



Structure and temporal variation of the phytoplankton of a macrotidal beach from the Amazon coastal zone

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Manuscript received on October 7, 2015; accepted for publication on April 18, 2016

ABSTRACT

The present study aimed to analyze the structure and the temporal variation of the phytoplankton of Ajuruteua beach (Bragança, Pará) and to investigate the influence of environmental variables on the dynamics of this community to provide a basis about the trophic state of this environment. Biological, hydrological and hydrodynamic samplings were performed during a nyctemeral cycle in the months of November/08, March/09, June/09 and September/09. We identified 110 taxa, which were distributed among the diatoms (87.3%), dinoflagellates (11.8%) and cyanobacteria (0.9%), with the predominance of neritic species, followed by the tycho plankton species. Chlorophyll-a concentrations were the highest during the rainy period (24.5 mg m⁻³), whereas total phytoplankton density was higher in the dry period (1,255 x 10³ cell L⁻¹). However, phytoflagellates density was significantly higher during the rainy period. Cluster Analysis revealed the formation of four groups, which were influenced by the monthly differences in the environmental variables. The Principal Component Analysis indicated salinity and chlorophyll-a as the main variables that explained the components. Spearman correlation analysis supported the influence of these variables on the local phytoplankton community. Overall, the results obtained suggest that rainfall and strong local hydrodynamics play an important role in the dynamic of the phytoplankton of Ajuruteua beach, by influencing both environmental and biological variables.

Key words: Amazon beaches, biomass, microalgae, seasonal variation.

INTRODUCTION

The Amazon Coastal Zone (ACZ) encompasses the littorals of the Brazilian states of Amapá, Pará and Maranhão, which are characterized by complex hydrodynamic processes resulting from wave action and local currents (Nittrouer and DeMaster 1996),

high volumes of freshwater, solutes, and particulate matter being discharged from the Amazon and Pará rivers (Smith and DeMaster 1996, Santos et al. 2008, Pereira et al. 2013), and the input of dozens of other minor estuaries (Pereira et al. 2012a). The ACZ is composed of a complex mosaic of vitally important aquatic ecosystems (Moraes 1999, Prost et al. 2001, Souza Filho 2005) which, combined with its enormous area and rich biodiversity,

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contribute to this region being considered to be of the highest priority for conservation among Brazilian coastal environments. While the region is relatively sparsely populated (Santos et al. 1999), there have been increasing anthropogenic impacts in some local areas over the past few decades (Small and Nicholls 2003, Sousa et al. 2011, Pereira et al. 2012b, Silva et al. 2013).

The beaches in this region are unique high-energy environments that are strongly influenced by northeasterly winds, high precipitation rates, and semi-diurnal macrotides (Meade et al. 1985, Marengo 1995, Monteiro et al. 2009a). In the surf zone of these high-energy beaches, high concentrations of primary producers (phytoplankton and phytobenthos) can typically be found (Costa et al. 2011). These organisms constitute the basic food supply for many primary consumers in the local coastal ecosystems and adjacent marine waters (Sousa et al. 2009).

Coastal phytoplankton are the primary organisms responsible for the production and flow of organic matter and energy in the food webs of these environments, sustaining – directly or indirectly – herbivores and animals of higher trophic levels, including economically important vertebrate species (Dring 1992). The net primary production of the phytoplankton in coastal environments is regulated by a range of abiotic (e.g., nutrient flow, light availability, and physical oscillations) and biotic (trophic interactions such as herbivory and competition) variables (Glé et al. 2008). In these ecosystems, the continuous input of nutrients and organic matter derived mainly from rivers and other continental drainage, help to sustain the local populations of microalgae (Bouman et al. 2010).

Phytoplankton communities are highly dynamic and respond quickly to physical and chemical changes in the aquatic environment. For this reason, they are extremely important for the ecological characterization of coastal environments (Valiela 1995, Eskinazi-Leça et al. 2002). In this

sense, the monitoring of the short-term (daily) variation in phytoplankton communities represents a preliminary step in the analysis of the broader relationships between planktonic assemblages and environmental fluctuations (Abboud-Abi Saab 1992).

While the phytoplankton of Ajuruteua beach in the municipality of Bragança (northeastern Pará) have been the subject to a number of studies in recent years (Santana et al. 2005, Melo et al. 2005, Costa et al. 2011), these studies have been limited to the analysis of a small set of hydrological variables. The occurrence and distribution of phytoplankton have been analyzed on other beaches in northeastern Pará, such as Princesa beach on Algodual Island (Matos et al. 2012, 2013) and Atalaia beach, in the town of Salinópolis (Costa et al. 2013), but no general pattern has yet been determined in this region. Given this, the present study evaluates the composition and temporal variation in the phytoplankton community of Ajuruteua beach, considering variables not previously analyzed, such as dissolved nutrient concentrations, together with other local hydrological, hydrodynamic and climatic variables in order to improve the knowledge of the dynamics of phytoplankton populations in the Amazon Coastal Zone.

MATERIAL AND METHODS

DESCRIPTION OF THE STUDY AREA

Ajuruteua beach is 36 km north of the town of Bragança, in the northeastern portion of the Brazilian state of Pará (Figure 1). This beach is approximately 2.5 km long and receives thousands of visitors during the summer season, being considered one of the main tourism centers of northeastern Pará (Monteiro et al. 2009a). Like other areas on the northern coast of Brazil, this beach is dominated by semi-diurnal macrotides that can reach up to 6 m during the equinoctial spring tides (Souza Filho et al. 2003). Waves generated by the NE trade winds reach up to 2 m in height, while the ebb tide flows in a SE-NW direction and the flood tide in

a NW-SE direction (Monteiro et al. 2009b). The local climate is of the Am type in the Köppen classification system, characterized by a rainy season between the months of January and July, and a dry season during the remaining months of the year, with annual rainfall of about 2500 mm and average annual air temperature of around 26°C (Moraes et al. 2005).

DATA COLLECTION AND PROCESSING

Hydrodynamic, hydrological, and biological data were collected during the spring tide in the months of December 2008, and March, June and September 2009, at a fixed station (00°49'9.4" S, 46°36'8.6" W) located in the surf zone of Ajuruteua beach. Total rainfall, and mean and maximum wind speeds and directions were obtained from the Brazilian

Meteorology Institute's (INMET) A-226 weather station located in the municipality of Bragança, Pará.

Hydrodynamic data were obtained using a bottom-mounted mooring with a mini current meter (SENSORDATA SD6000), a CTD (XR-420, RBR), and wave and tide data loggers (TWR, 2050). These devices were programmed to process the mean readings every 10 minutes, and were moored over a 24-hour period at a depth of 1.7 m at low spring tide. Water temperature and salinity were measured *in situ* using a CTD, while the other hydrological variables (dissolved oxygen, pH, turbidity and dissolved nutrients) and chlorophyll-*a* concentrations were measured through the analysis of subsurface water samples (0-1 m) collected with Niskin oceanographic bottles every 3 hours.

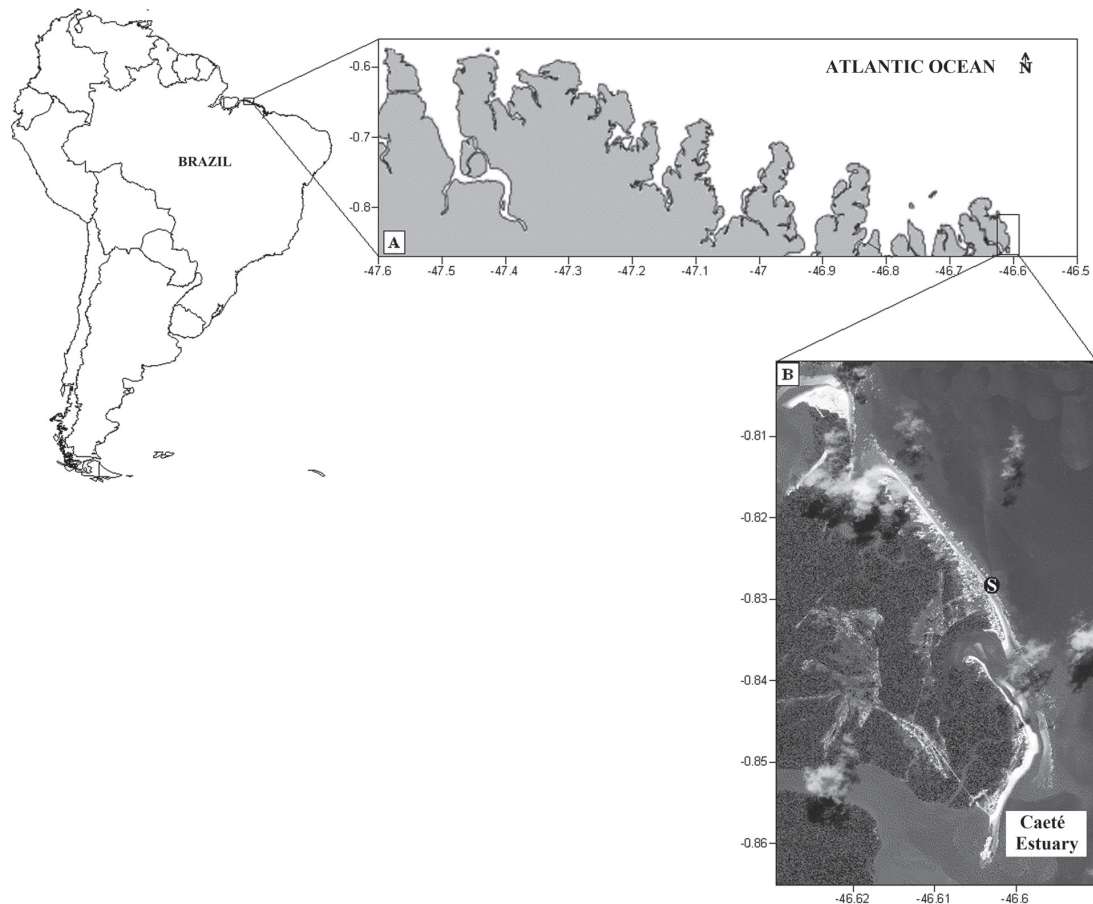


Figure 1 - Study area: (A) Municipality of Bragança, Pará, Brazil; (B) Ajuruteua beach (Northeastern Pará), showing the location of the fixed sampling station (black symbol - Modified from Sousa et al. 2011).

Dissolved oxygen (DO) concentrations were determined using the modified Winkler method described by Strickland and Parsons (1968), whereas pH was measured with a PHS-3B pH meter and turbidity with a Hanna HI 39703 turbidity meter. Dissolved inorganic nutrients (nitrite- NO_2^- , nitrate- NO_3^- , phosphate- PO_4^{3-} , and silicate- SiO_2) were analyzed according to the methods described by Strickland and Parsons (1968) and Grasshoff et al. (1983). Chlorophyll-*a* concentrations were determined spectrophotometrically according to the method described by Parsons and Strickland (1963).

The biological samples were taken every six hours. Samples for the qualitative study of the phytoplankton were obtained with a plankton net (64 μm mesh) which was used to filter 400 L of subsurface water in the surf zone of the beach. The material collected was preserved in a 4% buffered formalin-seawater solution and analysis of the microphytoplankton was conducted using temporary slides, which were observed under a binocular microscope (Zeiss - AxioSkop 40). Samples for quantitative studies were also collected using a Niskin bottle in the subsurface of the water column, and preserved in Lugol's solution. The Utermöhl (1958) sedimentation method was employed to determine the phytoplankton density (cells.L^{-1}) by counting the total area of the chamber (volume of 7 mL) under an inverted microscope (Zeiss – Axio Observer A1; 400x). Phytoflagellates were identified and counted to the group level.

The classification of the microphytoplankton was based on Round et al. (1990) for the diatoms, Steidinger and Tangen (1997) for the dinoflagellates and Desikachary (1959) for the cyanobacteria. The ecological classification of the species was conducted according to Moreira Filho et al. (1990) and Valente-Moreira et al. (1994). All species names were checked in ALGAEBASE (www.algaebase.org).

Following the identification and quantification of the organisms the frequency of occurrence was estimated following Matteucci and Colma (1982) and the relative abundance of the different taxa as in Koenig and Lira (2005). Species diversity (Shannon 1948) and evenness (Pielou 1977) were also calculated.

Statistical analyses included a one-way analysis of variance (ANOVA), followed by Fisher's post-hoc test (significance level of 5%). The non-parametric Mann-Whitney test (U) was applied to non-normal data. All analyses were run in the STATISTICA 6.0 package. Additional multivariate cluster analyses, SIMPER (Similarity Percentage), ANOSIM (Analysis of Similarities), and PCA (Principal Components Analysis) were run in PRIMER (Plymouth Routines Multivariate Ecological Research), version 6.0. Spearman rank correlation coefficients were also used to verify the relationship between abiotic and biotic variables.

RESULTS

CLIMATE AND HYDRODYNAMIC VARIABLES

Total monthly rainfall ranged from 1.8 mm, in September 2009 to 835.8 mm (May, 2009), with over 90% of the year's precipitation falling during the rainy season (January to June, 2009). During the study, winds were predominantly northeasterly, with mean velocity ranging from $0.1 \pm 0.4 \text{ m s}^{-1}$ (May, 2009) to $2.1 \pm 1.4 \text{ m s}^{-1}$, in December 2008 (Figure 2).

Tidal currents flow predominantly in a NW-SE direction during the flood, and SE-NW direction during the ebb tides, with higher velocities, of up to 0.7 m s^{-1} , being recorded during the flood tide in March, 2009. Average wave heights ranged from 0.5 ± 0.4 in June 2009 to 0.6 ± 0.3 m in September, 2009, while the mean wave period varied from 3.7 ± 1.4 s in December 2008 to 5.6 ± 1.9 s in March, 2009, with significantly higher values being recorded in the rainy season ($F = 7.4$, $p < 0.05$).

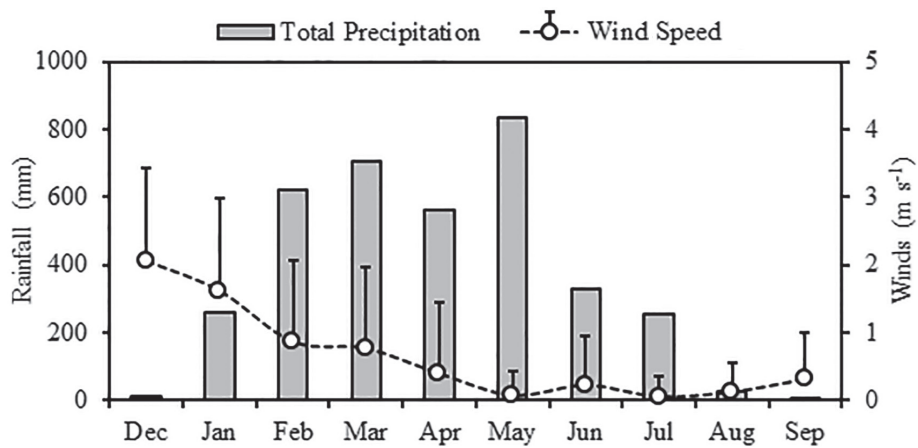


Figure 2 - Data of climatological variables during the period from December/08 to September/09: total rainfall (mm) and average wind speeds ($m s^{-1}$) (+SD). Source: INMET (Weather Station located in the municipality of Bragança, Pará). Vertical axes are plotted with different scales.

HYDROLOGICAL VARIABLES

Mean water temperature ranged from $28.2 \pm 0.4^{\circ}C$ in March 2009 to $28.7 \pm 0.5^{\circ}C$ in June. Mean salinity ranged from 6.5 ± 1.0 in June 2009 to 36.7 ± 0.0 in December 2008, with significantly higher values being recorded during the dry season ($U = 0.0$, $p < 0.05$). Dissolved oxygen concentrations varied from $6.0 \pm 0.4 mg L^{-1}$ (December, 2008) to $7.9 \pm 0.3 mg L^{-1}$ (September, 2009) with significantly higher values being recorded in September ($U = 3.0$, p

< 0.05). The mean pH of the water ranged from 7.7 ± 0.3 in June 2009 to 8.6 ± 0.2 in March 2009, and was significantly higher in the latter month ($U = 0.0$, $p < 0.05$). Turbidity varied from 24.5 ± 7.0 NTU (December, 2008) to 67.9 ± 65.1 NTU, in March 2009 (Figure 3).

Nitrite concentrations varied from $0.2 \pm 0.0 \mu mol L^{-1}$ (December 2008) to $0.5 \pm 0.2 \mu mol L^{-1}$ (September 2009), with significantly higher values being recorded in June and September ($F = 12.1$, $p < 0.05$). Nitrate concentrations were significantly

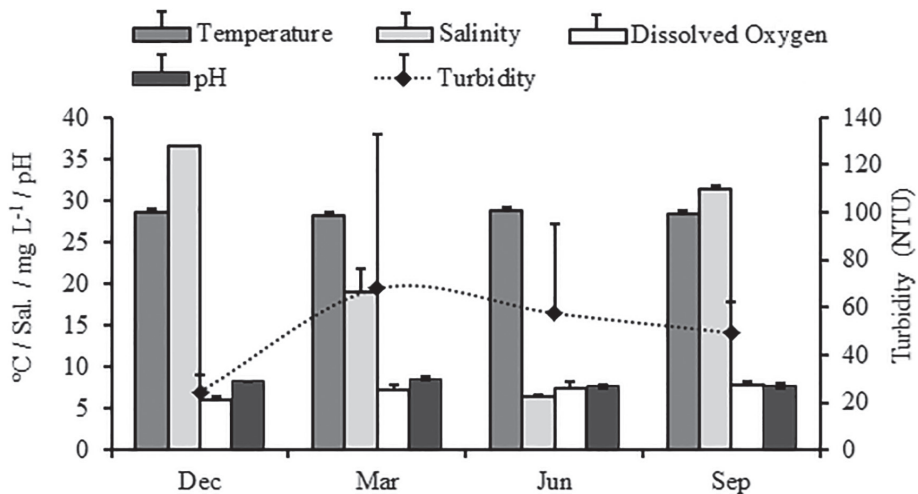


Figure 3 - Monthly average ($\pm SD$) of hydrological variables at Ajuruteua beach (Bragança, Pará) during the period of study: (A) turbidity (NTU), temperature ($^{\circ}C$) and salinity; dissolved oxygen ($mg L^{-1}$) and pH. Vertical axes are plotted with different scales. Only positive deviation appears for variables with negative values.

higher in the rainy season ($U = 67.0$, $p < 0.05$), ranging from $1.1 \pm 0.4 \mu\text{mol L}^{-1}$ in December, 2008, to $5.5 \pm 6.0 \mu\text{mol L}^{-1}$ in March, 2009. Phosphate (from $0.2 \pm 0.0 \mu\text{mol L}^{-1}$ in June, 2009, to $1.2 \pm 2.9 \mu\text{mol L}^{-1}$ in March) and silicate concentrations ($23.7 \pm 6.3 \mu\text{mol L}^{-1}$ in December, 2008, to $331.9 \pm 6.6 \mu\text{mol L}^{-1}$ in June, 2009) followed the same general pattern (Figure 4), and were significantly higher in the rainy season ($U = 19.0$, $p < 0.05$; $F = 29.1$, $p < 0.05$, respectively). Nutrient concentrations are shown in figure 4.

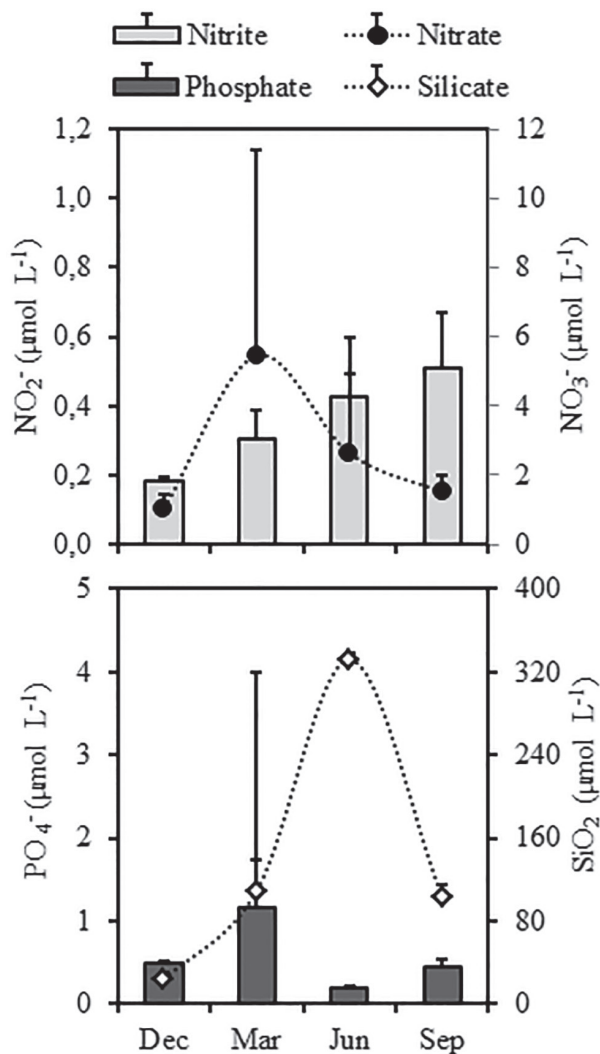


Figure 4 - Monthly average (\pm SD) concentrations of dissolved nutrients ($\mu\text{mol L}^{-1}$) at Ajuruteua beach, Bragança, Pará: (A) nitrite and nitrate; (B) phosphate and silicate. Vertical axes are plotted with different scales. Only positive deviation appears for variables with negative values.

PHYTOPLANKTON

The microphytoplankton community of Ajuruteua beach included 110 taxa (82 species and 28 morphospecies) distributed among the Cyanobacteria, Dinophyta, and Ochrophyta. Diatoms, algae with cell walls (frustules) made of silica (hydrated silicon dioxide), were the most diverse group, with 87.3% of the identified species, followed by the dinoflagellates (11.8%) and cyanobacteria (0.9%). Marine neritic (33.3%) and marine littoral (tychoplankton) species (30.9%) dominated the local phytoplankton.

Diatoms comprised three classes, nine subclasses, 20 orders, 32 families and 50 genera. *Chaetoceros* Ehrenberg (13 taxa) and *Coscinodiscus* Ehrenberg (10 taxa) were the predominant genera. The Class Dinophyceae, with five orders, seven families and seven genera, represented dinoflagellates. The order Gonyaulacales was the most diverse (three families) and the genus *Protoperidinium* Bergh had the higher number of taxa (three). Only one Cyanobacteria family – Oscillatoriaceae (with one morphospecies) – was observed.

In the qualitative analysis, *Coscinodiscus jonensianus* (Greville) Ostefeld, *Coscinodiscus perforatus* Ehrenberg, *Dimeregramma minor* (Gregory) Ralfs, *Ditylum brightwellii* (West) Grunow, *Odontella mobiliensis* (Bailey) Grunow, *Odontella sinensis* (Greville) Grunow and *Thalassionema frauenfeldii* Grunow were found to be very frequent species. No abundant species were found, but *Coscinodiscus jonensianus* (reaching 35.8% of the total phytoplankton in June 2009), *Asterionellopsis glacialis* (Castracane) Round (29% in September 2009), *Ceratium fusus* (Ehrenberg) Dujardin (18.9% in March 2009), *Coscinodiscus concinnus* W. Smith (16.6% in March), *C. perforatus* (19.8% in March), *Dimeregramma minor* (13.5% in December 2008), *Skeletonema* sp. (12.3% in December) and *Thalassionema frauenfeldii* (20.5% in December) presented low relative abundances (Figure 5).

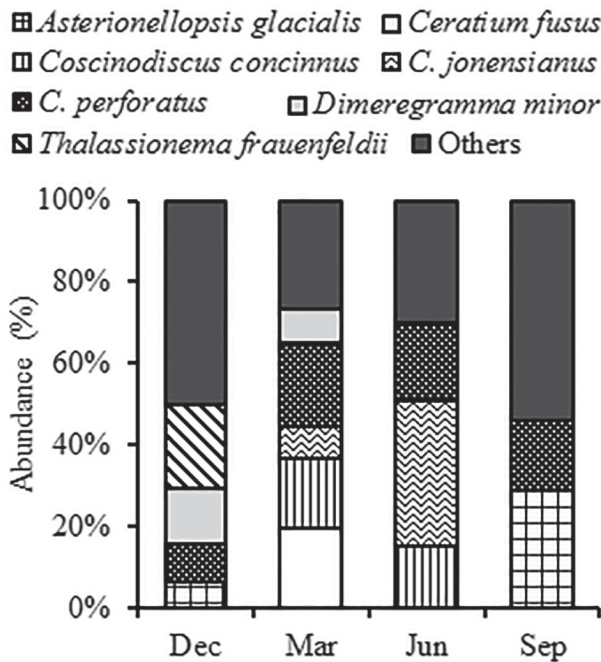


Figure 5 - Relative abundance of the main microphytoplankton species identified at Ajuruteua beach, Bragança, Pará.

Mean phytoplankton biomass (chlorophyll-a) ranged from $6.1 \pm 2.6 \text{ mg m}^{-3}$ in December 2008 to $24.5 \pm 6.8 \text{ mg m}^{-3}$ in March 2009, with significantly higher values being observed in the rainy season ($U = 41.0, p < 0.05$). Total phytoplankton density (mean \pm SD) oscillated from $878 \pm 53 \times 10^3 \text{ cells L}^{-1}$ in June 2009 to $1255 \pm 245 \times 10^3 \text{ cells L}^{-1}$ in December, 2008, with significantly higher values being recorded in the dry season ($F = 6.5, p < 0.05$). Average microphytoplankton density was significantly higher in the dry season ($F = 21.3, p < 0.05$), ranging from $266 \pm 49 \times 10^3 \text{ cells L}^{-1}$ in June, 2009, to $874 \pm 196 \times 10^3 \text{ cells L}^{-1}$ December, 2008, while phytoflagellate densities increased from $380 \pm 63 \times 10^3 \text{ cells L}^{-1}$ in December to $611 \pm 57 \times 10^3 \text{ cells L}^{-1}$ in March, 2009, with significantly higher values being recorded in the rainy season ($F = 46.2, p < 0.05$; Figure 6).

Overall, in the quantitative study, *Dimeregramma minor* was the most important species, averaging 82% of the microphytoplankton in the dry season (December, 2008) and 59% in the rainy season (March, 2009). This species was followed

by *Plagiogramma* sp. (10.6% in December, 2008), *Campylosira Cymbelliformis* (Schmidt) Grunow (8.3% in March, 2009), *Ceratium fusus* (6.9% March, 2009) and *Skeletonema* sp. (6.1% March, 2009).

Diversity ranged from very low to high, oscillating between $1.0 \pm 0.2 \text{ bits.cell}^{-1}$ in December 2008 and $2.5 \pm 0.5 \text{ bits.cell}^{-1}$ in March 2009, with significantly higher values being recorded in the rainy period ($F = 7.6, p < 0.05$). Evenness returned a similar pattern in the rainy season ($F = 9.5, p < 0.05$), ranging from 0.2 ± 0.0 in December 2008 to 0.5 ± 0.1 in March 2009 (Figure 7).

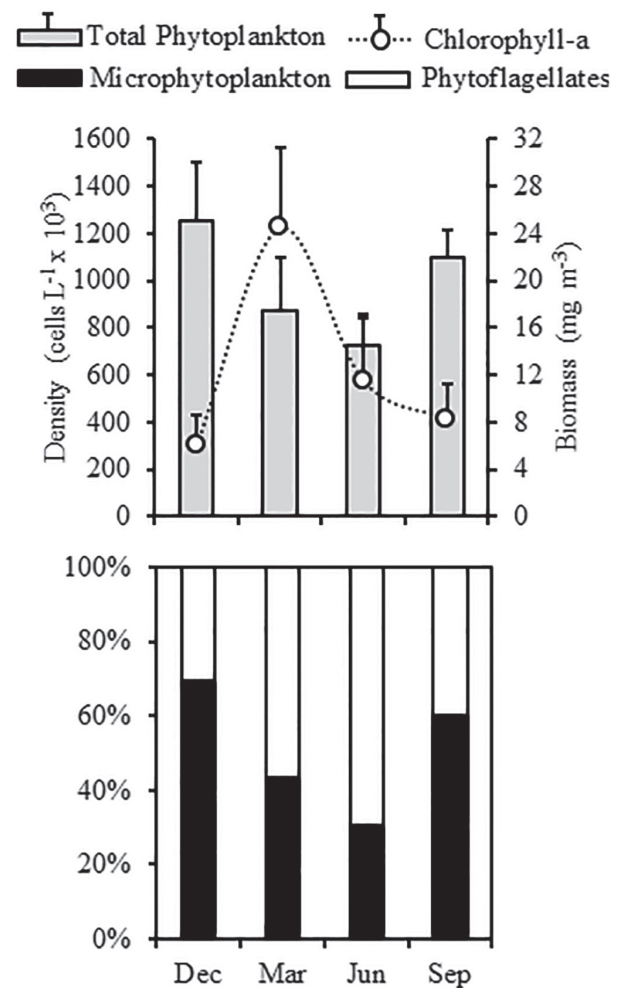


Figure 6 - Monthly average (\pm SD) of total phytoplankton density and biomass in terms of chlorophyll-a (A); and (B) relative abundance of Microphytoplankton and phytoflagellates at Ajuruteua beach, Bragança, Pará.

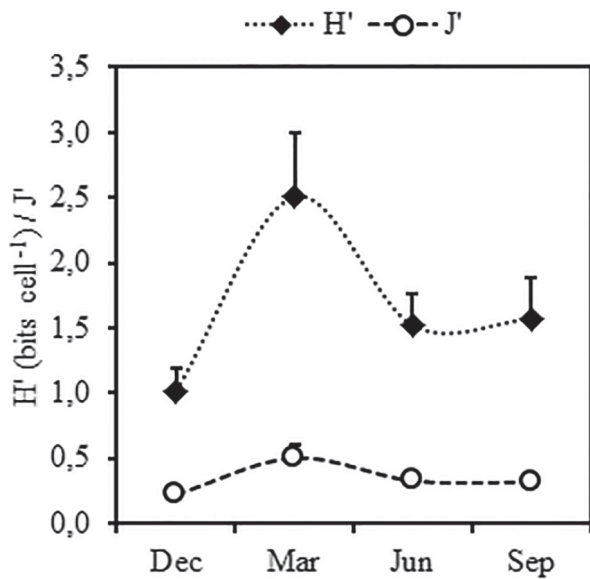


Figure 7 - Monthly average (\pm SD) of diversity indexes (H') and evenness (J') at Ajuruteua beach, Bragança, Pará.

MULTIVARIATE ANALYSES

The cluster analysis revealed four groups with a similarity of 64% (Figure 8). Differences between

groups were based mainly on the monthly variation (ANOSIM global $R = 0.7, p < 0.05$).

Group 1 included the samples from March 2009, which had the highest levels of diversity and evenness. This group was defined by the presence of the dinoflagellate *Gonyaulax grindleyi* Reinecke (SIMPER (Sim/SD) = 25.9) and the contribution of the diatom *Skeletonema* sp. (SIMPER (Sim/SD) = 23.4). Group 2 was made up of the samples from June and one sample from December, and was defined by the presence of *Campylosira Cymbelliformis* (SIMPER (Sim/SD) = 12.4). *Thalassionema frauenfeldii* (SIMPER (Sim/SD) = 25.7) was responsible for the association of the samples from September, together with one from December, to form group 3. Group 4 included the remaining two samples from December, and was defined by the presence of the dinoflagellate *Oxytoxum* sp. (SIMPER (Sim/SD) = 11.8).

The Principal Components Analysis (PCA; Figure 9) showed that the first two components to-

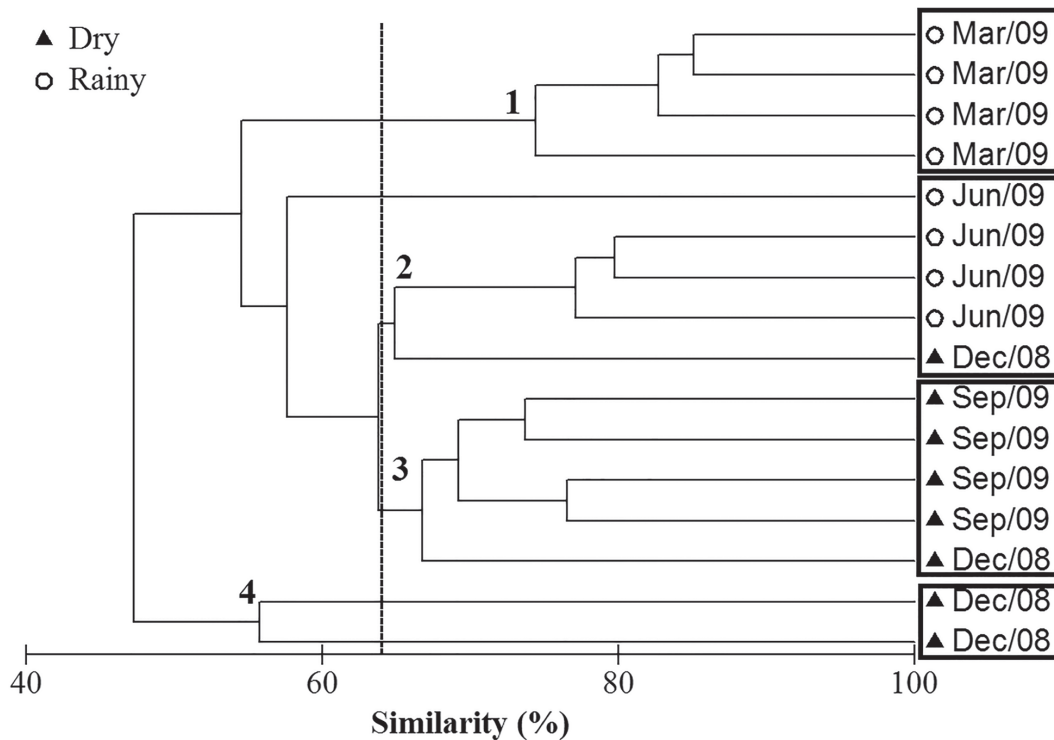


Figure 8 - Cluster analysis based on the density of phytoplankton species recorded during the study period at Ajuruteua beach, Bragança, Pará.

gether explained 46% of the data variation. Component 1 was defined by salinity (coefficient: 0.45) and component 2 by chlorophyll-a concentrations (coefficient: 0.48). The first component explained the seasonal oscillations, separating the month of December from all the others due to its high salinity. This component also encompassed an inverse relationship between salinity and silicate (coefficient: -0.50), with the highest concentration of this nutrient being observed in June. Component 2 also accounted for the trophic conditions that distinguished March, which presented the highest concentrations of chlorophyll-a. This component also correlated positively with nitrate (coefficient: 0.41), which reached high concentrations during this month.

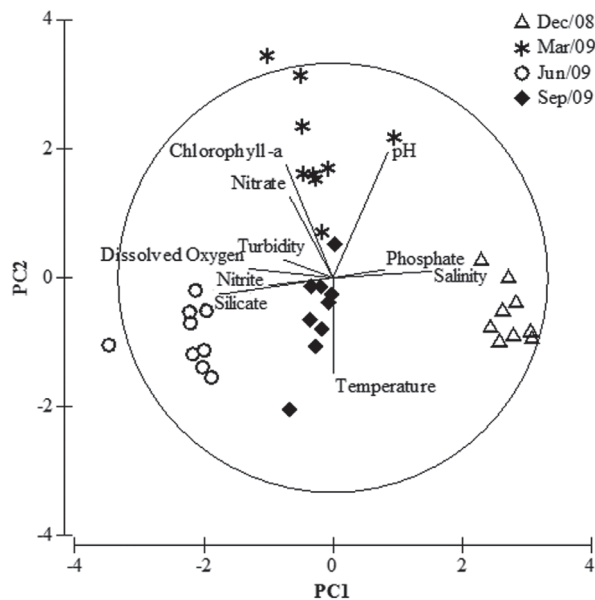


Figure 9 - Principal Component Analysis (PCA) of the environmental variables studied at Ajuruteua beach, Bragança, Pará.

Spearman correlation coefficient (r) - Significant correlations ($p < 0.05$) were observed between salinity, chlorophyll-a and dissolved nutrient (phosphate and silicate) concentrations and the characteristics of the phytoplankton community. Salinity correlated positively with total phytoplankton den-

sity ($r = 0.8$) and the density of microphytoplankton ($r = 0.9$), but negatively with the density of phytoflagellates ($r = -0.8$). Chlorophyll-a concentrations correlated positively with phytoplankton diversity ($r = 0.7$) and evenness ($r = 0.7$). Phosphate concentrations were correlated negatively with the chlorophyll-a ($r = -0.7$) and phytoflagellate densities ($r = -0.7$), whereas silicate concentrations were correlated negatively with microphytoplankton densities ($r = -0.7$) and positively with those of phytoflagellates ($r = 0.8$).

DISCUSSION

Phytoplankton population structure is directly related to both physical and chemical characteristics of the water which, combined with other environmental factors, influence the establishment of populations (Phlips et al. 2002). Previous studies at Ajuruteua beach indicated that rainfall is the main factor controlling environmental oscillations, thus influencing the biological characteristics of the local pelagic and benthic organisms (Melo et al. 2005, Costa et al. 2011, Pinheiro et al. 2011).

During the present study, rainfall patterns were typical of the coastal region of northeastern Pará, with two well-defined seasons, rainy and dry (see Moraes et al. 2005). Seasonal oscillations in rainfall and related environmental variables have a major influence on the dynamics of the phytoplankton populations of the Amazon littoral (Paiva et al. 2006, Sousa et al. 2009, Matos et al. 2011, 2012).

In Amazonian coastal environments, the strong local hydrodynamics, related to the macrotidal regimen (strong tidal currents) and strong waves and winds, have a marked influence on coastal dynamics (Monteiro et al. 2009b). In the surf zone, the re-suspension of sediments results in the exchange of benthic microalgae, which become part of plankton (tychoplankton), thus causing dramatic changes in the structure of the phytoplankton community as a whole (Sousa et al. 2009, Costa et al. 2011, 2013, Matos et al. 2013). At Ajuruteua beach, the strong

winds observed in December, together with strong currents and waves, may have further accentuated the resuspension of sediments and benthic organisms, favoring the development of the phytoplankton, especially some tychoplanktonic diatoms.

Temperature is also an important ecological parameter in most ecosystems, acting as a limiting factor for the reproduction, growth, and distribution of organisms (Passavante 1979). At Ajuruteua, however, the temperature of the water oscillated only discreetly over the course of the study period. This is typical of tropical coasts, where temperature has a reduced influence on the growth and abundance of phytoplankton (Agawin et al. 2003). Similar results have been obtained at other sites on the Brazilian coast (Azevedo et al. 2008, Ferreira et al. 2010, Sodr e et al. 2011), confirming the secondary role of this parameter in the structuring of phytoplankton communities in tropical and equatorial environments.

In the present study, salinity ranged from mesohaline to euhaline (Venice System 1959) and oscillations were linked directly to the seasonal variation in rainfall. However, other factors, such as tidal and coastal currents, and winds which have a direct or indirect effect on surface waters (see Pritchard 1967) may also contribute to this variation. This situation appears to be common in Amazonian beaches, in particular in northeastern Par a, where the combination of tides, longitudinal currents, and evaporation affect salinity on a smaller scale (Costa et al. 2008, Sousa et al. 2008, 2009, Matos et al. 2011).

The dissolved oxygen concentrations were high due to strong local hydrodynamics and the action of waves on the surf zone (high energy), which combined to accentuate the ocean-atmosphere interface, and the oxygenation of the water, as seen on other Amazonian beaches (Sousa et al. 2009, Sodr e et al. 2011). Even so, the high phytoplankton biomass, which is typical of coastal environments worldwide (Bouman et al. 2010, Lips and Lips

2010), and in the Amazon in particular (Santos et al. 2008, Sousa et al. 2009, Costa et al. 2013), also contributed to the high oxygen concentrations observed at Ajuruteua and, consequently, to the high pH values. Although the pH of coastal regions is determined primarily by the buffering effect of seawater (Schmiegelow 2004), the consumption of CO₂ and the release of dissolved oxygen into the water by photosynthesizing phytoplankton also contributes to the elevation of this variable (Branco et al. 2002, Bastos et al. 2005).

In comparison with other regions of Brazil (see Koenig et al. 2002, Le o et al. 2008), the waters of the Amazon coast are relatively turbid throughout the year. The strong local hydrodynamics, together with the fluvial input – influenced in turn by rainfall levels – were responsible for the high levels of turbidity recorded during the rainy season. This resulted in lower phytoplankton densities in March and June, whereas the highest densities were recorded in the dry season, due to the increased sunlight penetration, which stimulates the development of microalgae.

In aquatic ecosystems, nitrogen (in its various forms) and inorganic phosphorus are the main elements limiting the production of organic matter by phytoplankton (Tundisi and Tundisi 1976), and thus are essential to primary producers. Silicate salts are also necessary, however, given that siliceous frustules are the structural basis of the cell wall of diatoms (Darley 1982).

Nutrient concentrations in coastal waters are typically much higher than those observed in the open sea, leading to a greater primary productivity in these areas (Passavante et al. 1989). In coastal waters, nutrient salts are rapidly absorbed by the phytoplankton and the low nutrient concentrations observed in the present study in December may have been related to their consumption by the phytoplankton, which reached high densities in this month. This may have been further influenced by the diluting effects of tidal currents, as well

as by the reduction in fluvial runoff. On the other hand, the high concentrations of dissolved nutrients recorded in the rainy season may have been influenced by the increase in fluvial runoff (high rainfall levels) and the organic matter washed out of the adjacent mangroves, which together contribute to the increase in the concentrations of these nutrients on the beach. These concentrations were higher than those recorded in other Brazilian coastal environments (Brandini et al. 2001, Branco et al. 2002, Koenig et al. 2002, 2009), reflecting the role of the extensive area of local mangroves (Souza Filho et al. 2005), which reinforce the availability of nutrients and productivity of the coast waters of Pará.

In general, diatoms are the most common and abundant group of microalgae in coastal waters (Devassy and Goes 1988, Estrada et al. 1999, Puigserver et al. 2002). The predominance of these organisms in coastal environments confirms that their abundance is determined by their euryhaline characteristics (Patrick 1967). This pattern has been observed in a number of different regions of Brazil (Sassi and Kutner 1982, Lacerda et al. 2004), reflecting the marked adaptability of these organisms to variations in salinity, which allows the establishment of populations in both in marine and estuarine environments.

In the present study, the principal microphytoplankton forms were centric diatoms. The genus *Chaetoceros* Ehrenberg was the most numerous taxon, as observed in previous studies of the Amazon shelf (Wood 1966, Sousa et al. 2008, Matos et al. 2011). This genus is one of the most common in Brazilian coastal waters, and is responsible, in part, for the high algal biomass and productivity observed in these environments (Moreira Filho et al. 1990, Passavante and Feitosa 2004, Sousa et al. 2009).

Among the diatoms, *Coscinodiscus jonensianus*, *Coscinodiscus perforatus*, *Dimeregramma minor*, *Odontella mobiliensis* and *Thalassionema*

frauenfeldii were very frequent, but not abundant in the study area. These species are well represented in marine and estuarine environments on the Amazon coast (Sousa et al. 2008, Santana et al. 2010, Matos et al. 2011) and can be considered to be typical of the northern Brazilian littoral. However, the structure of the diatom communities was defined by the presence of *Dimeregramma minor* – a polyhalobe diatom – which was recorded in both seasons and was relatively more abundant during the dry season. This species is often associated with microphytobenthos in shallow sandy coastal environments, presenting high rates of photosynthesis and thus contributing significantly to primary production (Cook and Roy 2006, Hassan et al. 2006). This species is common on the Amazon coast (Sousa et al. 2009, Matos et al. 2011, 2012, Costa et al. 2011, 2013), and its polyhalobe status has been challenged by the fact that it occurs indiscriminately during the rainy and dry seasons (Sousa et al. 2009, Matos et al. 2012, Costa et al. 2013).

In Amazonian coastal environments, the increase in precipitation – and consequently, of runoff – during the rainy season reduces the penetration of sunlight and limits the development of phytoplankton, resulting in a decline in population density (Paiva et al. 2006). At Ajuruteua, phytoplankton densities were highest in the dry season, when the light intensity was greatest. During this period, low rainfall rates, combined with intense winds and currents, and high salinity, contributed to the resuspension and development of *Dimeregramma minor*, resulting in high densities values, but low diversity and evenness.

The chlorophyll-a concentrations at Ajuruteua were highest during the rainy season. This pattern has been recorded at a number of sites worldwide (Eyre 2000, Burford et al. 2012), in Brazil (Feitosa et al. 1999, Grego et al. 2004), and on the Amazon littoral (Sousa et al. 2008, 2009, Pamplona et al. 2013). This indicates that the onset of the rainy season affects the resuspension of nutrients from the

bottom into the water column, favoring the increase in phytoplankton biomass. This is possible because, at the beginning of the rainy season, turbidity is still low and has yet to affect sunlight penetration. However, the relationship between phytoplankton cell density and chlorophyll-a concentrations is not always easy to determine (Parsons et al. 1984), because the amount of chlorophyll is also affected by factors such as cell size and species composition (Malone 1980). According to Raven (1998), nanoplankton fraction (phytoflagellates) has a higher surface-volume ratio, and thus uses the available resources (mainly dissolved nutrients) more efficiently than larger phytoplankton cells. Therefore, despite the lower densities of microphytoplankton cells recorded during the rainy season, the high chlorophyll-a concentrations observed in the study area may have been related to the higher densities of phytoflagellates recorded during this season.

The cluster analysis indicated that monthly patterns were the primary factor influencing grouping, whereas the Principal Components Analysis (PCA) indicated that salinity and chlorophyll-a were the principal variables, being affected directly by rainfall. The correlation coefficients reconfirmed the importance of salinity and chlorophyll-a, as well as that of dissolved nutrients on the dynamics of the local phytoplankton community, being determined, in turn, by rainfall levels.

The results of the present study thus indicate that rainfall is the primary factor controlling phytoplankton community dynamics at Ajuruteua beach, through its effects on environmental and biological parameters. The taxonomic richness of the study area was influenced primarily by the diversity of diatoms, whereas dinoflagellates and cyanobacteria made only a minor contribution. The strong local hydrodynamics generated by the tides, winds, and coastal currents regulated the population dynamics of some of the more common microalgae in the study area, in particular the tychoplankton

species such as *Dimeregramma minor*, determining the structure of the local phytoplankton community, especially during the dry season. This appears to be typical of the phytoplankton of Amazonian beaches, although data from other beaches on this littoral will be needed to define general patterns.

ACKNOWLEDGMENTS

The first author is grateful to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the concession of PhD scholarship. This research was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq/Brazil) (Grant Numbers 552126/2005-5 and 563967/05-6) and Fundação Amazônia de Amparo a Estudos e Pesquisas (FAPESPA) (Grant Numbers 116/2008 and 070/2008). The authors Luci Cajueiro Carneiro Pereira and Rauquírio Marinho da Costa would like to thank CNPq for their research grants (310909/2014-7 and 200629/2014-0, and 309527/2014-7 and 200622/2014-5, respectively).

REFERENCES

- ABBOUD-ABI SAAB M. 1992. Day-to-day variation in phytoplankton assemblages during spring blooming in a fixed station along the Lebanese coastline. *J Plankton Res* 14(8): 1099-1115.
- AGAWIN NSR, DUARTE CM, AGUSTÍ S AND MCMA-NUS L. 2003. Abundance, biomass and growth rates of *Synechococcus* sp. in a tropical coastal ecosystem (Philippines, South China Sea). *Estuar Coast Shelf S* 56: 493-502.
- AZEVEDO ACG, FEITOSA FAN AND KOENING ML. 2008. Distribuição espacial e temporal da biomassa fitoplanctônica e variáveis ambientais no Golfão Maranhense, Brasil. *Acta Bot Bras* 22(3): 870-877.
- BASTOS RB, FEITOSA FAN AND MUNIZ K. 2005. Variabilidade espaço-temporal da biomassa fitoplanctônica e hidrologia no estuário do rio Una (Pernambuco – Brasil). *Tropical Oceanography* 33(1): 1-18.
- BOUMAN HA, NAKANE T, OKA K, NAKATA K, KURITA K, SATHYENDRANATH S AND PLATT T. 2010. Environmental controls on phytoplankton production in coastal ecosystems: A case study from Tokyo Bay. *Estuar Coast Shelf S* 87: 63-72.
- BRANCO ES, FEITOSA FAN AND FLORES MONTES MJ. 2002. Variação sazonal e espacial da biomassa fito-

- planctônica relacionada com parâmetros hidrológicos no estuário de Barra das Jangadas (Jaboatão dos Guararapes-Pernambuco-Brasil). *Tropical Oceanography* 30(2): 79-96.
- BRANDINI FP, PELLIZARI FM, FERNANDES LF, SILVA ET AND FONSECA ALO. 2001. Production and biomass accumulation of periphytic diatoms growing on glass slides during a year cycle in a coastal subtropical environment (Bay of Paranaguá, southern Brazil). *Mar Biol* 138: 163-171.
- BURFORD MA, WEBSTER IT, REVILL AT, KENYON RA, WHITTLE M AND CURWEN G. 2012. Controls on phytoplankton productivity in a wet-dry tropical estuary. *Estuar Coast Shelf S* 113: 141-151.
- COOK PML AND ROY H. 2006. Advective relief of CO₂ limitation in microphytobenthos in highly productive sandy sediments. *Limnol Oceanogr* 51(4): 1594-1601.
- COSTA KG, PEREIRA LCC AND COSTA RM. 2008. Short and long-term temporal variation of the zooplankton in a tropical estuary (Amazon region, Brazil). *Bol Mus Para Emilio Goeldi, sér Ciências Naturais* 3: 127-141.
- COSTA RM, MATOS JB, PINTO KST AND PEREIRA LCC. 2013. Phytoplankton of a dynamic Amazon sandy beach. *J Coastal Res SI* 65: 1751-1756.
- COSTA VB, SOUSA EB, PINHEIRO SCC, PEREIRA LCC AND COSTA RM. 2011. Effects of a high energy coastal environment on the structure and dynamics of phytoplankton communities (Brazilian Amazon littoral). *J Coastal Res SI* 64: 354-358.
- DARLEY WM. 1982. Algae and mankind. In: WILKINSONS JF (Ed), *Algal biology: a physiological approach*, London: Blackwell, p. 143-151.
- DESIKACHARY TS. 1959. *Cyanophyta*. New Delhi: Council of Agriculture Researcher, 686 p.
- DEVASSY VP AND GOES JI. 1988. Phytoplankton communities' structure and succession in a tropical estuarine complex (Central West Coast of India). *Estuar Coast Shelf S* 27: 671-685.
- DRING MJ. 1992. *The biology of marine plants*. Cambridge: Cambridge University Press, 208 p.
- ESKINAZI-LEÇA E, MOURA ANM, SILVA-CUNHA MGG AND KOENING ML. 2002. Microalgas marinhas do estado de Pernambuco. In: TABERELLI M ET AL (Eds), *Diagnóstico da biodiversidade de Pernambuco, Recife: SECTMA e Editora Massangana*, p. 79-96.
- ESTRADA M, VARELA RA, SALAT J, CRUZADO A AND ARIAS E. 1999. Spatio-temporal variability of the winter phytoplankton distribution across the Catalan and North Balearic fronts (NW Mediterranean). *J Plankton Res* 21(1): 1-20.
- EYRE BD. 2000. Regional evaluation of nutrient transformation and phytoplankton growth in nine river-dominated sub-tropical east Australian estuaries. *Mar Ecol-Prog Ser* 205: 61-83.
- FEITOSA FAN, NASCIMENTO FCR AND COSTA KMP. 1999. Distribuição espacial e temporal da biomassa fitoplanctônica relacionada com parâmetros hidrológicos na bacia do Pina (Recife-PE). *Trab Oceanog Univ Fed PE* 27(2): 1-13.
- FERREIRA LC, SILVA-CUNHA MGG, KOENING ML, FEITOSA FAN, SANTIAGO MF AND MUNIZ K. 2010. Variação temporal do fitoplâncton em três praias urbanas do litoral sul do estado de Pernambuco, Nordeste do Brasil. *Acta Bot Bras* 24(1): 214-224.
- GLÉ C, AMO YD, SAUTOUR B, LABORDE P AND CHARDY P. 2008. Variability of nutrients and phytoplankton primary production in a shallow macrotidal coastal ecosystem (Arcachon Bay, France). *Estuar Coast Shelf S* 76: 642-656.
- GRASSHOFF K, EMRHARDT M AND KREMLING K. 1983. *Methods of seawater analysis*, 2nd ed., Weinheim: Verlag Chemie, 419 p.
- GREGO CKS, FEITOSA FAN, HONORATO DA SILVA M AND FLORES MONTES MJ. 2004. Distribuição espacial e sazonal da clorofila a fitoplanctônica e hidrologia do estuário do rio Timbó (Paulista-PE). *Tropical Oceanography* 32(2): 181-199.
- HASSAN GS, ESPINOSA MA AND ISLA FI. 2006. Modern diatom assemblages in surface sediments from estuarine systems in the southeastern Buenos Aires Province, Argentina. *J Paleolimnol* 35: 39-53.
- KOENING ML, ESKINAZI-LEÇA E, NEUMANN-LEITÃO S AND MACÊDO SJ. 2002. Impactos da construção do Porto de Suape sobre a comunidade fitoplanctônica no estuário do rio Ipojuca (Pernambuco-Brasil). *Acta Bot Bras* 16(4): 407-420.
- KOENING ML AND LIRA CG. 2005. O gênero *Ceratium* Schrank (Dinophyta) na plataforma continental e águas oceânicas do Estado de Pernambuco, Brasil. *Acta Bot Bras* 19(2): 391-397.
- KOENING ML, WANDERLEY BE AND MACEDO SJ. 2009. Microphytoplankton structure from the neritic and oceanic regions of Pernambuco State-Brazil. *Braz J Biol* 69(4): 1037-1046.
- LACERDA SR, KOENING ML, NEUMANN-LEITÃO S AND FLORES-MONTES MJ. 2004. Phytoplankton nyctemeral variation at a tropical river estuary (Itamaracá-Pernambuco-Brazil). *Braz J Biol* 64(1): 81-94.
- LEÃO BM, PASSAVANTE JZO, SILVA-CUNHA MGG AND SANTIAGO MF. 2008. Ecologia do microfítoplâncton do estuário do rio Igarassu, PE, Brasil. *Acta Bot Bras* 22(3): 711-722.
- LIPS I AND LIPS U. 2010. Coastal upwelling and phytoplankton community structure. *J Plankton Res* 32(9): 1269-1282.
- MALONE TC. 1980. Algal Size. In: MORRIS I (Ed), *The physiological ecology of phytoplankton, studies in Ecol-*

- ogy, vol. 7, Los Angeles: University California Press, p. 433-463.
- MARENCO JA. 1995. Interannual variability of deep convection over the tropical South American sector as deduced from ISCCP C2 data. *Int J Climatol* 15(9): 995-1010.
- MATTEUCCI SD AND COLMA A. 1982. La metodología para el estudio de la vegetación, 22nd ed., Serie de Biología. Washington: Organización de los Estados Americanos, 168p.
- MATOS JB, SODRÉ DKL, COSTA KG, PEREIRA LCC AND COSTA RM. 2011. Spatial and temporal variation in the composition and biomass of phytoplankton in an Amazonian estuary. *J Coastal Res SI* 64: 1525-1529.
- MATOS JB, SILVA NIS, PEREIRA LCC AND COSTA RM. 2012. Caracterização quali-quantitativa do fitoplâncton da zona de arrebentação de uma praia amazônica. *Acta Bot Bras* 26(4): 979-990.
- MATOS JB, CARDOSO EHN, PEREIRA LCC AND COSTA RM. 2013. Diatomáceas cêntricas da zona de arrebentação de uma Ilha Amazônica. *Tropical Oceanography* 41: 54-66.
- MEADE RH, DUNNE T, RICHEY JE, SANTOS UM AND SALATI E. 1985. Storage and remobilization of suspended sediment in the lower Amazon River of Brazil. *Science* 228(4698): 488-490.
- MELO NFAC, PAIVA RS AND SILVA MMT. 2005. Variação diurna da densidade planctônica na região intertidal da praia de Ajuruteua (Bragança-Pará). *Bol Mus Para Emilio Goeldi, sér Ciências Naturais* 1(2): 153-180.
- MONTEIRO MC, PEREIRA LCC AND OLIVEIRA SMO. 2009a. Morphodynamic changes of a macrotidal sand beach in the Brazilian Amazon coast (Ajuruteua-Pará). *J Coastal Res SI* 56: 103-107.
- MONTEIRO MC, PEREIRA LCC, GUIMARÃES DO AND COSTA RM. 2009b. Ocupação territorial e variações morfológicas em uma praia de macromaré do litoral Amazônico, Ajuruteua-PA, Brasil. *Revista da Gestão Costeira Integrada* 9(2): 91-99.
- MORAES ACR. 1999. Contribuições para a gestão da zona costeira do Brasil: Elementos para uma geografia do litoral brasileiro. São Paulo: Hucitec-Edusp, 229 p.
- MORAES BC, COSTA JMN, COSTA ACL AND COSTA MH. 2005. Variação espacial e temporal da precipitação no Estado do Pará. *Acta Amaz* 35(2): 207-214.
- MOREIRA FILHO H, VALENTE-MOREIRA IM, SOUZA-MOSIMANN RM AND CUNHA JA. 1990. Avaliação florística e ecológica das diatomáceas (Chrysophyta, Bacillariophyceae) marinhas e estuarinas nos Estados do Paraná, Santa Catarina e Rio Grande do Sul. *Estud Biol* 25: 5-48.
- NITTROUER CA AND DEMASTER DJ. 1996. The Amazon shelf setting: tropical, energetic, and influenced by a larger river. *Cont Shelf Res* 16(5-6): 553-573.
- PAIVA RS, ESKINAZI-LEÇA E, PASSAVANTE JZO, SILVA-CUNHA MGG AND MELO NFAC. 2006. Considerações ecológicas sobre a fitoplâncton da Baía do Guajará e Foz do Rio Guamá (Pará, Brasil). *Bol Mus Para Emilio Goeldi, sér Ciências Naturais* 1(2): 133-146.
- PAMPLONA FC, PAES ET AND NEPOMUCENO A. 2013. Nutrient fluctuations in the Quatipuru River: A macrotidal estuarine mangrove system in the Brazilian Amazonian basin. *Estuar Coast Shelf S* 133: 273-284.
- PARSONS TR AND STRICKLAND JDH. 1963. Discussion of spectrophotometric determination of marine plankton pigments with revised equations of ascertaining chlorophyll a and carotenoids. *J Mar Res* 21(3): 155-163.
- PARSONS TR, TAKAHASHI MT AND HARGRAVE B. 1984. *Biological oceanographic processes*, 3rd ed., Oxford: Pergamon Press, 330 p.
- PASSAVANTE JZO. 1979. Contribuição ao estudo dos dinoflagelados da plataforma continental de Pernambuco (Brasil). *Trab Oceanog Univ Fed PE* 14: 31-54.
- PASSAVANTE JZO, GOMES NA, LEÇA EE AND FEITOSA FAN. 1989. Variação da clorofila a do fitoplâncton na plataforma continental de Pernambuco. *Trab Oceanog Univ Fed PE* 26: 145-154.
- PASSAVANTE JZO AND FEITOSA FAN. 2004. Dinâmica da produtividade fitoplanctônica na zona costeira marinha. In: ESKINAZI-LEÇA E, NEUMANN-LEITÃO S AND COSTA MF (Orgs), *Oceanografia – Um cenário tropical*, Recife: Universidade Federal de Pernambuco, p. 353-373.
- PATRICK R. 1967. Diatoms communities in estuaries. In: LAUFF GH (Ed), *Estuaries*, Washington: American Association for the Advance of Science, p. 311-315.
- PEREIRA LCC, PINTO KST, COSTA KG, VILA-CONCEJO A AND COSTA RM. 2012b. Oceanographic conditions and human factors on the water quality at an Amazon macrotidal beach. *J Coastal Res* 285: 1627-1637.
- PEREIRA LCC, SILVA NIS, COSTA RM, ASP NE, COSTA KG AND VILA-CONCEJO A. 2012a. Seasonal changes in oceanographic processes at an equatorial macrotidal beach in northern Brazil. *Cont Shelf Res* 43: 95-106.
- PEREIRA LCC, OLIVEIRA SMO, COSTA RM, COSTA KG AND VILA-CONCEJO A. 2013. What happens on an equatorial beach on the Amazon coast when La Niña occurs during the rainy season? *Estuar Coast Shelf S* 135: 116-127.
- PHILIPS EJ, BADYLAK S AND GROSSKOPF T. 2002. Factors affecting the abundance of phytoplankton in a restricted subtropical lagoon, the Indian River Lagoon, Florida, USA. *Estuar Coast Shelf S* 55: 385-402.
- PIELOU EC. 1977. *Mathematical Ecology*, 2nd ed., New York: J Wiley & Sons, 385 p.
- PINHEIRO SCC, LEITE NR, COSTA VB, COSTA KG, PEREIRA LCC AND COSTA RM. 2011. Spatial-temporal influence of hydrological variables on the diversity and abundance of copepods on

- an equatorial macrotidal beach in the Brazilian Amazon region. *J Coastal Res* SI 64: 425-429
- PRITCHARD DW. 1967. What is an estuary? Physical viewpoint. In: LAUFF GH (Ed), *Estuaries*, Washington: American Association for the Advance of Science, p. 3-5.
- PROST MT ET AL. 2001. Manguezais e estuários da costa paraense: Exemplo de estudo multidisciplinar integrado (Marapanim e São Caetano de Odivelas). In: PROST MT AND MENDES AC (Orgs), *Ecosistemas costeiros: Impactos e gestão ambiental*, Belém: Museu Paraense Emílio Goeldi, p. 25-52.
- PUIGSERVER M, RAMON G AND MOYA G. 2002. Spatial and temporal distribution of phytoplankton in a Mediterranean estuarine canal system. *J Coastal Res* 18(1): 39-51.
- RAVEN JA. 1998. The twelfth Tansley Lecture. Small is beautiful: the picophytoplankton. *Funct Ecol* 12: 503-513.
- ROUND FE, CRAWFORD RM AND MANN DG. 1990. The diatoms: biology e morphology of the genera. New York: Cambridge Universit Press, 747 p.
- SANTANA DS, PAIVA RS AND MELO NFAC. 2005. Diatomáceas cêntricas da região entre marés da praia de Aju-teua (Bragança - Pará). *Bol Mus Para Emílio Goeldi, sér Ciências Naturais* 1(3): 109-116.
- SANTANA DS, PAIVA RS, PEREIRA LCC AND COSTA RM. 2010. Microphytoplankton of the Marapanim Estuary (Pará, Northern Brazil). *Tropical Oceanography* 38(2): 161-172.
- SANTOS JUM, GORAYEB IS AND BASTOS MNC. 1999. Diagnóstico, avaliação e ações prioritárias para a conservação da biodiversidade da zona costeira e marinha amazônica. Belém: MMA/PRONABIO, 80 p.
- SANTOS MLS, MEDEIROS C, MUNIZ K, FEITOSA FAN, SCHWAMBORN R AND MACÊDO SJ. 2008. Influence of the Amazon and Pará Rivers on water composition and phytoplankton biomass on the adjacent shelf. *J Coastal Res* 24(3): 585-593.
- SASSI R AND KUTNER MBB. 1982. Variação sazonal do fitoplâncton da região de Saco Ribeira (Lat. 2330' S, Long. 4507' W), Ubatuba, Brasil. *Bol Inst Oceanogr* 31(2): 29-42.
- SCHMIEGELOW JMM. 2004. O planeta azul: uma introdução às ciências marinhas. Rio de Janeiro: Interciência, 202 p.
- SHANNON CE. 1948. A mathematical theory of communication. *Bell Syst Tech J* 27: 379-423.
- SILVA IR, PEREIRA LCC, TRINDADE WN, MAGALHÃES A AND COSTA RM. 2013. Natural and anthropogenic processes on the recreational activities in urban Amazon beaches. *Ocean Coast Manage* 76: 75-84.
- SMALL C AND NICHOLLS RJ. 2003. A Global analysis of human settlement in coastal zones. *J Coastal Res* 19(3): 584-599.
- SMITH WO AND DEMASTER DJ. 1996. Phytoplankton biomass and productivity in the Amazon river plume: correlation with seasonal river discharge. *Cont Shelf Res* 16(3): 291-317.
- SODRÉ DKL, MATOS JB, COSTA KG, PEREIRA LCC AND COSTA RM. 2011. Tide-induced changes in the phytoplankton communities of three Amazon estuaries (Pará-Northern Brazil). *J Coastal Res* SI 64: 1574 - 1578.
- SOUSA EB, COSTA VB, PEREIRA LCC AND COSTA RM. 2008. Microfitoplâncton de águas costeiras amazônicas: Ilha Canela (Bragança, PA, Brasil). *Acta Bot Bras* 22(3): 626-636.
- SOUSA EB, COSTA VB, PEREIRA LCC AND COSTA RM. 2009. Variação temporal do fitoplâncton e dos parâmetros hidrológicos da zona de arrebentação da Ilha Canela (Bragança, PA, Brasil). *Acta Bot Bras* 23(4): 1084-1095.
- SOUSA RC, PEREIRA LCC, SILVA NIS, OLIVEIRA SMO, PINTO KST AND COSTA RM. 2011. Recreational carrying capacity of three Amazon macrotidal beaches during the peak vacation season. *J Coastal Res* SI 64: 1292-1296.
- SOUZA FILHO PWM, TOZZI HAM AND EL-ROBRINI M. 2003. Geomorphology, Land-Use and Environmental Hazards in Aju-teua Macrotidal Sandy Beach, Northern Brazil. *J Coastal Res* SI 35: 580-589.
- SOUZA FILHO PWM. 2005. Costa de manguezais de macromaré da Amazônia: cenários morfológicos, mapeamento e quantificação de áreas usando dados de sensores remotos. *Rev Bras Geofis* 23: 427-435.
- SOUZA FILHO PWM, CUNHA ERSP DA, SALES MEC, SOUZA LFMO AND COSTA FR DA. 2005. Bibliografia da Zona Costeira Amazônica. Belém: Museu Paraense Emílio Goeldi, Universidade Federal do Pará, 401 p.
- STEIDINGER K AND TANGEN K. 1997. Dinoflagellates. In: TOMAS C (Ed), *Identifying Marine Phytoplankton*, New York: Academic Press, p. 387-584.
- STRICKLAND JDH AND PARSONS TR. 1968. A Practical handbook of seawater analysis. *Bull Fish Res Board of Can* 167: 1-311.
- TUNDISI JG AND TUNDISI TM. 1976. Produção orgânica em ecossistemas aquáticos. *Cienc Cult* 28(8): 864-887.
- UTERMÖHL H. 1958. Zur Vervollkommnung der quantitativen Phytoplankton-Methodik. *Mitt Int Ver Theor Angew Limnol* 9:1-38.
- VALENTE-MOREIRA IM, MOREIRA FILHO H AND CUNHA JA. 1994. Diatomáceas (Chrysophyta, Bacillariophyceae) em biótopo de manguezal do rio Perequê, em Pontal do Sul, Paranaguá, Estado do Paraná, Brasil. *Acta Biol Parana* 23(1, 2, 3, 4): 55-72.
- VALIELA I. 1995. *Marine ecological processes*, 2nd ed., New York: Springer-Verlag, 686p.
- VENICE SYSTEM. 1959. The final resolution of the symposium on the classification of brackish waters. *Archo Oceanogr Limnol* 11(suppl): 243-248.
- WOOD EJF. 1966. A phytoplankton study of the Amazon region. *B Mar Sci* 16(1): 102-123.