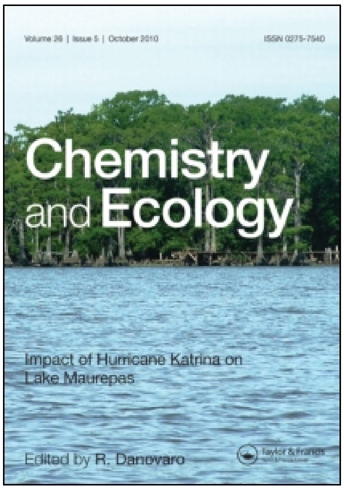

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RELATIONSHIPS BETWEEN NUTRIENTS AND MACROALGAL BIOMASS IN A BRAZILIAN COASTAL LAGOON: THE IMPACT OF A LOCK CONSTRUCTION

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The Piratininga Lagoon is a coastal, choked, and brackish ecosystem in SE Brazil, where uncontrolled discharge of domestic sewage led to eutrophication, increasing massive proliferation of benthic macroalgae, and decrease of the lagoon mean depth. In 1992, a dam was constructed by the local Municipality at its tidal channel aiming at stabilising its water level. Main physico-chemical parameters, together with macroalgae biomass, nutrient concentrations in the water column, particulate organic carbon, and chlorophyll *a* were recorded monthly at 4 sampling stations within the Piratininga lagoon from April 1994 to April 1995. The data, compared with "before-lock" existing studies, show that nutrients and chlorophyll *a* concentrations significantly increased after the lock construction. Based on the functioning of the ecosystem, we propose to harvest the algal mats before their decomposition period in order to partly remove the nutrient stocks from the lagoon and the future ecosystem modelling to predict the impact of natural and anthropogenic eutrophication.

Keywords: Coastal lagoon; Eutrophication; Nutrients; Algal biomass; Environmental impact

1 INTRODUCTION

Coastal lagoons provide nursery areas to many marine species, thereby supporting fisheries, and, becoming increasingly important tourism zones (Knoppers *et al.*, 1999; Lacerda and Gonçalves, 2001). They comprise about 13% of the world's coastline, varying considerably in shape, size, climate, hydrology, and trophic state, and are also efficient sediment and nutrient traps (Nixon, 1995; Windom *et al.*, 1999). Coastal lagoons often receive large anthropogenic inputs of nutrients, and their limited seawater exchange and circulation may lead to system eutrophication (Herbert, 1999; Kjerfve, 1986; Knoppers, 1994; Mallin *et al.*, 2000). The impact of nutrient additions normally promotes high primary production rates, increasing autochthonous organic matter production, and intense benthic microbial activity. As a result of

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TABLE I Past and Present Dimensions of the Piratininga Lagoon.

Data	*Piratininga (1948)**	*Piratininga (1992)†*
Length (km)	4.5 (E–W)	3.7 (E–W)
Width (km)	2.0 (N–S)	1.27 (N–S)
Surface area (km^2)	4.1	2.6
Maximum depth (m)	4.0	1.5
Mean depth (m)	0.5	0.6
Perimeter (km)	9.7	7.4
Water volume (m^3)	2.1×10^6	1.6×10^6

* Oliveira (1948).
† Niterói (1992).

the high decomposition rates, oxygen demand, especially in the sediment, is high and may lead to temporary anoxic conditions in the overlying water-column with the concomitant release of sulphide (Herbert, 1999). This phenomenon known as dystrophic crisis occurs mainly during summer, and may cause fish mass mortality (Plante-Cuny *et al.*, 1998).

Over the last three decades, the Piratininga lagoon has been suffering from the combined effects of uncontrolled domestic sewage discharge (from rivers, tidal channel, and non-point sources, Souza and Wasserman (1996)) and low seawater renewal rate (Knoppers *et al.*, 1991). During this period, the lagoon lost almost 50% of its original surface (Tab. I) due to urbanisation, and evolved into a hypertrophic system characterised by massive benthic algal growth (*Chara hornemanii* Wallm; Carneiro *et al.* (1994)). This fast macroalgae development has contributed with large amounts of organic matter to the sediments, rapidly reducing water depth and prohibiting navigation and leisure activities in the lagoon (mean depth = 0.6 m; Wasserman *et al.* (1998)). In order to counteract further degradation in the system and to stop the illegal land fillings, the Municipality of Niterói installed a lock at the tidal channel in 1992, aiming at increasing the water level of the lagoon, thus diluting nutrient concentrations, and favouring the decrease in algal growth (Fig. 1). Although the lock

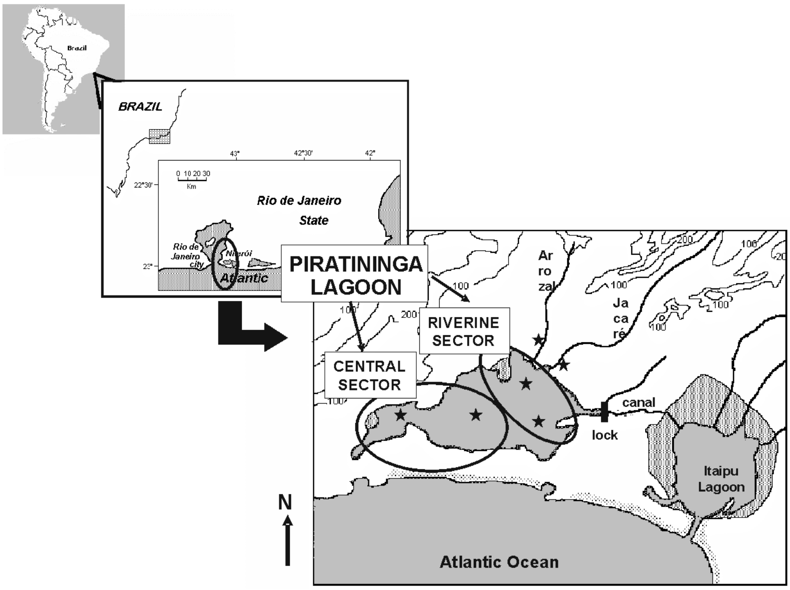

FIGURE 1 Localisation of the study area; (★) corresponds to the sampling stations.

construction aimed at improving water quality, no previous study of the environmental impact or the determination of future scenarios were carried out. Restoration policy of the water body is crucial, in order to maintain fisheries, tourism activities, and avoid future losses in real estate and tax values. According to Wasserman (in press), the properties around the lagoon may loose up to 50% of their value (circa U$ 299 millions) in the next 10 years if the eutrophication problem persists.

This work is focused on the effects of the channel lock on nutrient and biomass cycling in the Piratininga lagoon. As a result of the present study, we propose an easy and low-cost environmental management, based on the macroalgae removal from the system, in order to decrease nutrient loads therefore improving the ecosystem health and avoiding further nutrient accumulation.

2 STUDY AREA

The eastern Rio de Janeiro coast (SE Brazil) harbours an unique series of coastal lagoons, embedded within a narrow coastal plain of about 120 km long and 10 km wide. The lagoons are backed by a steep relief and protected from the sea by elongated sand barriers. These ecosystems were formed during the Pleistocene high sea level of 123000 years before present (BP), but acquired its actual outline between 7000 and 5000 years BP (Turcq *et al.*, 1999). Until the onset of urbanisation, the lagoon underwent a natural ageing process imposed by sediment and organic matter accumulation (Perrin, 1984). This process was accelerated by the effects of deforestation, urbanisation, changes in hydrological balance and untreated sewage discharge (Barroso and Bernardes, 1995).

Figure 1 shows the Piratininga-Itaipu system. The Piratininga shallow coastal lagoon (mean depth ≈ 0.6 m) has a narrow ($\approx$5–20 m) connection with the Itaipu Lagoon through which water exchanges with the Atlantic Ocean are ensured. Water exchange between Itaipu and Piratininga Lagoon is ensured through the Camboatá Canal (2 km long, constructed in 1946; Oliveira (1948)), heavily contaminated with domestic sewage (da Cunha, 1996). Fresh water is supplied by the Arrozal and Jacaré streams, also strongly contaminated with domestic sewage (mean discharge $= 0.3\,\mathrm{m}^3\,\mathrm{s}^{-1}$, (Wasserman *et al.*, 1998)).

Tidal prism is the main water exchange mechanism between this lagoon system and the Atlantic Ocean (Kjerfve and Magill, 1989), and the half-life (T50%) water flushing estimated for the Piratininga Lagoon before the construction of the canal lock was 16 days (Knoppers *et al.*, 1991). After the canal lock construction, T50% estimates increased to 95 days, as a consequence of lock regular opening and closing during flood tide cycles (da Cunha, 1996). Such estimate of the residence time of water in the Piratininga Lagoon assumes an ideal mixing and does not consider the ecosystem geometry (sea water at flood tide first flushes the Itaipu Lagoon, then the Camboatá Canal, and finally the Piratininga Lagoon), so that the actual renewal times might be under-estimated (Alves and Wasserman, 2002).

Eutrophication of shallow coastal lagoons normally promotes fast phytoplankton and macroalgae growth, while benthic microalgae are progressively eliminated due to reduced light availability (Herbert, 1999; Knoppers, 1994). However, in the shallow Piratininga Lagoon, during the last years, a shift from phytoplanktonic to benthic macroalgae (*Chara. hornemanii*) primary production was observed. Macroalgal biomass consumes the entire nutrient stock therefore avoiding phytoplankton to evolve in Piratininga (Carneiro *et al.*, 1994; da Cunha, 1996).

3 MATERIAL AND METHODS

3.1 Sampling

Water column measurements and macroalgal biomass samplings were performed on a monthly basis at four stations in the Piratininga Lagoon and at two stations in the Arrozal and Jacaré streams (Fig. 1) from April 1994 to April 1995. Temperature, pH and salinity were measured *in situ*, and water surface samples were collected in polyethylene (for dissolved nutrient measurements) and glass (for dissolved oxygen by the Winckler titration) bottles. Concentrations of dissolved inorganic nitrogen (DIN = sum of ammonium, nitrite, and nitrate concentrations) and dissolved inorganic phosphorus (DIP, as orthophosphate) were determined after filtration on pre-weighed and combusted Whatman GF/C filters. Filters were frozen and stored in the dark prior to chlorophyll *a* determination, or dried to determine total suspended matter (TSM) and particulate organic carbon (POC). All analyses were performed according to the spectrophotometric (nutrients and chlorophyll *a*) and titration (dissolved oxygen) procedures described by Strickland and Parsons (1972), Grasshof *et al.* (1983) and Lorenzen and Downs (1980). The biomass of *Chara hornemanii*, the dominant macroalgal species, was estimated after the collection of two samples from a metallic quadrat of 25 × 25 cm ($6.3 \times 10^{-2}\,m^2$, standard error = 7%). Macroalgal samples were transported to the laboratory in dark polyethylene bags, rinsed with tap water, and after the accurate removal of epiphytes and sediments, damp-dried with blotting-paper. Macroalgal dry weight was determined after desiccation at 60 °C for 48 hours (dry:wet weight ratio ≈ 0.1).

3.2 Macroalgal Nutrient Stocks

Dense macroalgal stands grow in the Piratininga Lagoon and they largely control inorganic nutrient availability in the lagoon. Based on the riverine nutrient loads to the lagoon (Arrozal and Jacaré streams) (Tab. II), *Chara hornemanii* tissue nutrient concentration analysis (C:N:P ratio = 64:12:1; Carneiro *et al.* (1994), and its net production rates ($111\,mmol\,C\,m^{-2}\,day^{-1}$, during blooming period, and $79\,mmol\,C\,m^{-2}\,day^{-1}$, during decomposition period, measured by the O_2 diurnal curve method (Knoppers *et al.*, 1999), we estimated nutrient stocks recycled by macroalgal stands through a life cycle in the Piratininga lagoon.

TABLE II Temporal Variation of TSM, POC and Chl *a* in the Piratininga Lagoon.

	Riverine sector			*Central sector*		
1994–95	*TSM ($mg\,L^{-1}$)*	*POC ($mmol\,L^{-1}$)*	*Chl a ($\mu g\,L^{-1}$)*	*TSM ($mg\,L^{-1}$)*	*POC ($mmol\,L^{-1}$)*	*Chl a ($\mu g\,L^{-1}$)*
April	57.15	1.12	24.95	30.55	0.91	7.80
May	34.15	1.02	77.70	26.35	0.70	22.70
June	14.95	0.85	59.10	5.10	0.47	47.80
July	–	–	–	–	–	–
August	15.75	0.02	25.80	14.85	0.01	28.60
September	17.25	0.01	21.70	17.10	0.02	64.70
October	17.00	0.33	123.60	26.85	0.40	47.40
November	60.50	0.70	32.40	27.00	0.23	31.70
December	82.65	0.05	42.05	66.70	0.13	11.20
January	30.15	0.55	31.20	8.65	0.03	16.30
February	120.40	0.71	60.95	36.50	0.57	37.70
March	8.10	0.22	78.05	14.30	0.19	43.90

3.3 Statistical Analysis

The statistical *t* and Wilcoxon tests were applied to the 1989–90 and 1994–95 nutrient concentration, salinity and biomass data sets in order to verify if after the construction of the canal lock in 1992, significant alteration in the ecosystem occurred. The tests of significance were employed in the parameters: DIN, DIP, salinity, macroalgal biomass, TSM, POC, and chlorophyll *a*.

4 RESULTS AND DISCUSSION

In order to provide a more compelling scenario we arbitrarily divided the lagoon system into two sectors: a riverine sector, near the rivers and the canal lock, and a central sector, where most of the macroalgal biomass is concentrated (Fig. 1).

4.1 Salinity and Dissolved Oxygen

Temporal variations of salinity in both sectors are illustrated in Figure 2(a). Higher salinity values were found in the riverine sector (mean salinity = 22), near the canal lock (where the sea water enters the lagoon), especially during the dry spring-summer period. This implies that riverine discharge was masked by tidal mixing. Lower salinity values were observed during winter, when riverine discharge is higher. In the central sector, Piratininga Lagoon displayed lower salinity values (mean = 18), but no correlation with rainfall. Variations of salinity in this sector might depend on riverine discharge, tidal mixing and evaporation.

On average dissolved oxygen (DO) concentrations were higher than saturation (%DO) limits, as a result of *C. hornemanii* primary production (Fig. 2(b)). (Carneiro *et al.*, 1994) also observed high DO concentrations in the Piratininga Lagoon during the 89–90 cycle. In the riverine and central sectors, dissolved oxygen temporal pattern followed macroalgal development, *i.e.*, high values up to 9.7 mg O_2 L^{-1} (149 %DO), riverine, and 11.4 mg O_2 L^{-1} (179 %DO), central were found during late spring algal biomass peak. The lowest DO concentration observed in December (2.7 mg O_2 L^{-1} or 40 %DO) was attributed to a very hot and dry period, suggesting that organic matter decomposition processes were consuming part of this oxygen. Oxygen depletion in March–April (1.6 mg L^{-1} in both sectors, corresponding to 24 %DO, riverine, and 39 %DO, central) coincided with macroalgae decomposition, when two massive fish mortality events were registered in the lagoon. High dissolved oxygen variation was also reported by Sfriso *et al.* (1992) in the Venice Lagoon where %DO saturation reaches 360% during macroalgae biomass peaks and anoxia was associated to the macroalgal collapse.

4.2 Total Suspended Matter, Particulate Organic Carbon and Chlorophyll A

On average the total suspended matter (TSM) concentrations in the riverine sector was about twofold higher than those in the central sector (42 and 25 mg/L, respectively), although temporal patterns were similar in both sectors (Tab. II). In the riverine and central sectors, TSM variations were mainly affected by riverine and Camboatá canal inputs and the concentration peaks corresponded to the period of macroalgal decomposition. In 1989–90, Carneiro *et al.* (1994) found the same TSM spatial and temporal behaviour and higher average TSM amounts in both sectors. The decrease in TSM concentration after the lock construction may reflect the lower riverine discharge observed in 94–95 (1×10^{-1} m^3 s^{-1}) compared with 89–90 (3×10^{-2} m^3 s^{-1}). Higher riverine discharge provided suspended material from stream

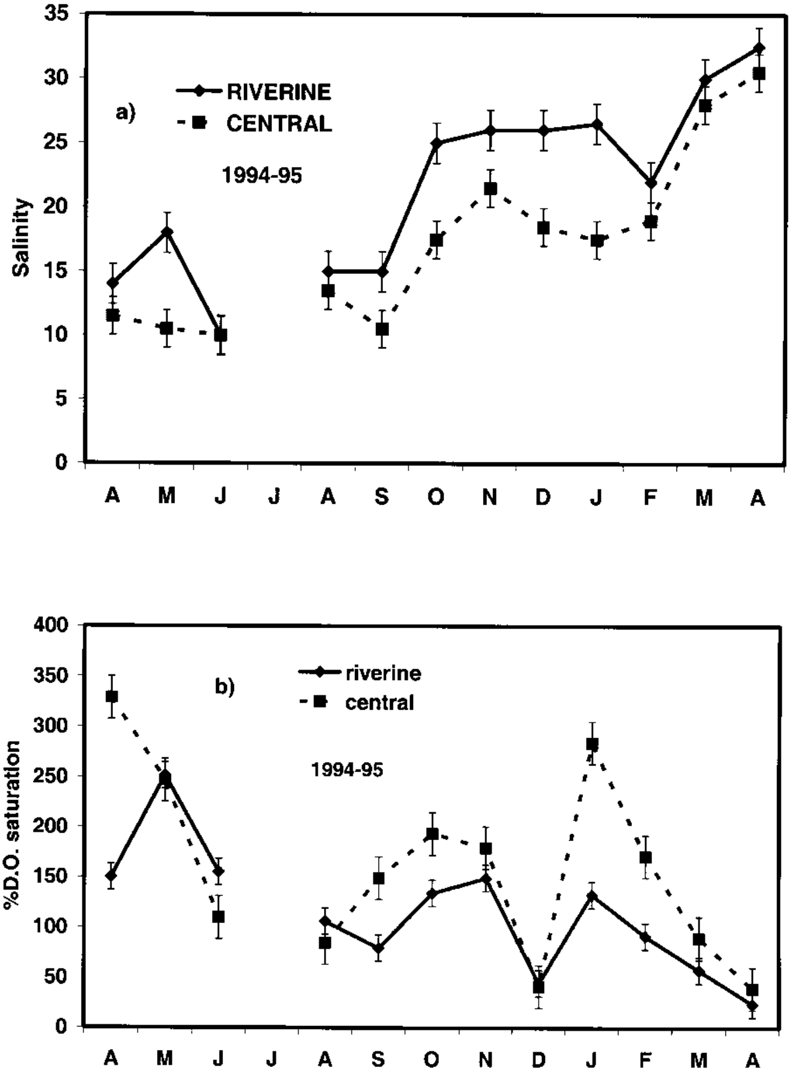

FIGURE 2 Temporal variation of (a) Salinity, and (b) % of dissolved oxygen saturation (%DO) in the Piratininga Lagoon.

banks erosion. Additionally, the lack of tidal flushing in the system after the lock construction prevented TSM inputs by creeks flowing into the Camboatá Canal (Fig. 1) (Knoppers and Moreira, 1990).

Particulate organic carbon (POC) concentrations displayed wide fluctuations, and higher values were observed during autumn and summer (Tab. II). POC temporal patterns were inverse to macroalgae development, suggesting that this parameter in the Piratininga Lagoon is strongly affected by *Chara hornemanii* life cycle. Compared with the 1989–90 data (Carneiro *et al.*, 1993) POC values after the lock construction lowered, reflecting the decrease in TSM concentrations. Nevertheless, POC contribution to TSM pool (as %) increased after the lock construction, especially in the riverine sector (8% in 89–90 and 18% in 94–95) suggesting that although TSM was diluted, its mineral component was reduced.

Chlorophyll *a* (Chl *a*) concentrations were higher in the riverine sector (Tab. II), peaking in spring and autumn. Chl *a* higher values in the central sector occurred in the presence of low macroalgal biomass. This fact can be attributed to competition for nutrients ($r = -0.73$, $p > 95\%$, $n = 12$). (Carneiro *et al.*, 1994) observed the same Chl *a* behaviour in the Piratininga Lagoon although macroalgal concentrations in 89–90 were lower.

This shift from algae to phytoplankton production during decomposition period was also observed in other coastal lagoons by Machado and Knoppers (1988) and Knoppers *et al.* (1999). The higher Chl *a* concentrations observed after the lock construction may be attributed to the increase in available inorganic nutrients and to the drastic end-summer decrease in *Chara hornemanii* biomass in 94–95. Chlorophyll *a* over POC ratios (Chl *a*:POC) were higher in 94–95 (4.9×10^{-2}, riverine, and 7.3×10^{-2}, central sector) than in 89–90 (0.3×10^{-2} in both sectors), suggesting that the increase in the average depth of the lagoon due to the lock construction, accompanied by reduced light penetration that probably limited macroalgal growth and favoured phytoplankton production. Apparently there is a very tight competition between phytoplankton and macroalgae production in the system that renders its ecological equilibrium extremely sensible (Tab. II, see discussion below).

4.3 Nutrients

4.3.1 Dissolved Inorganic Nitrogen (DIN)

In the Piratininga Lagoon, the predominant form of dissolved inorganic nitrogen (DIN) was ammonium (56%), reflecting the domestic sewage origin. Changes of DIN concentration in the riverine sector were mainly related to nutrient input fluctuations from the rivers. In the central sector DIN showed an inverse pattern compared to macroalgal growth. In fact, the peaks of DIN concentration (Fig. 3(a)) corresponded to the period of algal biomass collapse, clearly showing intense consumption of nitrogen during growth periods. In the Venice Lagoon, Italy, DIN temporal pattern was similar to that observed in Piratininga. During the rainy season an increase in the nutrient concentrations due to larger river inputs was encountered, while during macroalgal growth period DIN concentration in the water column strongly decreases (Sfriso *et al.*, 1992).

4.3.2 Dissolved Inorganic Phosphorus (DIP)

Dissolved inorganic phosphorus (DIP), in the form of PO_4^{3-}, presented the same behaviour as DIN (Fig. 3(b)), in both riverine and central sectors of Piratininga Lagoon. Inorganic phosphorus was negatively correlated with macroalgae biomass in the central sector ($r = -0.67$, $p > 95\%$, $n = 12$). DIP average concentration in the lagoon (2.8 μmol L^{-1}) was higher than observed in former studies in the Piratininga Lagoon: 1.9 μmol L^{-1} in 89–90, (Carneiro *et al.*, 1993) and 1.2 μmol L^{-1} in 91–92, (Souza and Wasserman, 1996).

Between March and April 1995 two fish mortality events coincided with the peaking of DIP concentration. The depletion in dissolved oxygen promotes orthophosphate diffusion from the sediment, due to variations in the redox conditions of the environment, causing a flux of phosphorus in the water column (Sfriso and Marcomini, 1999; Sfriso *et al.*, 1994). The opposed trend between DIP and dissolved oxygen was also observed in the Piratininga Lagoon by Carneiro *et al.* (1994) in 89–90.

4.4 Biomass

Primary production in the Piratininga Lagoon is mainly based on macroalgae, contrasting to other neighbouring coastal lagoons in the Rio de Janeiro coast (Knoppers *et al.*, 1991).

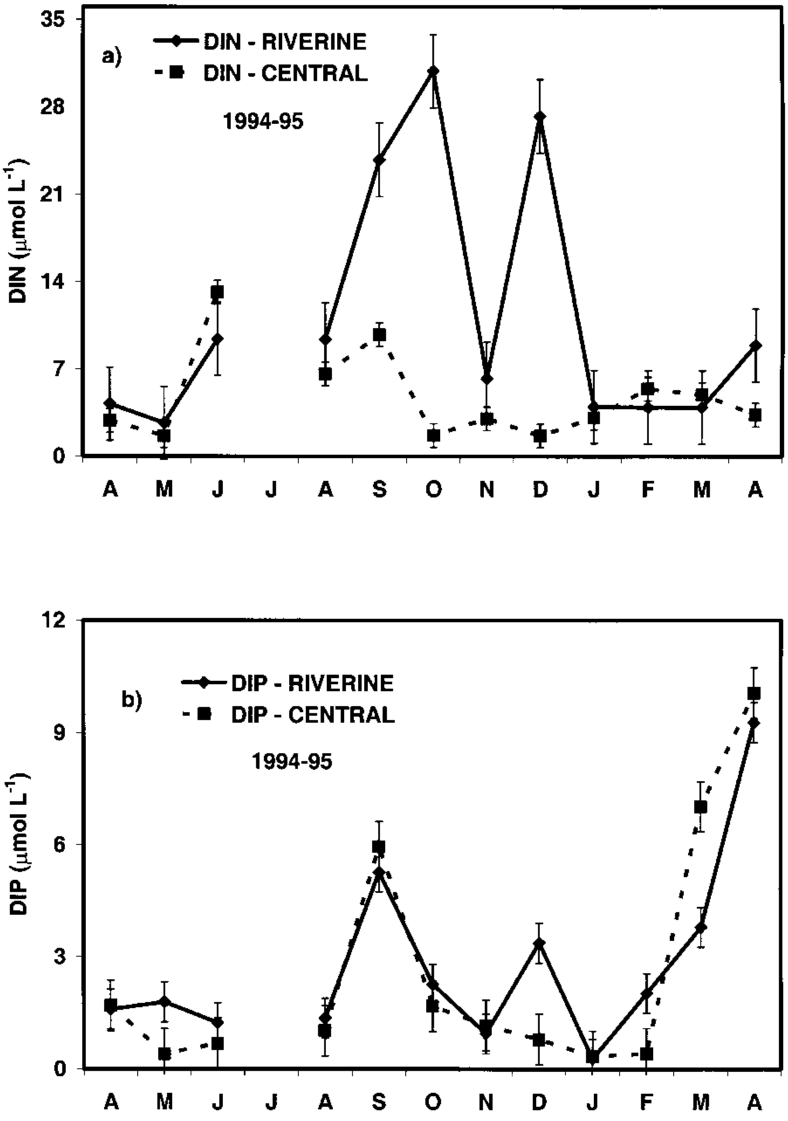

FIGURE 3 (a) Dissolved inorganic nitrogen (DIN), and (b) phosphorus (DIP) temporal variation in the Piratininga lagoon.

Although eutrophication is also observed in many of these ecosystems, phytoplanktonic production dominates since depths are >1 m (Knoppers, 1994). Other examples of eutrophic coastal environments that shifted from seagrasses or phytoplankton dominance to macroalgae-based (benthic) production are the Waquoit Bay (USA; Valiela *et al.*, 1992), Cancún coastal lagoons (Mexico; Merino *et al.*, 1990) and Venice Lagoon (Italy; Sfriso *et al.*, 1992).

Macroalgal stands are distributed throughout the lagoon where depths are <1 m and where inputs of suspended matter are reduced. The main difference in biomass distribution between the riverine and central sectors is the presence of massive *Chara hornemanii* stands in the latter (Fig. 4a). In the riverine sector, we found smaller macroalgal stands and higher TSM and chlorophyll *a* concentrations during the summer (see Tab. II). Biomass distribution

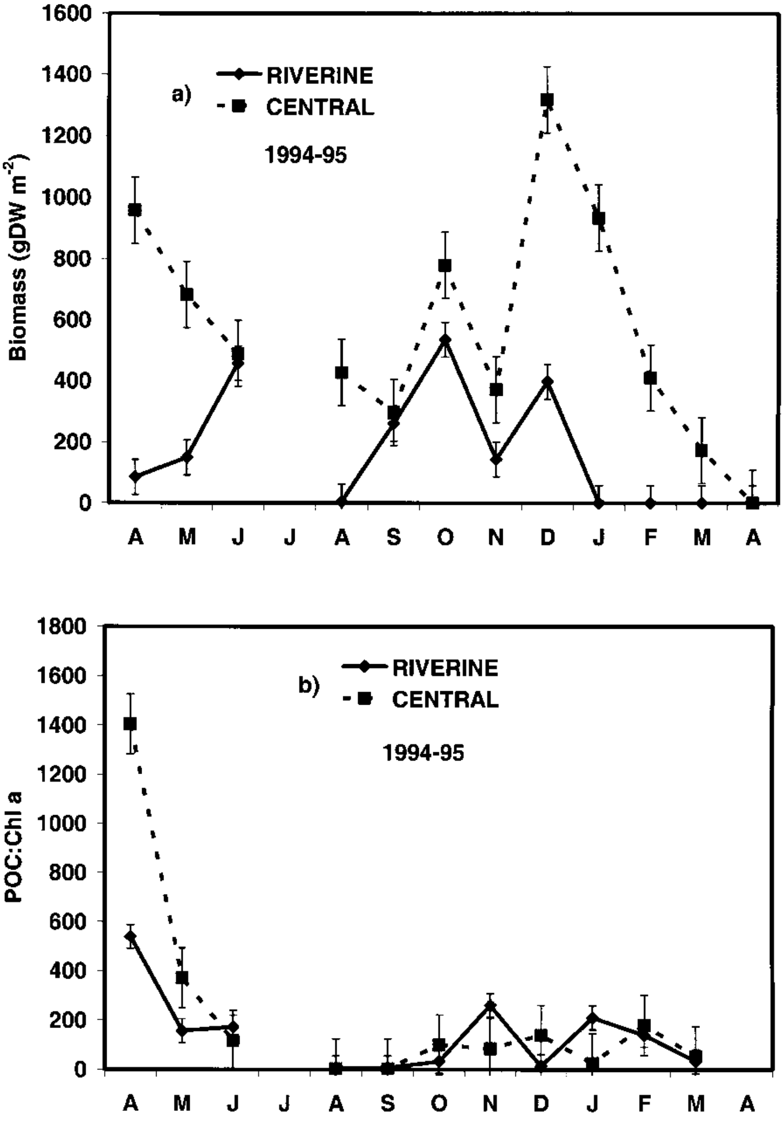

FIGURE 4 (a) Macroalgae biomass (*Chara hornemanii*), and (b) POC:Chl a ratio temporal variation in the Piratininga lagoon.

in the Piratininga Lagoon may be related to the decreasing salinity gradient in the lagoon, from the riverine to the central sector. Furthermore, *C. hornemanii* is typical of brackish water environments, according to Round (1983) and Mallin *et al.* (2000). Drastic decrease in biomass in November is attributed to intense rainfall that preceded this sampling. In that case, water column turbidity might have limited light penetration affecting photosynthesis, as previously observed in the Piratininga Lagoon by Carneiro *et al.* (1994).

During the growth period (winter–spring), algal stands occupied approximately 70% of the total lagoon area, with a mean biomass of *ca.* 580 g m^{-2} (dry weight), corresponding to a standing stock of 1100 t. During the decomposition period (end-summer), the algae-covered area corresponded to 20% of the lagoon surface and the biomass values decreased to 200 g DW m^{-2}, corresponding to a stock of 114 t.

4.4.1 Nutrient Stocks in Macroalgae

Data on riverine nutrient loads (Tab. III), macroalgae C, N, P contents and production, and nutrient concentration in the water column were gathered in order to estimate a nutrient balance of the lagoon. The nutrient stocks in the water column were calculated using the mean concentration values for each season multiplied by the total water volume of the lagoon Niterói (1992), whereas sediment elemental composition was previously described by Knoppers *et al.* (1999). The studied period was divided in three seasons: macroalgal growth (April to August), biomass peak (September to December), and decomposition (January to March) periods, using literature net production values in cold (June, $110\,\text{mmol C m}^{-2}\,\text{day}^{-1}$; growth; Carneiro *et al.* (1994)) and warm (February, $79\,\text{mmol C m}^{-2}\,\text{day}^{-1}$; decomposition; Carneiro *et al.* (1994)) seasons. During the humid April/ August period, water column nutrient availability and riverine discharge are at their maximum (Fig. 5(a)). When macroalgae reach their maximum biomass (September/December), we can observe a decrease in the water column nutrient concentrations (Fig. 5(b)). Finally, during macroalgal decomposition (January/March), part of the nutrients stocked in the biomass is returned to the water column and probably to sediments (Fig. 5(c)). Unfortunately, the absence of seasonal data for nutrient stocks in the sediments or nutrient benthic fluxes in Piratininga restricts our conclusions. *Chara hornemanii* production and nutrient uptake change during the year, as can be seen in Figures 6(a) and 6(b), but the nutrient balance indicate that there are not sufficient inputs from rivers or water column to supply the algal needs. This leads to the conclusion that there must be a considerable nutrient recycling within the water column-algae-sediment compartments. This feature was also observed in the Venice Lagoon (Italy), where the amount of N and P annually recycled by benthic macrophytes was larger than the total amount of nutrients entering the lagoon (Sfriso and Marcomini, 1999). A nutrient balance study in the coastal Patos Lagoon (South Brazil) over an annual cycle indicated that production in the lagoon effectively removes dissolved nutrients supplied by rivers, and that nutrient regeneration (organic matter remineralisation) within the sediments is an important process affecting nutrient distribution in this ecosystem (Windom *et al.*, 1999). According to Knoppers and Duarte (1990), in the Piratininga Lagoon and other coastal lagoons (Capblanq, 1995), the remineralisation of nutrients in the sediments associated to vertical

TABLE III Riverine Loads of DIN, DIP and POC to the Piratininga Lagoon.

	Arrozal River			*Jacaré River*		
1994–95	*DIN ($mmol\,s^{-1}$)*	*DIP ($mmol\,s^{-1}$)*	*POC ($mmol\,s^{-1}$)*	*DIN ($mmol\,s^{-1}$)*	*DIP ($mmol\,s^{-1}$)*	*POC ($mmol\,s^{-1}$)*
April	–	–	–	–	–	–
May	–	–	–	–	–	–
June	16.30	1.25	57.83	4.65	0.55	1.56
July	–	–	–	–	–	–
August	2.20	0.40	0.82	–	–	0.01
September	7.39	1.09	13.01	7.31	0.77	0.10
October	3.68	0.52	16.36	–	–	–
November	1.16	0.05	2.81	11.05	0.45	44.61
December	5.46	0.96	3.73	1.93	0.76	4.34
January	2.74	1.25	14.20	2.07	1.05	11.00
February	6.52	0.37	1.21	6.38	0.96	1.60
March	0.91	0.45	0.17	0.63	0.21	0.13
April	–	–	–	0.97	0.33	–

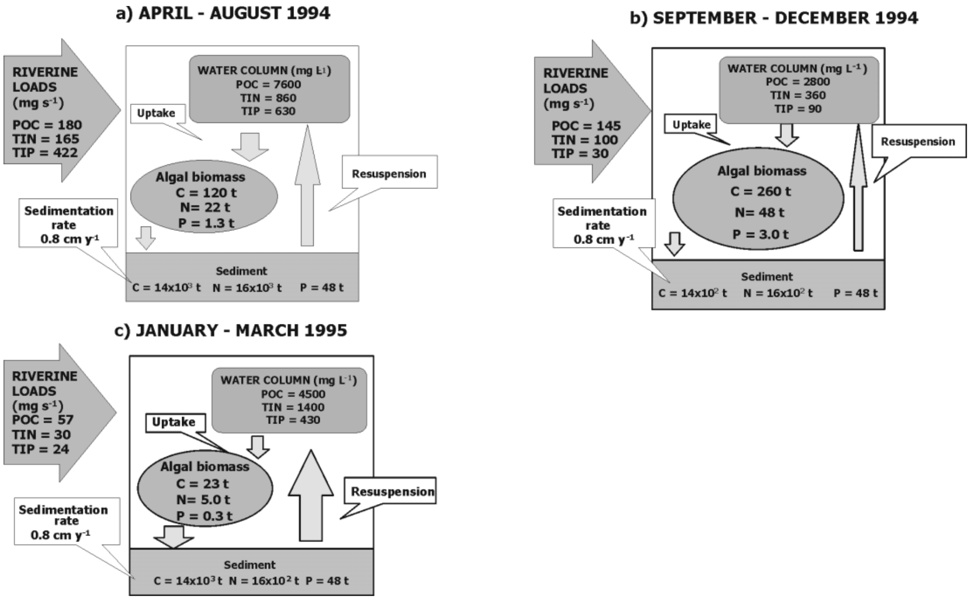

FIGURE 5 Scheme of nutrient stocks in the Piratininga lagoon during the (a) macroalgae growth, (b) biomass peak, and (c) decomposition periods. Algal C, N, P contents were previously estimated by (Carneiro *et al.*, 1994). Sediment accumulation rate and C, N, P contents were estimated by (Knoppers *et al.*, 1999).

diffusion are very important to maintain algal productivity. Thus, *Chara hornemanii* stands in the Piratininga Lagoon would be a "sink" for riverine-loaded nutrients, and sediment-recycled nutrients probably play an important role in maintaining high macroalgal biomass in the ecosystem.

4.5 Impact of the Canal Lock

The significant Wilcoxon and the *t*-test results for the 89–90 and 94–95 parameter comparison are listed in Table IV. Most of the significant alterations in the Piratininga Lagoon were noticed in the riverine sector, close to the Camboatá canal and the lock. Higher salinity and elevated nutrient concentration indicate that opening the canal lock during flood tide was not sufficient to "dilute" N and P stocks in the water column. Before the lock construction, sea water flushing in the system, although reduced, played an important role in nutrient export to the adjacent Itaipu lagoon and the sea. Additionally, significant decrease in TSM concentrations combined with an increase in POC content in TSM (%TSM) and Chl *a* concentrations indicate that after the canal lock construction, particulate organic matter present in the system has shifted to a strong autochthonous component (macroalgae/organic detritus and phytoplankton). Nutrient balance in the lagoon showed that the necessary amounts of nutrients to ensure macroalgae development are recycled within the system.

Although macroalgal biomass did not show statistically significant differences after the lock construction, the mean value is higher in 94/95 and we can also observe differences in the growth pattern (Fig. 7). During 89/90, biomass values levelled out at $100\,\mathrm{g\,DW\,m^{-2}}$ until the onset of the growth period, while in 94/95 *Chara hornemanii* stands completely disappeared during the same period (late-summer and early autumn). The contrast

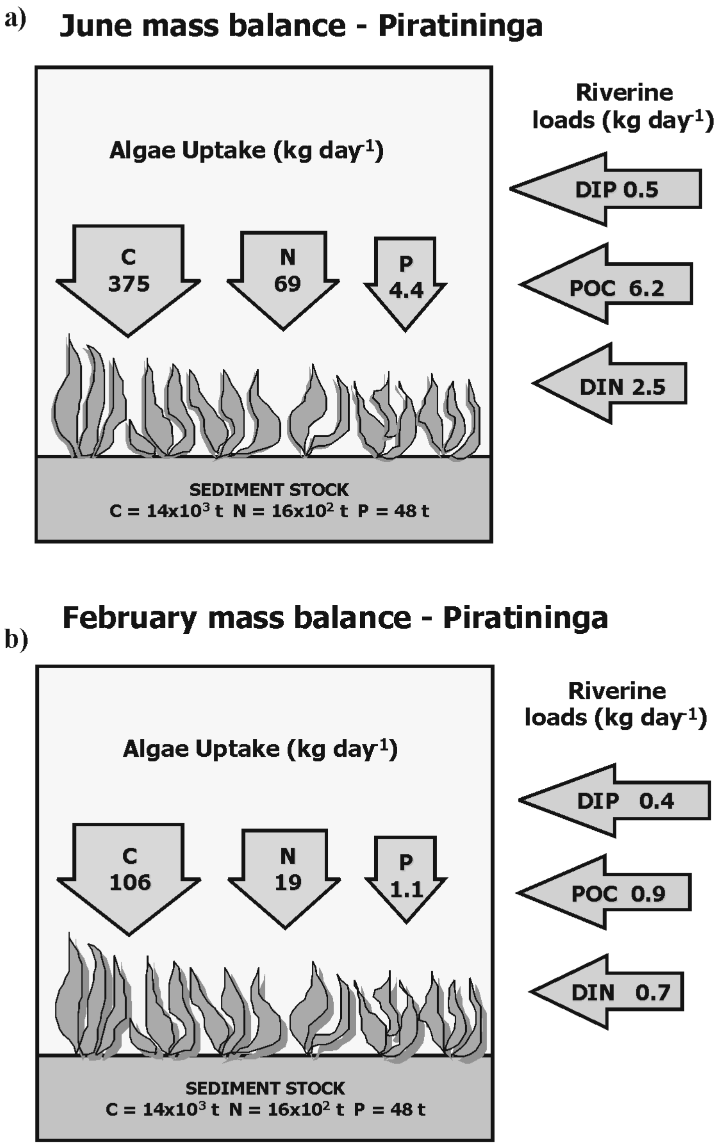

FIGURE 6 Scheme of nutrient mass balance in the Piratininga lagoon. For June (a) and February (b), algal uptake was calculated according to (Knoppers *et al.*, 1999). Riverine loads correspond to the sum of nutrient fluxes from Jacaré and Arrozal rivers. Sediment C, N, P contents were previously estimated by (Knoppers *et al.*, 1999).

between a "gradual" growth cycle and an "exponential growth–total biomass collapse" cycle suggests that the lock induced quantitative and qualitative changes in the ecosystem. Annual changes in climate conditions may also affect biomass growth, but precipitation accumulated in both sampling periods were comparable (1110 mm for 89/90; Carneiro *et al.* (1994) and 1164 mm for 94/95; da Cunha (1996)). Nutrient retention due to the lack of tidal flushing might have enhanced new macroalgal biomass production. When nutrients were not available fast enough to maintain high production levels, combined with higher salinity conditions (~30, see Fig. 2), high temperatures, and oxygen depletion, an accelerated decomposition

TABLE IV Significant Differences Between 1989/90 (before the Canal Lock) and 1994/95 (after the Canal Lock) Nutrient and Biomass Mean Values at the Piratininga Lagoon.

Parameter	*Year*	*Mean ± Std. error*	*t-test*	*Wilcoxon test probability*
DIN[a] – riverine	89–90*	4.2 ± 1.1	0.056 (*n* = 21)	0.023
	94–95†	11 ± 2.9		
DIP[a] – riverine	89–90	1.0 ± 0.2	0.019 (*n* = 21)	0.012
	94–95	2.8 ± 0.5		
POC[b] – central	89–90	13 ± 2.1	0.005 (*n* = 16)	0.007
	94–95	4.0 ± 1.1		
TSM[b] – riverine	89–90	108 ± 21.7	0.021 (*n* = 20)	0.006
	94–95	43 ± 10.9		
TSM[b] – central	89–90	127 ± 26.7	0.003 (*n* = 16)	0.001
	94–95	25 ± 5.2		
Salinity[c] – riverine	89–90	16 ± 1.6	0.013 (*n* = 23)	0.019
	94–95	22 ± 1.6		
Chl a[d] – riverine	89–90	18.6 ± 5.3	0.003 (*n* = 20)	0.002
	94–95	52.5 ± 8.5		
Chl a (%POC) – riverine	89–90	0.3 ± 0.1	0.002 (*n* = 20)	0.003
	94–95	4.9 ± 1.2		
Chl a (%POC) – central	89–90	0.3 ± 0.1	0.036 (*n* = 13)	0.001
	94–95	7.3 ± 2.7		
Chl a (%TSM) – riverine	89–90	$2.0 \times 10^{-2} \pm 0.1$	0.012 (*n* = 18)	0.000
	94–95	0.2 ± 0.1		
Chl a (%TSM) – central	89–90	$4.0 \times 10^{-2} \pm 0.1$	0.020 (*n* = 14)	0.005
	94–95	0.2 ± 0.1		
POC (%TSM) – riverine	89–90	8.1 ± 1.0	0.028 (*n* = 18)	0.025
	94–95	17.6 ± 4.0		

*Carneiro *et al.* (1994).
†This study.
Legend: [a] = μmol/L; [b] = mg/L; [c] = P.S.U.; [d] = μg/L.

process immediately started. According to Herbert (1999), fast growing macroalgae assimilate and store nutrients in excess of their growth requirements, enabling them to exclude other competing primary producers. This fast growth may be followed by a rapid collapse of the biomass.

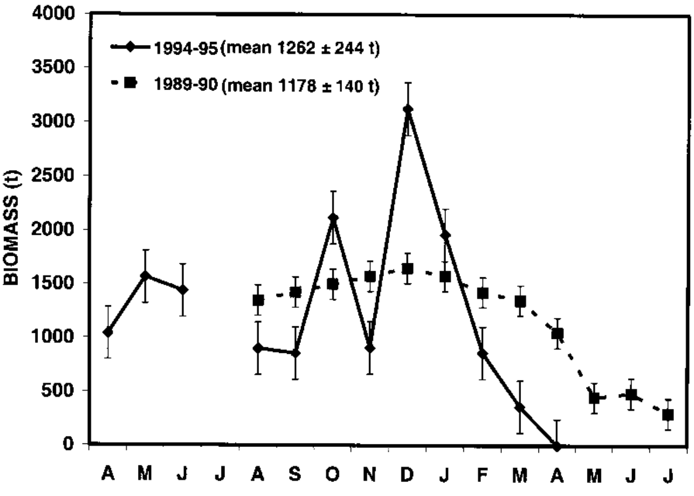

FIGURE 7 *Chara hornemanii* stocks in the Piratininga Lagoon. Comparison between 1989–90 (before the lock, Carneiro *et al.* (1994)) and 1994–95 (after the lock, this study) growth cycles.

5 CONCLUSIONS

The Piratininga Lagoon nutrient cycle is mainly controlled by the macroalgal stands. During its decomposition period, higher DIN and DIP concentrations are found in the water column and there is a shift to phytoplanktonic production in the lagoon.

After the construction of the lock, the system became a "sink" of nutrients, since riverine inputs are enriched in nitrogen and phosphorus and due to the absence of tidal flushing a larger volume of polluted waters enter the lagoon. The increase in macroalgal biomass, phytoplankton, salinity, and nutrient concentrations, as well as the decrease in TSM concentrations, especially in the riverine sector, were caused by an increase in water turn-over time. Additionally, TSM showed higher POC and chlorophyll *a* percentages than before the canal lock construction. Thus, the lock construction might have worked efficiently to avoid further surface losses in the Piratininga Lagoon (one of the original aims of its construction) but, on the other hand, it worsened the lagoon trophic conditions. Future detailed studies on the phytoplankton composition in the Piratininga Lagoon would greatly improve the understanding of the ecosystem metabolism (macroalgae *vs.* phytoplankton production)

Major critical habitat and resources issues remain to be solved in the Piratininga Lagoon area since, until recently, the Municipality of Niterói was not concerned about the eutrophication problems existing in this touristic area. The construction of the canal lock was the first measure trying to improve water quality in the ecosystem, but unfortunately this had inadequate results for improving ecosystem health. Additionally, the canal lock was removed by the Municipality in May 1995 after two consecutive fish mortality events, coerced by local population. Thus, we were not able to evaluate long-term effects in the lagoon ecosystem.

The best solution to improve water quality in the Piratininga Lagoon is to install wastewater treatment plants and enhance tidal exchanges. Nevertheless, these are expensive measures and the necessary resources are not available. Based on this nutrient and biomass cycling study, we propose a proactive low-cost measure to reduce nutrients, organic matter and biomass accumulation in the ecosystem: harvesting the macroalgal stands at the end of the growth period (early summer). According to Sfriso and Marcomini (1997), in the Venice Lagoon (Italy), the method of harvesting excess macroalgae biomass has been regularly applied since 1990 to avoid acute anoxia events. During the last years the biomass was naturally reduced and it could be completely harvested. This intervention concurred to accelerate macroalgal decrease (Sfriso and Marcomini, 1996). As a result, the decline of macroalgae biomass significantly improved water quality and sediment oxygenation, and reduced nutrient stocks in the sediment (Sfriso and Marcomini, 1999).

Finally, the application of an ecological model capable of predicting the response of the system to natural and anthropogenic perturbations could assist policy-makers to solve problems in the area. Although there are many fundamental differences between modelled and real ecosystems, mathematical modelling helped to understand nutrient dynamics or to predict anoxic crisis in Mediterranean lagoons (Chapelle *et al.*, 2000; Petihakis *et al.*, 1999).

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