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Chapter

# Subtropical Coastal Lagoon from Southern Brazil: Environmental Conditions and Phytobenthic Community Structure

*Leticia Donadel and Lezilda Torgan*

## Abstract

The chapter is about the study of environmental conditions and the structure of the benthic diatoms community in Peixe Lagoon, which is inserted in a National Park in southern Brazil. The study was carried out covering four seasons from 2011 to 2012. The system is shallow (<60 cm) located parallel to the coastline, and it is connected to the ocean through a single channel, which occurs naturally or through human action. In this lagoon, during the study, the water temperature ranged between 15.3 and 32.1°C, and the dissolved oxygen presented higher value in the winter (12.5 mg.L$^{-1}$) and lower value in the summer (7.5 mg.L$^{-1}$). The lagoon ranged from mesotrophic to hypereutrophic conditions. The salinity varied between 1.3 and 36.2%, and these variations were mainly related to meteorological conditions. The community of diatoms in Peixe Lagoon is composed by 62 taxa distributed in 30 genera composed largely of marine, brackish, and few freshwater species. Among the attributes of the community, composition better reflects the environmental variations. The opening and closing of the channel, salinity, temperature, and the action and direction of the wind are variables influencing the dynamics of the microphytobenthic community.

**Keywords:** environmental variables, diatoms, community attributes, microphytobenthos, system dynamic

## 1. Introduction

The shallow coastal lagoons are low depth water column mixing systems in which phytoplankton and microphytobenthos communities, microscopic eukaryotic photosynthetic algae, and cyanobacteria which live on the seabed [1] play a key role in the primary production and recycling of matter and nutrients. The role of microphytobenthos is quite important where macrophytes are absent and light radiation penetrates down to the bottom [2].

Microphytobenthos are composed of a set of microorganisms distributed in very diversified taxonomic groups, among which the diatoms are an important and often dominant component in estuarine and shallow coastal environments. These algae have varied adaptive strategies for adhesion and migration on different substrates, and there is a very large number of species sensitive to environmental changes.

Traditionally, benthic diatoms are classified according to the substrate in which they live. Those that live on thin sediment are called epipelic and those that live on sandy substrate are called epipsammic [3].

Diatoms studies in coastal lagoon were mainly concentrated in the world's largest water bodies, the Baltic, Black, and Caspian seas, which are ecosystems impacted by the anthropogenic actions and global climate changes. The eutrophication happened due to the increased nitrogen and phosphorus loads during the last century, and the increase in water temperature related to climate was detected by the changes in subfossil diatom assemblages. The accumulation of heavy metals from surrounded waters can be monitored due to the capacity of these algae to accumulate metals attached to the outside of the cell wall. There is an excellent literature review about these and other impacts; see the Snoeijs and Weckström chapter [4]. We can also find excellent information about the composition, spatial distribution of modern diatom assemblages, diversity, production, and ecology of the sediment-inhabiting diatoms in the estuaries [5–11]. In the smaller shallow lagoon from the east coast of Uruguay (South America) the diatoms studies were used to infer the paleosalinity, trophic and climate changes in relation to the sea level variation [12–16].

So far, most studies concentrated on phytoplankton at Patos Lagoon [17–24], Tramandaí-Armazém Lagoon [25–29], and Peixe Lagoon [30–34]. Regarding microphytobenthic, studies were limited to salt marshes and to the Patos Lagoon estuary [35–43].

The knowledge of the diatoms at Peixe Lagoon began with investigations on diatom assemblages in current and fossil sediments that allowed paleoenvironmental reconstruction. It demonstrated that the lagoon behaved as a deeper and more extensive lagoon system connected to the ocean by one or more permanent linking channels during the Holocene [44]. Later, studies were carried out on the taxonomic composition of diatoms in the marginal sediment of the lagoon. One study emphasizes the genus *Diploneis* Ehrenb. ex Cleve, rich in species [45]. Another investigation highlights the occurrence of *Cocconeis sawensis* Al-Handal et Riaux-Gobin, recently described for saline lakes in southern Iraq as an epiphyte in *Chara* sp. Linnaeus (1753: 1156). It was also recorded on an island in the South Pacific and epizoic on manatee in Florida Bay, USA [46]. The other species of the community were described, illustrated, and compiled with information on ecology and distribution in these coastal systems [47].

Studies about phytoplankton in subtropical coastal lagoon from south of Brazil showed that the structure and dynamic of the phytoplanktonic community were regulated by hydrological factors (inflow-outflow of continental and coastal waters in the system) as well as by meteorological conditions (wind and rainfall) and limnological variables (temperature and salinity) [18, 19, 33]. We have a set of factors that can act simultaneously while being difficult to recognize a main factor. Our question is to know if the structure and dynamic of the benthic diatoms in the Peixe Lagoon are related with these same factors. In order to answer this question, the study objectives were: (1) to know the composition of the diatoms community; (2) to verify the community structure and its spatial and temporal variation; and (3) to relate the variations of the community to environmental variables over an annual cycle.

In this chapter, firstly, we present information about the geographic, environmental, and climatic features where the Peixe Lagoon is situated. To be a case study, the methods are also included. Secondly, we describe the physical and chemical conditions of the lagoon and the benthic diatoms composition. Thirdly, we present and discuss the environmental variables related to the composition and spatial and temporal variation of the community attributes. Finally, we review the relationships of organisms occurring in plankton and sediment that should not be overlooked in studies in shallow coastal lagoons.

## 2. Study area

Peixe Lagoon is the only intermittent lagoon of the extreme south of Brazil and it is situated in the Lagoa do Peixe National Park (31°00′46″ S; 51°09′51″ W and 31°29′00″ S; 50°46′31″ W). This park is recognized by the Ramsar Convention as a Wetlands site, as well as an area of the UNESCO Atlantic Forest Biosphere Reserve, an Important Bird and Biodiversity Area (IBA) and a designated a site of international importance by the Western Hemisphere Shorebird Reserve Network (WHSRN). The coast is characterized by a microtidal regime, with a mean amplitude of 0.45 m [48].

Peixe Lagoon is a shallow, elongated system (35 km long and 1 km wide), parallel to the coastline (**Figure 1**) connected to the Atlantic Ocean through a single narrow channel (chocked lagoon) (**Figure 2**). The channel occlusion occurs due to deposition of sand caused by the predominance of the north and northeast winds [49, 50]. The connection with the ocean usually occurs during winter and spring, when the precipitation becomes more pronounced and the marshes and fields marginal to the lagoon are flooded. During these periods, an artificial opening of the channel is carried out by means of machines, since a natural opening only occurs sporadically [50]. The margins of the lagoon are covered by salt marshes vegetation dominated by *Paspalum vaginatum* Sw., *Cotula coronopifolia* L., *Sporobolus montevidensis* (Arechavaleta) P.M. Peterson & Saarela (= *Spartina densiflora* Brong), *Hydrocotyle bonariensis* Lam., *Androtrichum trigynum* (Spreng.) H. Pfeiff., *Bacopa monnieri* (L.) Wettst., and *Juncus acutus* L. [51]. The surface sediments at the bottom are essentially sandy. On the sites with greater depth of the lagoon, the sediments are thinner, with addition of silt and clay [49].

The system is located in subtropical climate where the rainfall is distributed throughout the year. In the period of studies, the highest rainfall (145.8 mm) occurred at the end of the fall (June 2011), decreasing in the following months and then increasing (131.2 mm) in early spring (October 2011). November had the lowest cumulative precipitation (23.0 mm). The average monthly temperature varied between 12.6 and 18°C in the autumn/winter seasons and between 18.3 and 24.4°C in spring/summer (**Figure 3**).
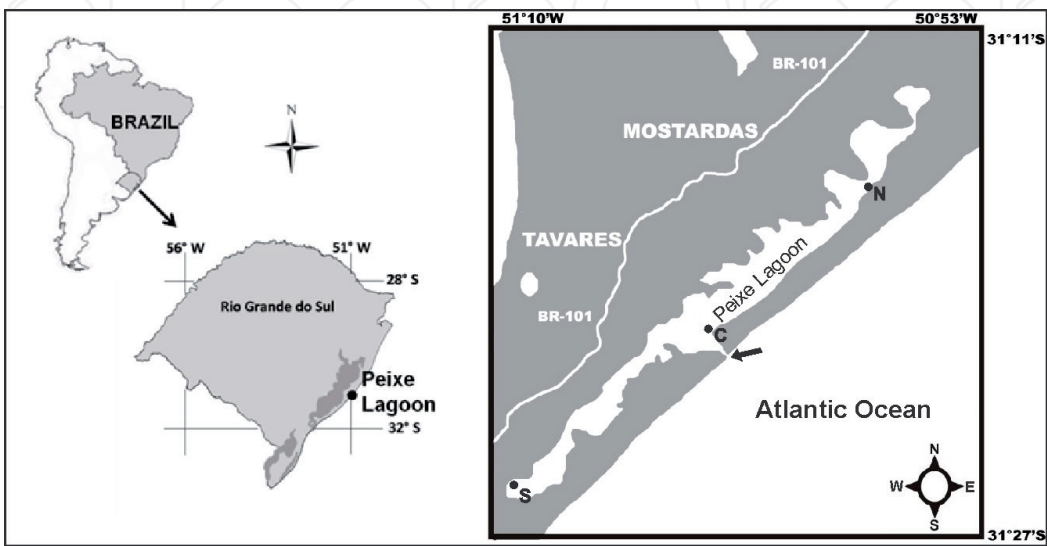


**Figure 1.**
*Location of Peixe Lagoon area in the state of Rio Grande do Sul, southern Brazil, the sampling stations (North = N, Center = C, South = S) and the channel of connection with ocean (arrow).*

**Figure 2.**
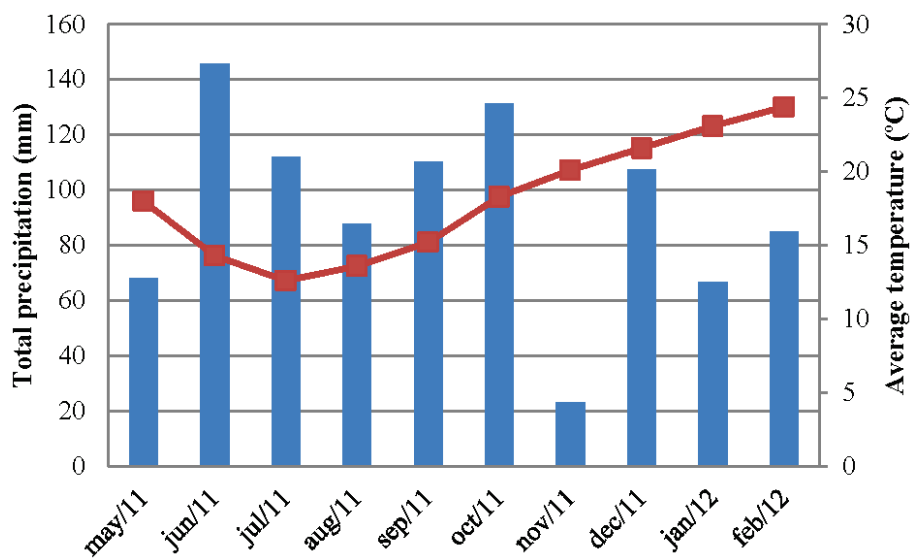*Aerial view of the Peixe Lagoon channel. Source: Lagoa do Peixe National Park (PNLP).*



**Figure 3.**
*Total precipitation (mm) and average monthly temperature (°C) recorded by the meteorological station of Mostardas/RS. Source: National Institute of Meteorology (INMET).*

## 3. Methods

### 3.1 Sampling

The study was based on samples collected at three sampling stations in the lagoon. North (**Figure 4**) is close to a narrow channel that interconnects the north-ernmost sealed bodies with a central portion of the lagoon; Center (**Figure 5**) is next to the channel that connects to the ocean; and South (**Figure 6**) is at the south end of the lagoon. Sampling occurred in the four seasons, fall (June 2011), winter (August 2011), spring (November 2011), and summer (February 2012). During the first sampling, in the fall, the channel was closed. It was open days before winter sam-pling and remained open for the remainder of the sampling period. For the diatoms analysis, sediment samples were collected at depths of 2 cm with a spatula, at the lagoon margin, and packed in glass pods for transport to the laboratory.

### 3.2 Abiotic variable

Conductivity (mS.cm$^{-1}$), salinity, pH, water temperature (°C), dissolved oxygen—DO (mg.L$^{-1}$), and oxidation-reduction potential—ORP (mg.L$^{-1}$) were

**Figure 4.**
*Sampling station: North.*



**Figure 5.**
*Sampling station: Center.*



**Figure 6.**
*Sampling station: South.*

measured with a HORIBA U52 probe. Depth and water transparency (cm) were measured with a Secchi disk. Precipitation, wind velocity, and wind direction data were obtained from the National Institute of Meteorology—INMET.

Laboratory analyses were performed as follows: total phosphorus—TP (mg.L$^{-1}$) by absorptiometry reduction of ascorbic acid, total nitrogen—TN (mg.L$^{-1}$), according to the Kjeldahl method (NBR 10560-1988, 13796-1997), and total silicate (mg.L$^{-1}$) with the silicomolybdate method [52]. The classification of salinity was based on the Venice System [53]. Trophic level was determined by the modified system of Vollenweider [54].

### 3.3 Diatom analysis

The sediment samples (1g) were dried in an oven and cleaned with potassium permanganate and hydrochloric acid according to the Simonsen technique [55]. For light microscopy (LM) analyzed, a Zeiss Axioplan Microscope (Carl Zeiss, Oberkochen, Germany) was used. The relative abundance of the taxa was carried out in slides seeking the minimum sample efficiency of 80% [56]. Species richness was estimated by the number of taxa present in the samples. The specific diversity was assessed using Shannon index (H′) [57] and Evenness equitability (E). The analysis of variance (ANOVA) was applied to test the significance among the community attributes, since the data presented a normal distribution. The PAST® software was used for these analyzes. The relationship between biotic and abiotic variables with canonical correspondence analysis (CCA), PC-ORD® version 6.08 was used. For the construction of the biotic matrix, only species with a frequency equal to or >5% were considered in at least one sample unit and for the abiotic matrix, 10 environmental variables were included (**Table 1**). The data were transformed into $log10(x + 1)$ in order to normalize the variances [58]. The Monte Carlo permutation test was carried out to verify the significance of the ordination axes.

| | Fall | | | Winter | | | Spring | | | Summer | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | C | S | N | C | S | N | C | S | N | C | S |
| Depth | 65 | 35 | 25 | 90 | 20 | 40 | 80 | 30 | 30 | 50 | 25 | 42 |
| Secchi | 65 | 35 | 25 | 30 | 20 | 40 | 60 | 25 | 30 | 50 | 25 | 42 |
| Temp | 15.3 | 17.2 | 17.6 | 17.0 | 17.6 | 17.4 | 28.3 | 26.1 | 29.3 | 29.8 | 32.1 | 31.9 |
| pH | 7.9 | 7.9 | 8.4 | 7.6 | 8.0 | 7.7 | 7.9 | 8.2 | 8.8 | 8.1 | 8.3 | 8.2 |
| ORP | 275 | 282 | 263 | 290 | 291 | 283 | 235 | 205 | 202 | 214 | 198 | 214 |
| DO | 10.1 | 10.3 | 12.3 | 12.3 | 11.3 | 12.5 | 10.7 | 9.8 | 9.3 | 7.5 | 9.0 | 9.4 |
| Salin | 31.2 | 28.3 | 10.8 | 4.5 | 17.0 | 1.3 | 7.1 | 36.2 | 10.9 | 34.9 | 36.0 | 29.5 |
| Cond | 32.2 | 30.4 | 12.1 | 8.1 | 27.8 | 2.5 | 12.4 | 34.6 | 18.5 | 52.9 | 54.6 | 45.5 |
| Sil | 3.8 | 1.7 | 1.1 | 17.0 | 18.0 | 17.4 | 1.0 | 2.7 | 6.6 | 7.8 | 0.0 | 9.1 |
| PT | 0.03 | 0.07 | 0.08 | 0.15 | 0.12 | 0.06 | 0.08 | 0.13 | 0.07 | 0.07 | 0.05 | 0.06 |
| NT | 0.61 | 0.16 | 0.43 | 0.87 | 0.68 | 0.90 | 0.01 | 0.09 | 0.02 | 0.55 | 0.65 | 0.60 |

**Table 1.**
*Physical and chemical variables analyzed in Peixe Lagoon in the four seasons, from June 2011 to February 2012, in the North (N), Center (C), and South (S) sampling stations. Depth (cm); Secchi = Secchi transparency (cm); temp = temperature (°C); ORP = oxide-reduction potential (mV); cond = conductivity (mS.cm⁻¹);* $DO$ *= dissolved oxygen, salin = salinity (ppt); sil = silica* $(mg.L^{-1})$*; PT = total phosphorus* $(mg.L^{-1})$*; NT = total nitrogen* $(mg.L^{-1})$*.*

## 4. Environmental conditions

The lagoon has a mean depth (<60 cm) and the Secchi disk depth generally coincides with the total depth. The water temperature varies between 15.3 and 17.6°C in the colder seasons (fall and winter) and from 26.1 to 32.1°C in the hottest seasons (spring and summer). The pH varies from 7.6 to 8.8 and the oxidation-reduction potential as well as the dissolved oxygen present similar trends, with higher values in the cold seasons and lower in the hot seasons (**Table 1**).

In relation to nutrients, total phosphorus varies between 0.03 and 0.08 mg.L⁻¹ in fall and summer at 0.12–0.15 mg.L⁻¹ in winter and spring, from eutrophic to hypereutrophic conditions. Total nitrogen presented higher values (0.68–0.90 mg.L⁻¹) in winter (mesoeutrophic conditions), with a decline in spring (0.01–0.09 mg.L⁻¹) and elevation in the summer (0.55–0.65 mg.L⁻¹), changing to mesotrophic conditions. Silica concentrations are higher in winter sampling (mean of 17.5 mg.L⁻¹). When the

channel of connection with ocean was open, the total nitrogen concentrations at all stations elevated as well as the total phosphorus in the north and center in winter. This may have been due to the water runoff from the land around the lagoon, used for livestock (**Table 1**).

The salinity demonstrated outstanding spatial and seasonal variations. These variations were mainly related to the meteorological conditions. Spatially, the salinity varies between 1.3% in the South station in the winter (oligohaline zone) and 36.2% in the Center during the summer (euhaline zone). The station with the highest salinity variation is the North (4.5% min./winter and 34.9% max./summer), followed by the South station (1.3% min./winter and 29.5% max./summer). The Center station maintained higher values of salinity in all the climatic seasons due to its proximity with the ocean. Seasonally, salinity has the highest values in summer and the lowest in winter. These low values can be attributed to the action of the wind, predominantly northeast, that propelled the waters from the Ruivo Lake which are less saline, to the Peixe Lagoon [33]. In the summer, the decrease of the precipitation and intensity of the wind causes the outstanding increase of the salinity. This dynamic was also observed in the system from 1991 to 1996 [50]. The South station of the lagoon presents less marine influence, therefore, lower salinity.

The variation of water levels of the lagoon is also strongly controlled by the winds regime, both intensity and direction, as well as precipitation. In the periods of predominant south wind (fall) and low precipitation (spring), the lowest levels of depth were observed. The Center is located next to the connection channel with the ocean and has a low average depth (30 cm). It is constantly saline (poly to euhaline zone). Due to the predominant northeasterly winds for most of the year, the water body of the lagoon is pushed to the west bank. The variation of the intensity of the winds can vary in the periods of day and night, causing great extensions of marginal sediment to be exposed and to be submerged again in a matter of hours [50].

The wind velocity during the period of studies had the lowest averages in the fall. It intensified in the following months of winter, with a peak in August
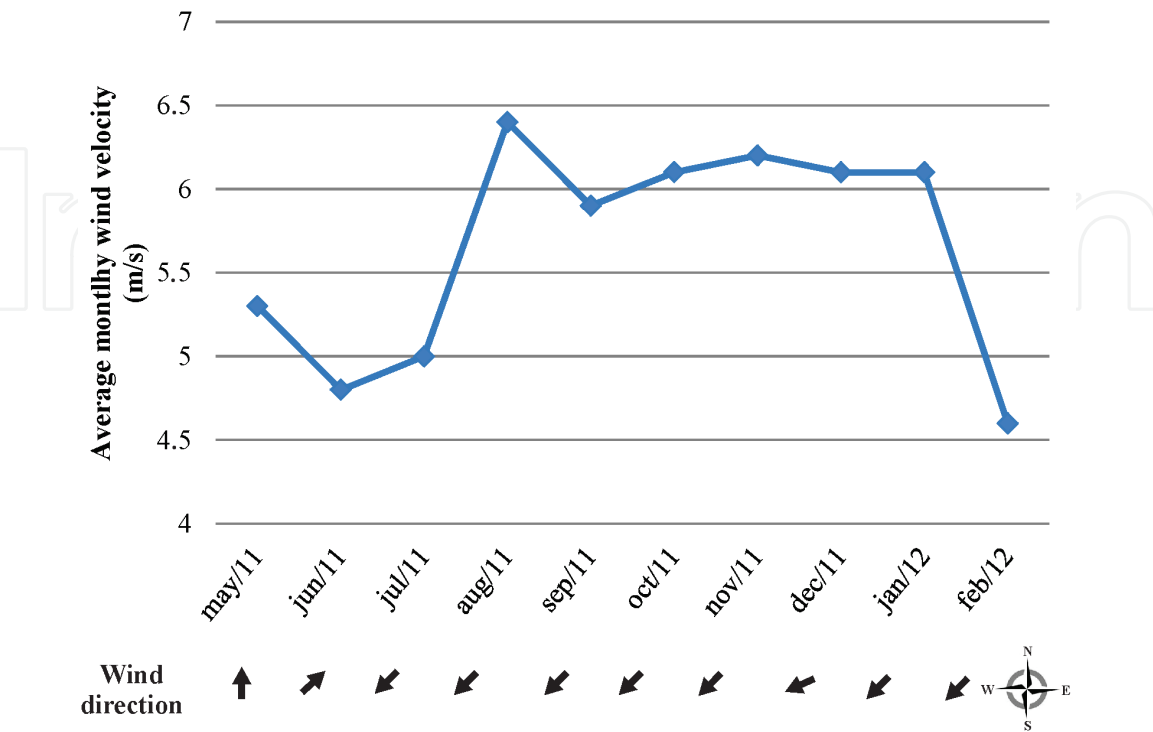


**Figure 7.**
*Average monthly wind velocity (m/s) and predominant monthly wind direction (arrows indicate direction). Data recorded by the Meteorological Station of Mostardas/RS. Source: INMET.*

(6.4 m/s). A sharp decrease occurred in February 2012 (4.6 m/s). The predominant direction of the wind in the fall was south and southwest, shifting northeast in July and in the following months (**Figure** 7).

## 5. Benthic diatoms composition

The diatoms community in Peixe Lagoon is composed by 62 taxa distributed in 30 genera composed largely of marine, brackish, and few freshwater species (**Table 2**). Similar results were recorded in an area adjacent to this study [28], where a total of 73 predominantly benthic and brackish taxa were found.

The genera with the greatest number of taxa are *Amphora* Ehrenberg ex Kützing, *Nitzschia* Hassall, and *Diploneis* Ehrenberg ex Cleve. The freshwater species that probably tolerate the wide variation of salinity are *Amphora ectorii*, *Cocconeis neodiminuta*, *C. euglypta*, *Chamaepinnularia truncate*, *Diploneis aestuari*, *D. didyma*, *Nitzschia palea*, *N. scalpelliformis*, *N. frustulum*, *N. vitrea* var. *salinarum*, and *Planothidium delicatulum*. More than 50% of taxa are cosmopolitan, and the remaining are restricted to a large extent to South America. An aspect to be highlighted is

| | FALL | | | WINTER | | | SPRING | | | SUMMER | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TAXON | N | C | S | N | C | S | N | C | S | N | C | S |
| *Achnanthes curvirostrum* Brun | - | - | X | - | - | - | - | - | - | X | X | X |
| *A. intermedia* Kützing | - | X | - | - | - | - | X | - | - | - | - | - |
| *Amphora* aff. *baicalensis* Skvortzow & Meyer | - | X | - | - | - | - | X | - | - | - | - | - |
| *A. ectorii* Levkov | X | X | X | X | X | X | X | X | X | X | X | X |
| *A. maracaiboensis* Levkov | X | - | X | - | - | - | X | - | X | X | X | - |
| *A. fusca* Schmidt | X | - | - | X | - | - | X | - | - | X | X | - |
| *Amphora* sp.1 | - | - | - | - | - | - | X | - | - | - | - | - |
| *Amphora* sp. 2 | - | - | - | - | - | - | - | - | - | X | - | - |
| *Amphora* sp. 3 | - | - | X | - | - | - | - | - | - | - | - | - |
| *Caloneis permagna* (Bailey) Cleve | X | - | - | - | - | - | - | - | - | - | - | - |
| *Caloneis* sp.1 | - | - | - | - | - | - | - | - | - | X | - | - |
| *Campylosira cymbelliformis* (Schmidt) Grunow ex Van Heurck | - | X | - | - | X | - | - | - | - | - | - | - |
| *Catenulaadhaerens* (Mereschkowsky) Mereschkowsky | - | - | X | - | - | - | - | X | - | - | X | - |
| *Chamaepinnularia truncata* (König) Witk.,Lange-Bert. & Metz. | - | X | - | - | - | - | - | - | - | X | - | - |
| *Cocconeis euglypta* Ehrenberg | - | - | X | - | - | X | - | - | X | - | - | - |
| *C. sawensis* Al-Handal et Riaux-Gobin | - | X | - | - | X | - | - | - | - | - | - | - |
| *C.neodiminuta* Krammer | - | - | - | - | - | - | - | X | - | - | X | - |
| *Dimeregramma minus* (Gregory) Ralfs | - | - | - | - | - | - | - | X | - | - | X | - |
| *Diploneis aestuari* Hustedt | - | - | - | - | X | - | - | - | - | - | - | - |
| *D. didyma* (Ehrenberg) Cleve | X | - | X | X | X | - | - | X | - | - | X | - |
| *D. interrupta* var. *interrupta* (Kützing) Cleve | - | X | - | X | X | - | - | - | - | - | - | - |
| *D. litoralis* var. *clathrata* (Østrup) Cleve | - | - | - | - | X | - | X | - | - | - | X | - |
| *D. smithii* (Brébisson) Cleve | X | - | X | X | - | - | X | - | - | - | - | - |
| *Diploneis* sp. 1 | X | - | - | - | - | - | X | - | - | - | - | - |
| *Ehrenbergia granulosa* | X | - | - | X | - | - | - | - | - | - | X | - |
| *Fallacia florinae* (Moeller) Witkowski | - | X | X | - | - | X | X | - | X | - | - | X |
| *F. subforcipata* (Hustedt) Mann | X | - | - | X | X | - | X | X | - | X | X | - |
| *F. tenera* (Hustedt) Mann | - | - | - | X | - | - | - | - | - | - | - | - |
| *Fragilaria eichhornii* Witkowski & Lange-Bertalot | - | - | - | X | - | - | X | - | - | X | - | X |
| *Halamphora coffeaeformis* (Agardh) Kützing | - | - | - | - | - | - | - | - | - | X | X | X |
| *H. subholsatica* (Krammer) Levkov | - | - | - | - | X | - | - | - | - | - | - | - |
| *H. turgida* (Gregory) Levkov | X | X | X | - | - | X | - | - | - | - | X | - |
| *Halamphora* sp. 1 | - | - | X | - | - | - | - | - | - | - | X | - |
| *Luticola simplex* Metzeltin, Lange-Bertalot & García-Rodríguez | X | - | - | X | - | - | - | - | - | - | - | - |
| *Mastogloia braunii* Grunow | - | - | - | - | - | - | - | - | - | - | - | X |
| *M. pusilla* (Grunow) Cleve | - | - | X | X | - | - | - | - | - | - | - | - |
| *Navicula flagellifera* Hustedt | X | - | - | - | - | - | - | - | - | X | X | - |
| *N. juanitalinda* Metzeltin, Lange-Bertalot & García-Rodríguez | - | X | - | - | - | - | - | - | - | - | - | - |
| *N. phylleptosomaformis* Seddon et Witicowski | - | X | - | X | - | - | X | - | - | X | - | - |
| *Nitzschia dissipatoides* Archibald | X | - | - | - | - | - | - | - | - | - | - | - |
| *N. frustulum* (Kützing) Grunow | - | X | - | X | - | X | X | - | - | X | X | - |
| *N.palea* (Kützing) Smith | - | - | - | - | - | - | X | - | X | - | - | - |
| *N. scalpelliformis* Grunow | X | - | - | X | - | - | - | - | - | - | - | - |
| *N. spathulata* Brébisson ex W.Smith | - | - | - | - | - | - | - | - | - | - | - | X |
| *N. vitrea* var. *salinarum* (Grunow) Grunow | X | - | - | - | - | - | - | - | - | - | - | - |
| *Nitzschia* sp. 1 | X | - | - | - | - | - | - | - | - | - | - | - |
| *Opephora* aff. *mutabilis* (Grunow) Sabbe & Vyverman | - | - | X | - | - | - | X | X | - | X | X | - |
| *O. pacifica* (Grunow) Petit | - | - | - | - | - | - | - | X | - | - | X | - |
| *Paralia sulcata* (Ehrenberg) Cleve | X | - | - | X | - | - | - | - | - | X | - | - |
| *Petroneis marina* (Ralfs) Mann | - | - | - | - | - | - | - | X | - | X | X | - |
| *Placoneis elegantula* Metzeltin, Lange-Bertalot & García-Rodríguez | - | X | X | - | X | - | - | - | - | X | - | - |
| *Planothidium delicatulum* (Kützing) Round & Bukhtiyarova | - | - | X | - | - | - | X | X | - | - | - | - |
| *Pseudostaurosiropsis geocollegarumm* (Witkowski) Morales | - | - | - | X | - | - | X | - | - | - | X | - |
| *Rhopalodia musculus* (Kützing) Müller | - | - | - | - | X | - | - | - | - | - | - | - |
| *R. runrichiae* Krammer | X | - | - | X | - | - | - | - | - | - | - | - |
| *Seminavis eulensteinii* (Grunow) Danielidis, Ford & Kennett | - | - | - | X | - | - | - | - | - | - | - | - |
| *Seminavis pusilla* (Grunou) Cox & Reid | - | - | - | X | - | - | X | - | - | - | - | - |
| *S.strigosa* (Hustedt) Danielidis e Economou-Amilli | - | X | - | - | X | - | - | - | - | X | X | - |
| *Stauroforma* sp.2 | - | - | - | - | - | - | - | - | - | X | - | - |
| *Staurophora soodensis* (Krasske) L.Bahls | - | - | X | - | - | - | - | - | - | - | - | - |
| *Terpsinoë americana* (Bailey) Grunow | X | - | - | X | - | - | X | - | - | X | - | - |
| *Tryblionella hungarica* (Grunow) Frenguelli | - | - | - | - | - | X | - | - | - | - | - | - |
| RICHNESS | 18 | 12 | 22 | 16 | 11 | 9 | 18 | 10 | 8 | 23 | 17 | 7 |

**Table 2.**
*Distribution of the diatoms at the North—N, Center—C, and South—S in the four seasons of the year in Peixe Lagoon, from June 2011 to February 2012.*

the predominance of birraphid and monoraphid diatoms, which are organisms that have raphe. This structure is a selective characteristic of the epipelic species [59–63] because it promotes the movement of organisms in search for better light and humidity conditions, since it allows the secretion of polymeric substances produced by their cells.

## 6. Structure of the community *versus* environmental conditions

### 6.1 Spatial and temporal variation

The community attributes (richness, diversity, and evenness) showed a decreasing spatial gradient from the North to the South stations. The specific diversity ranged between 2.3 bits/ind. at North and 0.4 bits/ind. at South and the evenness varied between 74 and 20% at North and South stations.

Seasonally, in fall, without connection with the ocean, the community attributes presented the highest values. After the channel opening, the richness was similar in winter and spring, rising in the summer. The values of evenness and diversity increased from winter (0.6–1.7 bits/ind.) to summer (0.8–2.3 bits/ind.) (**Figure 8**). However, these attributes did not differ significantly between the seasons and the station sampling.

### 6.2 Diatoms composition related to environmental variables

The composition of the diatoms and the physical and chemical variables of the water in the canonical correspondence analysis (**Figure 9**) of the abundant species (25 species with more than 5% abundance) can better demonstrate the community dynamics in the system.

The sampling units of the South station are grouped on the negative side of axis 1. They were related to the lower values of conductivity and salinity. The species associated with this axis were *Cocconeis sawensis*, *Fragilaria eichhornii*, *Cocconeis euglypta*, *Fallacia florinae*, and *Halamphora coffeaeformis*. In this axis, it is also possible to observe the separation of the sampling units from the North, mainly due to the difference in temperature between hot and cold seasons, in fall and winter months. The related species were *Nitzschia scalpelliformis*, *Luticola simplex*, *Ehrenbergia granulosa*, *Rhopalodia runrichiae*, *Diploneis smithii*, and *D. didyma*. The sampling units of the Center station are grouped on the positive side of axis 2, where higher values of salinity and temperature were observed in the hotter seasons, as well as the lower values of silica and ORP. The species *Opephora pacifica*, *Catenula adhaerens*, and *Opephora* aff. *mutabilis* were related to this axis (**Figure 10**).

During the study, we observed periods with higher and lower marine influence, due to the opening of the channel. In fall, the only season in which the channel was closed, the composition of diatom species was distinct in the north and south of the lagoon. The south and south-west quadrant wind might also have been an influence factor for the distinction of community composition.

After the channel opening, it is possible to observe the difference in the composition of the community at the southern portion in relation to the north and center portions of the lagoon. The species highlighted in the south (*Cocconeis sawensis*, *C. euglypta*, *Fallacia florinae*, and *Halamphora coffeaeformis*) are found in brackish and marine waters, with the exception of *C. euglypta*, a characteristic species of freshwater, but it supports high conductivity water [64]. So, the marine influence appeared as one of the main factors affecting spatial diatom composition and spatial distribution in the lagoon.
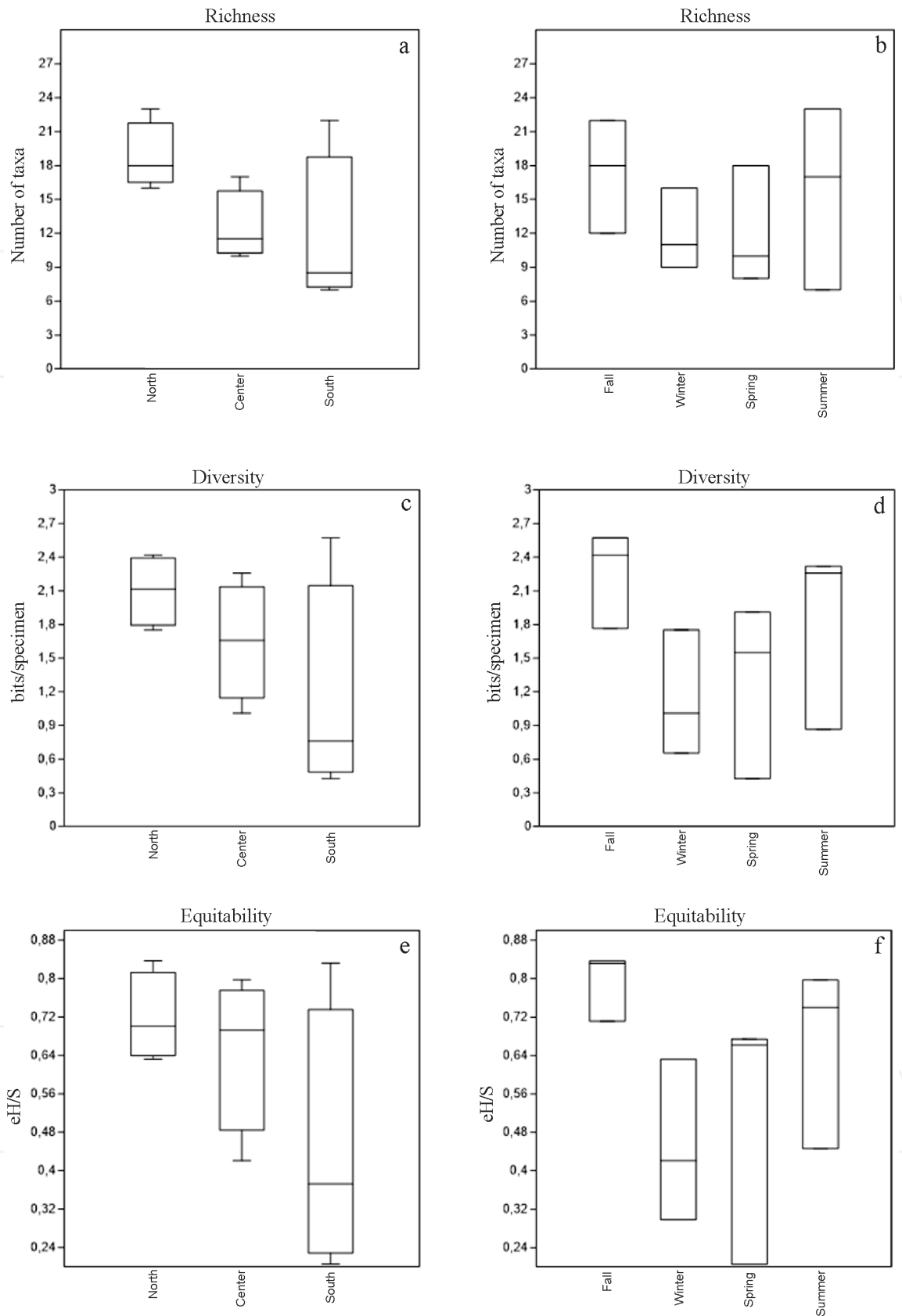
**Figure 8.**
*(a–f) Distribution of community attributes related to sampling stations and the seasons of the year in Peixe Lagoon from June 2011 to February 2012.*

However, the salinity cannot be considered as the only driving force that determines the composition of diatom species in environments with marine influence in subtropical and temperate regions. Temperature is also considered a very important environmental factor [11]. In Peixe Lagoon, the temperature difference between hot seasons (spring and summer) and cold seasons (fall and winter) also differentiated
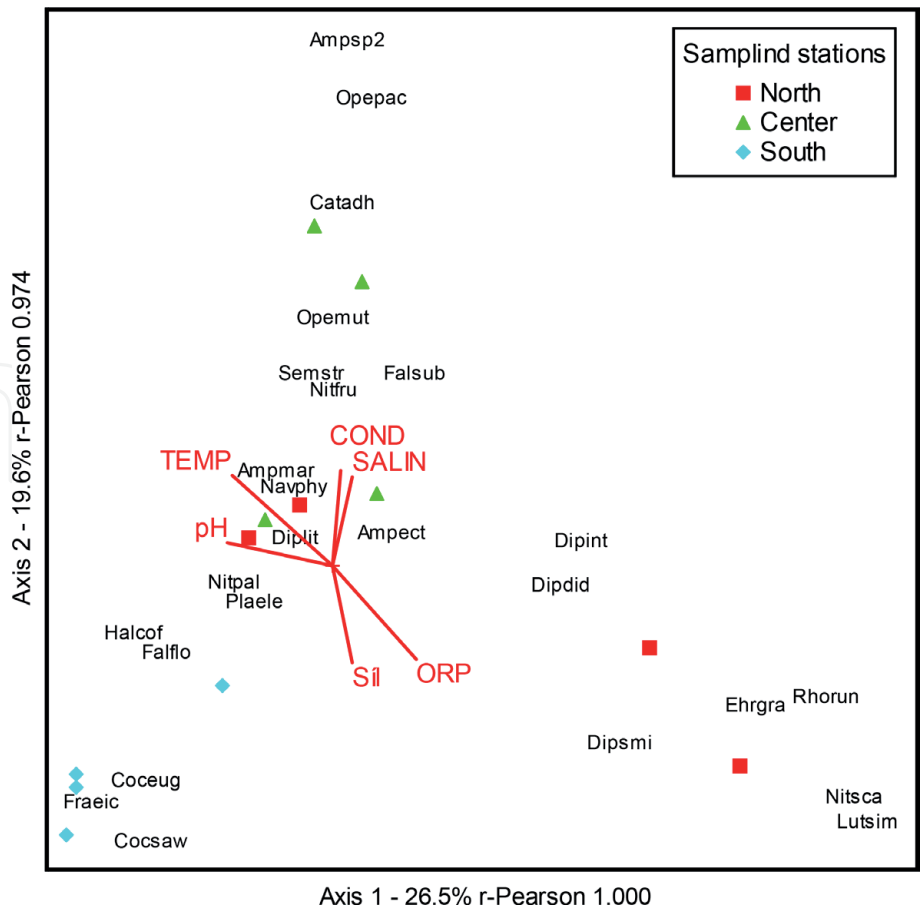
**Figure 9.**
*Canonical correspondence analysis (CCA) of the abundant species in the sampling stations and seasons fall, winter, spring, summer in Peixe Lagoon. For legends of the variables, see **Table 2**. Amphora ectorii (Ampect), A. maracaiboensis (Ampmar), Amphora sp.2 (Ampsp2), Catenula adhaerens (Catadh), Cocconeis euglypta (Coceug), C. sawensis (Cocsaw), Diploneis didyma (Dipdid), D. interrupta (Dipint), D. litoralis (Diplit), D. smithii (Dipsmi), Ehrenbergia granulosa (Ehrgra), Fallacia florinae (Falflo), F. subforcipata (Falsub), Halamphora coffeaeformis (Halcof), Luticula simplex (Lutsim), Navicula phylleptosomaformis (Navphy), Nitzschia frustulum (Nitfru), N. palea (Nitpal), N. scalpelliformis (Nitsca), Opephora aff. mutabilis (Opemut), O. pacifica (Opepac), Placoneis elegantula (Plaele), Rhopalodia runrichiae (Rhorun), Seminavis strigosa (Semstr), Fragilaria eichhornii (Fraeic).*

the composition of the species. *Diploneis interrupta*, *D. didyma*, *D. smithii*, *N. scalpelliformis*, and *Luticola simplex* were related to the colder seasons. This was also observed for species of *Diploneis* in the sediment of sublittoral zone of the Gulf of Trieste [65]. *Catenula adhaerens*, *Nitzschia frustulum*, *Opephora aff. mutabilis*, *O. pacifica*, and *Seminavis strigosa* were related to the sampling units with higher temperatures and salinities.

## 6.3 Diatoms related to sediment

Another important factor regarding diatom distribution is the sediment characteristic [66, 67]. In the Center and South stations, the surface of the Peixe Lagoon is essentially covered by sandy sediments, in which we find *Campylosira cymbelliformis*, *Catenula adhaerens*, *Dimeregramma minus*, and *Staurophora soodensis* species usually associated with sand grains.

In deeper sites of the lagoon, such as near the North, the sediments are thinner, with addition of silt and clay [49]. In this station, where muddy sand is present, we observed more clearly the seasonal variation of the diatom community. This site also showed highest diversity (1.7–2.4 bits/ind.) and richness (16–26 táxons) and the presence of more exclusive epipelic species; among these are the following: *Caloneis permagna*, *Luticola simplex*, *Nitzschia dissipatoides*, *N. scapelliformis*,
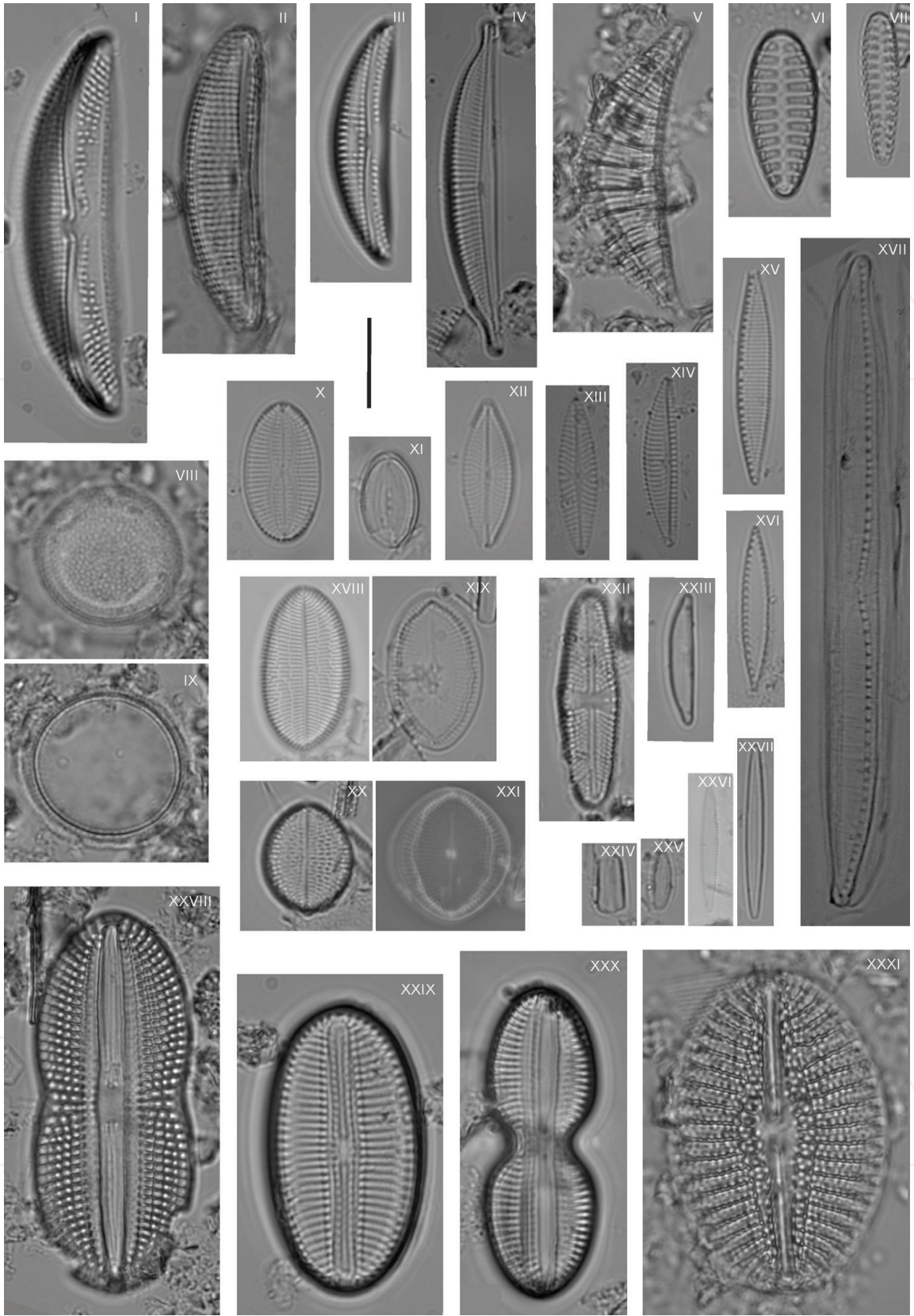
**Figure 10.**
*I. A. maracaiboensis. II. Amphora sp. 2. III. A. ectorii. IV. Halamphora coffeaeformis. V. Rhopalodia runrichiae. VI. Opephora pacifica. VII. O. aff. mutabilis. VIII,IX. Erhembergia granulosa. X. Fallacia subforcipata. XI. F. florinae. XII. Placoneis elegantula. XIII. Navicula phylleptosomaformis. XIV. Seminavis strigosa. XV. Nitzschia frustulum. XVI. N. palea. XVII. N. scalpelliformis. XVIII,XIX. Cocconeis euglypta. XX,XXI. C. sawensis. XXII. Luticola simplex. XXIII. Catenula adhaerens. XXIV-XXVII. Fragilaria eichhornii. XXVIII. Diploneis didyma. XXIX. D. litoralis var. clathrata. XXX. D. interrupta. XXXI. D. smithii. Scale bar = 10 µm.*

*N. vitrea* var. *salinarum*, *Rhopalodia runrichiae*, and *Terpsinöe americana* (**Table 2**). In agreement with other studies, the epipsammic fraction appeared to be much more stable than epipelic assemblage [9, 67].

## 7. Sediment and water interaction

We expected to find planktonic forms in the sediment due to the low depth of the lagoon and because of the fact that the sediment usually integrates planktonic and periphytic taxa [3]. The absence of planktonic forms could be explained by the hydrographic processes that tend to transport nonliving, unattached forms out of the system, similar to estuaries [67]. Furthermore, the location of the sampling stations, since the material was collected on the lagoon margin, was outside the water surface. However, it is known that in periods with decreasing wind intensity, water tend to return flooding areas that had been exposed [50]. A few planktonic species in the sediment were also recorded in a study of microphytobenthos in the Gulf of Trieste, Europe, although the collections were made in submerged sediment [65].

Comparing with an earlier study about phytoplankton at Peixe Lagoon, with sampling performed during the same period, *Asterionellopsis glacialis* (Castracane) Round, *Chaetoceros gracillis* Pantocsek, and *Skeletonema potamos* (Weber) Hasle were found in abundance in plankton samples. In this study, however, these species were not found in the sediment; whereas *Diploneis didyma*, a highlighted species found in benthos, was also present in the plankton. The species *Cocconeis sawensis* was recorded at the southern benthos of the lagoon, and it was also observed in the plankton and epiphyton in association with the macroalgae *Cladophora* sp. in the fall and winter seasons [33, 46]. This suggests that in shallow environments, the plankton receives a greater contribution of benthic species than the opposite. Similar results were found in shallow estuarine zone of Patos Lagoon [19].

Estuary and shallow coastal waters develop the process of resuspension whereby sediment particles with diatoms enter the water column. Examination of diatoms in the water revealed that 75% of frustules belonged to pennate forms and we concluded that flooding tides were responsible for a net transport of epipelic diatoms from the mudflat to a salt marsh. The resuspension of the diatoms can be the source of the chl *a* peak in the plankton [68]. So, this organism may greatly augment the primary production in water [69, 70]. Other investigations have showed large number of benthic diatoms in the water column [71, 72]. The wind, flooding tides, and tidal inducing waves and currents are the causes of this process.

## 8. Conclusions

In the Peixe Lagoon, the benthic diatoms were present in high diversity. Among the attributes of the community, the taxonomic composition best responded to the environmental variables. The quantitative attributes did not show significant relationships. The connection with the ocean, salinity, rainfall, wind action, and temperature were strongly related to the spatial and seasonal variation of the composition of the diatom community in this lagoon system. These organisms substantiate their use as indicators of environmental variations, mainly regarding salinity and temperature in subtropical coastal systems.

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