Taxonomy and ecology of order Surirellales (Bacillariophyceae) in tropical reservoirs in Southeastern of Brazil

Taxonomia e ecologia da ordem Surirellales (Bacillariophyceae) em reservatórios tropicais no Sudeste do Brasil

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Abstract: Aim: The aim of this study was to inventory the diatom species of order Surirellales present in the surface sediments of tropical reservoirs (São Paulo State, Brazil) and to correlate their distribution with environmental (pH, total phosphorus, and total nitrogen) and spatial predictors. **Methods:** Samplings were carried out in 31 reservoirs from 2009 to 2014. Vertical profile of water samples was collected in the summer and winter along the reservoirs, and their water column mean results were used to characterize each sampling site. We measured water transparency, euphotic zone, water depth, pH, dissolved oxygen, total nitrogen, and total phosphorus. Surface sediment samples (2 cm top) were collected for diatom analyses. A partial RDA was performed between species abundance data (response matrix) and environmental and spatial variables (predictor matrices). **Results:** 14 species of Surirellales were identified from the surface sediment samples, five of them being identified only at the genus level. Overall, partial RDA showed that the species distribution is constrained by both environmental and spatial predictors. Species were mainly ordinated in relation to pH and light availability. **Conclusion:** Our results demonstrated that the Surirellales species revealed ecological preferences to low nutrient concentrations, neutral to slightly acidic waters, and higher light availability. Moreover, our results suggest that both environmental and spatial factors are important for their species distribution.

Keywords: surface sediment; *Stenopterobia*; *Surirella*; Brazil.

Resumo: Objetivo: O objetivo do estudo foi inventariar as espécies de diatomáceas da ordem Surirellales presentes em sedimentos superficiais de represas tropicais (Estado de São Paulo, Brasil) e correlacionar sua distribuição com preditores ambientais (pH, fósforo total e nitrogênio total) e espaciais. **Métodos:** As amostragens foram realizadas em 31 represas entre 2009 e 2014. Amostras de água foram coletadas no verão e inverno ao longo do perfil vertical da represa e os resultados médios da coluna d'água foram utilizados para caracterizar cada estação amostral. Transparência da água, zona eufótica, profundidade, pH, oxigênio dissolvido e nitrogênio e fósforo totais foram medidos. Sedimentos superficiais foram coletados no inverno aproveitando-se os dois primeiros centímetros para a análise das diatomáceas. Foi realizada RDA parcial entre a abundância das espécies (matriz resposta) e as variáveis ambientais e espaciais (matrizes preditoras). **Resultados:** Foram identificadas 14 espécies de Surirellales nas amostras de sedimentos superficiais, das quais cinco foram identificadas apenas em nível gênero. A RDA parcial mostrou que a distribuição das espécies é influenciada, em geral, pelos preditores ambientais e espaciais. As espécies foram ordenadas principalmente em relação ao pH e à

disponibilidade de luz. **Conclusão:** Os resultados demonstraram que as espécies de Surirellales apresentam preferência por ambientes com baixa concentração de nutrientes, águas neutras a levemente ácidas e maior disponibilidade de luz. Além disso, os resultados sugerem que fatores espaciais e ambientais são importantes na distribuição das espécies.

Palavras-chave: sedimento superficial; *Stenopterobia*; *Surirella*; Brasil.

1. Introduction

The order Surirellales is mainly characterized by solitary cells with a canal raphe system often raised by a keel. Such canal raphes are usually found in the valve margin and may be raised by wings or keels (Ruck & Theriot, 2011). The presence of a "keeled" raphe is important to improve structural stability between the canal raphe and substrate such as unconsolidated sediments (Round et al., 1990). Surirellales comprise more than 1.300 nominal species (Fourtanier & Kociolek, 2011), and includes three families (Entomoneidaceae, Auriculaceae and Surirellaceae) and 10 genera (Ruck et al., 2016), which occur in a variety of freshwater, estuarine and marine ecosystems, with some species entirely restricted to acidic waters (Lowe, 2003).

In Brazil, 62 species and 19 varieties were reported in the literature (Eskinazi-Leça et al., 2015, Menezes et al., 2015). Nevertheless, this still is a poorly known diatom group in terms of taxonomical and ecological features, since they are usually recorded in floristic surveys (Silva et al., 2010; Bartozek et al., 2013) or mentioned in ecological studies without detailed information about the species (Bortolini & Bueno, 2013; Rosa & Garcia, 2015) with few taxonomic studies (Torgan & Weber 2008; Salomoni & Torgan 2010; Oliveira et al., 2012).

For the state of São Paulo, 15 species were reported and nine new records for the Parque Estadual das Fontes do Ipiranga were recently registered by Ferreira & Bicudo (2017): *Stenopterobia delicatissima* (F.W.Lewis) L.A. Brébisson *ex* H. van Heurck, *S. pelagica* F.Hustedt, *S. planctonica* D. Metzeltin & H. Lange-Bertalot, *S. curvula* (W.Smith) K. Krammer, *Surirella angusta* F.T.Kützing, *S. guatimalensis* C.G.Ehrenberg, *S. stalagma* M.H.Hohn & J.Hellerman, *S. splendida* (C.G.Ehrenberg) F.T.Kützing and *S. tenera* W.Gregory.

The ecological studies about Surirellales for tropical and subtropical regions are still very scarce and address pH preferences, trophic state, and physical and chemical water parameters (e.g. Cocquyt et al., 2014; Cocquyt & Taylor, 2015; Cocquyt et al., 2017). This is partially because most ecological studies considered Surirellales rare taxa in terms of abundance and/or occurrence and, therefore, exclude them from further analysis. Nevertheless, rare taxa may constitute the largest component of species richness in an assemblage (Marchant et al., 1997; Gillett et al., 2011) being, therefore, important components of biodiversity. Furthermore, rare taxa are expected to have narrow ecological niches and to be sensitive to anthropogenic impacts (Gillett et al., 2011).

Besides identifying which environmental factors are influencing species distribution, another important issue is to know whether such species are being constrained by geographical factors that limit species dispersion (Potapova & Charles, 2002). Thus, the study of ecological preferences and distribution of diatoms based on taxonomy and ecological information is important for their successful use, for instance, in water quality bioassessment (Ponader et al., 2007) and to understand the anthropogenic influence on freshwater ecosystems (Dudgeon et al., 2006; Smith et al., 2006).

The present study uses a large data set on tropical reservoirs from southeastern Brazil, covering a wide range of trophic states (from oligo to hypereutrophic) to describe the diversity of Surirellales species and to expand their ecological information. Thus, the objective of this study is (1) to identify and describe the main Surirellales species occurring in surface sediments samples from tropical reservoirs, and (2) to correlate then to environmental factors (pH, total phosphorus and total nitrogen) and spatial predictors. This information would be very important to improve the understanding about the distribution and ecological preferences of Surirellales species, which still is a poorly known diatom group in terms of ecological features in tropical regions.

2. Material and Methods

2.1. Study area

The state of São Paulo has a total area of 248.222.362 km², which is equivalent to 3% of the Brazilian territory (IBGE, 2017). Climate is tropical with dry winter and rainy summer and annual average temperature between 18-22 °C (CEPAGRI, 2015). This study was carried out in 31 reservoirs (123 sampling sites) located in five drainage basins of the Northeast São Paulo (Upper Tietê, Medium

Tietê/Upper Sorocaba, Piracicaba River Basin, Upper Paranapanema and Ribeira do Iguape and Litoral; Figure 1). The reservoirs range from small to large area (0.2-18.9 km²), oligo- to eutrophic conditions, acidic to slightly alkaline (pH: 5.2-8.2) and with different land uses (recreational, power, public water supply). One to five sampling sites were placed in each reservoir, and the number of sites and their position was chosen considering the maximum depth (dam zone) and size of the reservoirs, as well as the position of the main tributaries.

2.2. Sampling and samples treatment

Samplings were carried out from 2009 to 2014. Water samples were collected during the summer and winter with a van Dorn bottle along the reservoir vertical profile (subsurface, mean depth and 1 m above the sediments), and the mean values of the water column were used to characterize each sampling site. The following variables were measured: water transparency (based on Secchi disk), water depth, pH (Horiba U-50), dissolved oxygen (DO, mg L^{-1}), total nitrogen (TN, µg L^{-1}) and total phosphorus (TP, µg L^{-1}), according to Standard Methods (APHA, 2005). Euphotic zone (Z_{eu}) was calculated multiplying the water transparency value by 2.7 (Esteves, 1998). Surface sediment samples were collected using a gravity core, saving the top 2 cm section for diatom analyses.

Sediment samples were cleaned for diatom analysis according to Battarbee et al. (2001) using 35% H_2O_2 and 37% HCl at 80 °C. Permanent slides were mounted using Naphrax. Optical microscopy analysis was performed using a Zeiss Axio Imager A2 equipped with Differential Interference Contrast (DIC) and a high-resolution digital camera (MRC5) under 1000x magnification. Taxonomic study was carried out after population analysis and measurement of length (L), width (W), number of striae (S), fibula (F), ribs (R), wing projection (WP) and alar canals (AC) in 10 µm. Species identification followed classic works and recent publications (e.g. Hustedt, 1985; Krammer & Lange-Bertalot, 1991; Lange-Bertalot & Metzeltin, 1996; Cocquyt & Jahn, 2005), and the online catalogue of valid names (California Academy of Sciences, 2012). Terminology of valve morphology was based on Ross et al. (1979) and Barber & Haworth (1981). Taxonomic framing was based on Medlin & Kaczmarska (2004) for
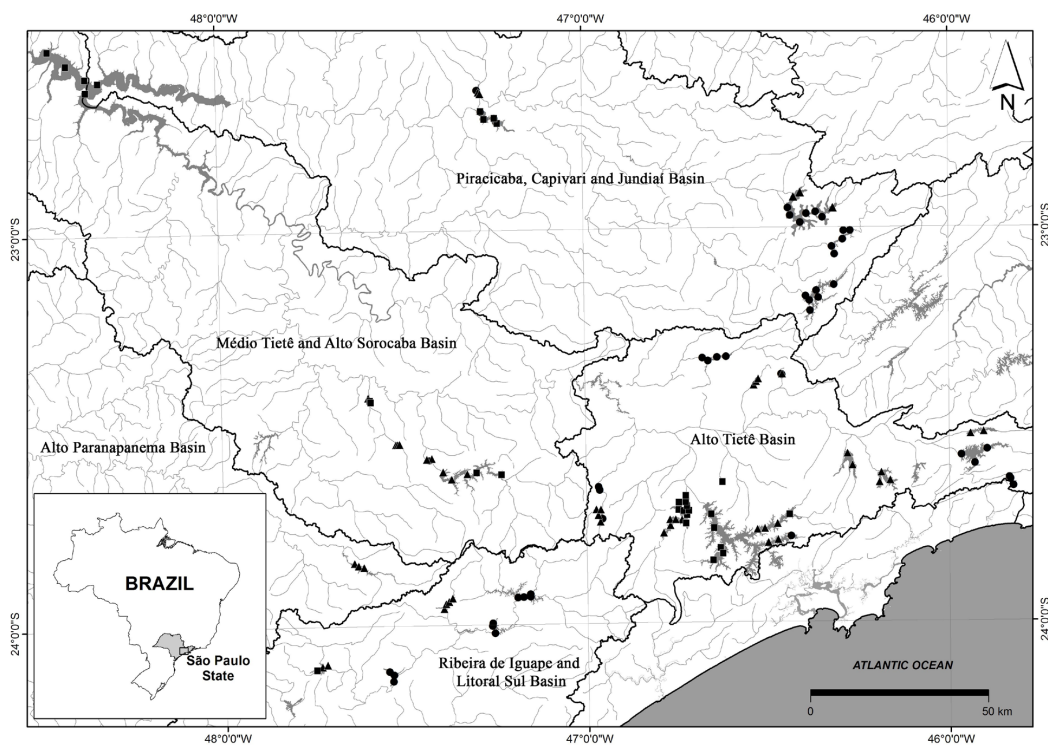

Figure 1. Map with the location of the 31 reservoirs studied (Southeastern Brazil). Black circles represent oligotrophic sampling sites, black triangles represent mesotrophic sampling sites, and black squares represent eutrophic sampling sites. Adapted from Bicudo et al. (2016).

supra-ordinal categories and Round et al. (1990) for subordinal categories. Sediment samples were deposited in the "Herbário Científico do Estado Maria Eneyda P. Kauffmann Fidalgo" (SP), Brazil. Finally, at least 400 valves were counted per slide at 1000× magnification using a Zeiss Axioskop 2 to determine species richness and abundance (Battarbee et al., 2001). Species abundances were expressed as a percentage of the total diatom counts in each sample. Diatom species codes followed the OMNIDIA software (Lecointe et al., 1993).

2.3. Numerical analysis

Based on the available literature (e.g. Zorzal-Almeida et al., 2017b; Bicudo et al., 2016; Virtanen & Soininen, 2012), light availability (euphotic zone: depth ratio), total phosphorus, total nitrogen and molar N:P ratio were selected as the environmental predictors. These variables were log-transformed prior to the analysis (except pH). Principal Coordinates of Neighbor Matrices (PCNM) were used to obtain the spatial variables (Dray et al., 2006). This method uses geographic coordinates of each sampling site, calculates Euclidian distances (overland distances) among sites and produce orthogonal spatial variables to be used as spatial predictors in the canonical analysis (Borcard et al., 2011). Partial Redundancy Analysis (partial RDA) (Figure 2) was used to evaluate the variation within the diatom data set that could be explained by environmental variables without spatial effects. Variation partitioning was used to compute the pure effect of the environmental and spatial predictors in the variation of each taxon and for all diatom data set. This analysis disregards the
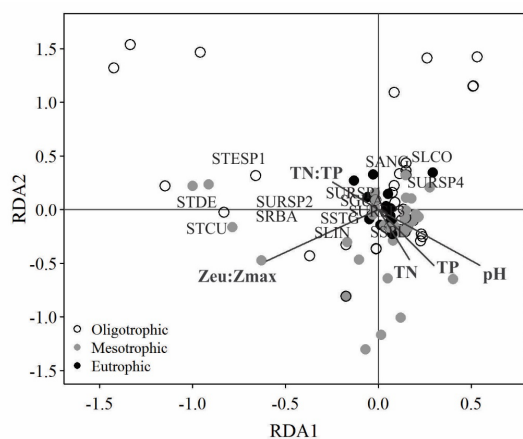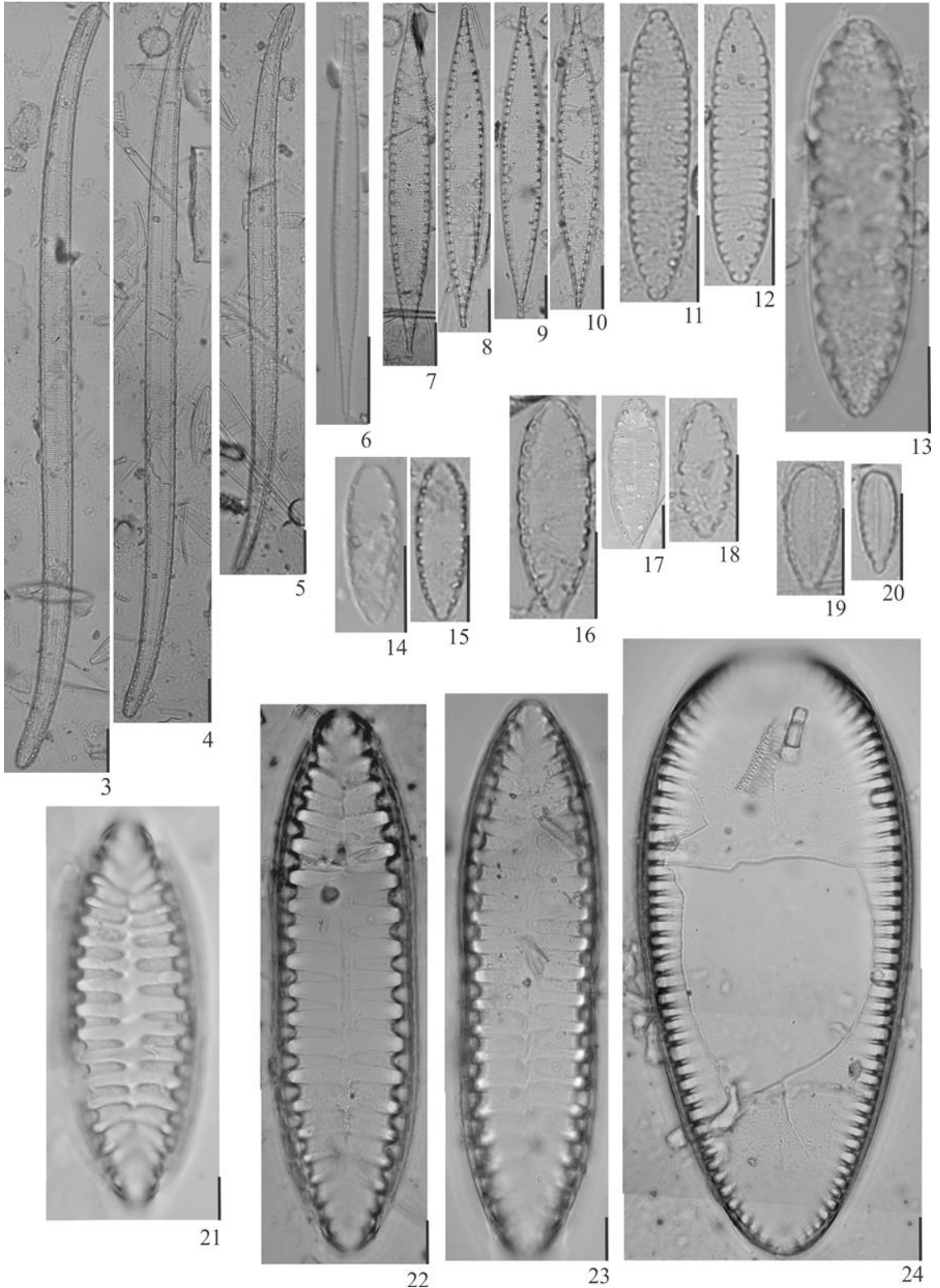

Figure 2. Results of partial RDA for the 14 Surirellales species from surface sediments. Environment variables codes are available in Table 1 and species codes in Table 3.

spatial contribution of the environmental data, and vice-versa, allowing access to the contribution of pure environmental and spatial predictors on the species variation (Peres-Neto & Legendre, 2010). All these statistical analyses were performed using the program R 3.3.1 (R Core Team, 2016) and the packages *PCNM* (Legendre et al., 2009) and *vegan* (Oksanen et al., 2017).

3. Results and Discussion

Our finding reports 14 taxa distributed in two genera and one taxonomic variety of the family Surirellaceae, order Surirellales. We presently found three taxa of *Stenopterobia* (Figure 3-10) and 11 of *Surirella* (Figure 11-33) . Five taxa were identified at the genus level and most likely represent new species. Below is included the taxonomical aspects of all infrageneric taxa and their ecological features according to the available literature for the group and those found in this study, as follows.

Reservoirs ranged from oligotrophic to eutrophic (Table 1), acidic to alkaline and low to high dissolved oxygen. Based on counting analysis, taxa of Surirellales were found in low abundances and frequency of occurrence in all samples (Table 2) and only in oligo- and mesotrophic reservoirs. *Surirella roba* was the most abundant species with 4.7% in the oligotrophic reservoir Cachoeira da Graça (Alto Tietê basin, pH 6.4), followed by *Stenopterobia curvula* with 4.0% in the mesotrophic reservoir Pedro Beicht (Alto Tietê basin, pH 6.1-6.2) (Table 2).

Stenopterobia Brébisson *ex* van Heurck
Stenopterobia curvula (W.Smith) K.Krammer, Bibliotheca Diatomologica 15: 108, pl. 58, fig. 1-4. 1987.

Figures 3-5
Valve isopolar, symmetric, sigmoid; valve ends rounded; axial area hyaline and narrow; ribs absent; fibulae parallel; striae visible, parallel. L: 130.7-176.4 µm; W: 6.6-7.2 µm; L/W: 19.9-24.4; F: 5-6 in10 µm; S: 19-22 in 10 µm.

S. curvula can be also distinguished from *Stenopterobia anceps* ssp. *gigantea* Metzeltin & Lange-Bertalot (2005) mainly due to the larger populations measures of the second species (L: 450.0 µm, W: 17.5 µm) and narrower valve poles of *S. curvula*.

Ecology: It was reported in 5.7% of the samples in oligo- and mesotrophic reservoirs, with water transparency ranging from 0.5 to 2.1 m and pH from 5.4 to 6.2.

Distribution: BRAZIL, São Paulo: Alto Tietê basin, Cachoeira da Graça reservoir, S 23°39.779'
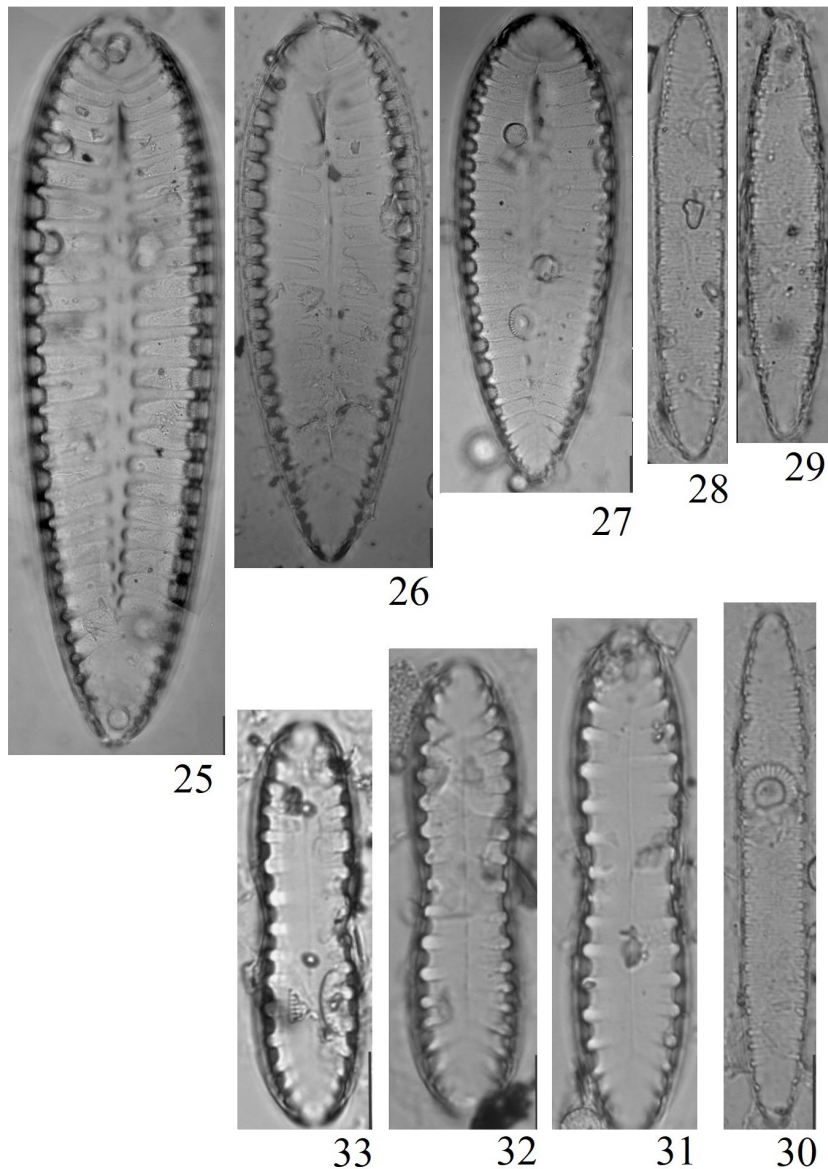
W46°57.928', *P.D.A. Silva & D.C. Bicudo* (SP427583); S 23°39.290' W 46°57.784', *P.D.A. Silva & D.C. Bicudo* (SP427584); Pedro Beicht reservoir, S 23°44.946' W 46°57.660', *P.D.A. Silva & D.C. Bicudo* (SP427578); S 23°44.008' W 46°57.409', *P.D.A. Silva & D.C. Bicudo*

Figures 3-24. Surirellales from surface sediments, São Paulo state, Brazil. Scale bar: 10 μm. 3-5. *Stenopterobia curvula*. 6. *Stenopterobia delicatissima*. 7-10. *Stenopterobia* sp. 1. 11-12. *Surirella angusta*. 13. *Surirella roba*. 14-15. *Surirella* sp. 3. 16-18. *Surirella* sp. 2. 19-20. *Surirella stalagma*. 21. *Surirella* sp. 4. 22-23. *Surirella linearis*. 24. *Surirella guatimalensis*.

Figures 25-33. Surirellales from surface sediments, São Paulo state. Brazil. Scale bar: 10 µm. 25-27. *Surirella splendida.* 28-30. *Surirella* sp. 1. 31-33. *Surirella linearis* var. *constricta.*

(SP427579); S 23°43.048' W 46°57.676', *P.D.A. Silva & D.C. Bicudo* (SP427580); S 23°44.095' W 46°587.160', *P.D.A. Silva & D.C. Bicudo* (SP427581); S 23°43.000' W 46°58.647', *P.D.A. Silva & D.C. Bicudo* (SP427582); Ribeirão do Campo reservoir, S 23°39'31.8" W 45°49'23.2", *A.C.R. Rocha & D.C. Bicudo* (SP468841); S 23°38'30.8" W 45°49'51.2", *A.C.R. Rocha & D.C. Bicudo* (SP468842); S23°38'15.2" W45°50'0.78", *A.C.R. Rocha & D.C. Bicudo* (SP468843).

Stenopterobia delicatissima (F.W.Lewis) L.A.Brébisson *ex* H.van Heurck, A treatise on the Diatomaceae: 374, figs. 19-51. 1986.

Figure 6

Valve isopolar, symmetric, elliptical-lanceolate; pointed apices; axial area hyaline and narrow; ribs absent; alar canals delicate; fibulae delicate; striae parallel, delicate. L: 46.1 µm; W: 3.0 µm; L/W: 15.6; F: 4-5 in 10 µm; S: 24-26 in 10 µm; AC: 11 in 10µm.

S. delicatissima differs from *Stenopterobia chilensis* Metzeltin & Lange-Bertalot (2005) mainly because the second species is wider (W: 7.5-8.5 µm) and presents smaller density of alar canals (4.5-5.5 in 10 µm).

Ecology: *S. delicatissima* is considered a cosmopolitan oligo-mesotrophic species (Krammer & Lange-Bertalot, 1988), existing in acidic waters

Table 1. Mean (minimum-maximum) of the environmental variables measured in the sampled reservoirs (n = 123 sites).

	All reservoirs	Oligotrophic reservoirs	Mesotrophic reservoirs	Eutrophic reservoirs
Depth (m)	11.4	16.4	8.3	9.0
	(0.5-42.5)	(0.5-39.5)	(0.8-42.5)	(3.0-18.0)
Water transparency (m)	1.7	2.2	1.5	1.1
	(0.3-4.2)	(0.5-4.2)	(0.5-2.9)	(0.3-1.5)
Light penetration	0.5	0.5	0.6	0.4
	(0.1-1.0)	(0.2-1.0)	(0.1-1.0)	(0.1-1.0)
pH	6.7	6.3	6.6	7.4
	(5.2-8.2)	(5.2-7.3)	(5.8-7.6)	(6.6-8.2)
DO (mg L^{-1})	5.7	5.8	5.7	5.5
	(2.3-10.7)	(3.7-8.6)	(3.3-7.2)	(2.3-10.7)
TN (µg L^{-1})	966.9	340.9	625.1	2452.9
	(152.0-10209.5)	(152.0-770.4)	(163.1-1735.7)	(400.3-10209.5)
TP (µg L^{-1})	37.8	10.1	23.9	101.8
	(4.0-442.1)	(4.0-24.5)	(11.7-81.2)	(25.4-442.1)
N:P	78.7	95.8	68.7	69.0
molar ratio	(23.9-354.6)	(31.4-257.6)	(23.9-354.6)	(28.7-170.4)

DO: dissolved oxygen; TN: total nitrogen (µg L^{-1}); TP: total phosphorus (µg L^{-1}); Light penetration: Z_{eu}:Z_{max} ratio.

Table 2. Surirellales relative abundance and frequency of occurrence in samples (n = 123 sites). Species codes according to OMNIDIA (except for material at generic level).

Species	Species codes	Abundance (%)	Frequency of occurrence (%)
Stenopterobia curvula	STCU	0.0-4.0	5.7
Stenopterobia delicatissima	STDE	0.0-0.4	6.5
Stenopterobia sp. 1	STESP1	0.0-3.0	2.4
Surirella angusta	SANG	0.0-0.3	0.8
Surirella guatimalensis	SGUA	0.0-0.2	0.8
Surirella linearis var. *linearis*	SLIN	0.0-0.8	0.8
Surirella linearis var. constricta	SLCO	0.0-0.2	1.6
Surirella roba	SRBA	0.0-4.7	0.8
Surirella splendida	SSPL	0.0-0.3	3.2
Surirella stalagma	SSTG	0.0-0.4	0.8
Surirella sp. 1	SURSP1	0.0-0.5	0.8
Surirella sp. 2	SURSP2	0.0-0.4	1.6
Surirella sp. 3	SURSP3	0.0-0.5	1.6
Surirella sp. 4	SURSP4	0.0-0.2	1.6

(Lowe, 2003). In our study, this species was distributed in 6.5% of all samples and exclusively found in oligotrophic conditions, with water transparency ranging from 0.5 to 2.0 m and pH of 5.4.

Distribution: BRAZIL, São Paulo: Alto Tietê basin, Ribeirão do Campo reservoir, S 23°38'30.8" W 45°49'51.2", *A.C.R. Rocha & D.C. Bicudo* (SP468842); S23°38'15.2" W45°50'0.78", *A.C.R. Rocha & D.C. Bicudo* (SP468843).

Figures 7-10

***Stenopterobia* sp. 1**

Valve isopolar, symmetric, linear to linear-lanceolate; pointed apices; axial area hyaline and narrow; ribs absent; fibulae parallel; striae visible, parallel. L: 69.4-81.2 µm; W: 8.7-9.5 µm; S: 11-16 in 10 µm; L/W: 7.3-8.8; AC: 4-5 in 10 µm; F: 10-12 in 10 µm.

Regarding the valve shape, the present material resembles *Stenopterobia hulli* Metzeltin & Lange-Bertalot (2005). However, the latter presents populations with smaller values of width (7-7.5 µm). In addition, *S. hulli* has valves fusiform and short protracted ends.

Ecology: This taxon occurred in 2.4% of samples in oligo and mesotrophic conditions, with water transparency ranging from 0.7 to 1.5 m and pH from 6.1 to 6.2.

Table 3. Results of partial RDA analysis and ecological range for each species.

| | Partial RDA | | | | | Ecological range | |
	Env	E+S	Spa	Res	pH	TN (µg L⁻¹)	TP (µg L⁻¹)
Stenopterobia curvula	**0.08**	0.10	**0.26**	0.55	6.1-6.2	163.1-278.8	9.6-15.7
Stenopterobia delicatissima	**0.25**	0.00	0.02	0.73	5.4-6.2	163.1-418.6	4.0-15.0
Stenopterobia sp. 1	**0.17**	0.02	**0.15**	0.65	5.4	292.7-425.6	4.0-4.4
Surirella angusta	0.01	---	---	1.00	6.1	218.7	14.7
Surirella guatimalensis	---	0.01	---	1.00	6.5	586.8	14.8
Surirella linearis var. *linearis*	0.00	0.00	0.06	0.95	7.6	1185.9	81.2
Surirella linearis var. *constricta*	0.01	0.02	---	1.00	6.0-6.4	201.8-360.2	12.3-24.5
Surirella roba	**0.29**	---	**0.18**	0.55	6.1-6.2	163.1-278.8	9.6-15.7
Surirella splendida	---	---	0.08	0.94	6.6-6.8	305.4-355.4	17.1-18.0
Surirella stalagma	---	0.01	---	1.00	6.7-6.9	284.5-748.7	19.1-25.5
Surirella sp. 1	0.02	---	0.08	0.95	6.4	305.5	10.2
Surirella sp. 2	**0.09**	0.01	---	0.92	5.2	465.5	4.0
Surirella sp. 3	0.00	0.02	---	1.00	7.0	410.7	35.2
Surirella sp. 4	0.04	0.02	---	0.96	6.9-7.1	167.3-203.7	8.1-11.6

Env: environmental variables, Spa: spatial variables, E+S: environmental and spatial variables, Res: residual, TN: total nitrogen, TP: total phosphorus. Species codes in Table 2. Bold numbers in partial RDA are significant results (P > 0.05). Negative results in partial RDA are not shown.

Distribution: BRAZIL, São Paulo: Alto Tietê basin, Cachoeira da Graça reservoir, S 23°39.779' W46°57.928', *P.D.A. Silva & D.C. Bicudo* (SP427583); S 23°39.290' W 46°57.784', *P.D.A. Silva & D.C. Bicudo* (SP427584); Pedro Beicht reservoir, S 23°44.008' W 46°57.409', *P.D.A. Silva & D.C. Bicudo* (SP427579); S 23°43.048' W 46°57.676', *P.D.A. Silva & D.C. Bicudo* (SP427580); S 23°44.095' W 46°587.160', *P.D.A. Silva & D.C. Bicudo* (SP427581); S 23°43.000' W 46°58.647', *P.D.A. Silva & D.C. Bicudo* (SP427582).

Surirella Turpin

Surirella angusta F.T.Kützing, Die Kieseslchaligen Bacillarien oder Diatomeen. 61, pl. 30, fig. 52. 1844.

Figures 11-12

Valve isopolar, symmetric, isobilateral, linear to linear-lanceolate; keel low; valve ends cuneate-rounded; axial area hyaline and narrow; ribs absent; wings projection absent; fibulae absent; costae raised; striae dense. L: 31.8-33.4 µm; W: 7.1-7.3 µm; L/W: 4.5-4.6; inconspicuous striae; C: 8-9 in 10 µm.

S. angusta differs from *Surirella antioquiensis* S.E. Sala, J.J. Ramírez, Plata-Díaz & Vouilloud (2012) mainly due to its larger valve dimensions (*S. antioquiensis* L: 14.0-32.0 µm). According to Sala et al. (2013), these species are different mainly due to the striae pattern (uniseriate in *S. antioquiensis* and multiseriate in *S. angusta*), ribs (narrow and visible in *S. antioquiensis*) and axial area (broad in *S. antioquiensis*).

Ecology: This is a cosmopolitan species reported in alkaline waters (Hustedt, 1938). Metzeltin & Lange-Bertalot (2005) found *S. angusta* in eutrophic lakes with high conductivity. Presently, it was found in 0.8% of all samples in oligotrophic conditions, with water transparency of 1.1 m and pH of 6.1.

Distribution: BRAZIL, São Paulo: Alto Tietê basin, Paiva Castro reservoir, S 23°19'43" W 46°38'11", *S.Z. Almeida & D.C. Bicudo* (SP469260).

Surirella guatimalensis C.G.Ehrenberg, Mikrogeologie: das erden und felsen schaffende Wirken des unsichtbar kleinen selbstständigen Lebens auf der Erde. 19, pl. 33, fig. 7. 1854.

Figure 24

Valve heteropolar, asymmetric; keel low; apical pole broadly rounded, basal pole rounded; axial area elongated; ribs absent; wings projection absent; fibulae visible, short. L: 139.5 µm; W: 62.8 µm; L/W: 2.2; striae inconspicuous; F: 8 in 10 µm.

This species is very similar to *Surirella davidsonii* Schmidt regarding its valve outline. However, *S. davidsonii* usually presents populations with smaller dimensions (L: 90.0-138.0 µm; W: 33.0-60.0 µm) and the presence of a linear axial area (Oliveira et al., 2012).

Ecology: Reported in tropical freshwater ecosystems with low water current (Rivera, 1974). In the present study, the species was found in 0.8% of all samples in mesotrophic conditions, with water transparency of 2.6 and pH of 6.5.

Distribution: BRAZIL, São Paulo: Alto Tietê basin, Cabuçu reservoir, S 23°24'00.6"

W 46°31'56.6", *S.A. Oliveira, D.C. Bicudo & C.E.M. Bicudo* (SP428923).

Surirella linearis var. ***linearis*** W.Smith, A Synopsis of the British Diatomaceae. 31, pl. 8, fig. 58. 1853.

Figures 22-23

Valve isopolar, symmetric, linear to linear-lanceolate; keel high; valve ends cuneate; axial area narrow; ribs parallel; wings projection parallel; fibulae absent; valve face ornamented with undulations; presence of small countless striae in valve face. L: 125.3-128.1 µm; W: 31.7-33.2 µm; L/M: 3.8-4.0; inconspicuous striae; R: 4 in 10 µm; WP: 4 in 10 µm.

S. linearis var. *linearis* differ from *S. linearis* var. *constricta* Grunow due to the absence of a constriction in the mid portion of valves (Lange-Bertalot, 2004).

Ecology: It is a cosmopolitan species (Foged, 1981), acidophilic (Schoeman, 1973) with pH optimum 6.0, common in rivers, springs and water tanks (Cholnoky, 1952). In the present study, *S. linearis* occurred in 0.8% of all samples in mesotrophic conditions, with water transparency of 0.5 m and pH of 7.6.

Distribution: BRAZIL, São Paulo: Alto Tietê basin, Cachoeira da Graça reservoir, S 23°39.779' W 46°57.928', *P.D.A. Silva & D.C. Bicudo* (SP427583); S 23°39.290' W 46°57.784', *P.D.A. Silva & D.C. Bicudo* (SP427584). Médio Tietê/Alto Sorocaba basin, Hedberg reservoir, S 23º 25' 55.86 W 47º 35' 33.06", *E.C.R. Bartozek & D.C. Bicudo* (SP469240).

Surirella linearis var. ***constricta*** A.Grunow, Verhandlungen der Kaiserlich-Königlichen Zoologisch-Botanischen Gesellschaft in Wien 12: 455, pl. 18. 1862.

Figures 31-33

Valve isopolar, symmetric, isobilateral; keel high; valve poles broadly rounded; axial area hyaline, narrow; ribs parallel; wings projection distinct, parallel; fibulae absent. L: 52.6-65.4 µm; W: 14.3-14.5 µm; L/M: 3.7-4.5; inconspicuous striae; R: 3 in 10 µm; WP: 2 in 10 µm.

This species is very similar to *Surirella dydima* Kützing in its valve outline. However, they are different because *S. dydima* has valve poles cuneate (Kützing 1844).

Ecology: This is a cosmopolitan species reported in freshwater environments with pH optimum in alkaline waters (Frenguelli, 1941). Nevertheless, Metzeltin et al. (2005) registered this species in acidic or slightly acidic waters. During the present study, *S. linearis* var. *constricta* was found in 1.6% of all samples in oligotrophic systems, with water

transparency ranging from 1.5 to 1.6 and pH from 6.0 to 6.4.

Distribution: BRAZIL, São Paulo: Piracicaba, Capivari e Jundiaí basin, Cachoeira reservoir, S 23°00'35" W 46°16'05", *S.Z. Almeida & D.C. Bicudo* (SP469248); Alto Tietê basin, Paiva Castro reservoir, S 23°20'15" W 46°39'41", *S.Z. Almeida & D.C. Bicudo* (SP469261).

Surirella roba L.Leclercq (1983), Bulletin du Jardin Botanique National de Belgique 53(3-4): 491-505.

Figure 13

Valve heteropolar, elliptic; keel short; apical pole broadly rounded, base pole cuneate; axial area narrow; wings projection parallel; fibulae absent. L: 45.8 µm; W: 12.4 µm; L/M: 3.7; striae inconspicuous; WP: 3 in 10 µm.

This species differs from *Surirella linearis* Smith due to its smaller populations and smaller number of wings projection in 10 µm (Krammer & Lange-Bertalot, 1991: *S. linearis*: L: 107.5-140.8 µm; WP: 4-6 in 10 µm).

Ecology: Registered in oligotrophic waters (Krammer & Lange-Bertalot, 1991). In the present study, the species occurred in 0.8% of all samples in oligo and mesotrophic conditions, with water transparency ranging from 0.7 to 1.4 m and pH from 6.1 to 6.2.

Distribution: BRAZIL, São Paulo: Alto Tietê basin, Cachoeira da Graça reservoir, S 23°39.779' W46°57.928', *P.D.A. Silva & D.C. Bicudo* (SP427583); S 23°39.290' W 46°57.784', *P.D.A. Silva & D.C. Bicudo* (SP427584).

Surirella splendida (C.G.Ehrenberg) F.T. Kützing, Die Kieselschaligen Bacillarien oder Diatomeen. 62, pl. 7, fig. 9. 1844.

Figures 25-27

Valve heteropolar, asymmetric; keel high; apical pole broadly rounded, basal pole cuneate; axial area hyaline, lanceolate with 1 spine; ribs parallel; wings projection parallel; fibulae absent. L: 122-189.9 µm; W: 42.7-52 µm; L/M: 2.9-3.6; striae inconspicuous; R: 4-6 in 10 µm; WP: 2-6 in 10 µm.

This species is very similar to *Surirella tenera* Gregory in Krammer & Lange-Bertalot (1988) regarding the valve outline and the presence of a spine at the apical pole. However, *S. splendida* presents larger valve dimensions than *S. tenera* (L: 84.0-140.8 µm; W: 30.7-40.8 µm) and basal pole slightly cuneate (Krammer & Lange-Bertalot, 1988).

Ecology: It is considered a cosmopolitan, benthonic and planktonic species. It can be found in coastal areas, especially in the margin of rivers (Frenguelli, 1941; Cholnoky, 1952; Hustedt, 1957).

We have presently recorded the occurrence of *S. splendida* in 3.2% of all samples in mesotrophic waters, with water transparency ranging from 1.9 to 2.3 and pH from 6.6 to 6.7.

Distribution: BRAZIL, São Paulo: Alto Tietê basin, Cabuçu reservoir, S 23°23'25.6" W 46°31'42.8", *S.A. Oliveira, D.C. Bicudo & C.E.M. Bicudo* (SP428921); Ribeira do Iguape and Litoral Sul basin, Salto do Iporanga reservoir, S 24°06'15.0" W 47°44'06.0", *G.C. Marquardt & D.C. Bicudo* (SP469418).

Surirella stalagma M.H.Hohn & J.Hellerman, Transactions of the American Microscopical Society 82: 327, pl. 4, fig. 6. 1963.

Figures 19-20

Valve heteropolar, spatulate; keel short; apical pole broadly rounded, basal pole capitated to subcapitated; axial area hyaline with a visible line in some specimens; ribs absent; wings projection absent; fibulae short and large. L: 11.8-14.5 µm; W: 4.5-6.4 µm; L/M: 2.3-2.6; striae inconspicuous; F: 7-8 in 10 µm.

This species resembles *Surirella atomus* Hustedt in its valve outline. However, *S. stalagma* forms populations with basal pole capitate and short fibulae, whereas *S. atomus* presents basal pole rounded and fibulae broad and short. *S. atomus* usually presents populations with smaller dimensions (L: 8-19 µm; W: 5-8 µm; English, 2011).

Ecology: We have recorded this species in 0.8% of all samples in mesotrophic conditions, with water transparency ranging from 1.2 to 1.9 and pH from 6.6 to 6.9.

Distribution: BRAZIL, São Paulo: Alto Paranapanema basin, Paineiras reservoir, S 23°51'13.8" W 47°36'54.8", *G.C. Marquardt & D.C. Bicudo* (SP469450); Alto Tietê basin, Guarapiranga reservoir, S 23°45'17.7" W 46°46'11.22", *S.B. Faustino & D.C. Bicudo* (SP428508).

Figures 28-30

Surirella sp. 1

Valve isopolar, linear or linear-lanceolate; keel high; valve ends rounded; axial area narrow, hyaline; ribs tenuous, parallel; fibulae distinct, parallel; striae delicate and visible in LM. L: 55.3-66.8 µm; W: 8.9-10.1 µm; L/M: 5.4-7.5; S: 15-19 in 10 µm; F: 4 in 10µm.

This taxon is very similar to *Surirella angusticostata* Hustedt in Simonsen (1987) due to their valve outline, ribs parallel and valve ends rounded. However, *Surirella* sp. 1 presents visible wings projections.

Ecology: This taxon was presently found in 0.8% of all samples in oligotrophic waters, with water transparency of 1.8 m and pH of 6.4.

Distribution: BRAZIL, São Paulo: Piracicaba, Capivari e Jundiaí basin, Atibainha reservoir, S 23°08'50" W 46°18'49" *S.Z. Almeida & D.C. Bicudo* (SP469253).

Figures 16-18

Surirella sp. 2

Valve heteropolar, asymmetric; keel short; apical pole broadly rounded, basal pole cuneate; ribs absent; wing projections distinct, parallel; fibulae absent. L: 17-31 µm; W: 6-13 µm; L/M: 2.4-2.8; striae inconspicuous; WP: 4-5 in 10µm.

This taxon resembles *Surirella pseudotenuis* Cholnoky reported in Cocquyt et al. (2017) on its valve outline. However, *S. pseudotenuis* is narrower (W: 7.0-9.6 µm) than *Surirella* sp. 2.

Ecology: This taxon was registered in 1.6% of all samples and exclusively in oligotrophic conditions, with water transparency of 1.2 m and pH of 5.2.

Distribution: BRAZIL, São Paulo: Alto Tietê basin, Rio Pequeno reservoir, S 23°47.027' W 46°26.188', *S. Wengrat & D.C. Bicudo* (SP401589).

Figures 14-15

Surirella sp. 3

Valve heteropolar, asymmetric, lanceolate; keel low; apical pole broadly rounded, basal pole acute; ribs absent; wings projections small and distinct, not reaching the axial area; fibulae absent. L: 18.3-18.5 µm; W: 5.9-6.7 µm; L/M: 2.7-3.1; striae inconspicuous; WP: 4-6 in 10 µm.

This taxon resembles *Surirella pseudotenuissima* Leclerq (1983) and *S. tenuissima* Hustedt emend. Leclerq (1983) due to valve outline. However, *Surirella* sp.3 differs to *S. tenuissima* mainly by absence of axial area undulate and fibulae parallel. *Surirella* sp. 3 differs to *Surirella pseudotenuissima* due to its smaller populations (*Surirella pseudotenuissima* L: 27-57 µm; W: 9.3-13 µm) and absence of striae conspicuous.

Ecology: In this study, it was recorded in 1.6% of all samples in mesotrophic conditions, with water transparency of 2.0 m and pH of 7.0.

Distribution: BRAZIL, São Paulo: Rio Piracicaba basin, Jaguarí reservoir, S 22°57.4.8' W 46°23.3', *M.N. Nascimento & D.C. Bicudo* (SP427353).

Figure 21

Surirella sp. 4

Valve isopolar, symmetric; keel high; valve ends cuneate; axial area narrow; ribs parallel; wings projections large, distinct; fibulae absent.

L: 87.4 μm; W: 30.6 μm; L/M: 2.9; striae inconspicuous; R: 4 in 10 μm; WP: 4 in 10 μm.

This taxon is similar to *Surirella biseriata* Brébisson due to its valve shape, narrow axial area and parallel ribs. However, *S. biseriata* presents apiculate poles (Wolle, 1890).

Ecology: This taxon was registered in 1.6% of all samples in oligotrophic conditions, with water transparency of 3.6 and pH of 7.1.

Distribution: BRAZIL, São Paulo: Rio Piracicaba basin, Jacareí reservoir, S 22°58.15' W 46°23.3', *M.N. Nascimento & D.C. Bicudo* (SP427354).

Partial RDA controlled for 12 significant and positive PCNM variables showed that environmental variables (pH, TP, TN, N:P ratio and $Z_{eu}:Z_{max}$ ratio) explained a total of 15% of the Surirellales species variation (Figure 2; R^2 adj.: 0.06; p < 0.001). The first axis mainly ordinated the species in relation to pH and light availability ($Z_{eu}:Z_{max}$ ratio) values. Species related to slightly less acid waters and less light availability were placed in the positive side of axis 1 (*Surirella* sp. 4 and *Surirella linearis* var. *constricta*), whereas the ones more closely associated to higher light availability and more acidic waters were depicted in the negative side of this axis (*Stenopterobia curvula*, *S. delicatissima* and *Stenopterobia* sp. 1). Variation partitioning analysis revealed that the pure effect of the environmental and spatial predictors on Surirellales species structure was highly significant (p < 0.001). Environment and space were responsible for 6% and 8%, respectively, of species variation. The shared fraction was low (1%), suggesting that the effects of environmental variables spatially structured were low. These findings indicate that the spatial distribution of environmental resources and conditions (e.g. light availability and pH) has low effects in the occurrence of such species.

Regarding ecological range, almost all species showed the preference for slightly acidic waters, except for *Stenopterobia* sp. 1 and *Surirella* sp. 2, which were found in more acidic waters (pH 5.4 and 5.2, respectively; Table 3). Besides, all taxa were mostly found in low nutrient waters (TN < 784.7 μg L^{-1}; TP < 35.2 μg L^{-1}), except for *Surirella linearis* that prefers to live in higher nutrients conditions (TN = 1185.9 μg L^{-1}; TP = 81.2 μg L^{-1}).

Several studies have been reported the effects of the spatial distribution in diatoms (Heino et al., 2010; Soininen et al., 2004), but species of Surireralles were often neglected. It is not surprising that we presently found significant effects of spatial variables in some taxa studied (Table 3), since they are not ubiquitous species. *Stenopterobia curvula*, *Stenopterobia* sp. 1 and *Surirella roba* showed relatively high effects of space variables (determined by geographic distance), suggesting that this group could have a geographical distribution. Until recently, distribution of microorganisms was not attributed to spatial factors such as geographic distance, but this paradigm has been altered with new findings such as those in the present study, as well as other studies (e.g. Soininen 2007; Heino et al., 2010; Zorzal-Almeida et al., 2017a).

In conclusion, our study presents taxonomical and ecological information for 14 taxa of Surirellales, five of them probably being new species for science. Furthermore, our results corroborate general information about Surirellales from the literature demonstrating that, despite their low abundance and occurrence in samples, Surirellales species have preferences for oligo- and mesotrophic conditions, neutral or slightly acidic waters and higher light availability values. Moreover, our results suggest that some Surirellales species (e.g. *Stenopterobia curvula*) can show some degree of geographical distribution.

Acknowledgements

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