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

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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 tychoplankton 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 10^3 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 Algodoal 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 (00º49'9.4" S, 46º36'8.6" 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.

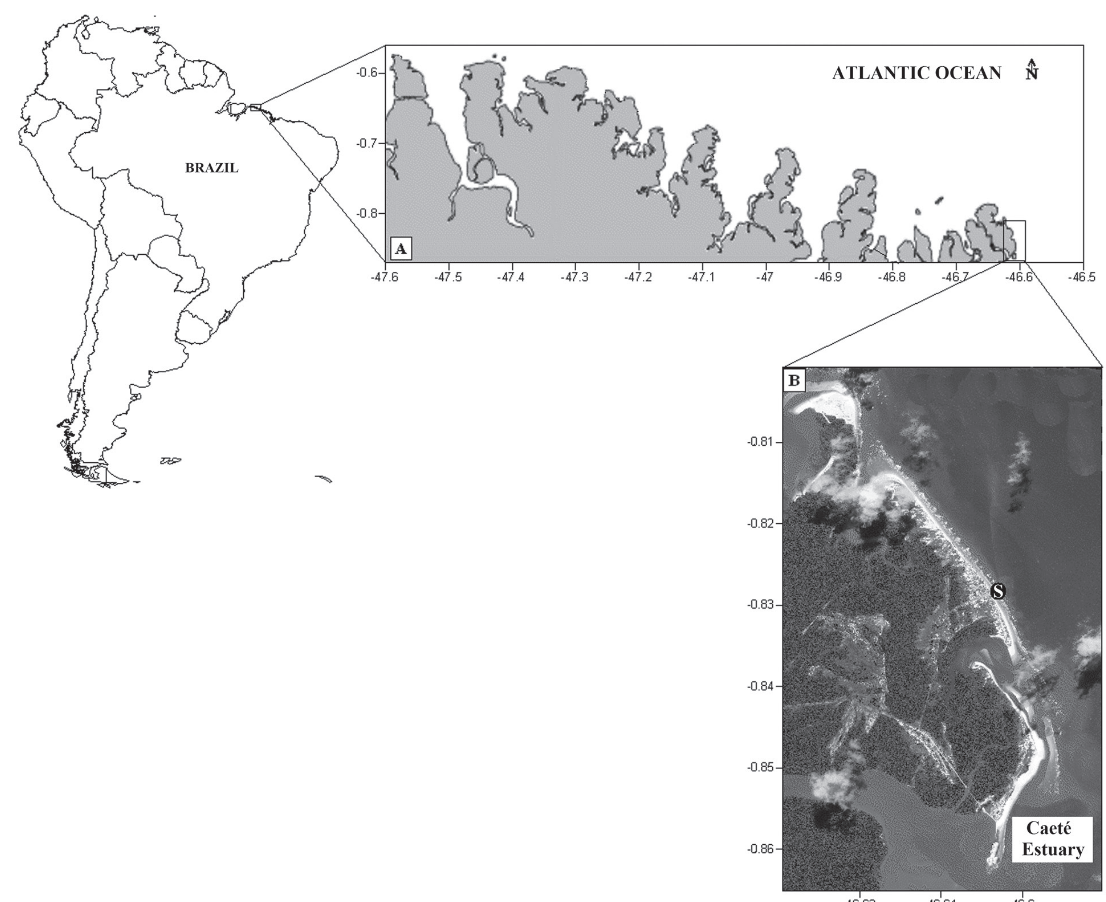

Figure 1 - Study area: (A) Municipality of Bragança, Pará, Brazil; (B) Ajuruteua beach (Northeastern Pará), showing the location of the fixed sampling station (black symbol - Modified from Sousa et al. 2011).

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 Koening 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±0.4 m s^{-1} (May, 2009) to 2.1±1.4 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 ($F = 7.4$, $p < 0.05$).

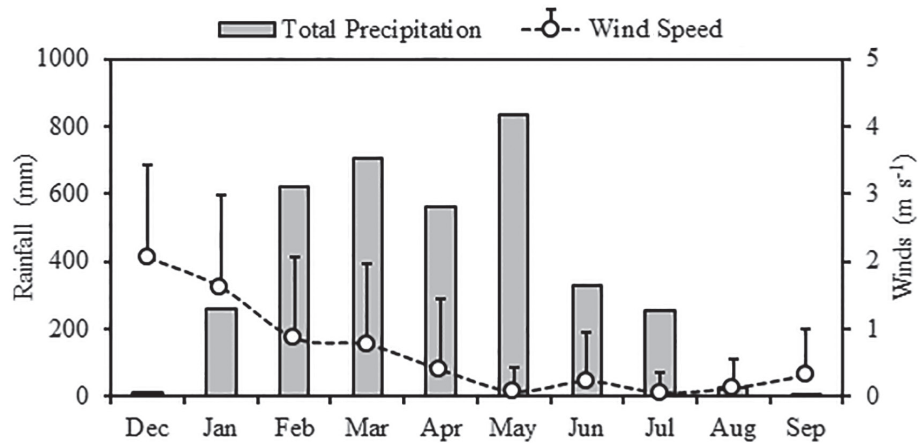

Figure 2 - Data of climatological variables during the period from December/08 to September/09: total rainfall (mm) and average wind speeds (m s^{-1}) (+SD). Source: INMET (Weather Station located in the municipality of Bragança, Pará). Vertical axes are plotted with different scales.

Hydrological Variables

Mean water temperature ranged from 28.2±0.4°C in March 2009 to 28.7±0.5°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±0.4 mg L^{-1} (December, 2008) to 7.9±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±0.0 µmol L^{-1} (December 2008) to 0.5±0.2 µmol L^{-1} (September 2009), with significantly higher values being recorded in June and September ($F = 12.1$, $p < 0.05$). Nitrate concentrations were significantly

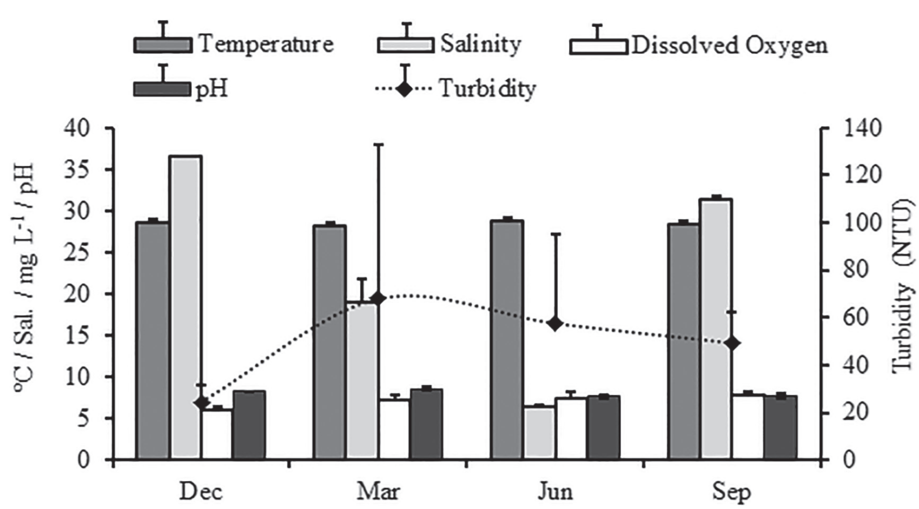

Figure 3 - Monthly average (±SD) of hydrological variables at Ajuruteua beach (Bragança, Pará) during the period of study: (A) turbidity (NTU), temperature (°C) and salinity; dissolved oxygen (mg L^{-1}) and pH. Vertical axes are plotted with different scales. Only positive deviation appears for variables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

higher in the rainy season (U = 67.0, $p < 0.05$), ranging from 1.1±0.4 µmol L^{-1} in December, 2008, to 5.5±6.0 µmol L^{-1} in March, 2009. Phosphate (from 0.2±0.0 µmol L^{-1} in June, 2009, to 1.2±2.9 µmol L^{-1} in March) and silicate concentrations (23.7±6.3 µmol L^{-1} in December, 2008, to 331.9±6.6 µmol 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.

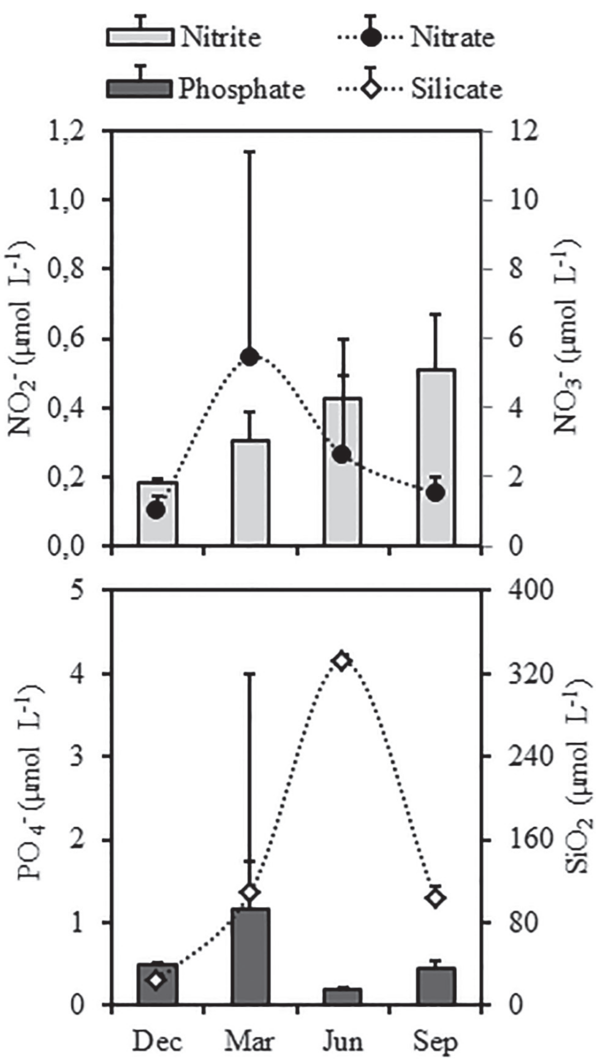

Figure 4 - Monthly average (±SD) concentrations of dissolved nutrients (µmol L^{-1}) at Ajuruteua beach, Bragança, Pará: (A) nitrite and nitrate; (B) phosphate and silicate. Vertical axes are plotted with different scales. Only positive deviation appears for variables with negative values.

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 Dinophycea, 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) Ostenfeld, *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).

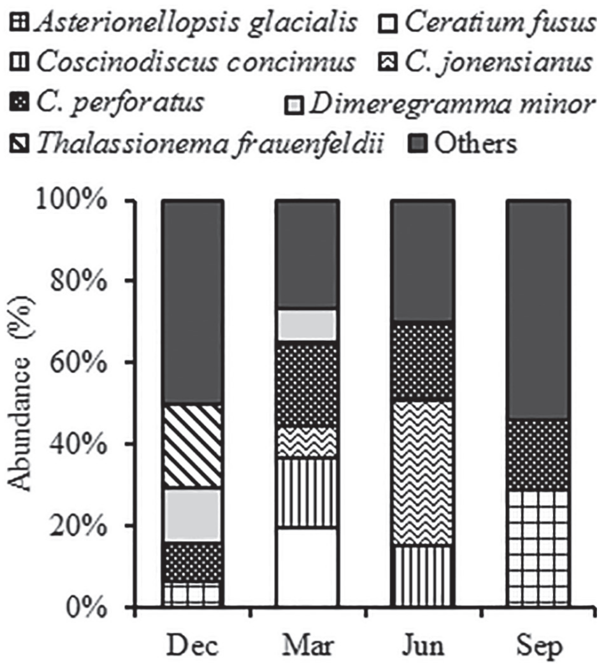

Figure 5 - Relative abundance of the main microphytoplankton species identified at Ajuruteua beach, Bragança, Pará.

Mean phytoplankton biomass (chlorophyll-a) ranged from 6.1±2.6 mg m^{-3} in December 2008 to 24.5±6.8 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±SD) oscillated from 878±53 x 10^3 cells L^{-1} in June 2009 to 1255±245 x 10^3 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±49 x 10^3 cells L^{-1} in June, 2009, to 874±196 x 10^3 cells L^{-1} December, 2008, while phytoflagellate densities increased from 380±63 x 10^3 cells L^{-1} in December to 611±57 x 10^3 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±0.2 bits.$cell^{-1}$ in December 2008 and 2.5±0.5 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).

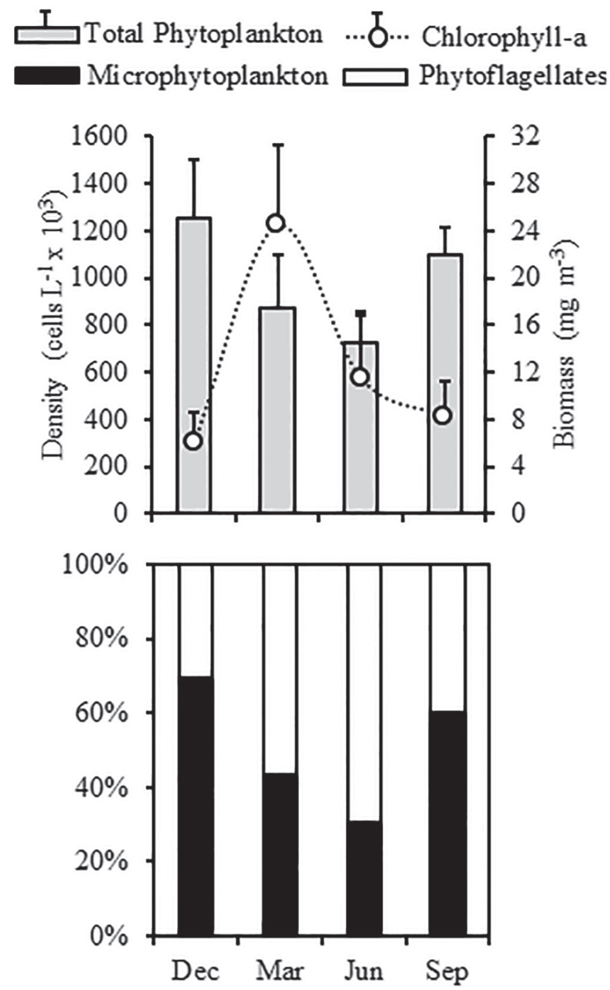

Figure 6 - Monthly average (±SD) of total phytoplankton density and biomass in terms of chlorophyll–a (A); and (B) relative abundance of Microphytoplankton and phytoflagellates at Ajuruteua beach, Bragança, Pará.

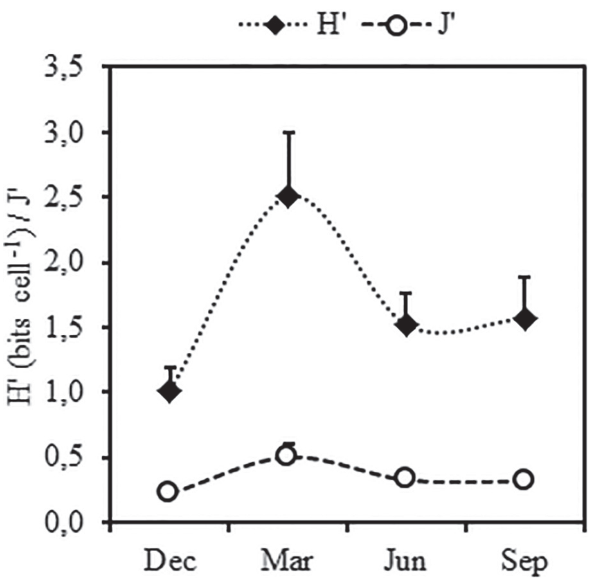

Figure 7 - Monthly average (±SD) of diversity indexes (H') and evenness (J') at Ajuruteua beach, Bragança, Pará.

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-

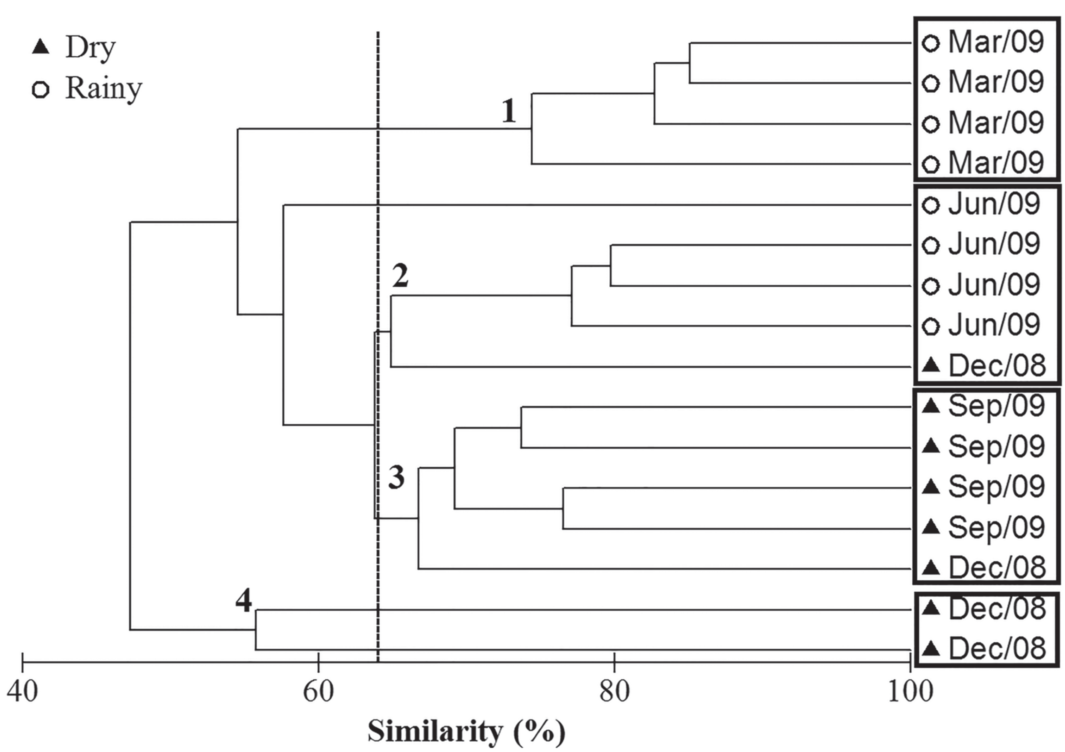

Figure 8 - Cluster analysis based on the density of phytoplankton species recorded during the study period at Ajuruteua beach, Bragança, Pará.

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.

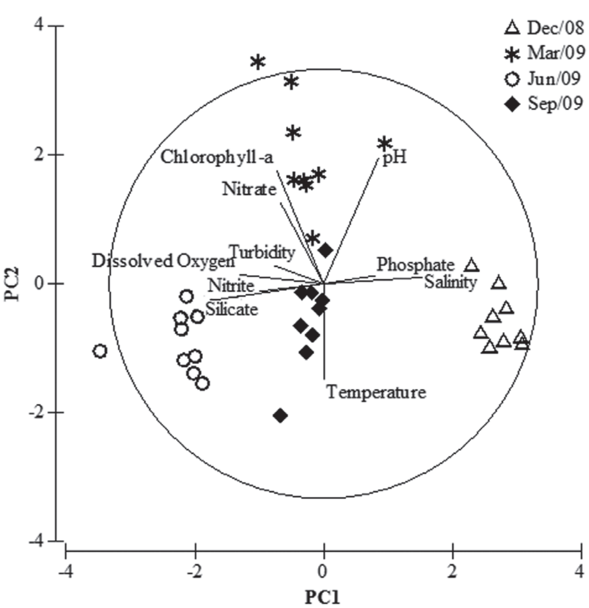

Figure 9 - Principal Component Analysis (PCA) of the environmental variables studied at Ajuruteua beach, Bragança, Pará.

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 density (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 resuspension 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, Sodré 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 Pará, 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, Sodré 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 CO_2 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 Koening et al. 2002, Leão 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, Koening 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.

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