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Field evidence of the influence of aquatic macrophytes on water quality in a shallow eutrophic lake over a 13-year period

Evidência em campo da influência de macrófitas aquáticas sobre a qualidade de água em um lago raso eutrófico em um período de 13 anos

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Abstract: Aim: The main objective of this work is to describe the changes in water characteristics of a shallow subtropical lake, in periods with and without growing of macrophytes, related to periods of clear-macrophyte dominance and turbid-phytoplankton dominance states. **Methods:** The study was conducted in Biguás Lake, in the south coastal plain of Brazil (32° 04' 43" S and 52° 10' 03" W). Samplings were carried out monthly between October 2000 and November 2013. The limnological variables measured in the water column were dissolved oxygen (DO), water temperature, pH, electrical conductivity (EC), chlorophyll-*a*, total nitrogen (TN), total phosphorous (TP) and suspended material (SM). Data were grouped according to periods with macrophyte growth dominance (MD) and without macrophytes, with phytoplankton dominance (PD), and applied *t*- tests among TP, TN, Chlorophyll-*a* and SM. During macrophyte growth we estimated the coverage (%) and biomass variation of plants. **Results:** Over the 13 years, the lake was well oxygenated, alkaline, and with a temperature variation according to subtropical seasonality. The lower values of all of the limnological variables were verified during periods of macrophyte growth, characterizing periods of clear and turbid waters. **Conclusions:** The influence of aquatic macrophytes in improving water quality in this shallow lake during the studied period, reducing nutrient concentrations, chlorophyll-*a* and suspended material in water, favoring the maintenance of a clear water state, was verified.

Keywords: floating macrophytes, submerged macrophytes, shallow subtropical lakes, clear and turbid waters, southern Brazil.

Resumo: Objetivo: O principal objetivo foi descrever as mudanças nas características de um lago raso subtropical em períodos com e sem crescimento de macrófitas, relacionando com estado de águas claras-dominância de macrófitas, e águas túrbidas, com dominância de fitoplâncton. **Métodos:** O estudo foi realizado no lago dos Biguás, planície costeira sul do Brasil (32° 04' 43"' S e 52° 10' 03" W). Foram feitas amostras mensais de Outubro de 2000 a Novembro de 2013. As variáveis limnológicas medidas na coluna d'água foram oxigênio dissolvido, temperatura, pH, condutividade elétrica, clorofila-*a*, nitrogênio total, fósforo total e material em suspensão. Os dados foram agrupados em períodos com dominância de macrófitas (MD) e dominância de fitoplâncton (PD), e foram comparados por teste-*t* as concentrações de nutrientes, clorofila-*a* e material em suspensão entre os períodos. Durante o crescimento de macrófitas foram estimadas a cobertura (%) e variação de biomassa. **Resultados:** Durante os 13 anos avaliados, o lago mostrou-se bem oxigenado, alcalino, e a temperatura variou conforme a sazonalidade subtropical. Os menores valores das variáveis analisadas foram verificados nos períodos com dominância de macrófitas, caracterizando os períodos de águas claras e túrbidas. **Conclusões:** Foi verificada a influência das macrófitas aquáticas sobre a qualidade de água neste lago raso durante o período estudado, através da redução da concentração de nutrientes, clorofila-*a* e material em suspensão, favorecendo a manutenção de águas claras.

Palavras-chave: macrófitas flutuantes, macrófitas submersas, lagos rasos subtropicais, águas claras e túrbidas, sul do Brasil.

1. Introduction

More than 207 million lakes have an area of less than 1 ha worldwide, and cover a larger total area than that covered by large lakes (Downing and Duarte, 2010). These ecosystems are typically shallow, and they are important in local contexts for maintaining biodiversity and hydrological buffering (Downing and Duarte, 2010). Shallow lakes are defined as lakes that do not stratify for long periods, mix frequently, have intense sediment-water interaction, and are mostly colonized by macrophytes (Scheffer, 1998).

The ecological theory applied to small and shallow lakes in temperate regions suggests the existence of stable states that alternate between clear water and turbid waters. In clear water, there is a single area of submersed macrophyte and low nutrient concentrations in the water column, whereas in turbid waters, there is a predominance of phytoplankton and high concentrations of nutrients, especially phosphorus (Scheffer, 1998). These states alter ecosystem functions and the structure of their communities (Peckham et al., 2006) because in a turbid water state, large blooms of phytoplankton and a loss of submerged macrophytes occur, associated with steep declines of water quality and biodiversity.

Recently, Scheffer and van Nes (2007) and Meerhoff and Jeppesen (2010) considered another alternative stable state, represented by a predominance of floating plants together with high concentrations of nutrients and a generally high stability of the water column. According to these authors, as these plants can be damaged by freezing temperatures, this state is most often found in regions with warmer climates, such as the tropics and subtropics. Most shallow lake ecosystems are thus either in a turbid macrophyte-free state or in a clear state with high vegetation coverage (Tátrai et al., 2009).

Aquatic macrophytes exert large proximate influence over shifts between clear macrophyte- and turbid, phytoplankton-dominated regimes (Kissoon et al., 2013). These shifts often occur over a short time period (within one year) or sometimes over several years (Bayley et al., 2007).

Floating macrophytes are among the main ecological types of aquatic plants that, by excessive proliferation, may cause severe alterations in continental aquatic ecosystems. The high growing rates, favored by clonal reproduction, favors these plants recovering great superficial areas, and alter physical, chemical and biological processes in the environment (Trindade et al., 2008, 2011). In addition, they could cause disorders to navigation, water harvesting, power generation and leisure activities (Mazzeo et al., 1993; Benassi and Camargo, 2000; Henry-Silva et al., 2008). On the other hand, these plants are recognized for their removal of nutrients from the water column, especially nitrogen and phosphorus, due to their high filtering ability (Reddy et al., 1989, 1990; Upadhyaya et al., 2007; Olguín et al., 2007; Henry-Silva et al., 2008).

Submerged macrophytes are described as being mainly responsible for the maintenance of clear water in shallow lakes, and the genera *Potamogeton* and *Chara* are cited as being the most representative for shallow lakes worldwide (Palma-Silva et al., 2002, 2004; Scheffer and Jeppesen, 2007; Meerhoff and Jeppesen, 2010). In general, the substantial development of submerged macrophytes leads to a decrease in the total phosphorous concentration in the water column, most likely due to assimilation of these macrophytes, with a corresponding low growth of phytoplankton. Another factor that could have contributed to the maintenance of clear waters is an allelopathic effect on phytoplankton caused by the *Chara* species, as discussed by Scheffer (1998), Hilt and Gross (2008) and Meerhoff and Jeppesen (2010).

The environments of the Brazilian south coastal plain include a large number of small shallow lakes. In these lakes, there are characteristic large stands of macrophytes, resulting in high levels of primary productivity (Palma-Silva et al., 2008; Trindade et al., 2009) and providing shelter for a large number of aquatic invertebrates (Albertoni et al., 2007).

Over a period of 13 years, the lake investigated in the present study showed changes in water quality characteristics, exhibiting periods with clear waters with submerged and floating macrophyte growth and the development of phytoplankton (turbid waters). During this period, we accomplish the limnological variables of this ecosystem. The main objective of this work is to describe the changes in water characteristics of a shallow subtropical lake, in periods with and without growth of macrophytes and related to different alternative states (clear-macrophyte dominance and turbid-phytoplankton dominance).

2. Material and Methods

2.1. Study area

The study was conducted in Biguás Lake, in the south coastal plain of Brazil (32° 04' 43" S and 52° 10' 03" W) (Figure 1). The climate in the area is

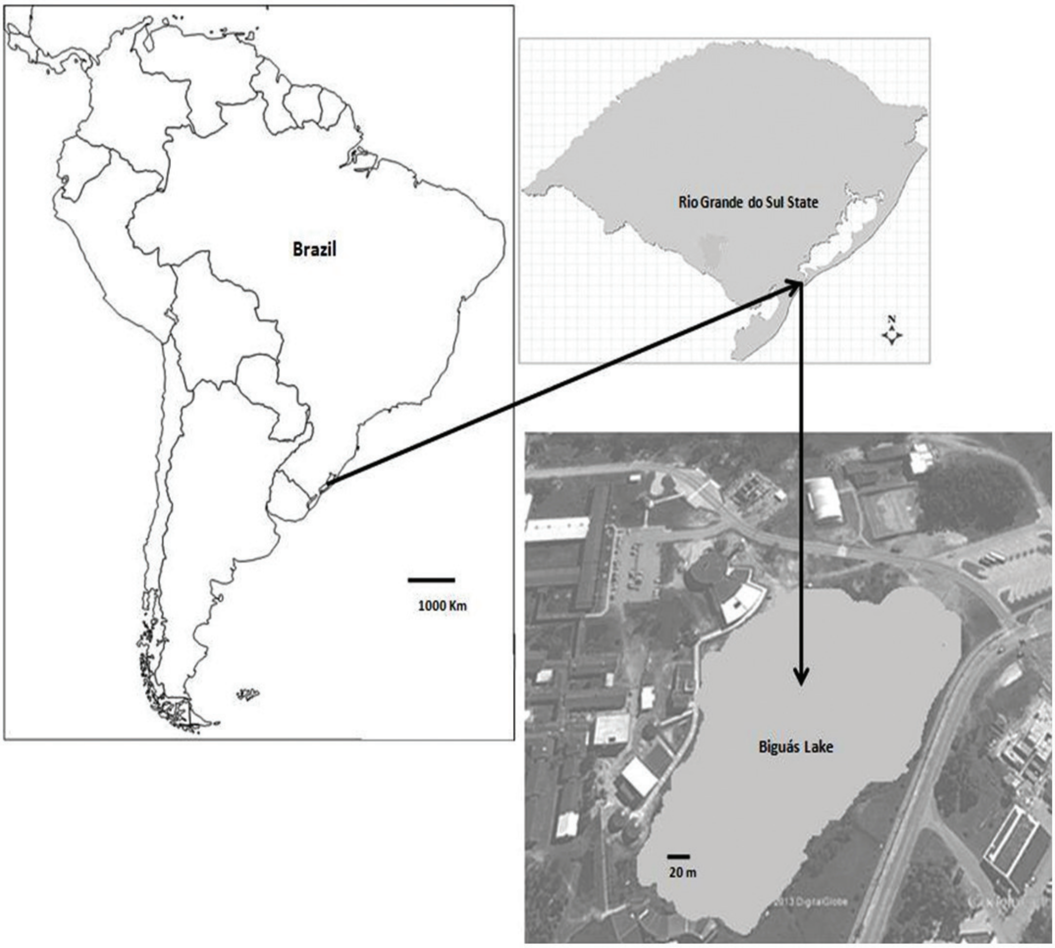

Figure 1. Geographic location of Biguás Lake on the southern coastal plain of Brazil (32°04'43" S and 52°10' 03" W) (Photo source: Google Earth®).

humid subtropical and is characterized by prevailing winds from the NE, an average annual temperature of 19 °C and annual rainfall of approximately 1,200 mm, which is well distributed throughout the year (Klein, 1998).

Biguás Lake is a shallow eutrophic lake with an area of approximately 1.5 ha. This lake was strongly influenced by the input of organic matter from birds, especially cormorants (*Phalacrocorax brasilianus* Gmelin, 1789), which inhabited two islands at its center. This caused an increase in nutrients in the water column and in the sediment and cyanobacteria blooms, short anoxic events and fish kills during the summer months (Trindade et al., 2009).

The study period comprised the years 2000 to 2013. During this period, the lake showed changes between three alternative stable states. Between 2000 and late 2002, the lake presented high transparency, and a light development of submersed (*Potamogeton pectinatus* L.) and floating leaves (*Nymphoides indica* (L.) O. Kuntze) macrophytes was observed. Beginning in the year 2003, it went through a severe process of eutrophication, showing major development of phytoplankton and turbid waters (Secchi transparency about 0.20 m). In the same year, the floating macrophyte *Pistia stratiotes* L. also began to develop in the lake, eventually covering its entire surface. After management activities that removed this macrophyte, there was a brief return to clear water conditions, and total transparency of the water column (maximum depth of 2.0 m), which persisted for around eight months. However, due to the increasing supply of nutrients via manure from birds, the lake returned to a turbid water state, associated with major growth of phytoplankton; this situation lasted until the year 2008. In the turbid water state, the mean Secchi transparency was 0.20 m.

From this period onward, when there was a pronounced decrease in the number of birds on the central islands of the lake, there was a shift from turbid waters to a clear water state, together with growth of the submerged macrophyte *Potamogeton pectinatus* L. and macroalga *Chara zeylanica* Klein & Willdenow. These macrophytes predominated in the lake and maintained the clear water state until the end of 2012. During 2012, the lake experienced a strong anthropic alteration, with construction building near the margins, the removal of lake shore vegetation and revolving part of sediment. This may have favored the release of sediment nutrients, which enhanced the growing of the floating macrophyte *Salvinia herzogii* de la Sota, covering its entire surface during 2013, and suppressed the submerged macrophytes. With this macrophyte, the clear water was maintained.

2.2. Sampling procedures

Samplings were carried out almost monthly between October 2000 and November 2013. The limnological variables measured were dissolved oxygen (DO, mg.L^{-1}), water temperature (°C), pH and electrical conductivity (EC, µS.cm^{-1}), using Hanna® and Horiba® sensors in the field. In the laboratory, a sample of surface water was analyzed for chlorophyll-*a* concentration (µg.L^{-1}) (Chorus and Bartram, 1999), total nitrogen (TN, mg.L^{-1}, Mackereth and Talling, 1978) and total phosphorous (TP, mg.L^{-1}, Valderrama, 1981). Suspended material (SM, mg.L^{-1}) was analyzed by gravimetric method (Paranhos, 1996).

Canfield Junior and Jones (1984) suggested that about 50% of a lake's area must be covered by macrophytes to produce a significant impact on nutrient cycling, and accordingly, the data were divided into two periods: we grouped data according to periods with macrophyte growth dominance (MD) and without macrophytes, with phytoplankton predominance (PD). To compare these periods, we applied unpaired *t*-tests (with Welch correction applied to unequal variances) among TP, TN, Chlorophyll-*a* and SM (data log (x+1) transformed), considering these as the main factors that reflect water quality and shifts between clear and turbid states of the lake. For the purpose of relating macrophytes to water quality, we grouped data from the two periods of macrophyte growth, and did not separate the alternative states with submerged and free-floating plants.

During floating macrophyte growth, macrophyte coverage for the whole lake was visually estimated – from January to August 2003 for *P. stratiotes* and from March to November 2013 for *S. herzogii* – and the coverage during the time was related to TN and TP values. Macrophyte biomass, both free-floating and submerged species, wasere sampled randomly (taking the whole lake into consideration) five times per sampling date, using a cylindrical collector with an area of 0.07 m^{-2}. The same was done to estimate the biomass of submerged macrophytes, with samplings inside stands of *P. pectinatus* and *C. zeylanica* from December 2009 to December 2012. After sampling, plants were taken to the laboratory, washed with tap water and oven-dried at 60 °C for approximately 72 hours to reach a constant weight for obtaining dry weight (DW). The biomass values are expressed in grams per square meter (g DW.m^{-2}).

3. Results

During the studied period, the lake presented an average value of dissolved oxygen of 8.83 (±3.03) mg.L^{-1}. Even with periods of strong eutrophication, there were short anoxic periods in the water column, in two fish kill events (December 2006 and December 2008), associated with a strong drought in the southern region of Brazil. The water temperature values average of 21.39 (±4.85 SD) °C follow the typical subtropical alternation among year seasons (Figure 2a). Values of pH showed a tendency toward being alkaline, with an average of 8.28 (±1.16 SD). Electrical conductivity presented an average value of 199.51 (±38.47 SD) µS.cm^{-1} (Figure 2b).

The lower values of all the limnological variables were verified during periods of macrophytes growth (Table 1). Figure 3 shows the average (±SD) values of nutrient concentrations (TP and TN), SM and chlorophyll-*a* in the water column during MD and PD.

During macrophyte dominance, both floating and submerged macrophytes get 100% of the lake's area coverage. Maximum biomass values were found to submerged, and *C. zeylanica* reached the highest values (Table 2). During floating plants growth, the decrease in nutrient concentrations of the water column was related to the surface area covered (Figure 4). For *P. stratiotes*, both TP and TN presented an inverse correlation with coverage [(y = -0.006 TP + 0.716, R^2 = 0.62 and y = -0.032 TN + 3.202 (R^2 = 0.44), respectively]. For *S. herzogii* there was an inverse correlation with TP [y = -0.001 x + 0.181 (R^2 = 0.15)] and a positive correlation with TN [Y = 0.006 x + 0.43 (R^2 = 0.23)].

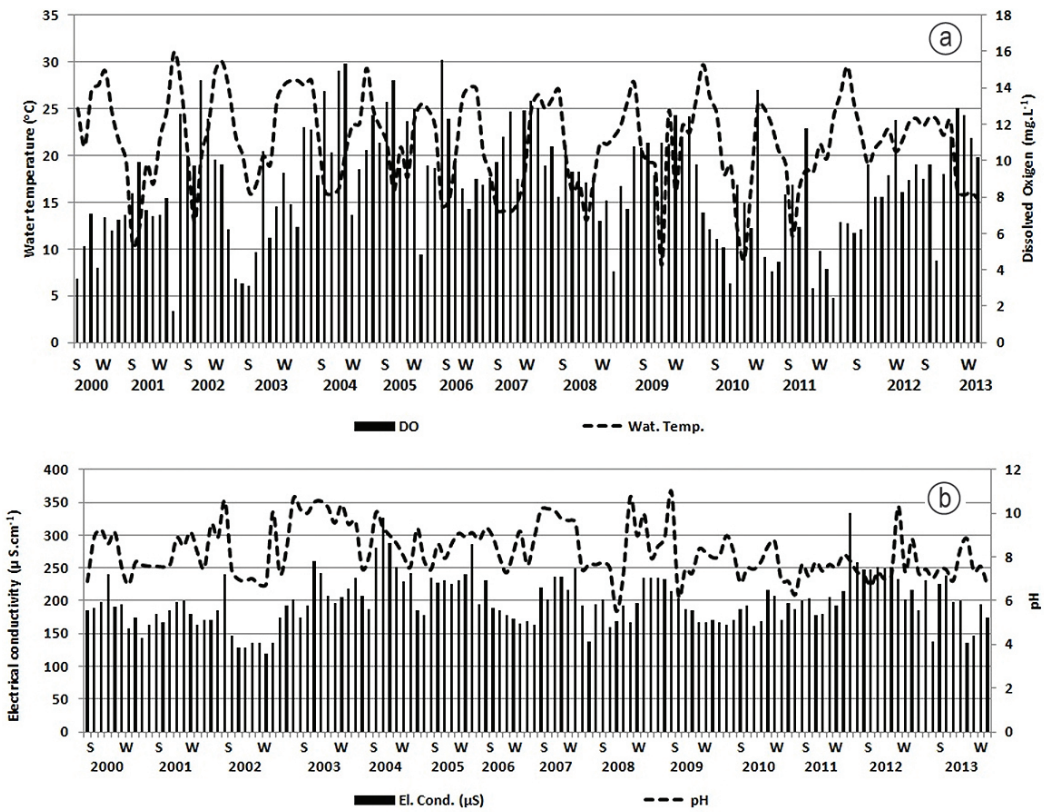

Figure 2. Total variation on abiotic variables during sampling period, between October 2000 and November 2013 at Biguás Lake. a = dissolved oxygen (DO- mg.L^{-1}) and water temperature (°C); b = electrical conductivity (µS.cm^{-1}) and pH; S = summer period; W = winter period.

4. Discussion

Worldwide studies have shown that both submerged and free-floating macrophytes have a high capability of improving water quality by removing heavy loads of nutrients and toxic metals from the water (Srivastava et al., 2008). Researchers have made it clear that macrophytes can reduce the concentrations of nutrient ions, such as P and N (Srivastava et al., 2008). Most researches explore water quality improvement by means of controlled investigations in the field or laboratory. Our data showed, through observations in the field, that over this 13-year period, the dominance of different macrophyte species or phytoplankton was a process controlled by multiple factors. For this shallow subtropical lake, we showed the ability of aquatic macrophytes to improve water quality, by the growing of floating or submerged macrophytes reducing nutrient concentrations in the water, chlorophyll-*a* and suspended material, favoring the maintenance of a clear water state.

In this shallow lake, the results we found indicate the important role of macrophytes determining limnological characteristics of Biguás lake, a result similar to that found by Kissoon et al. (2013). Aquatic macrophytes in lakes, mainly shallow ones, are recognized as preventing sediment resuspension, thus reducing suspended soils in the water (Horpilla and Nurminen, 2005).

The results showed the influence of aquatic macrophytes on limnological features of the Biguás lake. All of the measured variables (TP, NP, Chlorophyll-*a* and SM) were lower when macrophyte growth was high. Throughout the 13-years period, TP concentrations in the water column showed differences when macrophytes were growing and when phytoplankton was predominating. Meerhoff et al. (2003) found different results in a short field experiment, where the authors cited that the presence of macrophytes do not alter physico-chemical features of water column. During periods of active growth, macrophytes are a net sink for phosphorus (Carpenter and Lodge, 1986). Our results showed that both TP and TN presented high concentrations, characteristic of nutrient-rich water ecosystems, and this ecosystem was always classified as eutrophic to hypereutrophic, according

Table 1. Mean values (±SD) of total phosphorous (TP, mg.L^{-1}), total nitrogen (TN, mg.L^{-1}), suspended material (SM, mg.L^{-1}) and chlorophyll-*a* concentration (μg.L^{-1}) and comparison of results (unpaired *t*-tests, Welch correction applied) between periods with macrophyte dominance (MD) and phytoplankton dominance (PD) for each variable.

	TP MD (n=52)	TP PD (n=49)	TN MD (n=67)	TN PD (n=50)	SM MD (n=65)	SM PD (n=33)	Ch MD (n=67)	Ch PD (n= 49)
Mean (±SD)	0.14 (±0.16)	0.34 (±0.15)	0.77 (±0.48)	3.68 (±1.29)	8.38 (±8.46)	67.77 (±65.54)	19.44 (±13.69)	145.43 (±58.25)
t test results	*t*= 8.704, df= 95, p<0.0001		*t*= 12.955, df= 113, p<0.0001		*t*= 9,794, df= 84, p<0.0001		*t*=14.793, df= 103, p<0.0001	

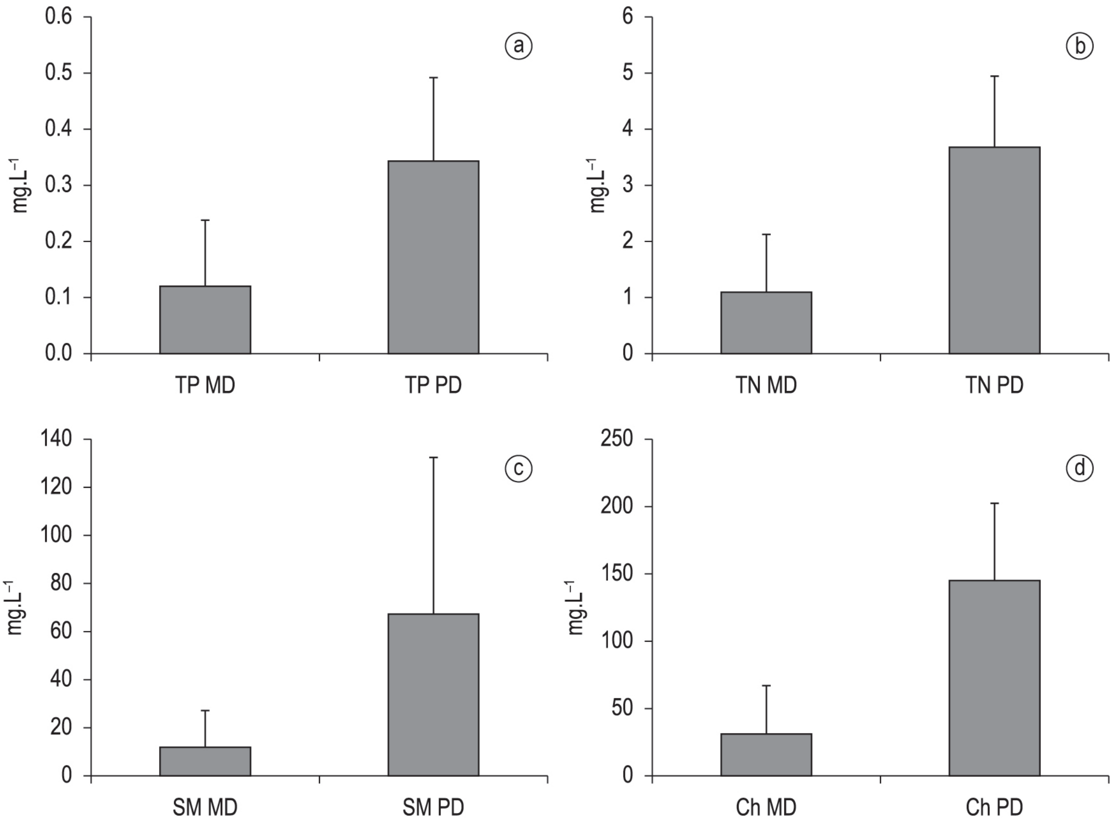

Figure 3. Mean values (±SD) of total phosphorous (a-TP, mg.L^{-1}), total nitrogen (b-TN, mg.L^{-1}), suspended material (c-SM, mg.L^{-1}) and chlorophyll-*a* (d-Ch, mg.L^{-1}) from October 2000 to November 2013 at Biguás Lake. MD = periods with macrophyte dominance; PD = periods with phytoplankton dominance.

to the criteria of SØndergaard et al. (2005). This trophic condition favored high productivity, both of phytoplankton, and different macrophytes. Also, it is recognized by Moss et al. (2013), in shallow lakes, that the increased loading of N changes the structure of macrophytes in these systems.

In an experimental study in a subtropical shallow lake, Meerhoff et al. (2003) showed that the effects of submerged vegetation on the physico-chemistry of the water were generally greater than those of free-floating plants. Most of the submerged species are limited by the attenuation of radiation and are indicative of environments with low nutrient concentrations (Scheffer, 1998; Thomaz, 2002; Camargo et al., 2003). Thus, by decreasing phosphorus and thereby increasing water clarity (low phytoplankton growth) the potential area of the lake bottom that can be inhabited by aquatic plants also increases (Backer et al., 2012), favoring sediment colonization by these kinds of macrophytes. Accordingly, the turnover effect of the removal of nutrients from sediment, and some allellopatic effects of submerged species (specially *Chara*) on phytoplankton (Hilt and Gross, 2008), are factors that could explain the lowest values of TP and TN in the water column, and the maintenance of clear water between the years 2009 and 2012.

Macrophyte growth and species composition in lakes are simultaneously influenced by multiple (and possibly limiting) environmental factors

Table 2. Maximum coverage of floating and submerged macrophytes, mean (±SD), minimum and maximum biomass values of *Pistia stratiotes* (January to August 2003), *Salvinia herzogii* (March to November 2013), *P. pectinatus* and *C. zeylanica* (December 2009 to December 2012) during growing periods at Biguás Lake.

	Floating		Submerged	
Maximum Coverage	95% to 100%		100%	
	Pistia stratiotes (n=11) gDW.m^{-2}	*Salvinia herzogii* (n=10) gDW.m^{-2}	*Potamogeton pectinatus* (n=12) gDW.m^{-2}	*Chara zeylanica* (n=6) gDW.m^{-2}
Mean (±SD)	84.32 (±18.54)	147.44 (±42.79)	333.68 (±180.06)	586.28 (±263.83)
Min-Max	61.28- 125.56	97.94-228.98	178.98-667.10	328.30-1007.71

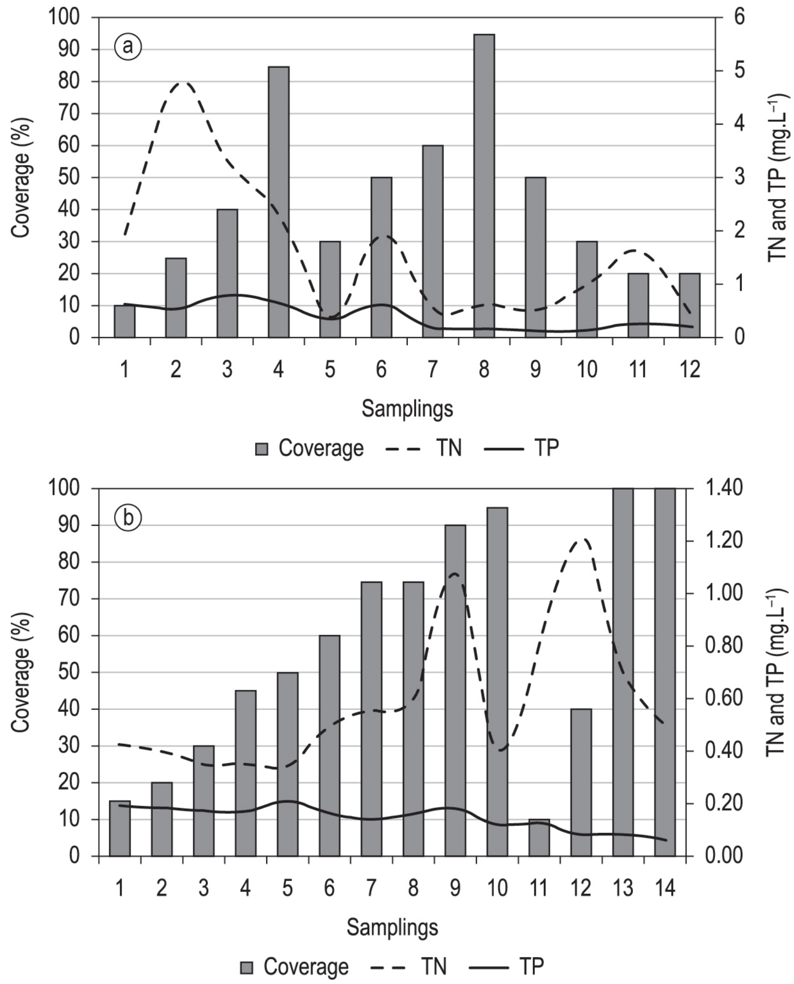

Figure 4. Variation of total nitrogen (TN) and total phosphorous (TP) (mg.L^{-1}) and coverage of surface lake area (%) of a: *Pistia stratiotes* (January to August 2003) and b: *Salvinia herzogii* (March to November 2013) at Biguás Lake.

(Backer et al., 2012). Several studies have documented that the trophic state and light conditions in the environment can influence the development and colonization of aquatic macrophytes (Scheffer, 1998; Penning et al., 2008; Rolon et al., 2008; Pereira et al., 2012).

Submerged vegetation can enhance water clarity by reducing resuspension of bottom material, providing zooplankton with a refuge from grazing by planktivorous fish (Meerhoff et al., 2003), suppressing algal growth by competing for nutrients, and releasing allelopathic substances that are toxic to algae (Takamura et al., 2003).

Also, Backer et al. (2012) stated that the growth of submerged species may be influenced by alkaline values of pH. As our pH values showed alkaline tendencies, this is another factor that may have contributed to the growth of submerged plants. It is recognized that submerged macrophytes favor lower levels of Chl-*a* concentrations (Takamura et al., 2003). All of the periods with macrophytes showed reduced phytoplankton biomass, a result that is recognized as common for temperate shallow lakes with submerged macrophytes (Scheffer, 1998). For tropical and subtropical shallow lakes and wetlands, the growth of floating plants also improves water quality (Henry-Silva and Camargo, 2002, 2005; Henry-Silva et al., 2008).

The growth of different species of floating macrophytes, first *P. stratiotes* and then *S. herzogii*, could be attributed to the distinct physiological requirements of the two species. According to Henry-Silva et al. (2008), *P. stratiotes* is favored by nutrient-rich waters, limited by N and P concentration in the water, and *S. molesta* showed no influence of nutrient concentration on their growth. Even the species of *Salvinia* at Biguás Lake differ from that studied by Henry-Silva et al. (2008), we believe that the same influence of water nutrient concentration could be taking place, because water levels of TP and TN were lowest when *S. herzogii* began their growing, then when *P. stratiotes* did. Floating macrophytes are commonly used for water treatment, for their high ability as removal nutrients (Nahlik and Mitsch, 2006). Their roots act as filters through mechanical and biological activity, removing suspended particles from the water and decreasing turbidity (Dhote and Dixit, 2009). The impact of *S. herzogii* on nutrients in the water column was weaker than that of *P. stratiotes*, mainly for TN. Some factors may contribute to this, such as physiological requirements, and the length of the absorption surface (roots of *P. stratiotes* versus modified leaf of *S. herzogii*).

As stated by Meerhoff and Jeppesen (2010) with regard to alternative states of shallow lakes, in tropical and subtropical ones the growing of floating macrophytes could occur at high nutrient levels. The eutrophic characteristics of Biguás Lake may have favored the two free-floating species that dominated Biguás Lake, thereby corroborating the authors. Scheffer et al. (2003) showed with models and experimental and field evidence that free-floating macrophytes showed a positive correlation to nutrient levels of the water column, whereas submerged plants were negatively related to nutrient levels.

The changes in dominant types of macrophytes may be due to different thresholds of nutrient levels, but multiple factors should be taken into consideration. According to Scheffer et al. (2003), although floating plants are obviously superior competitors for light, submerged plants may affect the growth of free-floating plants through a reduction of available nutrients in the water column. In Biguás Lake, the growing period of the submerged species was with lower levels of nutrient concentration in the water column, inhibiting phytoplankton growth and allowing the maintenance of an extensive period of clear waters. Our results showed that, during the observed period on water quality at Biguás Lake, when there were macrophytes growing, free-floating or submersed, nutrient levels in the water column decreased, and favored the maintenance of clear waters. In conclusion, over the 13-year period of monitoring at Biguás Lake, we could see changes in water quality and water characteristics (turbid/clear), and related this to the presence of macrophytes growth. The factors that enhanced macrophyte versus phytoplankton growth, and the consequent alternation between turbid and clear characteristics in this shallow lake, must be investigated with experimental studies.

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