ABIOTIC DIEL CYCLES AND PROFILES IN A BED OF SUBMERGED PLANTS IN THE COASTAL LAGUNA DE ROCHA (SW ATLANTIC)

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ABSTRACT

We determined the diel changes of abiotic profiles in the vegetated limnic littoral zone of the coastal Laguna de Rocha during summer days. Measurements were done in three sampling stations 40-55 cm deep every 2-3 hours and 5-10 cm. Submersed plants covered 100% of the sampling area and reached the surface of the water. Plant biomass was dominated by *Eleocharis* aff. *nana* (58%), *Myriophyllum quitense* (16%) and *Nitella* sp. (14%). *Potamogeton pectinatus* L., *Zannichellia palustris* L. and *Chara* sp. each represented less than 5% of total biomass. An evident diel cycle was observed for dissolved oxygen (1-12 mg L^{-1}) and pH (6.5-8.0), which was probably induced by plant respiration and photosynthesis. Conversely, temperature (25-30 ºC) and conductivity (3.2 - 11.7 mS cm^{-1}) showed some stratification favored by the presence of submerged vegetation, which impeded the circulation of water. The three sampling stations generally showed similar abiotic patterns despite their different plant composition and biomass. A short-term inverse stratification was produced by surface nocturnal cooling, where saline sea water lay below the river's freshwater. We discuss the importance and variability of littoral processes in coastal lagoons both in time and depth, and their implications for the knowledge of coastal lagoons.

Key words: Abiotic factors; Aquatic plants; Shallow water; Vertical profiles; Uruguay

RESUMO

Ciclos diários e perfis abióticos num leito de vegetação sumersa da lagoa costeira de Rocha (SW Atlântico)

As variações diárias dos perfis abióticos no litoral límnico e vegetado da lagoa costeira de Rocha foram determinadas em dias do verão. As medições foram feitas em três estações de amostragem (profundidade 40-55 cm) em intervalos de 2-3 horas e a cada 5-10 cm de profundidade. As plantas ocuparam o 100% da área de amostragem e atingiram a superfície da agua. A biomassa foi dominada pela *Eleocharis* aff. *nana* (58%), *Myriophyllum quitense* (16%) e *Nitella* sp. (14%). *Potamogeton pectinatus* L., *Zannichellia palustris* L. e *Chara* sp. representaram cada uma menos do 5% da biomassa total. Um ciclo diário foi observado para o oxigênio dissolvido (1-12 mg L-1) e pH (6.5-8.0), provavelmente induzido pela respiração e fotossíntese das plantas. A temperatura (25-30 ºC) e a condutividade (3.2 - 11.7 mS cm^{-1}) apresentaram uma estratificação favorecida pela vegetação submersa, que impedia a circulação da agua. As três estações de amostragem em geral mostraram padrões abióticos similares apesar se apresentarem uma diferente composição e biomassa de plantas. Uma estratificação inversa foi produzida pelo esfriamento superficial durante a noite, ao mesmo tempo que a água salgada do mar fica embaixo da água doce dos rios. Nos discutimos a importância e a variabilidade dos processos litorais nas lagoas costeiras, e suas implicações para o conhecimento destes ecossistemas.

PALAVRAS CHAVE: Fatores abióticos; Plantas aquáticas; Agua rasa; Perfis verticais; Uruguai

INTRODUCTION

Despite the importance of the littoral zone in determining the ecology of coastal lagoons, our knowledge is usually based on samples from one or a few usually deep central stations. Littoral shallowness influences the water environment through the influence of the sediment-water interface on the whole water column (Scheffer 1998), and also through the reduction of the water mass and consequently its heat content.

Furthermore, a high variation of water parameters occurs in inland waters on a diel cycle driven by solar radiation. Indeed, water in vegetated littoral zones responds rapidly to solar radiation and air temperature diel fluctuation. However, sampling strategies commonly neglect such variation, producing results that may be biased by the hour of sampling.

Although it is well recognized that vegetation radically alters the functioning of shallow lakes (Scheffer 1998, Hansen *et al.* 2000, Parker *et al.* 2001), little attention has been paid to its effects on the profile of abiotic parameters other than light and turbidity. Even when it is recognized that plants reduce sediment resuspension by reducing vertical mixing and fixing the sediment, their associated impacts on stratification are usually neglected.

Submerged plants impede water circulation and mixing (Dale & Gillespie 1977), promoting the development of local thermal structures. Furthermore, plants rapidly attenuate light (Sand-Jensen 1989) and respond themselves to changes in solar radiation by changing their photosynthetic rate, which in turn modifies the oxygen content and pH of the surrounding water.

Our aim is to illustrate the importance of diel changes of vertical structures in the shallow vegetated littoral zone of a, subtropical shallow (<1 m) coastal lagoon during summer days. If considerable changes occur the littoral abiotic profiles should not be neglected. It is not our intention to compare vegetated with unvegetated water, as this is done elsewhere

(Arocena 2007). In this paper we describe the variation of water temperature, conductivity, dissolved oxygen and pH on small scales of time (diel cycle) and depth (vertical profile at 5-10 cm resolution).

MATERIALS AND METHODS

Laguna de Rocha (34º 33´S, 54º 15´W) belongs to a chain of coastal lagoons along the southwestern Atlantic in Uruguay and Brazil. It is intermittently connected to the Atlantic Ocean, so that it has marine characteristics at the south end and freshwater characteristics at the north end, where sampling stations were placed for this study (Fig. 1). At times, strong winds from the south can move saline waters towards the northern end of the lagoon and establish a salinity gradient. Further information about this 72 km^2 lagoon can be found in Sommaruga and Conde (1990), Pintos *et al.* (1991), Conde *et al.* (1999) and Bonilla *et al.* (2005).

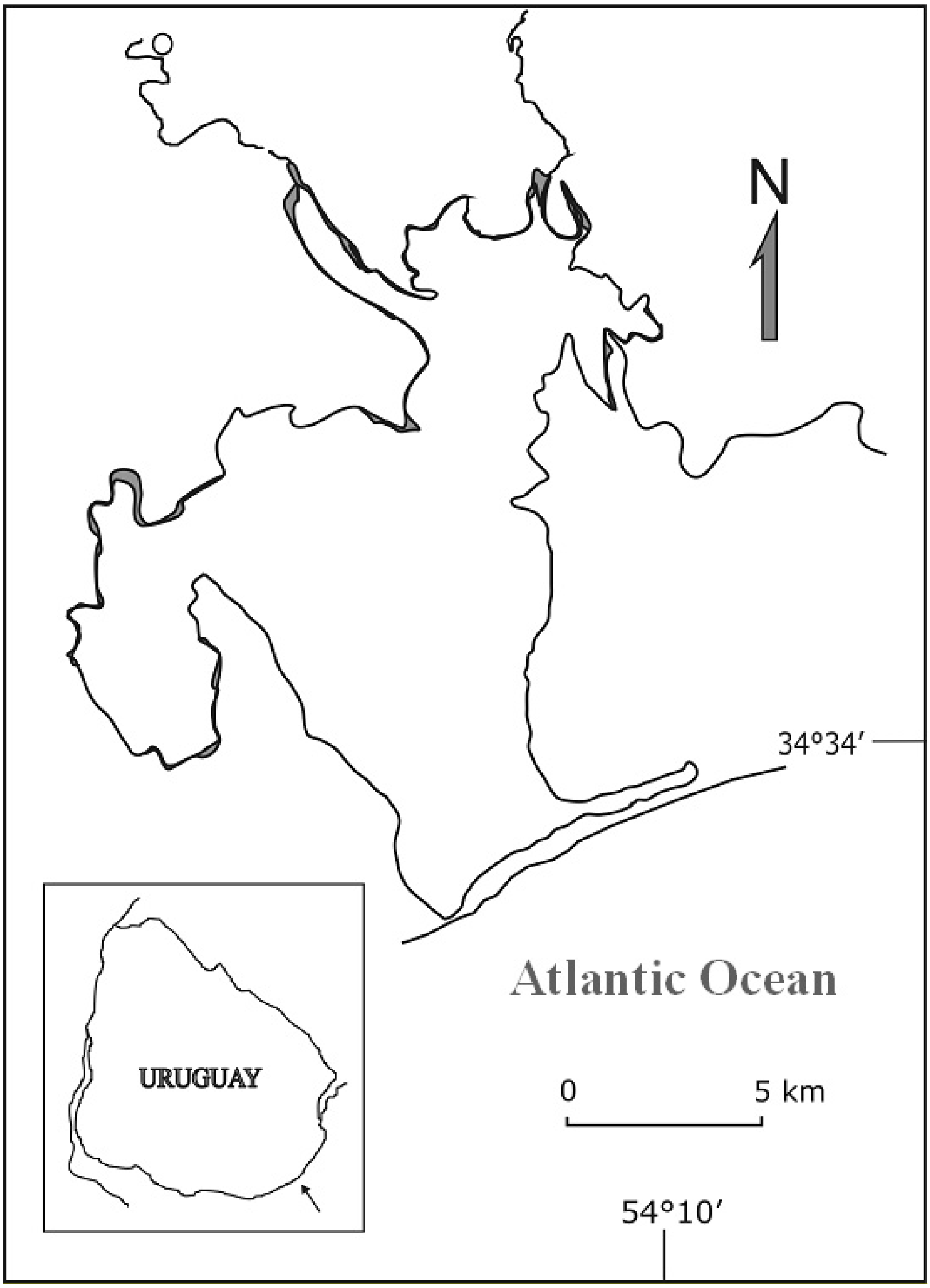

Figure 1. Location of Laguna de Rocha in Uruguay and the study area (circle with cross) in the North coast of the Lagoon.

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We sampled in a vegetated area of slow-moving water near the north shore of Laguna de Rocha on 22 and 23 February 2001. At that time, the coastal bar was closed and the lagoon was unconnected to the ocean. Water temperature and dissolved oxygen (DO, Horiba D25), and conductivity and pH (Horiba D24) were measured every 2-3 hours and every 5-10 cm in depth at three replicate stations. The probes where tightly attached to the end of a graduated vertical rod, which was gently submerged to avoid disturbance of the water. The stations were randomly selected within a 150 x 200 m grid.

This study was conducted only in the vegetated zone in accordance with our objectives, because the behavior of continuous mixing at the open shallow water in coastal lagoons is already well known, even in Laguna de Rocha (Pintos *et al.* 1991; Conde *et al.* 1999 and Bonilla *et al.* 2005). Nevertheless, results from measurements taken inside and outside this vegetated area during previous studies (Arocena 2000 and 2007 and Arocena & Prat 2006) are also discussed here.

Submersed plants were collected for taxonomic and biomass (dry weight) determinations, with an Ekman dredge (506 cm^2) in the same points after all the water measurements were completed. Because macrophytes were sparse and the littoral zone was shallow, grab samples adequately collected all macrophytes. Plants were repeatedly flushed with water over a sieve and then dried at 80 ºC for 48 h for dry weight determinations (Mazzeo 1999). Meteorological data of wind and air temperature were obtained from official records in the nearest meteorological station (10 km NW of the study site) for the sampling date.

Variation of water parameters in time and depth was tested by means of 2-way analysis of variance (ANOVA). Simple ANOVA was also run for variation each time, with stations considered as replicates. Since the test is robust enough, we did not transform the data nor use non-parametric statistics. Parametric correlations were also performed among all variables for every depth (n=10-11 times), station (n=21-22 depth x times) and for the pool of data (n=65).

RESULTS

Submersed plants covered 100% of the sampling area and reached the surface of the water (Fig. 2). Six species of plants were found with a mean species richness of 4.3 (0.6 SD). Mean biomass was 152.9 (83.8 SD) g DW m-2 (Fig. 3). The dominant species were *Eleocharis* aff. *nana* (58% of biomass), *Myriophyllum quitense* Kunth (16%) (Rocha, Laguna de Rocha, Rodríguez & Arocena 2001, 4220 MVFQ) and *Nitella* sp. (14%), whereas *Potamogeton pectinatus* L., *Zannichellia palustris* L. and *Chara* sp. each represented less than 5% of total biomass. Only *P. pectinatus* and *M. quitense* were present at all 3 stations. Whereas *Nitella* largely dominated in station 1, *Eleocharis* dominated in station 2 and was co-dominant together with *Myriophyllum* in station 3.

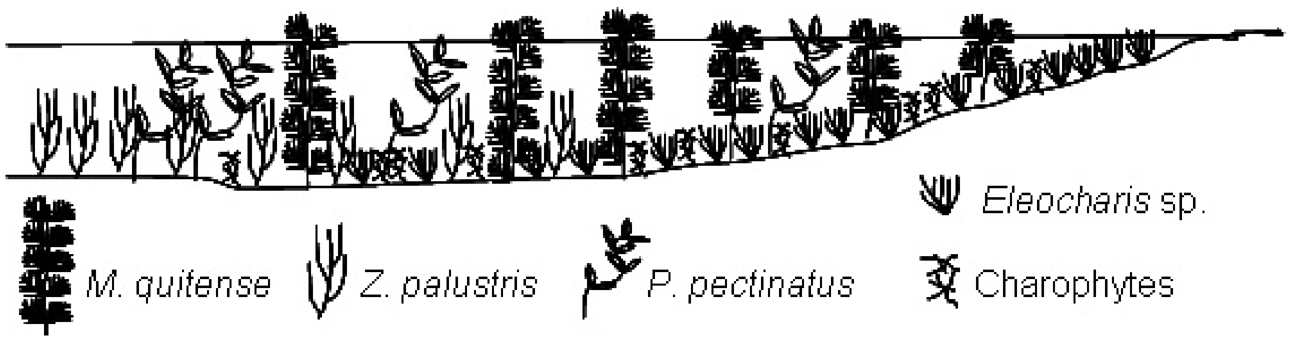

Figure 2. Spatial ditribution of the litoral submerged vegetation in Laguna de Rocha. *Chara* sp. and *Nitella* sp. were considered toghether as Charophytes.

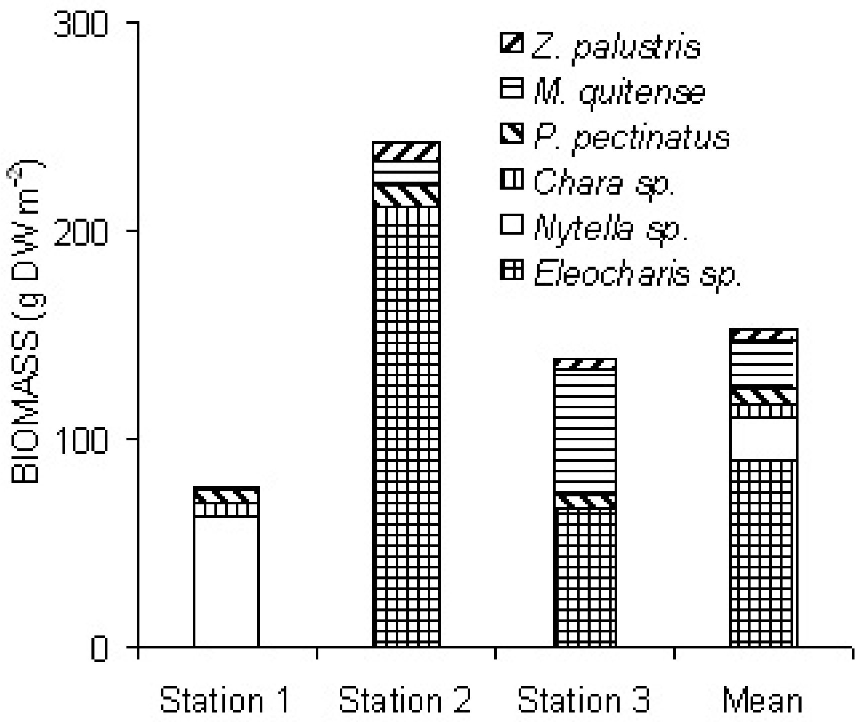

Figure 3. Macrophyte composition and biomass in the three stations and their mean values.

Wind fluctuated between 0 and 2 m s-1 at night and daytime, respectively. Air temperature ranged from 23.2 ºC at 6:00 to 32.4 ºC at noon. Water depth ranged between 40 and 55 cm at all sampling stations, but did not show any time pattern. Some representative data for water temperature (25-30 ºC), DO, conductivity and pH are shown in figure 5 for the 24 h of sampling. Water temperature followed the pattern of air temperature (Fig. 4) and showed a similar behavior at all stations. It was lower, more variable, and different among sites at 5 cm than at deeper sites (Fig. 5). Similar patterns of higher temperature at the bottom, mainly at night (Fig. 6), were seen at all stations ($F_{2, 3}$=7.2, $P<0.001$).

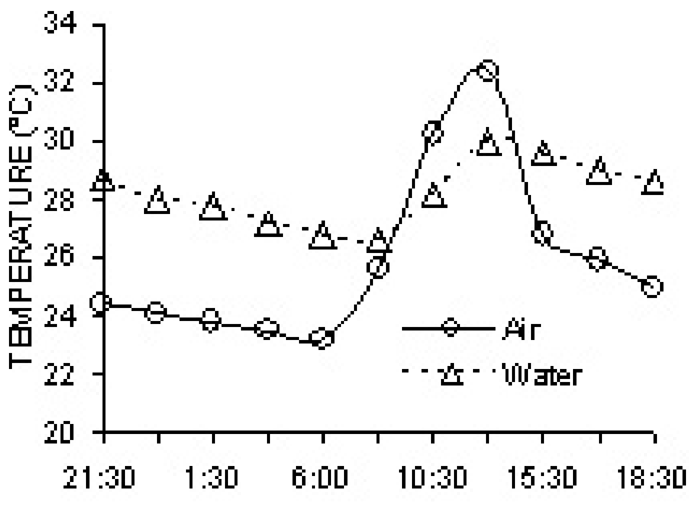

Figure 4. Air and water temperature (S1 at 10 cm depth) during the sampling period.

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An evident diel cycle was observed for DO, with a positive correlation with temperature (r=0.79, P<0.001). However, unlike temperature, DO did not fluctuate at the surface. DO concentration increased from 1 mg L-1 at 6:00 near the bottom to 12 mg L-1 at noon at the surface. It differed among stations during the night as much as 4 mg L-1 at 5 and 10 cm depth, but not at the bottom, where it was usually lower and more variable than in the upper layers. Nevertheless, a gradient was evident only in the early night and mainly at station 2. Oxygen profiles showed a progressive decrease with time (Fig. 5), although aerobic conditions were generally maintained throughout the diel cycle.

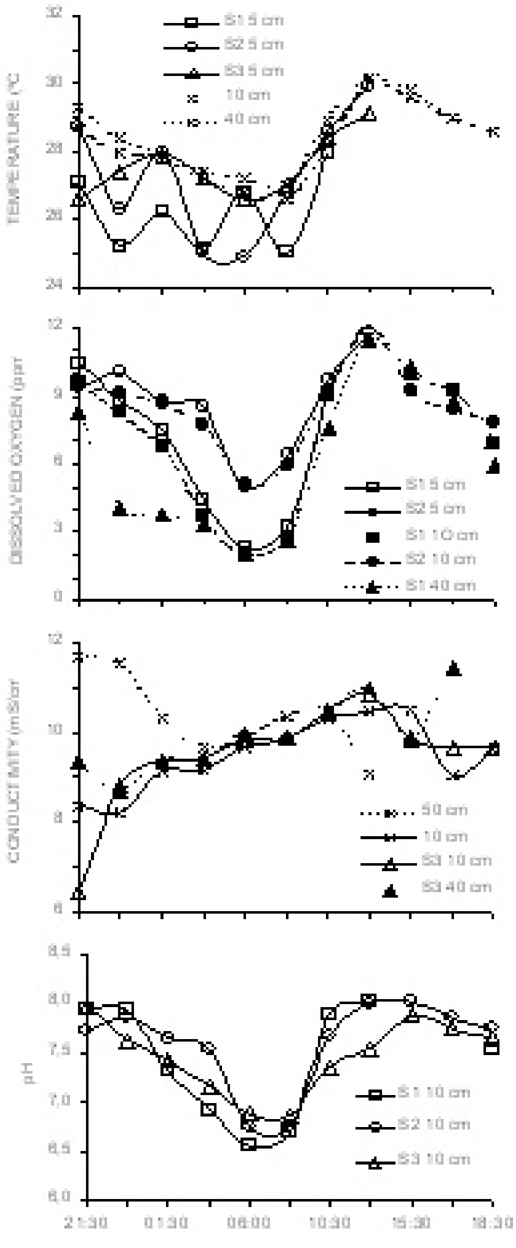

Figure 5. Diel cycle of water variables at selected stations (S1, S2, S3) and depths (cm) exhibiting extreme values. Where stations are not indicated, graphs represent all stations.

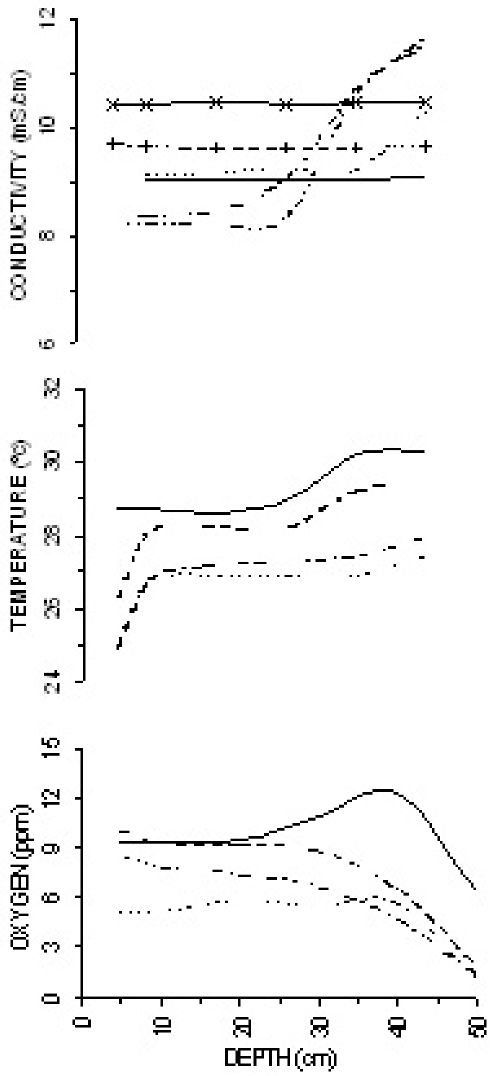

Figure 6. Profiles of temperature and oxygen at night, and 24 h conductivity at station 2. Similar patterns of higher temperature at the bottom at night were seen at all stations.

The oxygen saturation percentage followed the same pattern of variation as DO and was also similar to the temperature pattern. Despite some readings below 20% at the bottom, saturation ranged between 26% at sunrise and 163% at sunset.

Conductivity and pH were similar in the three sampling stations. At night, a clear saline stratification was observed (Fig. 5): conductivity fluctuated between 3.2 and 11.7 mS cm-1 at the surface and bottom respectively. Conductivity did not show differences among depths during daytime.

No significant differences in pH were found between the surface and the bottom except at station 2, but there were differences in time ($F_{2,10}$ = 37.19, $P<0.001$) following a diel cycle, with lower pH during the night. The pH decreased from about 8.0 to 6.5 during the night and then increased to 8.0 until noon. A slow decrease followed in the afternoon. As expected, pH was correlated with DO ($r=0.874$, $P< 0.001$) and with temperature ($r=0.842$, $P< 0.001$).

DISCUSSION

During the study period, the water level did not change as is usually observed in Laguna de Rocha, caused by strong diel fluctuations in wind speed that are mostly much higher than the 2 m s-1 registered here (Arocena *et al.* 2003). Such water level fluctuations should introduce an additional factor for variation of water parameters and for lake functioning in vegetated shallow areas (Coops *et al.* 2003) that were not observed on this occasion. Nevertheless, the calm conditions that prevailed during the sampling allowed for the analysis of stratification patterns of the water column in Laguna de Rocha.

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The most usual criterion of shallowness is that the water-body is 'nonthermal stratifying' or repeatedly mixed (Padisák & Reynolds 2003) or discontinuously polymictic (Lewis 1983). Shallowness permits fast changes in temperature and frequent mixing of the water column. Nevertheless, it also allows the settlement of macrophytes, which in turn may cause gradients of temperature, and sometimes conductivity, between surface and bottom waters, as in this study.

Vertical differences may be due to the presence of a dense bed of submerged macrophytes, composed of several species that reach different heights and have different biomass and metabolic rates in the water column. *Potamogeton pectinatus* and *M. quitense* are persistent rooted angiosperms with long and flexible submersed leaves, which concentrate most of their biomass under the water surface. *Eleocharis* sp. and Z. palustris have long rhizomes with sparse plants growing close to the bottom, while *Nitella* and *Char*a have dense rhizoids with patchy dense growth near the bottom.

We can expect a similar behavior of the water column at stations 2 and 3, both dominated mainly by the biggest angiosperms, and different from station 1 with the algae *Nitella*. The main difference between stations 2 and 3 is the higher biomass (170%) at the former. However, the three sampling stations generally showed similar abiotic patterns. Minor differences may be due to plant percent composition and density and time of sampling.

Inverse thermal stratification at station 2 may be due to: a) nocturnal cooling of surface layers prior to the deepest ones in water that is stagnant due to the submerged vegetation and low wind stress; and b) most likely, saline stratification that was observed at this site in the early night, that could also be favored by the macrophytes. For both possible causes it is relevant that station 2 had much more biomass of mainly *Eleocharis* than stations 1 and 3. This kind of short-term inverse stratification is common when surface nocturnal cooling produces a surface temperature minimum (Imberger 1985, Talling 2004).

Similar to temperature, oxygen and conductivity stratification, mainly at station 2, during the calm night may be due to the presence of a patch of plants that limits the water mixing. Saline masses of water coming from the sea are trapped in the lagoon where they lie below the freshwater coming from the rivers. Besides the oxygen decrease at the bottom due to its consumption by the sediment, other vertical variations may be due to photosynthetic and respiration differences among depth layers inside the dense bed of macrophytes.

Previous monthly measurements made in open waters from January to June 1995 (Arocena 2000, Arocena & Prat 2006) did not show differences between the surface and bottom for temperature (t=1.75, P=0.13, n=7), oxygen (t=1.04, P=0.34, n=7) nor conductivity (t=-1.14, P=0.34, n=4). Moreover, Bonilla *et al.* (2005) assert that between August 1996 and February 2000 the water column was always well oxygenated and permanently mixed. Nevertheless, temperature and oxygen from December 1998 and temperature measured in February and April 1999 showed a clear stratification in the vegetated area, whereas outside this area it was well mixed (Arocena 2007).

Respiration and photosynthesis processes induced pH changes up to 1.5 units together with oxygen changes. The daily cycle of the DO in the water column shows strong nighttime consumption. In general, the rate of photosynthesis is a function of time while the rate of respiration may be assumed as a constant (Odum 1956 in Liu 1982). Diurnal variation of photosynthetic oxygen production follows a similar pattern to incident solar radiation (Liu 1982) and therefore to temperature, which explains the correlation of temperature and DO. Although submerged plant productivity frequently exceeds respiratory losses, resulting in a daily oxygen surplus (Wetzel 2000), in these shallow systems diffusion to the atmosphere and sediment demand, represent other important oxygen sinks.

Although the effects of macrophytes on abiotic variables have been documented (Frodge *et al.* 1990, Viaroli *et al.* 1996, Plus *et al.* 2003, Peterson *et al.* 2004), they were not considered in Laguna de Rocha until now due to its apparently small vegetated area. The lagoon was considered to be continuously mixed throughout (Conde *et al.* 1999, Bonilla *et al.* 2005). Nevertheless, during the last few years, the expansion of macrophytes to new areas may have produced significant changes in this ecosystem.

The present study provides evidence of the partition of the water column facilitated by the presence of submerged plants. This stratification together with excessive biomass production and decomposition may have several effects in the ecosystem. It may for example reduce the concentration of DO at the bottom. This in turn may reduce the oxidized surficial sediments and thus facilitate the release of phosphorus and further related processes. Furthermore, the low DO concentrations would shift the community composition (Welch 1980, McCormick & Laing 2003). Consequently, it is necessary to understand the behavior of vegetated littoral zones as much as that of the central parts of the coastal lagoons.

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