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Zooplankton distribution and abundance related to the hydrochemistry in a tropical bay (south-east Brazil)

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Abstract: With the aim of determining space-time distribution of zooplankton related to the hydrochemistry in the Vitória Bay estuarine system (south-eastern Brazil), samples were collected at ten sampling stations using a 200 micron mesh size plankton net. Non-biotic parameters including salinity, temperature, dissolved oxygen, alkalinity and pH, as well as chlorophyll-*a* and dissolved nutrients (N-NO_3^-, N-NO_2^-, N-NH_4^+, TDN, P-PO_4^{3-} and H_4SiO_4) were studied. The estuary was characterized by two distinct regions in relation to the distribution of the hydrochemical parameters: an inner region under the influence of the continental water input, characterized by high nutrient concentration and temperature, and an outer region where the influence of coastal waters predominated with high salinity, alkalinity and dissolved oxygen values. Nutrient concentrations (N and P) were high mainly during the dry period, indicating a possible eutrophication state of the system. Copepoda dominated the zooplankton community with *Acartia lilljeborgi* Giesbrecht, 1892, *Acartia tonsa* Dana, 1848, *Temora turbinata* (Dana, 1849), *Bestiolina* sp (Sewell, 1912), *Oithona hebes* Giesbrechti, 1891, *Oithona oculata* Farran, 1913, *Paracalanus quasimodo* Bowman, 1971 and *Parvocalanus crassirostris* Dahl, 1894 being the most abundant species. Highest abundances occurred during summer and lowest in spring. The zooplankton community showed a seasonal distribution pattern where *Acartia lilljeborgi* and *A. tonsa* were more abundant in summer and winter, and copepodites of *Pseudodiaptomus* spp in spring. Regarding the spatial component, canonical correspondence analysis (CCA) revealed that the outer region of the estuary was characterized by estuarine and coastal species (e.g. *Acartia lilljeborgi*) and the inner region by the typical inner estuary species (e.g. *Pseudodiaptomus richardi* Dahl, 1894). The maintenance of this spatial pattern was influenced mainly by the interaction of coastal waters with the continental water input, since this interaction produced a horizontal gradient of salinity in the estuary, delimiting the two regions and, consequently, the distribution of the species.

Résumé : *Distribution et abondance du zooplancton en fonction des paramètres physico-chimiques dans une baie tropicale (sud-est du Brésil).* Dans le but de déterminer la distribution spatio-temporelle du zooplancton en relation avec les caractéristiques physico-chimiques des eaux du système estuarien de la Baie de Vitória (sud-est du Brésil), des échantillons ont été récoltés à dix stations avec un filet à plancton de 200 µm d´ouverture de maille. Les paramètres abiotiques tels que salinité, température, oxygène dissous, alcalinité, pH, chlorophylle-*a* et sels nutritifs (N-NO_3^-, N-NO_2^-, N-NH_4^+, TDN, P-

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PO_4^{3-} et H_4SiO_4) ont été mesurés. L´estuaire est caractérisé par la présence de deux régions distinctes en regard de la distribution des paramètres physico-chimiques : une région interne sous l´influence des entrées d´eaux continentales caractérisée par des concentrations de nutriments et une température élevées, une région externe où l´influence des eaux côtières prédomine et caractérisée par des valeurs élevées de salinité, alcalinité et oxygène dissout. Les concentrations d´azote et de phosphore étaient élevées, principalement durant la saison sèche, indiquant un possible état eutrophique du système. Les copépodes étaient le groupe dominant de la communauté zooplanctonique avec *Acartia lilljeborgi* Giesbrecht, 1892, *Acartia tonsa* Dana, 1848, *Temora turbinata* (Dana, 1849), *Bestiolina* sp (Sewell, 1912), *Oithona hebes* Giesbrechti, 1891, *Oithona oculata* Farran, 1913, *Paracalanus quasimodo* Bowman, 1971 et *Parvocalanus crassirostris* Dahl, 1894 comme espèces les plus abondantes. Les abondances étaient les plus élevées en été et les plus basses au printemps. La communauté zooplanctonique a varié saisonièrement *Acartia lilljeborgi* et *A. tonsa* étant plus abondants durant l´été et l´hiver et les copépodites de *Pseudodiaptomus* spp au printemps. En relation à composante spaciale, l´analyse canonique des correspondences (CCA) a montré que la région externe de l´estuaire est caractérisée par des espèces estuariennes et côtières (e.g. *Acartia lilljeborgi*) et la région interne par des espèces typiquement estuariennes (e.g. *Pseudodiaptomus richardi* Dahl, 1894). Le maintien de cette distribution spatiale est principalement influencé par l´interaction entre les eaux côtières et les entrées d´eaux continentales qui génèrent un gradient de salinité, séparant les deux régions et donc la distribution des espèces.

Keywords: Zooplankton ● Estuary ● Nutrients ● Salinity ● Space-time variation

Introduction

Estuaries are among the most dynamic of ecosystems, presenting diel and seasonal variations of tide, salinity, temperature, dissolved oxygen, currents and nutrients (Summerhayes & Thorpe, 1998). Such variations are of extreme importance to the survival, dispersion and development of the typical phytoplankton and zooplankton species found in these systems. According to Kennish (1986a) and Summerhayes & Torpe (1998), in estuaries, copepods, for example, go through space-time distributional variations in response to both biotic and non-biotic variations such as river flux, availability of food and water temperature.

The base of the food chain in aquatic systems is formed by planktonic organisms which establish important trophic relationships. Phytoplankton, as a producer, utilizes not only light in the photosynthetic process, but also several dissolved nutrients such as nitrogen and phosphorous. The availability of these nutrients directly controls the primary production in the aquatic environment and changes in the concentration of these nutrients can support alterations in the structure of the phytoplankton community (Kennish, 1990). Changes in nutrient concentration are associated with domestic and industrial sewage effluent inputs, as well as fertilizers used in agriculture (Le Pape & Menesguen, 1997). Increased concentrations of nutrients can promote a state of eutrophication in the environment, result in alterations in the plankton (Park & Marshall, 2000). Changes in the phytoplankton communities are reflected in the zooplankton community since zooplankton can act as a primary or secondary consumer, as well as acting as a consumer of detritus and bacteria, thus participating in other carbon cycle pathways.

Other studies that have related nutrients with zooplankton in temperate estuaries have noticed patterns such as the diminishing biomass of the mesozooplankton, changes in zooplankton species composition and trophic relations in response to nutrient variations and an increase in eutrophication in these environments (Holmes et al., 2000; Park & Marshall, 2000). Similar patterns have been found in tropical estuaries in Brazil (Lopes, 1996) and in mesocosms type studies (Sterza et al., 2002).

Interest in the study of zooplankton communities has been increasing with the usage of some species as environmental indicator of eutrophication, pollution and environmental perturbations such as the reduction of fishing stocks (Omori & Ikeda, 1992). Other interest in plankton is related to the transfer of invasive species by ballast water. The introduction of these species has caused alteration in the composition and functioning of ecological communities across the globe. Ballast water can transport bacteria, protists, dinoflagellates, diatoms and zooplankton, among others organisms. Some of these organisms survive after being released into the new environment and are able to establish a new population (Lavoie et al., 1999). The release of ballast water in port regions generally located close to or in estuarine areas has been show to impact the plankton. Among the impacts, the invasion of an exotic predatory species may have can be the reduction of a native predator, due to competition for resources, thus reducing local diversity (Cordell & Morrison, 1996).

Eutrophication in estuaries is a process that has been occurring in many estuarine ecosystems (Park & Marshall, 2000). The Vitória Bay estuarine system is no exception, especially as it is located in an urban system. This ecologically and economically importance estuary receives large quantities of domestic and industrial sewage from the surrounding cities on a daily basis. In addition, there is a port area located in the Vitória Bay region, with an intense daily loading and unloading of goods from ships, such as iron pellets, grains and automobiles. These anthropic activities can contribute to the eutrophication process and alterations in the structure of natural population, affecting not only plankton but the entire local biota. The purpose of this paper is to evaluate zooplankton responses to physical-chemical variables, and nutrients, in the Vitória Bay estuarine system (SE Brazil), focusing on the distributional patterns of these variables.

Material and Methods

Study area

Vitória Bay estuarine system (20º19'S, 40º20'W), located in southeast Brazil, has a mangrove area that occupies over 20 km^2. The estuary has an extension of approximately 25 km, with a horseshoe shape and two openings, one at the Vitória Bay and the other at the Passage Channel (Fig. 1). Small rivers flow into this system; among them are the Aribiri and Marinho rivers in the south portion of the estuary and the Bubu and Santa Maria rivers in the west portion. Local depth varies from 1.5 to 10 metres at the sampling locations. This region presents semi-diurnal tides with the predominance of floods and higher current velocities at the Passage Channel (Rigo & Chacaltana, 2006). According to Martin et al. (1993), regional climate is warm and wet, with the dry season during the months of June through October, and the rainy season for the months of November through March.

Sampling

Sampling was carried out every three months in the year 2000, during the spring tides. Ten sampling locations were selected along the study area (Fig. 1). Zooplankton was sampled with a 30 centimeter mouth opening, 200 µm mesh size plankton net fitted with a GO mechanical flow meter. Estimated water volume was given in cubic meters (Omori & Ikeda, 1992; Kramer et al., 1994). At each sampling station, subsurface tows (horizontal) were made in the water column to obtain integrated samples, with the boat at less than 2 knots, during a five minute period. Biological material was fixed in an aqueous solution of formaldehyde 5%, buffered with sodium tetra borate, for further laboratory analysis.

Each sampling station had temperature, salinity and dissolved oxygen measured in the water column "in situ" using a portable multi-sounder YSI85. At the stations that were more than 2 meters deep measurements were taken at the surface, middle and bottom of the water column and at stations that were less than 2 meters in depth measurements were taken at 0.5 meter intervals. Water samples were collected with a Van Dorn bottle at the surface and bottom depths, placed in plastic vials and cooled in ice to be transported to the laboratory for nutrient analysis and alkalinity determination.

Zooplankton analysis

For each sample, sub samples were taken using a Folsom plankton splitter according to the quantity of organisms in the sample. Individuals were identified and enumerated to the lowest taxonomic level possible, according to the available literature (Edmondson, 1959; Boltovskoy, 1981 & 1999; Matsumura-Tundisi & Rocha, 1983; Elmoor-Loureiro, 1997), using optical and stereoscopic microscopes.

Water analysis

In laboratory, an aliquot was taken to determine total alkalinity using the titration method (Gran, 1952). The remaining samples were filtered with a glass fiber filter (GF/F Whatman), with porosity of 0.7 µm, and frozen for further determination of nutrients. The filter used in the process was used for chlorophyll-*a* and pheopigment analysis (Nusch & Palme, 1975).

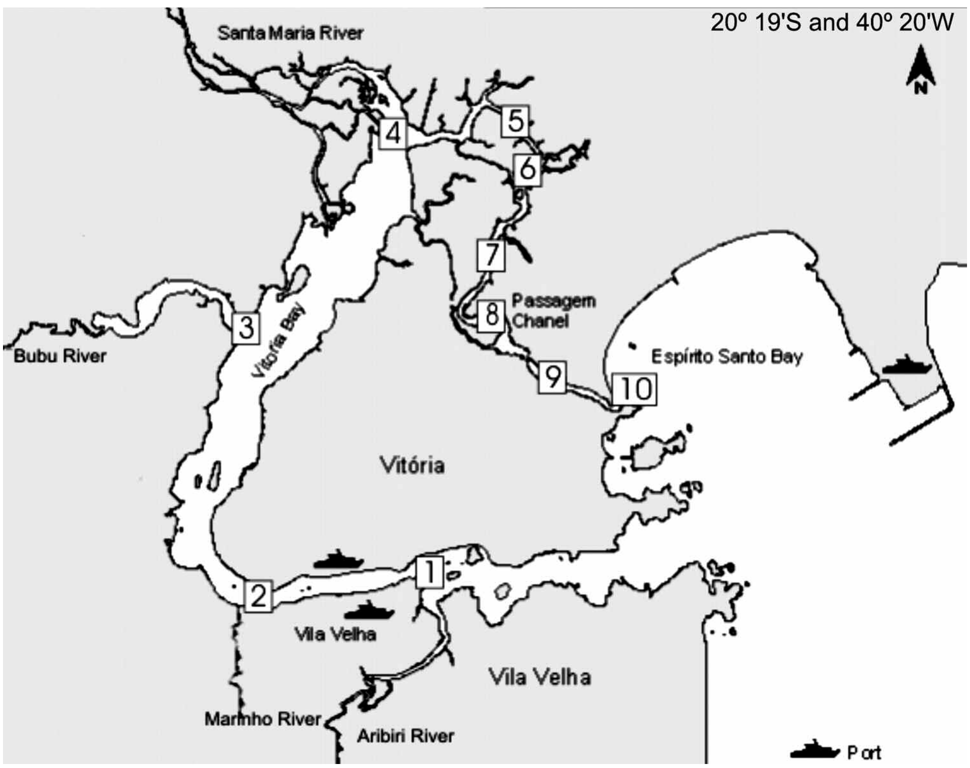
Nitrogenous forms such as nitrate, nitrite, ammonium and total dissolved nitrogen (TDN) were determined. TDN was determined after digestion with alkaline potassium persulphate. TDN, N-NO^-_3 and N-NO^-_2 were determined in duplicates through the colorimetric method in an automatic flow-through analytical system. N-NH_4^+, H_4SiO_4 and P-PO_4^{3-} concentrations were determined by the colorimetric method (Grasshoff et al., 1983; Koroleff, 1983; Carmouze, 1994). All data that presented a variation coefficient greater than 10% were rejected and redone.

Data treatment

Analysis of variance (ANOVA) was applied to the chemical-physical parameters and to the zooplankton abundance, to test differences between among seasons (temporal patterns) and among sites (spatial patterns).

Figure 1. Map of the study area with the sampling locations.

Figure 1. Carte de l´aire d´étude et localisation des stations d´échantillonnage.



Towards equalizing the variance and normalizing the distribution, all data used in the ANOVA were log transformed [$\log_{10}$ (x+1)]. When significant differences were detected by the ANOVA, Tukey´s Honestly Significantly Different (HSD) test was applied to identify sources of variation ($p < 0.05$).

A canonical correspondence analysis (CCA) was applied to evaluate the relationship between the nutrient and physical-chemical parameters and zooplankton community structure and distribution patterns. This method is known for selecting the linear combination of the environmental variables that maximizes the dispersion of the species values. In other words, CCA chooses the best weight for the environmental variables. It measures the association between species and the environment thought eigenvalues that gives an idea on how much of the species variation may be explained by the environmental variables (Jongman et al., 1987). In the diagram produced by the CCA, species and sampling sites are represented by dots and the environmental variables by vectors. Vector length and its position related to the axis represent the amount of the variable influence in the community variation. (Ter Braak, 1986; Jongman et al., 1987).

The analysis was performed using two matrices, one with the most abundant species (15 species) x sample date, and another with environmental variables (12 variables) x sample date. The twelve environmental variables (salinity, temperature, dissolved oxygen, alkalinity, pH, chlorophyll-*a*, $N\text{-}NO_3^-$, $N\text{-}NO_2^-$, $N\text{-}NH_4^+$, TDN, $P\text{-}PO_4^{3-}$, H_4SiO_4) were tested by the Monte Carlo permutation test, using only the ones that showed significance ($p < 0.05$).

Results

Physico-chemical data and dissolved nutrients

The water column was vertically homogeneous (well mixed) since no significant differences were found between surface and bottom depths for all environmental parameters and nutrients (HDS test, $p < 0.05$).

Salinity values varied from 8.7 to 37.0. The highest values found in the outer portion of the estuary (Stations 1, 2, 9 & 10) were significantly higher than those found in the inner portion of the estuary (Station 3 to Station 8). Also, spring values were significantly lower than for other seasons (Fig. 2 & Table 1).

Temperature varied from 21.0 to 29.2 ºC and showed an inverse pattern to salinity, with the highest numbers in the inner part of the estuary, although no significant differences were found. Winter values were significantly lower than the rest of the seasons (Fig. 2 & Table 1).

Dissolved oxygen, in general, followed the salinity gradient, presenting 1.0 $mg.L^{-1}$ at the inner region, and up

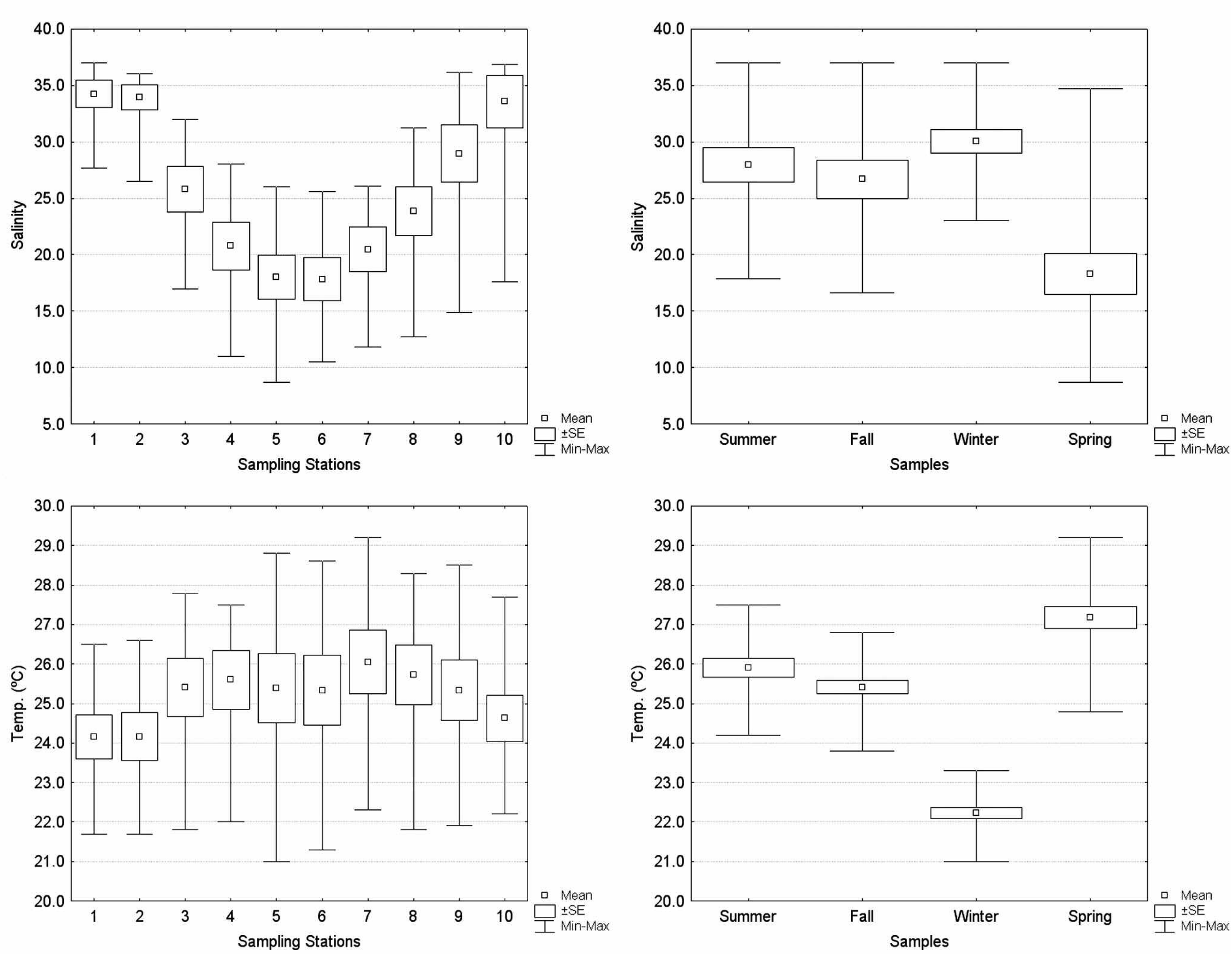
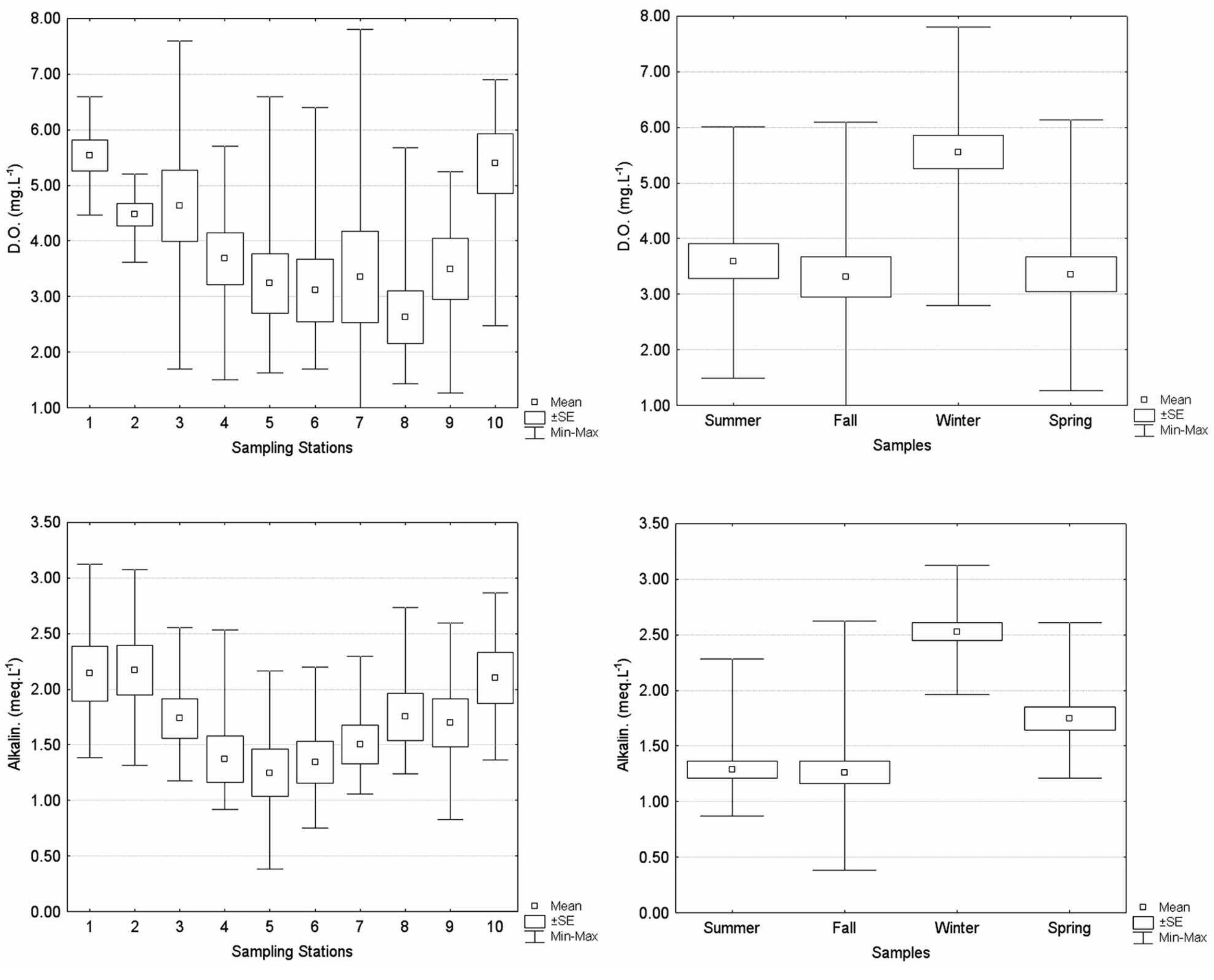


Figure 2. Average values (n = 4) for salinity and temperature of the water column at stations 1 to 10 along the yearly seasons. Error bars correspond to the standard error and maximum and minimum observed values.

Figure 2. Valeurs saisonnières moyennes (n = 4) de la salinité et de la température de la colonne d´eau aux stations 1 à 10. Les barres d´erreur correspondent à l'erreur standard et aux valeurs maximale et minimale.

Table 1. ANOVA for the environmental variables and zooplankton total abundance (n = 40). * $p < 0.05$, *post hoc* test (Tukey - HDS).
Tableau 1. ANOVA pour les paramètres physico-chimiques et l´abondance totale de zooplancton. (n = 40). * $p < 0.05$, test *a posteriori* (Tukey - HDS).

Dependent variables	Mean (range)	Std. Dev.	Independent variables	*F*	*p*	Independent variable	*F*	*p*
Salinity	25.7 (8.7-37.0)	8.2		11.0	0.00*		10.8	0.00*
Temp. (ºC)	25.1 (21.0-29.2)	2.0		0.76	0.64		94.3	0.00*
D. O. ($mg.L^{-1}$)	3.9 (1.0-7.8)	1.7		3.5	0.00*		10.95	0.00*
Alkalinitty ($meq.L^{-1}$)	1.70 (0.38-3.12)	0.64		2.6	0.01*		43.06	0.00*
pH	7.60 (6.80-8.70)	0.45		17.5	0.00*		1.76	0.16
PO_4^{3-} (µM)	1.98 (0.12-7.04)	1.64		1.5	0.14		53.70	0.00*
H_4SiO_4 (µM)	66.07 (3.80-188)	43.42	Sampling	11.9	0.00*	Seasons	3.84	0.01*
NH_4^+ (µM)	11.17 (0.43-49.0)	10.87	stations	6.7	0.00*		7.19	0.00*
NO_2^- (µM)	1.53 (0.15-4.46)	0.80		1.5	0.16		53.18	0.00*
NO_3^- (µM)	5.53 (0.03-16.6)	4.12		1.3	0.23		43.29	0.00*
NTD (µM)	50.19 (10.0-97.2)	23.04		1.6	0.12		64.83	0.00*
Clh-*a* ($\mu g.L^{-1}$)	1.80 (0.00-15.78)	2.30		1.8	0.07		2.52	0.06
Total Zooplankton ($Ind.m^{-3}$)	5.580 (423-30.451)	6.229		0.33	0.95		10.61	0.00*



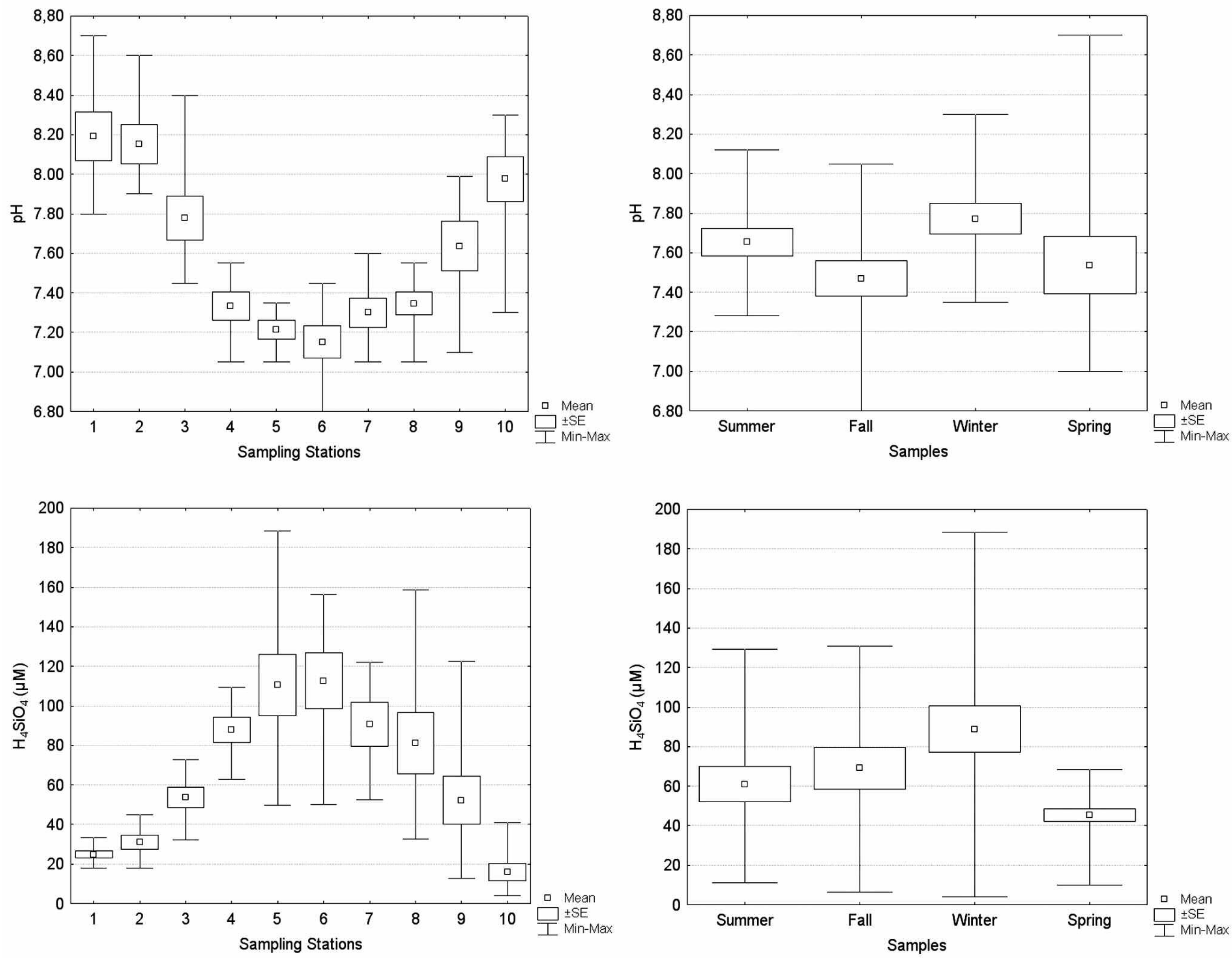


Figure 4. Average values (n = 4) of pH and silica of the water column at stations 1 to 10 along the yearly seasons. Error bars correspond to the standard error and maximum and minimum observed values.

Figure 4. Valeurs saisonnières moyennes (n = 4) du pH et de la concentration en silice dans la colonne d´eau aux stations 1 à 10. Les barres d´erreur correspondent à l'erreur standard et aux valeurs maximale et minimale.

to 7.8 mg.L^{-1} in the outer region of the estuary. Average concentration at station 8 was significantly lower than the concentration found at station 1. Winter concentrations were significantly higher than the other seasons (Fig. 3 & Table 1).

Alkalinity varied from 0.38 to 3.12 meq.L^{-1}. Although higher values occurred at the outer region of the estuary, no significant differences were found among sampling stations. Winter and spring values were significantly higher than summer and fall (Fig. 3 & Table 1).

The pH varied from 6.80 to 8.70. The values found at the outer estuary region were significantly higher than the ones at the inner region. No significant differences were found between the seasons (Fig. 4 & Table 1).

Regarding the nutrients, silica concentrations varied from 3.8 μM to 188 μM. The inner estuary region

Figure 3. Average values (n = 4) of dissolved oxygen and alkalinity of the water column at stations 1 to 10 along the yearly seasons. Error bars correspond to the standard error and maximum and minimum observed values.

Figure 3. Valeurs saisonnières moyennes (n = 4) de la concentration en oxygène dissous et de l'alcalinité de la colonne d´eau aux stations 1 a 10. Les barres d´erreur correspondent à l'erreur standard et aux valeurs maximale et minimale.

concentrations were significantly higher than the outer region. During winter, the dry season for this region, silica concentrations were significantly higher than registered for the spring (Fig. 4 & Table 1).

Orthophosphate concentrations varied form 0.12 to 7.04 µM. Although average concentrations were higher between station 7 and 9, no significant differences were observed among sampling stations. Spring concentrations were significantly higher than for the rest of the seasons (Fig. 5 & Table 1).

Chlorophyll-*a* values varied from 0.00 to 15.78 $\mu g.L^{-1}$. Chlorophyll-*a* concentrations presented the same distributional pattern as orthophosphate, since its highest concentrations occurred also in this inner portion of the estuary, although no significant differences between sampling stations and seasons were found (Fig. 5 & Table 1).

Nitrate presented a variation between 0.03 µM and 16.6 µM. Nitrite concentrations varied from 0.15 µM to 4.46 µM. The nitrogenous forms concentrations (nitrate and nitrite) had their highest values in the inner region, although no significant differences were found. Spring concentrations were significantly higher than for the other seasons (Fig. 6 & Table 1).

Ammonium concentrations varied from 0.43 µM to 49.0 µM, with average values at stations 7 and 8 significantly higher than the ones found between stations 1 through 5.

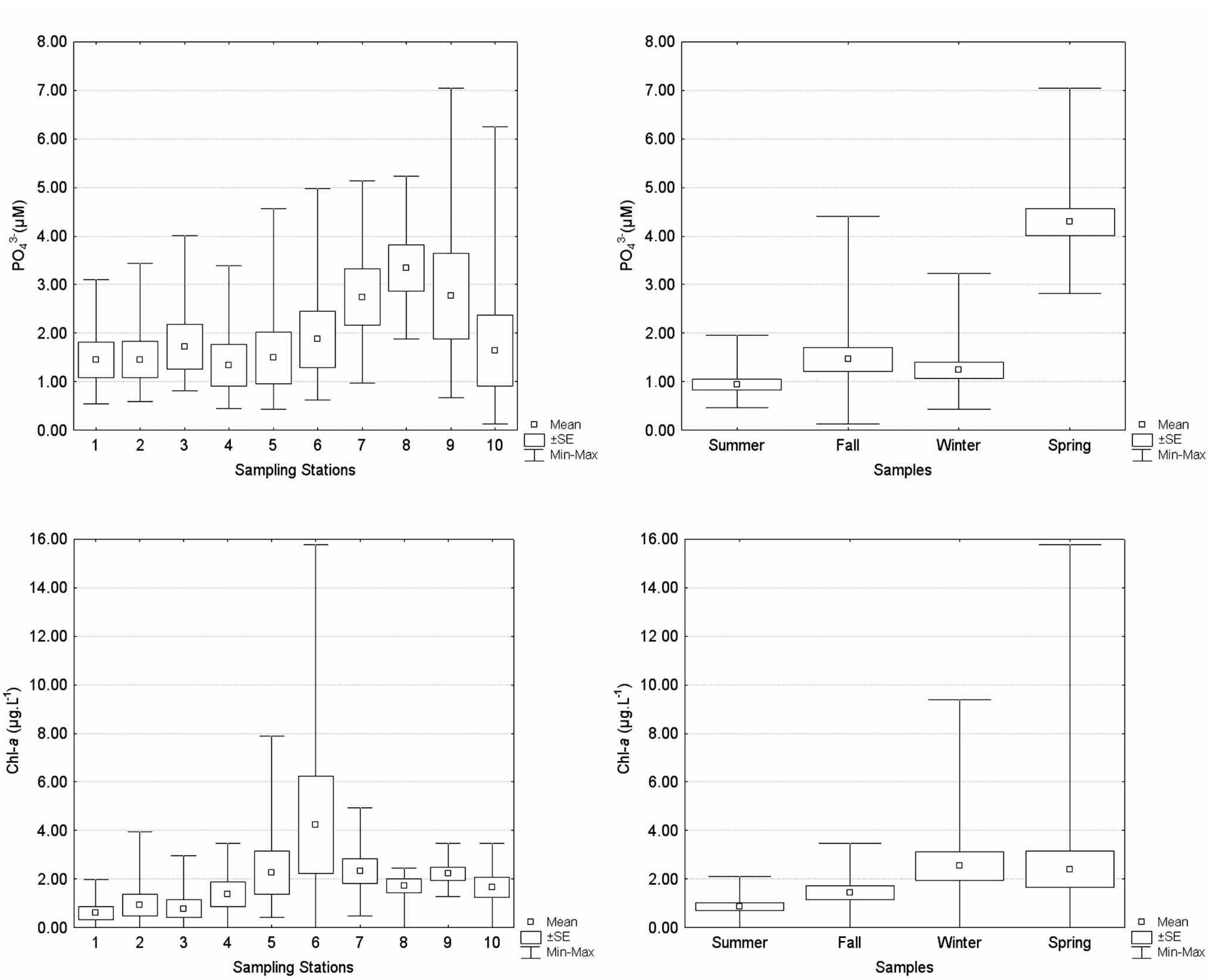


Figure 5. Average values (n = 4) of orthophosphate and chlorophyll-*a* of the water column at stations 1 to 10 along the yearly seasons. Error bars correspond to the standard error and maximum and minimum observed values.

Figure 5. Valeurs saisonnières moyennes (n = 4) de la concentration d´orthophosphate et de chlorophylle-*a* dans la colonne d´eau aux stations 1 à 10. Les barres d´erreur correspondent à l´erreur standard et aux valeurs maximale et minimale.

Spring concentrations were significantly higher than the ones found for the summer and winter (Fig. 7 & Table 1). The same happened with TDN (DON+N-NH_4^++N-NO_3^-+N-NO_2^-), that varied from 10.0 µM to 97.2 µM. Although higher concentrations have been observed at stations 7 and 8, no significant differences between sampling stations were found (Fig. 7 & Table 1).

Zooplankton

Copepoda, Cirripedia, Appendicularia, Pteropoda and Decapoda (larvae) were the most abundant groups (Fig. 8). Along the sampling stations, zooplankton varied from 423 to 30,451 ind.m^{-3}, although no significant differences were found among sampling stations. Total zooplankton abundance during summer was significantly higher than for the other seasons, whereas lowest abundances occurred during winter and spring (Fig. 9 & Table 1).

Zooplankton showed spatial and temporal variations. *Acartia lilljeborgi* (Giesbrecht, 1892) and *A. tonsa* Dana, 1848 were the most abundant copepod species during summer and winter, occurring predominantly at the stations located in the outer estuary region. During fall, the genus *Bestiolina* was the most abundant, mainly in the inner estuary. Cirripedia was the most abundant group in the winter and spring, markedly in the outer region. Regarding the other species, the occurrence and abundance of *Temora turbinata* (Dana, 1849) was more evident in summer and winter and was restricted to the stations located at the

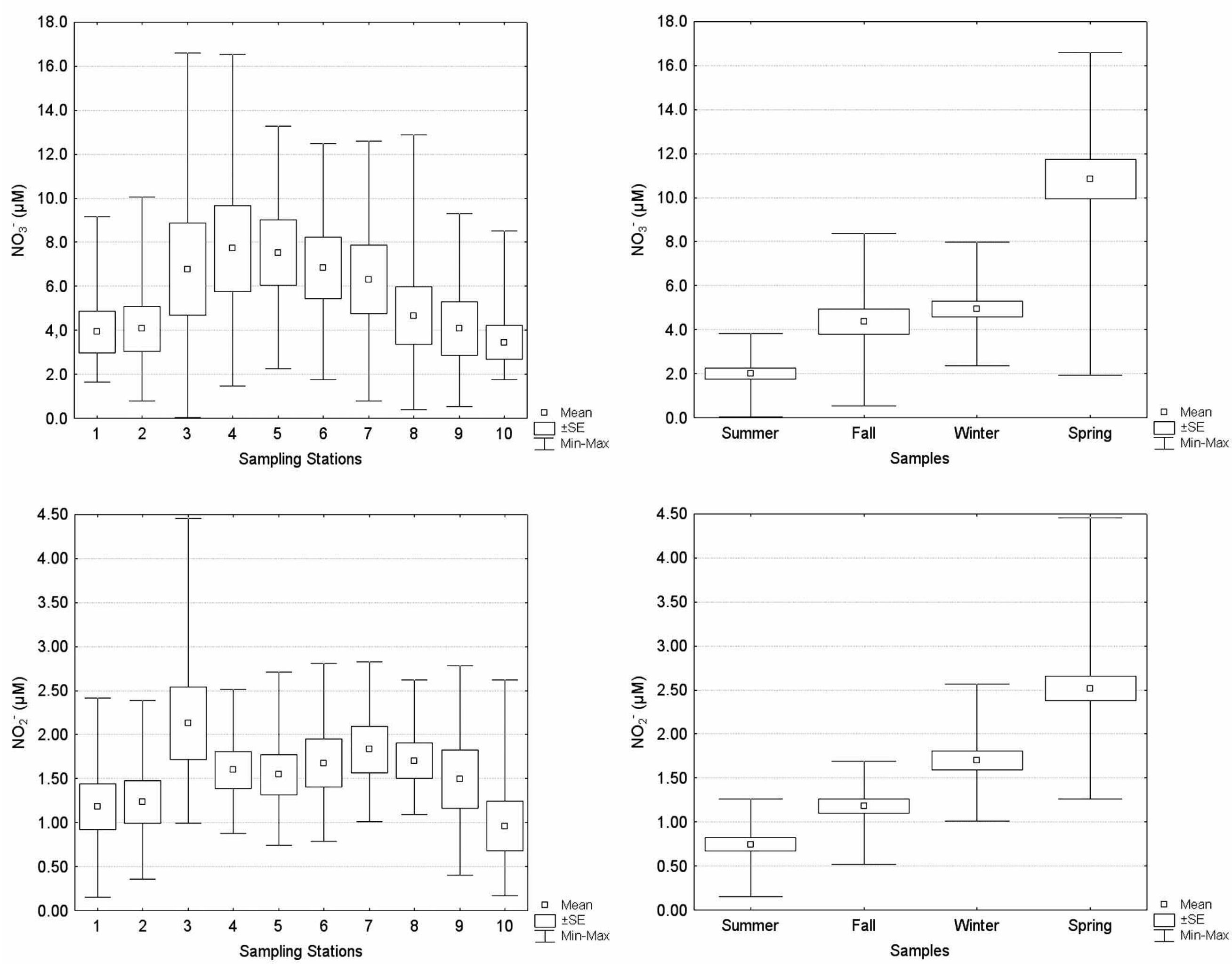


Figure 6. Average values (n = 4) of nitrate and nitrite of the water column at stations 1 to 10 along the yearly seasons. Error bars correspond to the standard error and maximum and minimum observed values.

Figure 6. Valeurs saisonnières moyennes (n = 4) de la concentration de nitrates et nitrites dans la colonne d´eau aux stations 1 à 10. Les barres d´erreur correspondent à l’erreur standard et aux valeurs maximale et minimale.

entrance of the Vitória Bay and the Passage Channel. *Oithona hebes* Giesbrecht, 1891 and *O. oculata* (Farran, 1913) were more abundant in the summer and fall, occurring throughout the estuary, but with higher abundances between stations 3 and 7. *Paracalanus quasimodo* Bowman, 1971 and *Parvocalanus crassirostris* (Dahl, 1894) were more abundant in the summer and fall seasons, and occurred also in the entire estuary, but with highest abundances between stations 7 and 10 (Fig. 10).

Canonical Correspondence Analysis (CCA)

The factorial diagram of the CCA show the distribution of zooplankton species and groups, as well as the sampling stations, seasons, and environmental variables (Fig. 11). From the twelve environmental variables tested, seven were selected by the Monte Carlo permutation test ($p < 0.05$): salinity, dissolved oxygen, temperature, alkalinity, PO_4^{3-}, H_4SiO_4 and TDN. The first two canonical axes explained 86.1% of the species/environment variance relation. Significance was registered in the two first canonical axes to the 95% level by the Monte Carlo permutation test. Axis I explained 50.6% of the total variance of species abundance. Salinity and dissolved oxygen were positively related with axis I, while PO_4^{3-}, H_4SiO_4, TDN, alkalinity and temperature were negatively related with the same axis. Axis II explained 35.5% of the

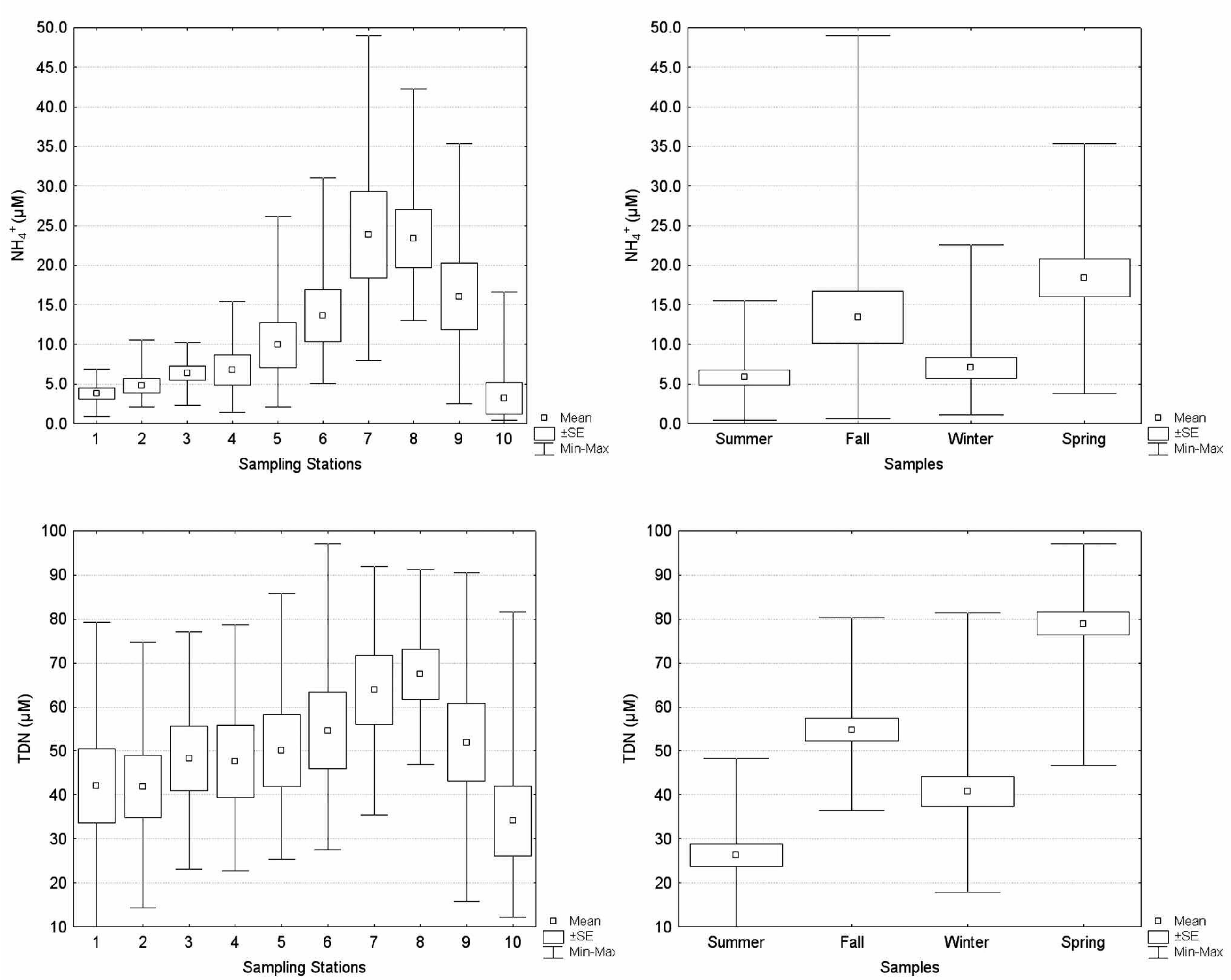


Figure 7. Average values (n = 4) of ammonium and total dissolved nitrogen of the water column at stations 1 to 10 along the yearly seasons. Error bars correspond to the standard error and maximum and minimum observed values.

Figure 7. Valeurs saisonnières moyennes (n = 4) de la concentration d´ammonium et d´azote total dissous dans la colonne d´eau aux stations 1 à 10. Les barres d´erreur correspondent à l'erreur standard et aux valeurs maximale et minimale.

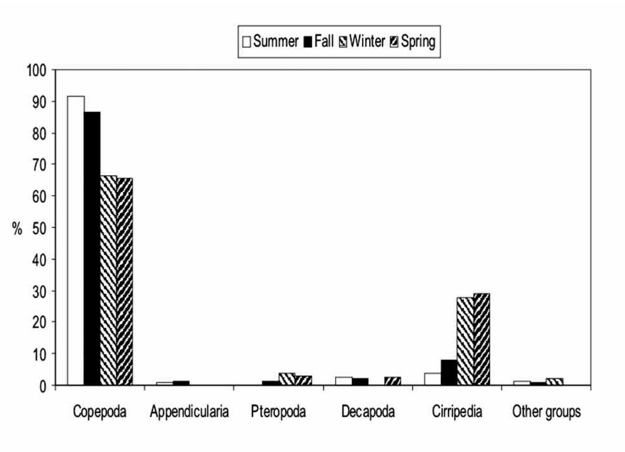


Figure 8. Relative abundance (%) of the zooplanktonic groups during the year 2000 along the seasons of the year.

Figure 8. Abondance relative (%) des groupes zooplanctoniques au cours des saisons de l´année 2000.

total variance of species abundance. Alkalinity and dissolved oxygen, salinity and PO_4^{3-}, were positively correlated with axis II, while temperature, H_4SiO_4 and TDN were negatively correlated with the same axis (Table 2).

Acartia lilljeborgi, *Temora turbinat*a and Appendicularia were positively associated with salinity and dissolved oxygen. *Oithona hebes*, *O. oculata* and mainly copepodites of *Pseudodiaptomus* spp. were correlated with TDN, H_4SiO_4 and temperature (Fig. 11).

Table 2. Weighted correlation coefficients between environmental variables and the first two CCA axes.

Tableau 2. Coefficient de corrélation pondéré entre les paramètres physico-chimiques et les deuxs premiers axes de la CCA.

	Axis I	Axis II
Salinity	0.8138	0.4776
Temperature	-0.2399	-0.5377
Dissolved oxygen	0.3425	0.8100
Alkalinity	-0.0195	0.7345
PO_4^{3-}	-0.5342	0.0083
H_4SiO_4	-0.5075	-0.5037
TDN	-0.5962	-0.2253

Discussion

Environmental variables

The influence of tides, rivers and wind are factors that can generate vertical and horizontal salinity gradients (Kennish, 1994). The high salinity found in the outer region of the estuary shows the strong influence of coastal waters in both Vitória Bay and the Passage Channel areas, corroborated also by the high alkalinity values. At the inner part of the estuary (Station 3 to Station 8), the large freshwater input from rivers, groundwater and also sewage outfalls, probably provoked a dilution of the water mass, diminishing the salinity values.

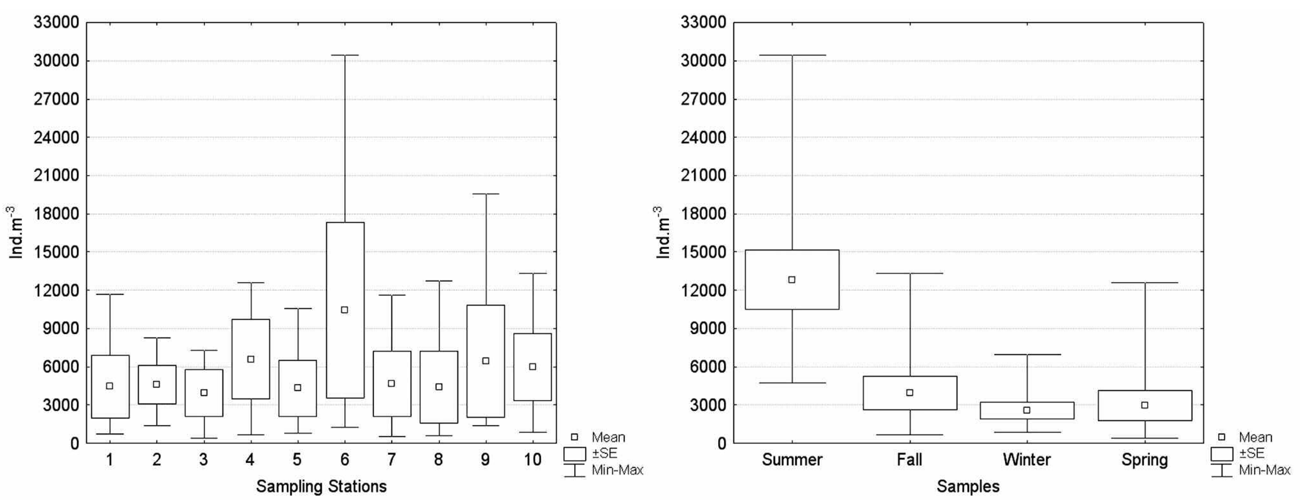


Figure 9. Average values of the total zooplankton abundance at stations 1 to 10 along the yearly seasons. Error bars correspond to the standard error and maximum and minimum observed values.

Figure 9. Valeurs moyennes de l´abondance totale du zooplancton aux stations 1 à 10. Les barres d´erreur correspondent à l'erreur standard et aux valeurs maximale et minimale.

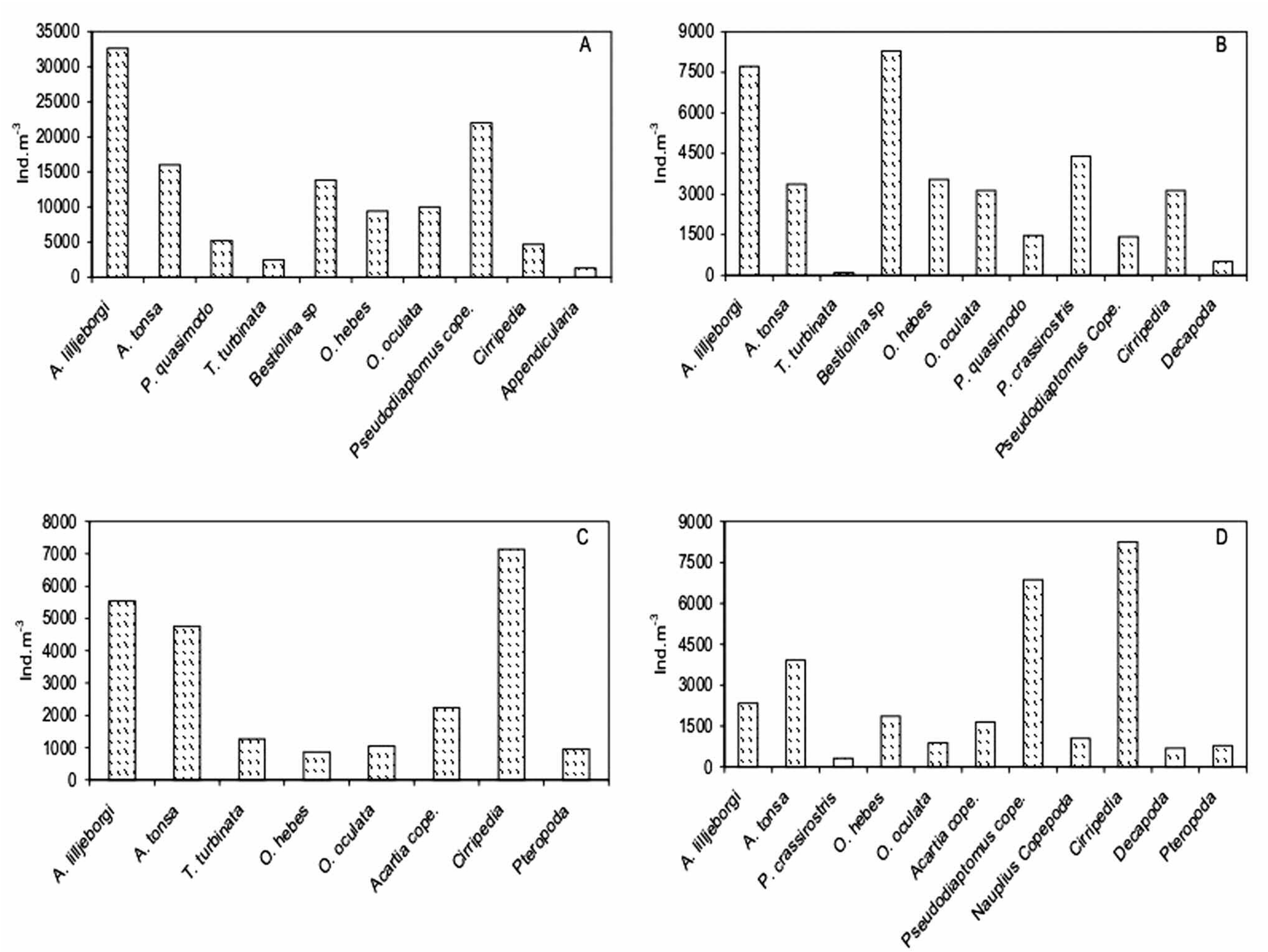


Figure 10. Total abundance of the main zooplanktonic species and groups along the year. A – Summer. B – Fall. C – Winter. D - Spring.

Figure 10. Abondance saisonnière totale des principales espèces et groupes zooplanctoniques. A – Eté. B – Automne. C – Hiver. D - Printemps.

Higher temperature and diminishing salinities are expected in the inner part of the estuary given that these areas are shallower and have restricted circulation, being subjected to a stronger influence of the warming processes via air-water interaction and by a greater contribution of warmer continental waters (Lopes et al., 1998). River and seawater temperatures, mixing processes and heat exchange between air-water interfaces primarily determine the temperature distribution in an estuary (Kennish, 1986a).

High dissolved oxygen in the outer region occurred due to the surface entrance of continental waters and deeper coastal waters generally being more productive and, consequently, having higher oxygen values. At the inner region, low oxygen concentrations evidenced a greater consumption in the organic matter decomposition processes (Chapman, 1992) that occur in a more intense way at these portions due to sewage and river inputs. This pattern is similar to that observed at the Guaraú river estuary (SP-Brazil), where oxygen values directly correlated with salinity and inversely with temperature (Lopes, 1994). Dissolved oxygen is a good indicator of estuarine pollution with low values reflecting the eutrophication status of a system (Chapman, 1992). A consequence of organic matter enrichment in estuaries is the depletion of dissolved oxygen, especially if there is not a rapid replacement of that by estuarine circulation. Low pH values in the inner region also indicate a greater decomposition rate occurring in this portion of the estuary, once this process involve H^+ ion production, modifying pH values (Carmouze, 1994).

Distribution of the dissolved nutrients

Orthophosphate highest concentrations in the Passage Channel are related to the river water input, sewage input

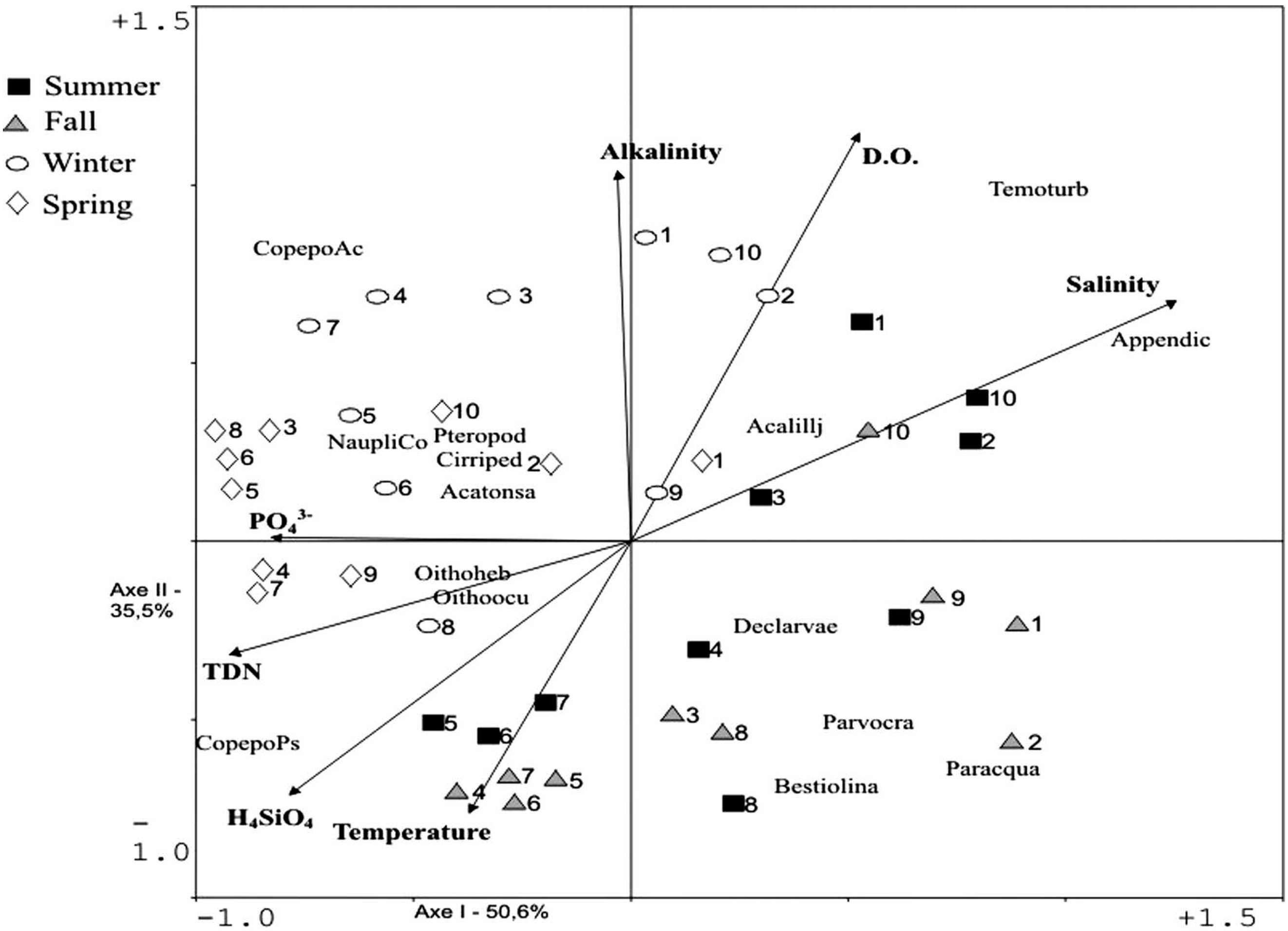


Figure 11. Canonical correspondence analysis (CCA). The number corresponds to the sampling location (1 to 10). Acalillj= *Acartia lilljeborgi*; Acatonsa = *Acartia tonsa*; Oithoheb = *Oithona hebes*; Oithoocu = *Oithona oculata*; Parvocra = *Parvocalanus crassirostris*; Paracqua = *Paracalanus quasimodo*; Temoturb = *Temora turbinata*; Bestiolina = *Bestiolina* sp; Appendic = Appendicularia; Cirriped = Cirripedia; Pteropod = Pteropoda; NaupliuCo = Copepoda nauplii; CopepoAc = Copepodite of *Acartia* spp*;* CopepoP = Copepodite of *Pseudodiaptomus* spp and LarvaDec = Decapoda larvae.

Figure 11. Analyse canonique des correspondances (CCA). Les nombres correspondent aux stations d´échantillonnage (1 à 10). Acalillj= *Acartia lilljeborgi*; Acatonsa = *Acartia tonsa*; Oithoheb = *Oithona hebes*; Oithoocu = *Oithona oculata*; Parvocra = *Parvocalanus crassirostris*; Paracqua = *Paracalanus quasimodo*; Temoturb = *Temora turbinata*; Bestiolina = *Bestiolina* sp; Appendic = Appendicularia; Cirriped = Cirripedia; Pteropod = Pteropoda; NaupliuCo = Nauplii de copépodes; CopepoAc = Copépodite d'*Acartia* spp; CopepoP = Copépodite de *Pseudodiaptomus* spp et LarvaDec = larve de Décapode.

and to a smaller effect of dilution, since the volume of coastal water in this portion of the estuary is less than at the Vitória Bay (Wollast et al., 1993).

High silicate concentrations at the inner estuary region are from the continental water contribution. The highest values during winter, a dry season for the region, are due to the lesser effect of dilution and the continuous input of sewage which is maintained constant along the year (Barroso et al., 1997). Estuaries receive silicate from river waters and ground waters in a dissolved form through mineral decomposition of silicate present in rocks and by soil lixiviation. Silicate concentration variations within the estuary are related to several factors such as river input, circulation and mixture of estuarine waters, as well as biological utilization of this nutrient by the phytoplankton (Kennish, 1986b).

In relation to the nitrogenous forms, the highest concentrations of nitrate that occurred in the dry period (winter) indicate possible sources of sewage outfalls, since during this time of year the input of freshwater from rivers and ground are minimal. Among the sources of N and P for the rivers, soil lixiviation processes and rock weathering constitute the most important ones, besides agricultural activities in its drainage basin system (Wollast et al., 1993). However, in urban areas, the highest entrance of N and P come from domestic and industrial sewage (Wollast et al., 1993).

Nitrite showed high concentrations in the dry period. Nitrite occurs in the aquatic environment as an intermediate product of the microbial reduction of nitrate, or in the ammonia oxidation that can be excreted by the phytoplankton (Grasshoff et al., 1983). Ammonium also showed high concentrations during the entire year. Ammonium occurs naturally in the aquatic environment, originating from the degradation of organic nitrogen and organic matter in the soil and water, as well as from excretion by animals and the reduction of N_2 (Chapman, 1992). High concentrations of nitrite and ammonium indicate low oxygenation of the environment and the effect of recent pollution in estuaries by sewers originated from domestic and industrial effluents (Grasshoff et al., 1983).

Total dissolved nitrogen followed the ammonium distributional pattern, with more elevated concentrations from station 7 to 8, characterizing this area as the most eutrophic one. In this area, in general, the highest nutrient concentrations occurred, mainly of ammonium and orthophosphate. This explains the incidence of higher concentrations of chlorophyll-*a* in this portion of the estuary, since the majority of the phytoplankton taxa utilizes orthophosphate and, preferentially, ammoniac nitrogen for production (Grasshoff et al., 1983).

The main sources of nutrients in estuaries are from river waters, seawater, atmospheric precipitation, soil lixiviation, groundwater, agricultural activities and sewage outfalls. However, the amount that enters via sewage is more constant than the other sources, which are connected to the hydrological cycle seasonality (Wollast et al., 1993). The sewage volume launched for the region is practically constant along the year, while the hydrological cycle is well defined, with the rainy season in the summer and the dry season in the winter (Barroso et al., 1997). So, it can be inferred that nitrogen and phosphorous, at the Vitória Bay estuarine system have, as their main sources, direct input of effluents, mainly sewage, in addition to endogenous processes such as decomposition of organic matter. Regeneration of nutrients through the decomposition of organic matter in the water column by bacterial action and benthic regeneration of the bottom sediment are processes of internal sources of nutrients to the water column (Kennish, 1986a).

Community structure and space-time variation of the zooplankton

Analysing total abundance of zooplankton, it was verified a great difference between summer sampling and the others, since total abundance was higher during the summer than the rest of the year. This same pattern of abundance was reported for other estuaries (Dias, 1994; Lopes, 1994; McKinnon & Klumpp, 1998).

CCA revealed that the structure of the zooplankton community is influenced by environmental variables where the distribution of some species and groups accompanied the division of the estuary into two distinct regions: the outer region, more influenced by the tides, with elevated values of salinity and dissolved oxygen, and the inner portion, influenced by the discharge of freshwater in this region, mainly by rivers, groundwater and effluents, carrying also nutrients.

Tidal hydrodynamics has a strong effect on the composition and zonation of resident and temporary organisms in estuaries. The effect of tides combined with the discharge of rivers has an influence on the regulation of planktonic communities by translocation of the individuals from one part to the other, within or outside the estuary (Villate, 1997). So, physical influence on the planktonic community is explained by the degree of mixing derived from the tidal stage and the extension of freshwater input (McKinnon & Klumpp, 1998). The greater abundance of the copepods *Acartia lilljeborgi*, *Temora turbinata* and Appendicularia, at the outer region of the estuary during summer, associated with higher salinity and dissolved oxygen, show a typical pattern observed in estuaries during rainy seasons, when a more accentuated salinity horizontal gradient is established. *Acartia lilljeborgi* generally is the dominant copepod in the majority of the Brazilian estuaries (Lopes, 1994), especially in the middle and outer regions. *T. turbinata* and Appendicularia are coastal organisms that enter the estuary during the flood tide, increasing their abundance values. Consequently, spatial distribution of abundance for these species is controlled by the salinity gradient. Some authors have found maximum total density of these species in salinities around 30 (Lopes, 1996).

An increase in Cirripedia larvae during winter indicates the probable beginning of the reproduction period of the group. From fall to spring, benthic invertebrates hatching increases, caused by temperature changes, generally resulting in meroplanktonic pulses that frequently contribute with peaks of zooplankton during this period (Kennish, 1994). In the spring, estuarine species such as copepodites of the genus *Pseudodiaptomus* (mainly *P. richardi* Dahl, 1894), *Oithona hebes* and *O. oculata* were associated with inner estuary waters having higher silica, total dissolved nitrogen and orthophosphate concentrations. Many studies report the occurrence of *P. richardi* at the inner part of an estuary, with this species being an excellent indicator of oligohaline areas (Lopes, 1994 & 1996; Lopes et al., 1998).

The other species and groups were not associated directly with any of the environmental variables; however they displayed more temporal and spatial patterns. Copepodites of the genus *Acartia*, Pteropoda, Copepoda nauplii, Cirripedia and *A. tonsa* were associated with the inner portion of the estuary and with the winter and spring sampling. *Acartia tonsa* develops well in intermediate and high salinities (Lopes et al., 1998) and is another species of Copepoda that is dominant in estuaries, particularly at Chesapeake Bay (Kennish, 1994). *Bestiolina* sp, *Parvocalanus crassirostris* and *Paracalanus quasimodo* also showed a seasonal and spatial distribution pattern, since it was associated with the stations located in the outer region during the fall and summer.

Distribution of nutrients at the inner portion of the estuary, where highest concentrations were observed, indicating an increase in phytoplankton biomass (Fig. 5), was also associated with the period with the lowest zooplankton abundance (winter and spring). This association shows that not only seasonality of the physical-chemical factors influence the zooplankton community, but also nutrients can influence it indirectly. The increase in nutrient concentrations not only stimulates phytoplankton growth, in general, but also affects the structure of the phytoplankton community, showing a reduction of its diversity once opportunist species of rapid growth start to dominate the environment (Mozetic et al., 1998). In the same area (Passage Channel) and year as the current study, Lucas et al. (2002) observed that Euglenophyceae and Bacillariophyceae presented higher densities in the Summer (wet period) and, during the dry period, high nutrient concentrations, specially ammonium nitrogen, favored Cyanophyceae and Chlorophyceae (r-strategists) growth, with the phytoplankton community dominated by *Synechocystis* cf *aquatilis* Sauvageau, 1892 and *Chlorella vulgaris* Kessler & Huss, 1992.

Nutrient concentration in the study area was higher than the registered in non-eutrophic environments (Meybeck et al., 1976; Grasshoff et al., 1983), allowing to say that the estuary is currently in an eutrophication process. Eutrophic conditions develop when nutrient enrichment exceeds the assimilation capacity of a system (Kennish, 1994). Assimilative capacity of a system to the nutrient enrichment is finite. Although small additions of nitrogen and phosphorous commonly increase productivity, quantities in excess can cause deleterious effects that compromise or interfere with feeding, growth, energetic development, population recruitment, development and reproduction, as well as changing the structure and dynamics of biotic communities (Kennish, 1990). In the Passage Channel, Lucas et al. (2002), noted that the excess of nutrients in the dry period was not converted into phytoplankton biomass. Yurkovskis (1998) observed that an increase in nutrients in the Gulf of Riga took the environment to an eutrophication state and, as a consequence, lead to a decrease in pelagic biota growth, as well as changes to species composition and trophic relations. Zooplankton responded to this eutrophication process with changes in their composition, with an increase in herbivores and species more tolerant to pollution. According to (Yurkovskis (1998), the increase in P concentrations led to an increased abundance of dinoflagellates, chlorophytes and cyanophytes, which in turn increased competition amongst zooplankton herbivores, corroborating with Lucas et al. (2002) in the Passage Channel.

In the present study, although an increase in phytoplankton biomass occurred with the increase in nutrient loading, a reduction in zooplankton abundance took place as well as changes to the community composition (Figs 5, 9 & 10). The influence of nutrients on the plankton is evidenced in several studies. Park & Marshall (2000) suggest that the community structure can characterize the increase in eutrophication of a system. The authors observed that with an increase in nutrient concentrations (N and P), there is also an increase in microzooplankton abundance and a decrease of the mesozooplankton, what leads to a decrease of zooplankton biomass. In experimental studies such as mesocosms (Sterza et al., 2002), an increase in nutrient loading caused a reduction in zooplankton abundance, probably due to alterations in the phytoplankton composition that affected the availability of food items for zooplankton, which in turn led to a decrease in their abundance.

Nutrient concentrations in this study were above the considered “natural values” for estuaries, even for those estuaries that suffer some type of anthropogenic effects, mainly at the stations located at the Passage Channel and during spring. Considering that the samples were taken during the flood tide, what may dilute concentrations, may be an indication of the environment eutrophication status. Zooplankton presented a spatial variation relating to the entrance of coastal water and freshwater to the system, what established a salinity horizontal gradient and determined the distribution of species. Temporal variation was observed mainly for zooplankton abundance, where high concentrations of nutrients in the water column were associated to lower zooplankton abundance. Although causes for this reduction may be varying, such as alteration in the composition or the reduction of phytoplankton (Yurkovskis, 1998; Lucas et al., 2002) and the reduction in oxygen values (Roman et al., 1993), it was evident the potential eutrophication effect on the zooplanktonic community.

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