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Nutrient budgets (C, N and P) and trophic dynamics of a Brazilian tropical estuary: Barra das Jangadas

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ABSTRACT

This paper focuses on the nutrient dynamics of a tropical estuary on the northeastern Brazilian coast, studied using the LOICZ biogeochemical budgeting protocol. We describe the methodology and assumptions underlying this model. Input data (monthly for rainfall, evaporation, river discharge, and concentrations of salt, phosphorus and nitrogen) were obtained during field campaigns in the Barra das Jangadas Estuary (BJE) over a 5 years period (1999 to 2003). Mass balance results indicate large inputs of nutrients to the system. The model shows that the seasonal variation of the Net Ecosystem Metabolism (NEM) indicates that the system passes from a stage of organic matter liquid production and mineralization during the dry season (–0.5 mmoles C m^{-2} d^{-1}) to liquid mineralization during the rainy season (–19 mmoles C m^{-2} d^{-1}). We suggest that the system varies slightly between autotrophy and heterotrophy during the year due to the rainfall regime, human activities in the basin (density population and sugarcane plantations), and associated DIP riverine loads. High per capita loads of N and P indicate a high population density and high runoff. The application of flux balance modeling was useful to understand the nutrient dynamics of this typical small tropical estuary.

Key words: Brazil, Barra das Jangadas Estuary, seasonal variations, heterotrophy, autotrophy, carbon dioxide.

INTRODUCTION

Estuaries are dynamic systems, in which biological populations fluctuate according to natural cycles. Water quality also varies, particularly as seasonal and annual climatic patterns change. In these systems tracking environmental changes can be challenging, and distinguishing impacts caused by human actions from natural variations can be even more difficult (Marone et al. 2005). Under normal estuarine spatial and temporal constraints, reactive materials, such as nutrients, behave non-conservatively due to modifications by biological recycling and chemical transformations acting independently of simple physical advection and mixing (Dale and Prego 2005).

Furthermore, estuaries are areas in which anthropogenic effects, such as increased nutrient loads, have their most direct influence, and where there is a danger of adverse impacts. Most of these impacts results from a complex chain of events varying over different scales in space and time, which can be ultimately attributed to the accumulation of anthropogenic nitrogen and phosphorus in river water on its way to the ocean (Tappin 2002).

The magnitude of these fluxes is such that the transfer of organic matter from land to ocean via rivers is a key link in global carbon cycles. Due to the intense anthropogenic disturbance, estuaries are often considered to be net heterotrophic ecosystems and act as a source of CO_2 (Biswas et al. 2004, Mukhopadhyay et al. 2006). The increased nutrient load leads to eutro-

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phication, enhances net ecosystem production, and shifts the system towards increased autotrophy (Gattuso et al. 1998). On the other hand, respiration of the organic carbon leads to increased heterotrophy. Additionally, light may become limiting for primary production in the upper part of estuaries (Irigoien and Castel 1997); respiration is then the dominant metabolic process, and an oxygen-depleted zone may occur, stimulating various anaerobic processes. It is well known that the chemical transformation pathways for nitrogen and phosphorus differ markedly from one another (Schlesinger 1997). In addition to being present in inorganic and organic dissolved forms, nitrogen is involved in biotic reactions and is the primary constituent of the atmosphere.

Besides direct uptake and release with respect to organic matter, the biotic processes of nitrogen fixation and denitrification actively move nitrogen between among the atmosphere (as nitrogen gas (N_2) and nitrous oxide (N_2O)) and both organic and inorganic forms of fixed nitrogen. Both nitrate (NO_3) and ammonia (NH_3) are highly soluble in water, and dissolved ammonia readily ionizes to ammonium (NH_4). Nitrate is an important byproduct of combustion, while ammonia is a highly volatile byproduct of animal waste. As a result, atmospheric transport and both wet and dry deposition are important pathways by which these materials are delivered to the landscape (Meyers et al. 2001). By contrast, phosphorus is involved in biotic reactions, primarily through the relatively simple (though still highly complex) pathways of organic production and oxidation. Phosphorus is also involved in various important mineral reactions (including both precipitation-dissolution of various forms of the mineral group apatite and adsorption-desorption reactions). In general, phosphorus is very particle-reactive and is taken up or released from the particles under changing conditions of pH, redox, and ionic strength. It has no significant gas phase.

The scatter in the loading ratio probably reflects, in large part, different chemical reaction pathways for DIN and DIP. The only real overlap in the reaction pathways for nitrogen and phosphorus involves production and oxidation of organic matter.

Because the composition ratio of nitrogen to phosphorus for most terrestrial organic matter is close to the DIN:DIP loading ratio we observed (approximately 19:1), decomposition of organic matter apparently dominates the inorganic nutrient loading, both in absolute range and loading ratio (Smith et al. 2003).

A close link is generally found between ecosystem metabolism and terrestrially derived nutrients in temperate ecosystems. It remains difficult to assess completely a function of estuarine ecosystem in response to the input of terrestrial nutrients in tropical area largely because of confounding physical and biogeochemical factors (Eyre and McKee 2002). Therefore, it is of interest to know whether a shallow coastal water body is a carbon source or sink, particularly in tropical areas Nutrient budgets can provide valuable information as to whether the system is a net exporter or importer of nutrients and can therefore determine its trophic status. Smith and Hollibaugh (1997) used the term "trophic status" to describe the net balance (net respiration or net synthesis) of organic carbon in an ecosystem. The results of these budgets and the use of stoichiometric tools provide estimates of processes such as net production/respiration and nitrogen fixation/denitrification (Gordon et al. 1996). To assess carbon sources and sinks through process studies is not a simple task (Gordon et al. 1996). However, proposed guidelines for the Land-Ocean Interactions in the Coastal Zone (LOICZ) programme to assess non-conservative nutrient fluxes and carbon budgets for well boundary-defined coastal systems. This steady state budgeting method provides an alternative method to evaluate the biogeochemical metabolism and fate of nutrients and carbon in coastal systems when direct measurements of productivity and respiration are not available. Net nutrient fluxes in the coastal zone can be also determined from budget calculations, which is essential to evaluate the effects of riverine discharges on coastal function and carbon metabolism.

The rivers of the Northeast and East are marked by a pattern of seasonal flow typically unimodal, but differ in amplitude. As the climate states, the rivers of the Northeast are subjected to marked seasonal variability, with high intakes of pulses and floods during the wet season flows and low to negligible in the dry season (Knoppers et al. 2009).

In tropical ecosystems, mangrove-fringed estuaries play important roles in global processes, economic issues, political concerns and conservation strategies. Among numerous other processes, these tropical ecosystems affect the global carbon cycle (Lal et al. 2000). Studies in tropical regions are of paramount importance for understanding the diversity of processes that occur at annual and seasonal scales and how these affect the biogeochemical cycles of the elements in these regions. Urbanization, industrialization, deforestation, agriculture, mining, and engineering works (i.e., dredging and damming) have changed the hydrological balance, material yields, and the water quality of estuarine systems, including those of the tropical Brazilian coast (Knoppers et al. 1999). This part of Brazil (Lat. 2°S to 22°S), harbors about 50 small and 7 medium-sized river estuaries subjected to either humid or semiarid climates (Ekau and Knoppers 1999), and includes the Barra das Jangadas.

The objective of the present work was to characterize and model the cultural eutrophication of the BJE to establish the mass balance of N and P throughout the year, considering detailed and complete (rainy and dry season) datasets from 1999 to 2003.

MATERIALS AND METHODS

STUDY AREA

The Barra das Jangadas Estuary (BJE) is the union of the lower course of the Pirapama and Jaboatão rivers, in the state of Pernambuco (Brazil). These basins cover semi-arid areas until they reach regions of intense urbanization along the coast, where they receive domestic and industrial effluents without previous treatment (CPRH 2003) (Noriega et al. 2009). Both rivers suffer the impact of domestic and agricultural effluents, mainly from the sugarcane agro-industry, under the form of high Biochemical Oxygen Demand (BOD), especially between November and March (dry season). During the rainy season, the higher freshwater discharge is the product of increased precipitation throughout the hydrographic basin (Araujo et al. 1999, Noriega et al. 2005a) and the controlled outflow from Pirapama Dam (Araujo et al. 2008).

The hydrographic basins of Jaboatão, Pirapama and other small rivers add up to 1000 km^2 of drainage area. BJE is a small estuarine area in which these rivers converge (8.7°S-8.8°S and 34.4°W-34.8°W). The estuary extends for approximately 13 km^2, with an average depth of 2.6 m (Branco 2002, Noriega et al. 2009) (Fig. 1).

The climate is typically tropical, hot and humid. The air temperature is 26±2.8°C, and the mean annual precipitation and evaporation are around 1.5 and 1.2 m, respectively (Araujo et al. 1999). The rainfall regime is subdivided into two well-defined periods: the dry season (September-February), when the precipitation is exceeded by evaporation; and the rainy season (March-August), when rainfall dominates evaporation (Fig. 2).

The drainage basin includes areas originally covered by the Atlantic Rain Forest, and is presently occupied by sugar-cane and high density populated areas (1100 inhabitants km^{-2}) (IBGE 2000). Despite the deforestation of the margins and the large volume of industrial and domestic effluents received, the estuary itself is surrounded by relatively well-preserved and highly productive mangrove forests. Organic matter pollution by the sugar-cane agroindustry substantially increases during the harvest and milling season, which is from September to February. CPRH (2003) reported high BOD in the harvest periods of 69.6 mg L^{-1} (Jaboatão River) and 152 mg L^{-1} (Pirapama River). The polluting organic load sources are represented mainly by domestic sewage in the Jaboatão river (14.46 t BOD d^{-1}) and by agro-industrial activities in the Pirapama river (24.13 t BOD d^{-1}) (CPRH 2003). Algal blooms are now more frequent during the year and consist of several species of Cyanophyceae, mainly *Microcystis aeruginosa*, *Oscillatoria* sp and *Euglena* sp (Euglenophyta), suggesting some degree of permanent impact on the environment (Branco 2002).

The river runoff is strongly controlled by rainfall (Fig. 2), with an average discharge of 15 m^3 s^{-1} (annual average) (SECTMA 1999). The tidal regime is semidiurnal, with a mean amplitude of 1.3 m (neap tides) and 1.8 m (spring tides) (Araujo et al. 1999). The estuary is well mixed, being classified as type 1 with an absence of vertical stratification (Araujo et al. 1999, Noriega et al. 2009).

SAMPLING AND COMPILATION OF EARLY DATA

The nutrient and salinity data used in this study are monthly, annual and seasonal average concentrations

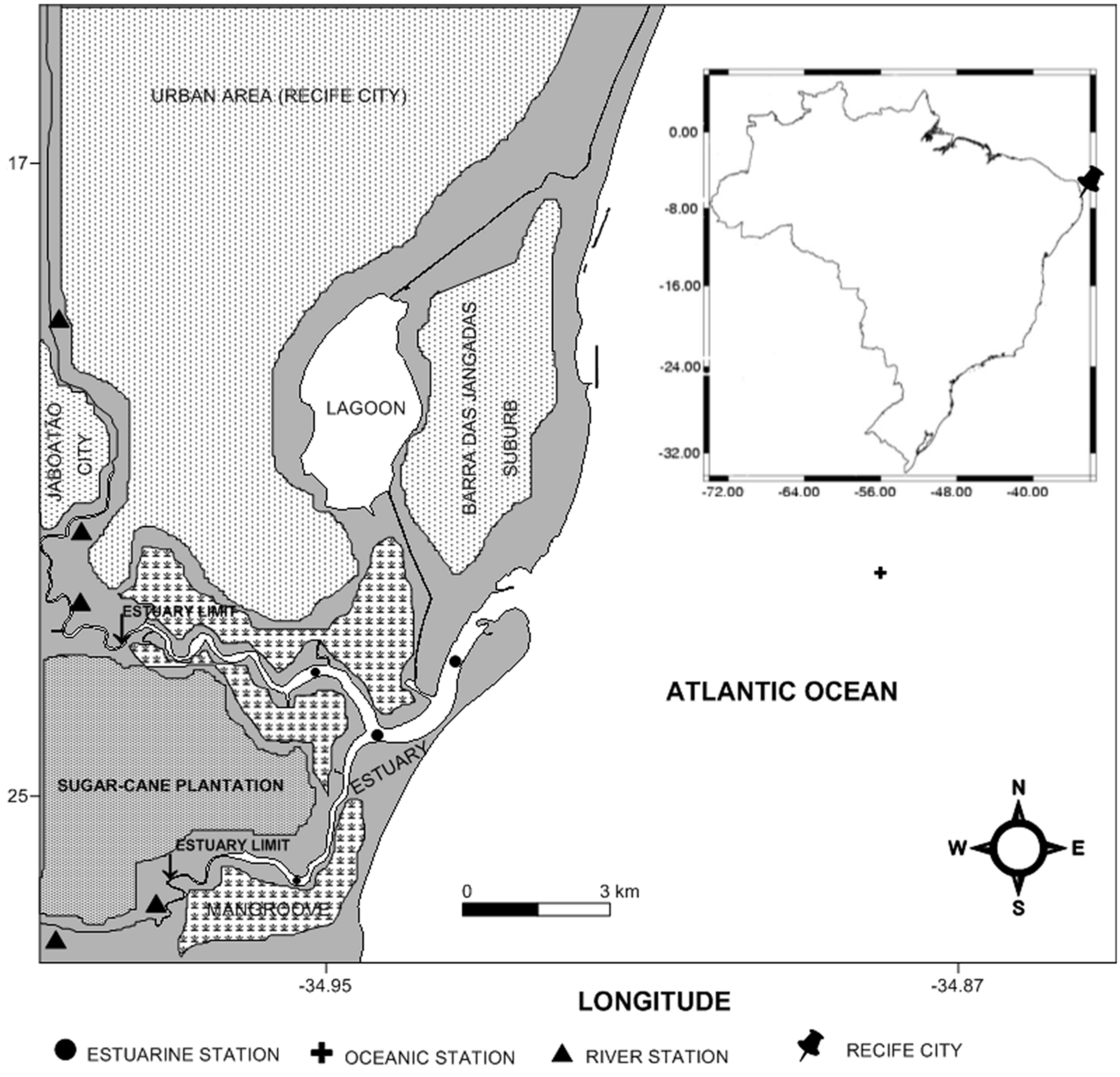

Fig. 1 – Map of the Barra das Jangadas Estuary (BJE), NE Brazil.

calculated from 1999 to 2003 for the BJE and Jaboatão and Pirapama rivers (CPRH 2003, Branco 2002, 2006, Noriega et al. 2005a, b, 2009). Coastal concentrations were obtained from BNDO (2004). These data were used to construct an annual nutrient budget using the LOICZ approach, as proposed by Gordon et al. (1996). The construction of balances (annual, wet and dry period) was made through the average of the monthly balance sheets, following the methodology proposed by Webster et al. (2000).

Data for river runoff were obtained from SECTMA (1999). In order to obtain monthly estimates for the years 2000-2003, a Schreiber's model modified by Holland (1978) was applied using the measured monthly precipitation and air temperature of the watershed, to calculate surface runoff, by calculating the differences between precipitation and evaporation over a drainage basin valid for tropical and temperate regions (Gordon et al. 1996). Meteorological data from 1999-2003 were obtained from INMET (INMET 2003).

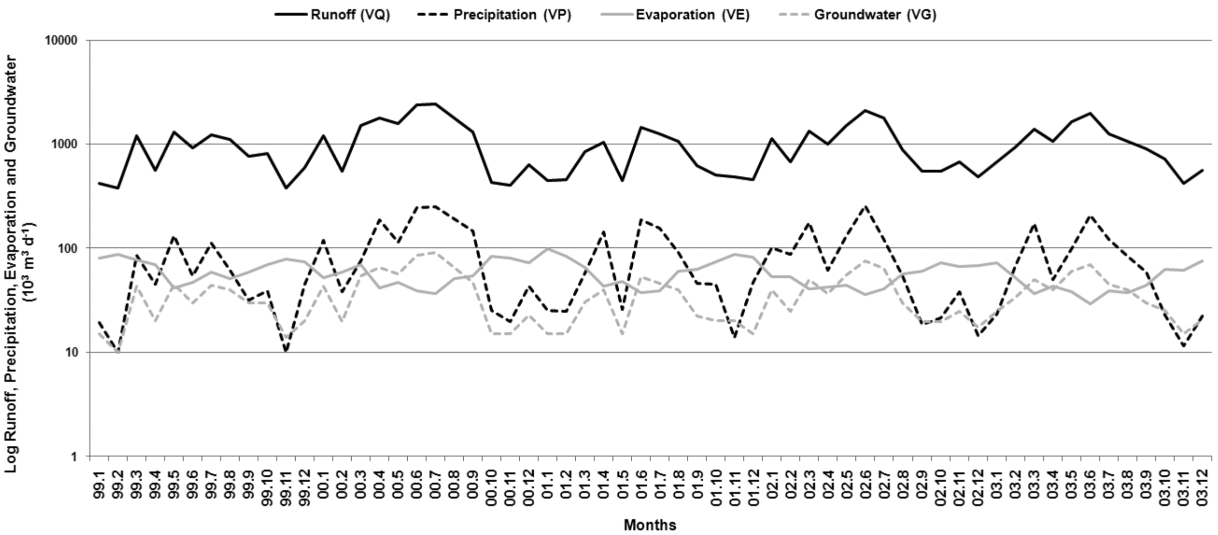

Fig. 2 – Monthly variation (averaged over 5 years, 1999-2003) of river flow discharge, evaporation and precipitation. Average historical rainfall and evaporation (1963-1990) at the BJE, Brazil.

WATER, SALT, AND FLUX CALCULATIONS FOR DIN AND DIP: THE LOICZ MODEL

The "Land Ocean Interactions in the Coastal Zone (LOICZ) Core Project" of the IGBP, established in 1993, is dedicated to understand the role of coastal subsystems in the functioning of the world oceans, including the role of the coastal zones and in the disturbed and undisturbed cycles of carbon, nitrogen and phosphorus (Gordon et al. 1996). The advantage of the LOICZ model is that extensive datasets are not required, so it is a suitable model for the Brazilian Northeast, where water quality data for most estuaries are extremely limited. The model is considered robust and uses a widely applicable, uniform methodology to provide information on the CNP fluxes in estuaries. Within the context of LOICZ biogeochemical modeling, the primary question to be addressed concerns the role of the coastal zone as a source or sink for carbon, nitrogen, and phosphorus (Wepener 2007).

The LOICZ biogeochemical model is based on the mass balance of water and materials (Gordon et al. 1996, Smith et al. 2005). Water and salt are assumed to not undergo significant biogeochemical transformations within the system, while nutrients behave as non-conservative compounds due to biogeochemical processing within the system. Hence, salt budgets and known water inputs and outputs are used to estimate water exchange between the system and the adjacent sea. The mass balance of essential non-conservative nutrients, namely dissolved inorganic phosphorus (DIP) and nitrogen (DIN), allows estimates to be made of rates of biological transformations and ecosystem processes, such as the net ecosystem metabolic (NEM) – i.e., the difference between primary production and community respiration – and the net nitrogen budget, which is assumed to depend on the difference between the nitrogen fixation and denitrification rates.

The water budget can be easily estimated using measurements of runoff (V_R), precipitation (V_P), groundwater (V_G), sewage or other inputs (V_O), and evaporative outflow (V_E). The compensating outflow or inflow that balances the water volume in the system is called the residual flow (V_R). The seawater volume necessary to maintain the salinity in the system (mixing flow, V_X) can be estimated using the conservative salt budget. The salt budget is calculated using the salinity difference between the system and the adjacent sea. DIP and DIN budgets are calculated from water budgets and concentration data. Deviations of budgets/concentrations (ΔDIP and ΔDIN) from predicted values are assumed to depend on non-conservative processes or internal transformations, and basically represent the net difference between nutrient sources and sinks.

In the LOICZ model, both NEM and the net nitrogen budget are calculated from ΔDIP and the molar

C:N:P ratios of the reacting organic matter, generally that of the dominant primary producers, but other material (e.g., sewage) may be considered if judged to be significant. This assumes that ΔDIP depends only on biological transformations.

The molar C:N:P ratios can be considered as the link among the cycles of these elements in the production and respiration processes, and deviations from the expectations based on these ratios can be quantitatively assigned to other processes. The net nitrogen budget is the difference between ΔDIN and ΔDIN expected from ΔDIP and the C:N:P ratios, and is considered to be the difference between nitrogen fixation and denitrification (nfix-denit). Care is required in interpreting ΔDIP because it is affected by benthic fluxes and sorptive processes with suspended materials, as well as biotic processes in the water column. These effects may be especially important in shallow and turbid water bodies. Moreover, the C:N:P stoichiometry and its effects on ecosystem processes vary greatly among primary producers (Hessen et al. 2004).

Linear regression was used to observe the correlation between the model results and variables associated with these calculations. All the analyses were produced with the statistical software STATISTICA 8.0 for Windows.

RESULTS AND DISCUSSION

WATER AND SALT BALANCES

Water flow, salinity, and nutrient concentrations for the BJE, based on the monthly averages of samples taken from January 1999 to December 2003 (Table I), were successfully fed into the model. The residual water flux (V_R, Gordon et al. 1996) from this system, which is necessary to balance the freshwater outflow, was approximately 2 times greater in the rainy season than in the dry season. V_R occurs as a result of river runoff, precipitation influx and evaporation outflow. The amount of freshwater flowing (V_Q) into the estuary was estimated at 638×10^3 and 1366×10^3 m^3, respectively (Fig. 3). Rainfall in the study area was seasonal. About 75% of rainfall occurred during the rainy season. The rain volume over the whole estuary area (13 km^2) was found to be 41 and 125×10^3 m^3 d^{-1}, respectively, with an annual value of 83×10^3 m^3 d^{-1}. Evaporation from the water surface was calculated to be 1.4 times greater in the dry season than in the rainy season (Fig. 3).

The residence time of water was estimated by dividing the estuary volume by the sum of the mixing exchange flux (V_X) and the residual flux (V_R). Therefore, the time of total water exchange in the BJE ranged between 7-21 days. As expected, higher residence times were observed during the dry season (>13 days), while during the rainy months they did not exceed 9 days (Table II).

DIP AND DIN BUDGET

The calculated four major components of the material balance ($V_R DIP_R$, V_X (DIP_{OC}-DIP_{SYS}), $V_G DIP_G$, $V_Q DIP_Q$), in the estuary indicated that BJE acts as a source for DIP (import-export = 1220 mol d^{-1}) (Fig. 4). Throughout the year, phosphorus (P) budgets in the BJE change sign according to the season. During the dry season, the balances are negative during four months (Table II). This implies that the BJE sequesters the difference between import and export, and acts as a sink for P during these months. This period of the year shows the smallest potential of exportation and higher residence times. The mixing outflow of DIP from this system is substantially larger than the residual inflow, and demonstrates that there must be DIP production (ΔDIP) of approximately + 57 mol d^{-1} in the system. We assume that this represents decomposition of organic matter. We have observed that there is very high release of DIP, especially from the sediments associated with sugar cane wastes, so this and other organic discharges into the system are assumed to support the high non-conservative flux of DIP.

This period (September-March) is when the sugar-cane harvest and milling occur. During the rainy season, the sign is positive. This implies that the BJE acts as a source for P, mainly in July, which is a characteristically high rainfall month (Table II).

Seasonal variations of river runoff ($V_Q DIP_Q$) DIP were found to be 2396 and 5782 moles d^{-1} during the dry and rainy seasons, respectively. SECTMA (1999) indicated a residual organic pollution load during the sugar-cane harvest of 5000 and 2000 kg of BOD d^{-1} for the Jaboatão and Pirapama rivers, respectively,

TABLE I
Input data for the monthly variation (averaged over 5 years, 1999 to 2003) and mean annual (±SD) and seasonal budgets of the Barra das Jangadas Estuary, NE Brazil.

Variable/Month	J	F	M	A	M	J	J	A	S	O	N	D	Mean annual	± s.d.	Mean dry season	Mean rainy season
Runoff (V_Q) (10^3 m^3 d^{-1}) [a]	777	601	1252	1095	1297	1768	1598	1183	827	601	474	546	1002	429	638	1366
Groundwater (V_G) (10^3 m^3 d^{-1}) [a]	28	21	46	40	46	63	58	43	30	22	18	19	36	15	23	49
Precipitation (V_P) (103 m^3 d^{-1}) [b]	58	46	114	97	101	189	152	97	60	31	19	34	83	52	41	125
Evaporation (V_E) (10^3 m^3 d^{-1}) [b]	72	67	58	48	44	37	43	51	56	72	75	74	58	14	69	47
River DIN (mmol m^{-3}) [c]	71	70	73	70	74	89	84	68	82	68	65	69	74	7.0	71	76
River DIP (mmol m^{-3}) [c]	3.7	3.5	3.5	3.8	3.9	5.0	5.0	3.8	4.3	4.0	3.3	3.2	3.9	0.6	4.0	4.1
River Salinity[c]	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.4	0.3	0.2	0.1	0.3	0.1
System DIN (mmol m^{-3}) [d e f h i]	11.1	10.2	10.5	10.6	11.3	14	13.5	10.4	11.7	10.3	9.3	10.3	11.1	1.4	10.5	11.7
System DIP (mmol m^{-3}) [d e f h i]	1.3	1.2	1.3	1.3	1.6	2.6	3.1	2.1	1.3	1.2	1.0	0.9	1.6	0.7	1.2	2.0
System Salinity [d e f h i]	26	25	23	26	24	21	19	22	23	24	24	25	23	2	24	22
Ocean DIN (mmol m^{-3}) [g]	0.6	0.5	0.8	0.7	0.6	0.9	0.9	0.7	0.6	0.5	0.5	0.5	0.7	0.1	0.6	0.8
Ocean DIP (mmol m^{-3}) [g]	0.02	0.02	0.06	0.05	0.06	0.08	0.08	0.06	0.03	0.02	0.01	0.02	0.04	0.03	0.02	0.07
Ocean Salinity [g h]	36.0	35.7	35.3	35.4	35.1	35.4	35.3	35.0	35.2	35.3	35.7	35.6	35.4	0.3	35.6	35.3

[a]SECTMA (1999), [b]INMET (2003), [c]CPRH (2003), [d]Branco (2002), [e]Noriega et al. (2005a), [f]Noriega et al. (2005b), [g]BNDO (2004), [h]Branco (2006), [i]Noriega et al. (2009).

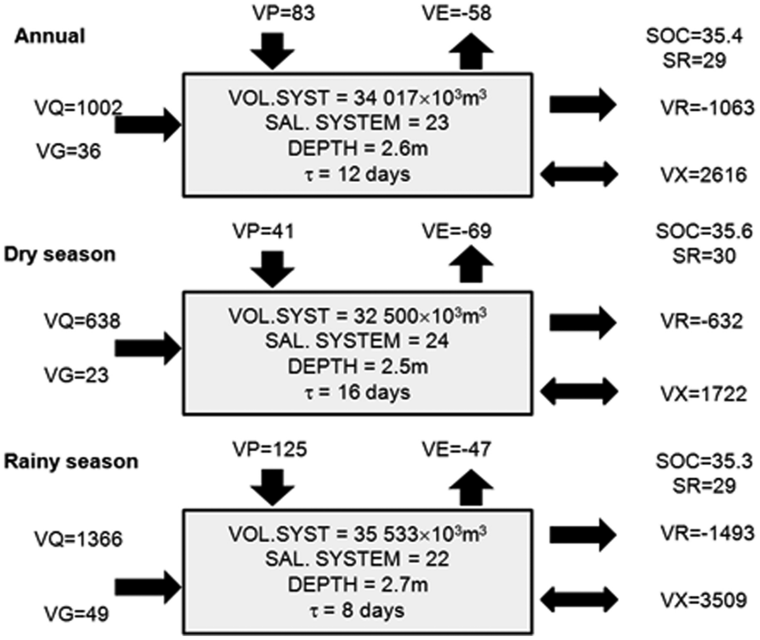

Fig. 3 – Annual and seasonal water (10^3 m^{-3} d^{-1}) and salt flux (10^3 psu) budgets, and residence time ($\tau = \mathrm{Vol}_{\mathrm{estuary}}/(V_X|V_R|)$, in days) at the BJE. (+) indicates source, and (−) indicates sink.

which represents 57.8 and 37.8 kg of DIP d^{-1}, according to the coefficients of San Diego-McGlone et al. (2000). The total estimated for this study was 95.6 kg of DIP d^{-1}, while our estimates were 74.2 kg of DIP d^{-1} for the period of the sugar-cane harvest (dry season).

According to CPRH (2003), the Jaboatão River showed concentrations of total phosphorus 1.3 times higher than the Pirapama River during the dry season (0.71 / 0.56 mg L^{-1}) from 1999 to 2003, and 1.5 times higher during the rainy season. The Jabotão River had a P total 1.3 times higher than the Pirapama River in the dry season, and 1.5 times higher in the rainy season (5 years monitoring) (CPRH 2003).

The daily DIP load from the watershed was 4089 moles d^{-1} (annual average) (Table II). This represents a riverine load in the BJE of 1492 moles of DIP per km^{-2} per yr^{-1} (or 46 kg of DIP per km^{-2} per yr^{-1}) ((Load $\mathrm{DIP_Q}$/Watershed area) × 365).

During the dry season, the flux per unit area of catchment was 874 moles of DIP per km^{-2} per yr^{-1}, and during rainy season it was estimated at 2110 moles of DIP per km^{-2} per yr^{-1}. According to Smith et al. (2003), the average concentrations of 6 mmoles m^{-3} correspond to a high population density (1000 people per km^{-2}) and high runoff (V_Q) per unit area (1 m yr^{-1}) in excess of 6300 moles per km^{-2} per yr^{-1}. These authors used a regression model to describe DIN and DIP exportation by analyzing 165 systems for which DIN and DIP flux data were available (http://data.ecology.su.se/MNODE/). In the present study, the June load reached 3154 moles per km^{-2} per yr^{-1}, a value 0.5 times lower than that estimated by Smith et al. (2003). The region presents a per capita load for the hydrographic basin of 1.4 moles of DIP per person per yr^{-1} ((Load $\mathrm{DIP_Q}$/Population Watershed) × 365) or 0.04 kg per person per yr^{-1} of DIP (annual average), a value that reflects the high population density and low runoff, according to Smith et al. (2003). The population density of the Jaboatão and Pirapama basins is about 1100 people per km^{-2}, with a total population of ∼1 100 000 hab. Bidone and Lacerda (2002) estimated a daily riverine load for estuarine or riverine areas in Northeast Brazil around 0.002 kg of P hab^{-1} d^{-1}. This value was computed taking into account 200-250 L hab^{-1}d^{-1} as the

TABLE II
Average of monthly balances of: water, salt and nutrients of the Barra das Jangadas Estuary, NE Brazil.

Variable/Month	J	F	M	A	M	J	J	A	S	O	N	D	Average annual	Average dry season	Average rainy season
Residual flow (V_R) (10^3 m^3 d^{-1})	–790	–600	–1354	–1185	–1400	–1983	–1765	–1271	–861	–581	–435	–525	–1063	–632	–1493
Mixing flux (V_X) (10^3 m^3 d^{-1})	2344	1750	3420	3998	3705	3914	3162	2855	2082	1503	1178	1478	2616	1722	3509
Residence time (τ) (days)	14	16	8	7	9	7	8	9	13	17	21	17	12	16	8
Daily load from watershed of DIP (mol d^{-1})	2897	2113	4267	3894	5216	8640	8054	4624	3526	2571	1519	1750	4089	2396	5782
Daily difference: sources – sinks (ΔDIP) (mol d^{-1})	1041	354	1141	1978	1612	3486	4094	1985	–501	–202	–199	–150	1220	57	2383
Daily load from watershed of DIN (mol d^{-1})	64 080	49 604	93 774	72 802	109 064	160 904	128 642	76 681	65 503	43 673	35 025	36 478	78 019	49 061	106 978
Daily difference: sources – sinks (Δ DIN) (mol d^{-1})	–36 944	–28 802	–58 639	–30 795	–63 083	–95 175	–80 865	–44 030	–41 926	–27 525	–22 619	–22 148	–46 046	–29 994	–62 098

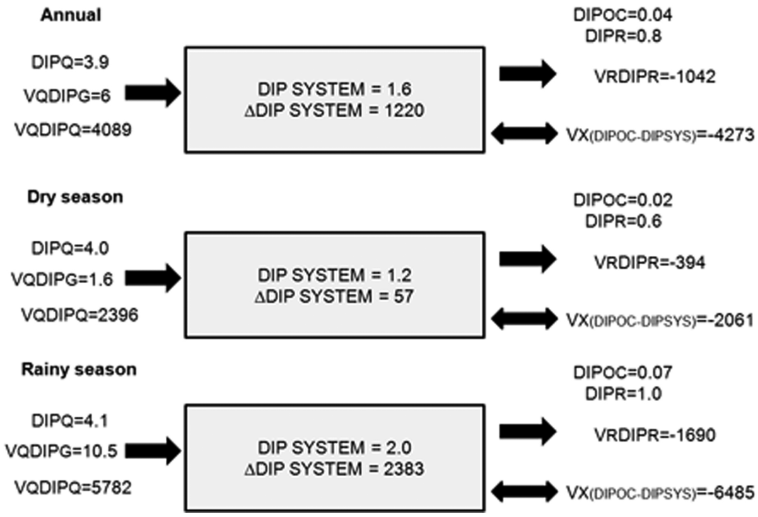

Fig. 4 – Annual and seasonal phosphorus flux (in moles d^{-1}) budget at the BJE. (+) indicates source, and (−) indicates sink.

typical water consumption for developing countries. This is actually overestimated compared to the real water consumption of 100-150 L $hab^{-1}d^{-1}$ in the Brazilian northeastern coastal area (I.M. Abreu et al., unpublished data). These figures would yield 0.01 kg of DIP per person per yr^{-1}, considering the San Diego-McGlone et al. (2000) transformations from P to DIP, which is 4-fold smaller than our previously calculated value. During the dry season, this value was nearer to that estimated by Bidone and Lacerda (2002) (0.02 kg of DIP per person per yr^{-1}). Therefore, during the rainy season, it was 6 times higher. Our estimates identify a high organic load as a result of unplanned activities in the hydrographic basin, such as disposal of domestic sewage, uncontrolled land runoff, and industrial and agro-industrial effluents.

The calculated four major components of the material balance ($V_R DIN_R$, V_X (DIN_{OC}-DIN_{SYS}), $V_G DIN_G$, $V_Q DIN_Q$), in the estuary indicated that BJE acts as a sink for DIN (import-export = –46 046 mol d^{-1}) (Fig. 5).

The nitrogen budget in the BJE shows a higher inflow contribution during the rainy season, due to freshwater runoff and reduced residual water flow (Fig. 5). ΔDIN is negative in all months, suggesting that inputs are higher than outputs and indicating a net sink of inorganic nitrogen in the BJE. Seasonal variations of river runoff DIN ($V_Q DIN_Q$) were found to be 46 061 and 106 978 moles d^{-1} during the dry and rainy seasons, respectively. According to SECTMA (1999), the daily loads of BOD during the sugar-cane harvest (dry season) for the Jaboatão and Pirapama rivers are 5000 and 2000 kg of BOD d^{-1}, respectively, which represents 950 and 380 kg of DIN d^{-1}, according to the coefficients of San Diego-McGlone et al. (2000). The total daily load estimated for this study was 1092 kg of DIN d^{-1}, while our estimates were 687 kg of DIN d^{-1} for the period of the sugar-cane harvest (dry season).

According to CPRH (2003), the Jaboatão River shows concentrations of ammonium 4 times higher than the Pirapama River (3.37/0.82 (dry season); 3.0/0.70 mg L^{-1} (rainy season)). The daily DIN load from the watershed was 78 019 moles d^{-1} (annual average) (Table II), which would represent a yield of 28 477 moles of DIN per km^{-2} per yr^{-1} (400 kg of DIN per km^{-2} per yr^{-1}), a value two times greater than the mean estimate (Smith et al. 2003).

During the dry season, the flux per unit area of the catchment was 17 907 moles of DIN per km^{-2} per yr^{-1}, while during the rainy season it was estimated as 39 047 moles of DIN per km^{-2} per yr^{-1}.

The computed per capita load was 26 moles of DIN per person per yr^{-1} (0.4 kg of DIN per person per yr^{-1}), a value 9 times greater than the scenario with high density and low runoff of Smith et al. (2003). According to Bidone (2000), the nitrogen (N) load for the regional scenario is 0.01 kg of N hab^{-1}d^{-1}, equivalent to 0.004 kg of DIN hab^{-1} d^{-1}.

STOICHIOMETRIC CALCULATIONS OF NET SYSTEM METABOLISM

The evolution of the BJE metabolism shows a tendency towards heterotrophy (Fig. 6). The negative net ecosystem metabolism (p-r) values indicate that the system is heterotrophic, with a net loss of organic matter from the BJE of ∼–10 mmoles C m^{-2} d^{-1} (annual average). We believe that these values can vary if we consider other rates (42:12:1 SanDiego-McGlone et al. (2000) for the waste load ratio), or with mangroves dominating the net production (rate of 1000:11:1 Smith and Camacho (2000)). In either cases, if the DIP uptake primarily represents net organic metabolism, rather than sorption or precipitation of inorganic P, this system is net heterotrophic. During the dry season (September-February), we observed a slightly heterotrophy of –0.5 mmoles C m^{-2} d^{-1} (seasonal average). The long residence time retains materials long enough to react internally during the dry season. In addition, the water quality is enhanced by a slightly deeper euphotic depth (Noriega et al. 2005, Branco 2002), which also favors the phytoplankton community. In the rainy season, the biggest nutrient contribution to the rivers occurs (–19 mmoles C m^{-2} d^{-1}; seasonal average). Mukhopadhyay et al. (2006) suggest that tropical estuaries with a shallow photic zone dominated by physical processes could cause the phytoplankton to not reach their maximum growth rates, which could contribute to the phytoplanktonic production of the estuary being limited. The objective is to modify the riverine flux of nutrients before it is released to the coastal water. These values demonstrate that outputs are higher than inputs at the BJE, with highlights on the mineralization of organic matter and a net source of CO_2 to the atmosphere.

The seasonal differences between heterotrophy (January to August) and autotrophy (September to December) indicate an extension of this second condition (Fig. 6).

Gordon et al. (1996) pointed out that p (primary production) and r (respiration) are within about 10% of one another. Assuming that p is known, this implies that the quantity $(p\text{-}r) = \pm 0.1\, p$. The lack of direct measures of primary productivity in the studied area was approached through the following: (i) mean annual and seasonal values of regional systems with biological characteristics similar to the phytoplanktonic biomass and species taxa (Passavante and Feitosa 2004), and (ii) studies in the literature about primary productivity for tropical systems (Berger 1989). The regional productivity is 128 mmoles C m^{-2} d^{-1} (annual mean), 101 mmoles C m^{-2} d^{-1} (rainy mean) and 155 mmoles C m^{-2} d^{-1} (dry mean) (Fig. 6). The literature reports values ranging from 15 to 399 mmoles C m^{-2} d^{-1}. So, the estimates from regional averages represent an appropriate value to validate the results from the present study. The (p-r) estimate of –10 mmoles C m^{-2} d^{-1} (annual mean) represents ∼10% of the primary production, which is considered appropriate. In this way, respiration would represent –138 mmoles C m^{-2} d^{-1}, and $p/r = 0.92$, which means that the system uses 8% more organic matter than it produces. During the dry season, the value of (p-r) is –0.5 mmoles C m^{-2} d^{-1}, considering that phytoplanktonic primary production is 155 mmoles C m^{-2} d^{-1}, $p/r = 0.99$. It follows that r is approximately 155.5 mmoles C m^{-2} d^{-1}. That is, the system produces about 0.1 more organic matter than it uses. On the other hand, during the rainy season, $(p\text{-}r) = -19$ mmoles C m^{-2} d^{-1} and primary production is 101 mmoles C m^{-2} d^{-1}, and so the value of r is ∼120 mmoles C m^{-2} d^{-1}, with $p/r = 0.84$. The system consumes about 16% more organic matter than it produces in this second case.

A simple linear regression was used to relate p-r values to the residence time (TR) ($P < 0.05$) (Fig. 7). Longer residence times indicate that the system remains closer to 0, with a small trend towards autotrophy. On the other hand, shorter residence times show oscillations between heterotrophy and autotrophy (Fig. 7).

Rainfall often favors heterotrophic aquatic metabolism due to the increase in the contribution of terrestrial organic lixiviation (Ram et al. 2003). However, rainfall intensification also increases nitrogen and phosphorus loads in estuaries (Schindler 1978), which would benefit autotrophic metabolism, especially in urban and agricultural areas. During periods with opposite rainfall characteristics, metabolism seems to oscillate between light autotrophy and light heterotrophy.

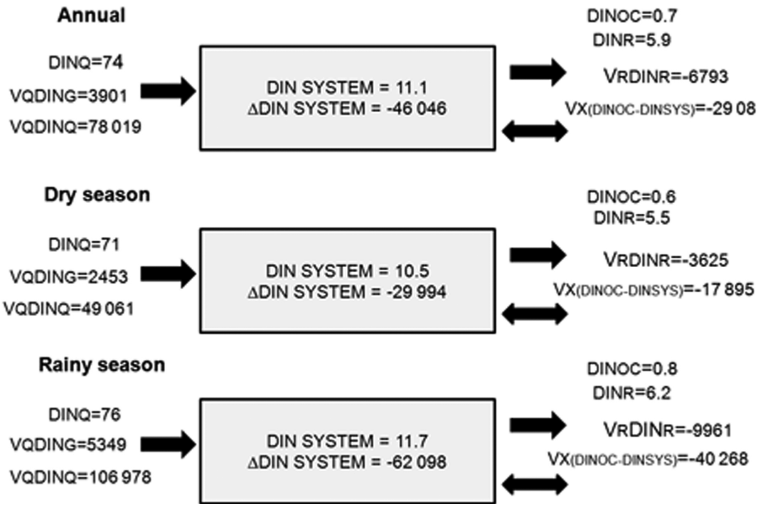

Fig. 5 – Annual and seasonal nitrogen flux (in moles d^{-1}) budget at the BJE. (+) indicates source, and (−) indicates sink.

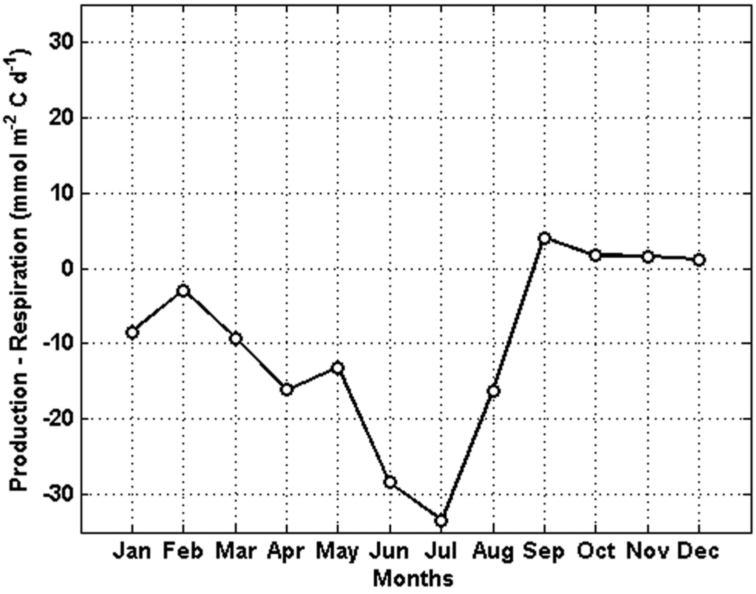

Fig. 6 – Monthly variation of the Ecosystem Net Metabolism (NEM) at the BJE. Negative and positive values indicate heterotrophy and autotrophy, respectively.

The nitrogen fixation and denitrification are important processes in coastal systems. Again, because the major source of reacting matter is unclear, two N/P ratios are used. The decomposing material has a mean C/P of 106/1, and N/P of 16/1, which is near the value of N/P of 11/1 quoted for mangrove litter (Gordon et al. 1996). Based on this ratio of N/P, we estimated that ΔDINobs-ΔDINesp ΔDIP* 11 = –5 mmoles m^{-2} d^{-1} (annual average). Smith and Camacho (2000) estimated that the differences between N fixation and denitrification are in general close to zero (with a dominance of denitrification), and that values above 5 moles m^{-2} yr^{-1} are rare. Our results in general suggest denitrification (Fig. 8).

The nitrogen fixation process is ordinarily slow in marine systems (< 1 mmoles m^{-2} d^{-1}), according to

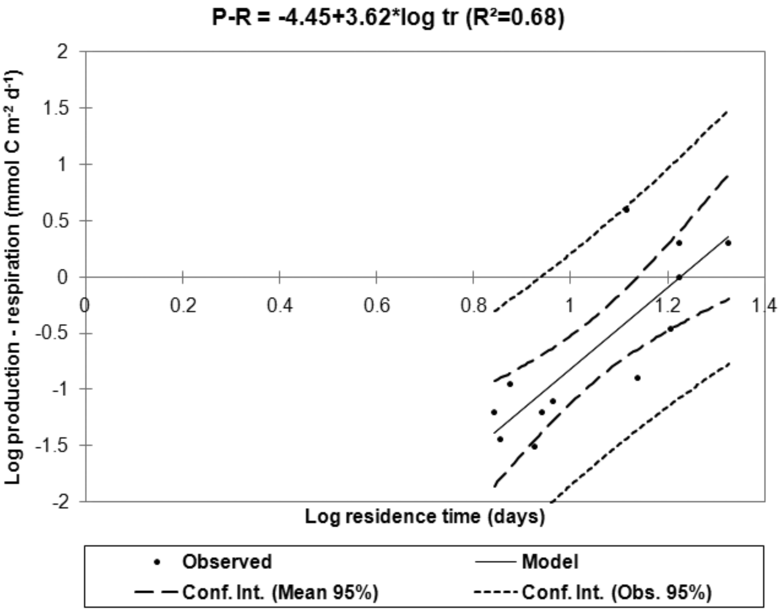

Fig. 7 – Budget monthly (p-r) as a function of the system exchange time (days).

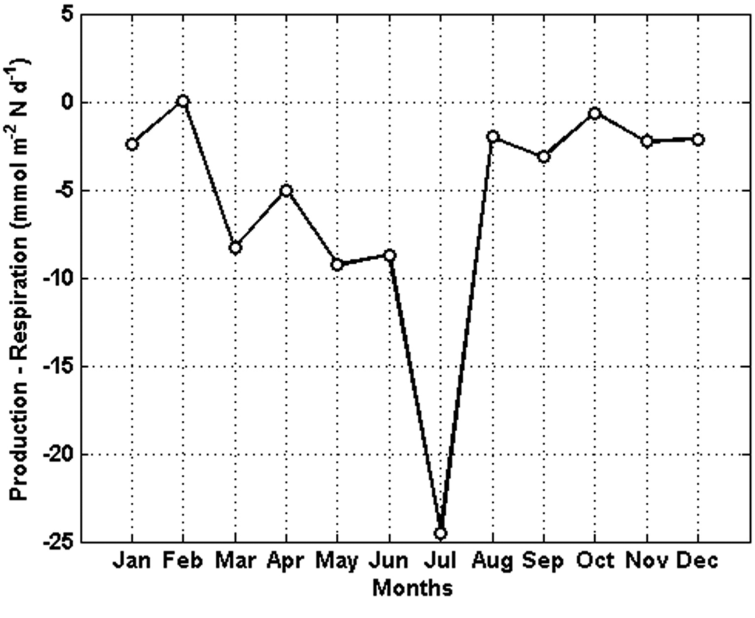

Fig. 8 – Monthly variation of N fixation and denitrification rates in the BJE. Negative and positive values indicate denitrification and fixation of nitrogen, respectively.

Swaney and Smith (2003), although they suggested that some coral reef, mangrove and tropical seagrass communities may exhibit rates >20 times this upper limit. As a general rule, few systems have nitrogen fixation faster than this rate. The value reported for the BJE in February was low, submitting to this limit, and indicating that the adjacent mangrove forest did not accelerate this fixation in the estuary.

The apparently high denitrification during the rainy season (–7 mmoles m^{-2} d^{-1}) indicates high benthic respiration (driven by high loads with labile organic matter such as sewage). Typical rates in benthic systems are around 0.5-2 mmoles N m^{-2} d^{-1}. Systems with high benthic respiration may have denitrification rates >10 mmoles m^{-2} d^{-1} (Swaney and Smith 2003). During the dry season, denitrification is lower (–2 mmoles m^{-2} d^{-1}) than in the rainy period. Other tropical estuaries, such as the Piauí River Estuary (Brazil), presented a denitrification rate of –0.13 mmoles m^{-2} d^{-1}, while the Sergipe River Estuary (Brazil) seems to fix nitrogen at 0.1 mmoles m^{-2} d^{-1} (Souza 2000).

CONCLUSIONS

We used a bulk modeling approach to evaluate the nutrient budgets (C, N and P) and the trophic state of a tropical estuarine system (BJE). Results show that variations in the annual cycle of the net ecosystem metabolism from 1999-2003 depend on seasonal forces, such as basin-scale runoff and DIP loads. Results obtained through mass balance indicate large amounts of anthropogenic nutrient inputs to the system. These loads act as a source for dissolved inorganic phosphorus during the dry and rainy season. The loads of dissolved inorganic nitrogen act as sinks throughout the year. During the winter, the BJE basin exceeded the values reported for DIP and DIN (moles km^{-2} yr^{-1}) in the literature for basins of up to 1000 km^2. These seasonal oscillations of heterotrophy and autotrophy show a moderate tendency to heterotrophy, indicating that the system passes to liquid production stages of organic matter when production surpasses mineralization (September-December) and liquid mineralization stages (March-August).

The linear regression between *p-r* and the residence time shows lower entropy in the dry season and autotrophy at lower rates than during the high residence times but, this needs to be confirmed in future studies.

Also evident is the importance of denitrification in the BJE, which establishes that the system is a net denitrificator at moderate rates, probably in association with the degradation of labile organic matter originated from sewage.

Consequently, both heterotrophy and denitrification are enhanced by the production of carbon and nitrogen during the rainy season, whereas heterotrophic systems mainly depend on the inputs or loads of organic carbon of the adjacent systems.

We considered that high-density human occupation in the basin contributes significantly to N and P emissions throughout the year. High per capita loads of N and P indicate a scenario of high population density and high runoff. However, it seems important to recognize that ignoring the uptake and release of nutrients (N and P) by abundant mineral particles in the estuary may cause errors in nutrient balances, although the evidence reported here helps us to understand the main processes driving the metabolism of poorly studied typical small low-latitude estuaries.

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RESUMO

Este trabalho se focalizou na dinâmica de nutrientes de um estuário tropical na costa nordeste brasileira, usando o protocolo LOICZ de balanços biogeoquímicos. Nós descrevemos a metodologia e os pressupostos subjacentes a este modelo. Os dados de entrada (precipitação e evaporação mensal, vazão do rio, e as concentrações de sal, fósforo e nitrogênio) foram obtidos durante as campanhas de campo no estuário de Barra das Jangadas – Brasil durante um período de 5 anos (1999 a 2003). Os resultados indicam grandes entradas de nutrientes ao sistema. O modelo mostrou que a variação sazonal do Metabolismo do Ecosistema (NEM) indica que o sistema passa de uma fase de produção de líquido da matéria orgânica, durante a estação seca (–0,5 mmoles C m^{-2} d^{-1}) para uma mineralização líquida durante a estação chuvosa (–19 mmol m^{-2} C d^{-1}). Sugerimos que o sistema varia ligeiramente entre autotrófica e heterotrófica durante o ano, devido ao regime de chuvas, as atividades antrópicas na bacia (densidade populacional e as plantações de cana de açúcar), e as cargas ribeirinhas de DIP associadas. A alta carga de N e P per capita, indica uma alta densidade populacional e um alto *runoff*. A aplicação da modelagem de balanço de fluxos foi útil para o entendimento da dinâmica de nutrientes em um pequeno estuário tipicamente tropical.

Palavras-chave: Brasil, Barra das Jangadas Estuário, variações sazonais, heterotrofia, autotrofia, dióxido de carbono.

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