (Cowan et al. 1996), and the Chesapeake Bay (Boynton & Kemp 1985). However, the NH_4 flux was smaller than the flux from eutrophied sediments of the Bay of Fundy, Canada (Anderson 1986), and a hypertrophic fish pond in Israel (Krom 1991). The results indicating a recovery from sewage pollution are also supported by concentrations of NH_4 which are within the range observed for the Strait of Georgia (Clifford et al. 1992). Therefore, our results show that the water column on Sturgeon Bank is no longer markedly contaminated by organic pollution from the sediment over a scale of the entire flat. Unfortunately, comparisons with pre-diversion data cannot be made, because there are no historical data on the flux of NH_4 from the sediments on Sturgeon Bank.

Nutrient dynamics in the water column and sediments are an essential process in the ecosystem of Sturgeon and Roberts Banks and form a central link among different components of the ecosystem. The finding that Sturgeon Bank is a sink for PN and chl *a* indicates that phytoplankton productivity in the Strait of Georgia provides a constant food source for Sturgeon Bank, which is the largest intertidal flat for the largest number of waterfowl in western Canada. In turn, Sturgeon Bank provides remineralized nutrients to the overlying water column that fuel primary productivity in the water column. This source of nutrients is particularly important during late spring and summer when nutrient concentrations are low in the Strait of Georgia (Yin et al. 1997b).

Most previous estimates of nutrient flux have been based on chamber incubations. We believe that our approach of treating the entire intertidal flat as an in-

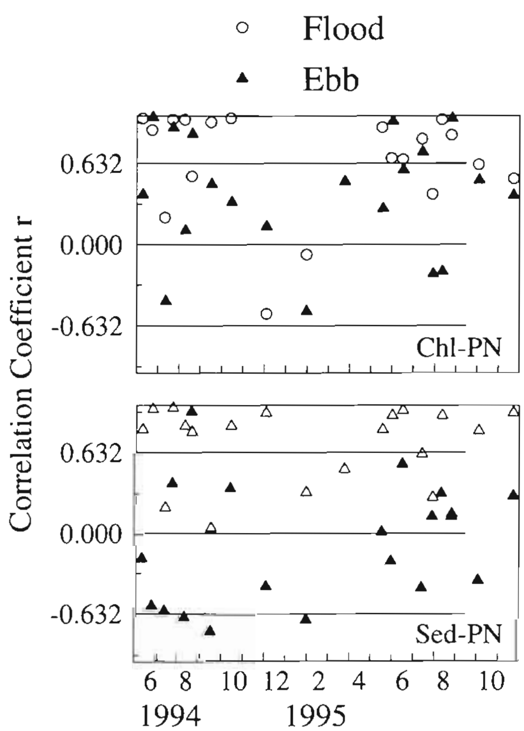

Fig. 11. Correlation between chl *a* and PN and between suspended loads (Sed) and PN. Each point represents a correlation coefficient r among 10 stations during a tidal flood or ebb. The 2 horizontal lines at −0.632 and 0.632 are critical values for r; points above 0.632 or below −0.632 are significant at $p < 0.05$ (Zar 1984)

Table 1. Correlation coefficient r between fluxes of different parameters for 1994 and 1995, calculated using Microsoft Excel (Ver. 7). *Significant correlation at $p < 0.05$ ($n = 20$). The statistical test for significance is based on critical values of r (Zar 1984) (Sal, salinity; Temp, temperature; Sed, suspended loads; PC, particulate carbon; PN, particulate nitrogen; C/N, PC/PN atomic ratios)

	Temp	Chl *a*	NH_4	NO_3	PO_4	Sed	PC	PN	C/N
Sal	–0.101	0.066	–0.002	0.032	0.292	0.029	0.042	0.088	–0.427*
Temp		0.161	0.291	–0.523*	–0.562*	–0.258	–0.126	–0.118	0.052
Chl *a*			–0.336	–0.301	–0.153	0.167	0.510*	0.584*	–0.204
NH_4				0.077	0.164	–0.091	–0.188	–0.171	0.157
NO_3					0.836*	0.090	–0.121	–0.061	–0.322
PO4						0.262	0.096	0.158	–0.385
Sed							0.875*	0.794*	0.231
PC								0.972*	0.107
PN									–0.097

Table 2. Comparison of NH_4 fluxes from the sediments in other studies. Values in mmol N m^{-2} h^{-1} in the literature were converted to mmol N m^{-2} d^{-1} by multiplying by 24

Location	Duration	NH_4 flux (mmol N m^{-2} d^{-1})	Source
Intertidal flat, Sturgeon Bank, Canada	Yearly	1.25 (yearly average)	This study
Shallow, York River, Virginia	Mar–Dec	–0.5 – 8.74	Rizzo (1990)
Lab. measurement, Kattegat sediment, Denmark	Oct	1.6 (maximum)	Sündback & Granéli (1988)
Intertidal beach, Nahant Bay, Massachusetts, USA	Yearly	<2.4 (typically)	Pregnall & Miller (1988)
Hypertrophic fish pond, Israel	Jan–Mar	16.1	Krom (1991)
Arctic 170–2577 m deep, Svalbard, Norway	Jun–Jul 1991	–0.02 – 0.34	Blackburn et al. (1996)
Subtidal, Mobile Bay, Alabama, USA	Yearly	–0.53 – 4.34	Cowan et al. (1996)
Chesapeake Bay, USA	Aug–May	1 – 13.5	Boynton & Kemp (1985)
Intertidal mudflat, Bay of Fundy, Nova Scotia, Canada	Aug–Dec	Control: 4.32 Detritus-enriched: 7.2	Andersen (1986)

cubation chamber is unique and innovative. Changes in physical, chemical and biological variables between flood and ebb tides represent real signals of processes over a spatial scale of the entire flat. This approach gave reasonable estimates of nutrient fluxes compared with other studies and offers a new way of studying the nutrient flux in an intertidal area. This approach is particularly important in studying environmental contamination of intertidal flats because observations are based on the entire flat and bear implications on an ecosystem level.

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