

TWO-DECADE REMAINING EFFECTS OF BAUXITE TAILINGS ON THE FISH TAXONOMIC STRUCTURE OF A CLEAR-WATER FLOODPLAIN LAKE IN CENTRAL AMAZON (BATATA LAKE, PARÁ STATE, BRAZIL)

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ABSTRACT

In recent decades, anthropic disturbances have led to major changes in biological communities. Batata Lake (Oriximiná, Pará State, Brazil) is located in the flood area of the right bank of Trombetas River and received effluents rich in mineral waste due to near mining activities in the 80's, which led to the siltation of 30% of its area and numerous local impacts. We monitored about to 20 years the ichthyofauna of Batata Lake and we assessed if there is still remaining effects of the siltation by bauxite tailings in the affected area. We sampled in Silted and Non-Silted areas in the filling period of 1991 to 2015, using a set of gillnets with mesh sizes between 15 to 70 mm. Differences in taxonomic structure (estimated richness, Simpson's dominance and Shannon's diversity) and in community composition among Silted and Non-Silted areas were evaluated with multivariate analysis, considering year as covariate. We sampled 10,435 individuals classified in 141 species. Only 41 species represented 90% of total abundance, which we considered the numerically dominant fishes in the lake. Among taxonomic indices, only estimated richness exhibited a significant trend through time; high estimated richness in the Silted area during the first years of monitoring and posterior decreasing. This negative slope was highly affected by a single point in 1992, so we considered it a particular case in time and not a real temporal trend. Significant changes in community composition occurred among areas by differentiation in species abundance, and not by species loss. These results show that siltation effects in Batata Lake did not express itself as a loss of biodiversity, but in the reconfiguration of the community composition according to species niche.

Keywords: fish assemblage; ichthyofauna; long-term monitoring; mining activities; siltation.

INTRODUCTION

Anthropogenic modification undoubtedly affects chemical parameters and habitat characteristics of aquatic systems, which alters environmental filters and thus local communities. Environmental filter is one of the predominant assumptions in several ecological studies in community scale, once it highlights species niche suitability to environment (Lebrija-Trejos *et al.* 2010). Despite other processes underlying community structure, the primordial role of environment in selecting species that can sustain viable populations and/or favor higher abundances of some species is the core of these studies.

In Neotropical fish communities, physicochemical parameters variability through seasonal or spatial gradients are often associated with changes in fish richness and composition (Ferreira &

Casatti 2006, Suárez *et al.* 2011), as well as habitat characteristics in different scales (Galacatos *et al.* 2004). Nonetheless, habitat alterations, as expected by an environmental filtering assumption, also led to numerous changes in both local and regional scales. Specifically in lakes, a variety of causes has been pointed to change habitats and communities: transhumance, the summer transferring of the livestock to highlands in European Alps, alters the trophic state of lakes near highly pressured pastures (Tiberti *et al.* 2014); tourism causes pollution and contamination (Dokulil 2014); mining activities that deposited tailings in lakes led to siltation and/or heightening of metal concentrations, affecting local biodiversity (Bozelli *et al.* 2000, Klaverkamp *et al.* 2002, McDonald *et al.* 2010). Mining activities have also been showed to cause loss in the diversity of primary producers (Niyogi *et*

al. 2002), loss of biomass of fishes and homogenization of fish fauna (Brosse *et al.* 2011, Hitt & Chambers 2014) in lotic environments.

A unique monitored case of mining effects in Brazilian Amazon occurs in the Batata Lake, located on the right bank of Trombetas River, Pará, Brazil. The lake received effluents rich on inactive mineral waste between 1979 and 1989 from bauxite exploration by Mineração Rio do Norte (MRN). Bauxite tailings silted 30% of total area of the lake and caused numerous local impacts, such as the death of the Igapó Forest and the increase of the water turbidity in the Silted area (Bozelli *et al.* 2000). In the impacted area, the benthic macroinvertebrate communities exhibited a drastic change in composition: a loss in diversity and abundance of Dipteran larvae (Callisto & Esteves 1996), oligochaetes and bivalves (Fonseca & Esteves 1999), while the Ephemeropteran nymphaea of *Campsurus notatus* (Needham & Murphey 1942) were well adapted to the siltation and exhibited higher densities and biomass in the Silted area (Leal & Esteves 2000).

Caramaschi *et al.* (2000) analyzed ten years of fish monitoring and observed evidences of recovery of the Silted area based on diversity and biomass, but Lin (2003) still found lower abundance and biomass of

fishes in the Silted area, which could be mediated by seasonal variation. Nevertheless, these studies did not evaluate the whole monitoring data to assess long-term impacts of the siltation in the fish fauna or the effects of the restoration of the Igapó in the Silted area. Thus, we analyzed almost 25 years (1991-2015) of monitoring of Batata Lake to assess if: (i) there was significant changes in estimated richness, dominance and diversity of the fish assemblage between areas; (ii) there was a temporal trend in the diversity indices in the Silted area; (iii) the community composition exhibits differences among both areas.

MATERIAL AND METHODS

Study area

Batata Lake is located in the flood area of the right bank of the Trombetas River, between coordinates 1°25' and 1°35' S, and 56°15' and 56°25' W (Figure 1), near Porto Trombetas, Oriximiná Municipality, Pará State, Brazil. The lake has clear water and vegetation predominantly of Igapó, it covers about 18 km² during dry season and 30 km² in rainy season and it is continuously connected to Trombetas River through its southern portion (Panosso 2000).

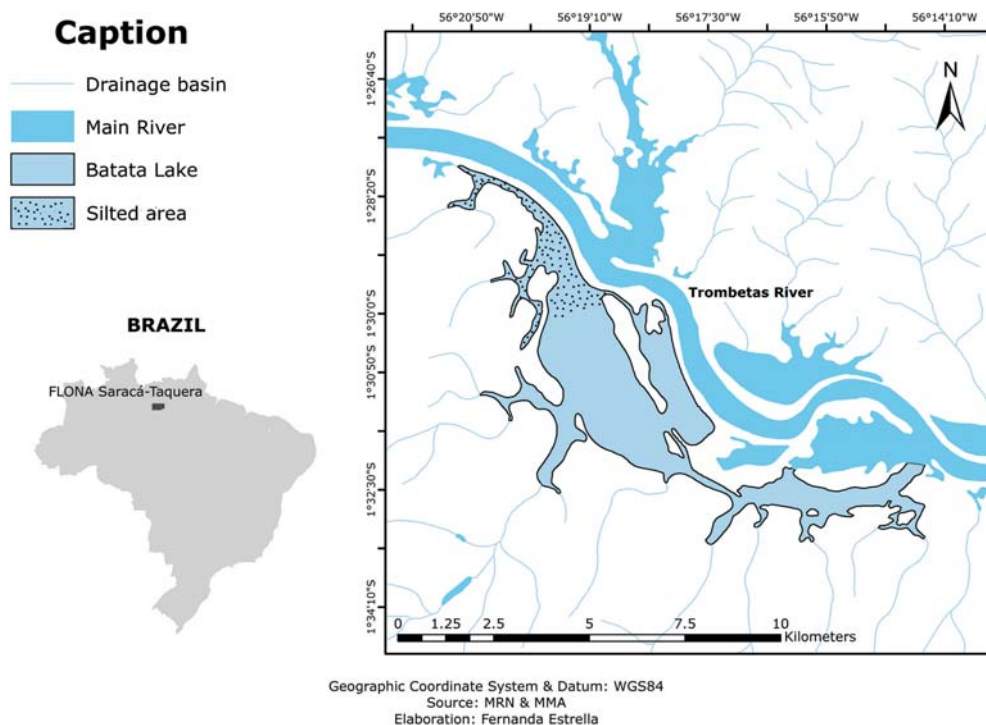


Figure 1. Batata Lake, Oriximiná Municipality, Pará State, Brazil. The National Forest Saracá-Taquera and the Trombetas River are highlighted, as well as the Silted area of the lake (dotted).

Due to mining activity in the National Forest Saracá-Taquera, a situation of spatial heterogeneity within the lake was built: a Silted area and a Non-Silted area. Even ten years later the stoppage of mineral waste emission, the Silted area still exhibited lower transparency and depth than the Non-silted area (Lin & Caramaschi 2005a).

Sampling design

Standardized sampling was carried out between 1991 and 2015 (except 1994-1996) during the filling period, usually on March. Fishes were caught using a set of gillnets with mesh sizes between 15 to 70 mm, setup among 04:00 pm and 06:00 pm, inspected and winkled out from 08:00 pm; resettlement at 03:30 am, inspected and removed from 08:00 am. Samplings occurred in two different areas of the lake: (i) the Silted area, which exhibits bauxite tailings located on the portion of the lake affected by siltation where the natural substrate of the lake is completely covered; (ii) and the Non-Silted area, with no evidence of bauxite tailings. Through the years, sampling occurred in different nearby points in each area.

Individuals were identified as morphotypes on field, fixed with formalin 10%, individually labeled and sent to determination on the Fish Ecology Laboratory at the Federal University of Rio de Janeiro (UFRJ). Voucher specimens were deposited in the collection of the Fish Ecology Laboratory/UFRJ (Appendix 1). Sampling methods were designed in the beginning of the monitoring (1990) and were maintained in order to grant the temporal analyses of the fish community, being described in detail by Caramaschi *et al.* (2000).

Data analysis

We analyzed differences on the taxonomic diversity and on the ichthyofauna composition among Silted and Non-Silted areas in Batata Lake. Only dominant fish species were considered for the analyses; dominant species were considered as the most abundant species in Batata Lake that summed up 90% of total abundance caught over the years.

As multiple factors interact in diversity structuring, we considered that the long time series could explain partially the diversity changes observed in our dataset. This could happen for two reasons: (i) temporal turnover is a ubiquitous phenomenon in natural communities that would lead to higher similarity the nearer in time samples are; (ii) the lake did not receive bauxite waste after the 90's and the Silted area partially recovered its Igapó Forest through the years, which would affect fish diversity. So, all of our analyses aimed to consider the effect of temporal changes in fish diversity.

We calculated three indices to evaluate different properties of the taxonomic diversity: (i) Jackknife 1 (estimated richness); (ii) Simpson's index (dominance); and (iii) Shannon's diversity. We used paired t-tests to analyze if there are differences between Silted and Non-silted areas for each index.

In order to evaluate if there was trends in the taxonomic indices in the Silted area through time, we calculated a ratio for each index between Silted and the Non-Silted area values in the same year. The higher the ratio value, the higher the index (richness, dominance or diversity) in the Silted area. We used a linear regression to evaluate if there are temporal trends in the ratios and, consequently, restoration to similar taxonomic structures. Thus, if there was a difference in the earlier years between areas (*e.g.*, lower richness in the Silted area) but not in the next years, an increasing trend in the richness ratio would be observed.

We also evaluated if fish composition varied among Silted and Non-Silted areas using an Analysis of Similarity (ANOSIM) of two factors. We used area as the first factor and a factor with five categories that include 5-years blocks (Period 1: 1991-1995; Period 2: 1996-2000; Period 3: 2001-2005; Period 4: 2006-2010; Period 5: 2011-2015). Herein, we report only the effect of the Area controlled by time variation on community composition. Afterwards, we used a Similarity Percentages analysis (SIMPER) to observe which species were determinants in the differences in the fish assemblage among areas.

We used the vegan package (Oksanen *et al.* 2016) to calculate diversity indices and analyses related to community composition in R (R Core Team 2016). All statistical tests considered 5% significance level.

RESULTS

Taxonomic diversity

We sampled 10,435 individuals identified in 141 species. Forty-one species, classified in five orders and 16 families, represented 90% of total abundance (9,412). Characiformes was the most abundant order (53.79% of total abundance), but the siluriform family Auchenipteridae was the most abundant family (27.45%), followed by Hemiodontidae (18.38%) and Curimatidae (12.15%). The most abundant species was *Auchenipterichthys longimanus* (Günther, 1864), which represented 22.4% of the most abundant species. The remaining most abundant species were *Curimata vittata* (Kner, 1858) (7.5% of total abundance), *Triportheus albus* Cope, 1872 (6%) and *Hemiodus argenteus* Pellegrin, 1909 (6%). The most abundant species that summed up 90% of total abundance in Batata lake were considered dominant (Figure 2a) and were used in subsequent analyses. Differences in species abundance between areas may be seen in Figures 2b and 2c.

Estimated richness ranged from 20 to 61 (36 ± 8). Richness did not exhibit differences among Silted and Non-Silted areas (Figure 3a; $t = 1.65$; $df = 19$; $p = 0.11$), but we observed a negative temporal trend (Figure 3b; $R^2 = 0.20$; $p = 0.03$); that is, richness was higher in the Silted area than in the non-Silted area in the first years (high Silted/Non-Silted ratio) and decreased after it. Although a linear regression was significant, we observe that this is not a steady trend; the high Silted/non-Silted ratio in the first years is represented by a single year (1992) that seems to be an outlier in the expected richness' temporal pattern (Figure 3b). When we exclude 1992 from the analysis, there is no temporal trend left ($R^2 = 0.05$; $p = 0.19$). Simpson's index ranged from 0.62 to 0.94 (0.85 ± 0.07). Dominance did not exhibit any patterns among areas (Figure 3c; $t = 0.31$; $df = 19$; $p = 0.76$) nor temporal patterns (Figure 3d; $R^2 = 0.04$; $p = 0.38$). Shannon's diversity ranged from 1.89 to 3.30 (2.63 ± 0.33) and also did not show spatial (Figure 3e; $t = 0.35$; $df = 19$; $p = 0.73$) or temporal (Figure 3f; $R^2 = -0.05$; $p = 0.90$) patterns.

Community composition

Ichthyofauna composition was slightly dissimilar among Silted and Non-Silted areas ($R = 0.26$; $p < 0.001$) due to variance in species' abundance in the same year. Species displayed higher abundances in different areas (Table 1); *Triportheus albus*, *Curimata vittata* and *Hemiodus argenteus* were more abundant in the Silted area, whereas *Hemiodus immaculatus* Kner, 1858 was more abundant in the Non-Silted area, for example. Fourteen species summed half the dissimilarity among Silted and Non-Silted areas, which highlights that some species are more/less prone to occupy a specific area than others.

DISCUSSION

Batata Lake does not display consistent alterations in species' richness or dominance responding to the siltation. However, ichthyofauna composition differed among the two areas due to species occupancy pattern; some species were more abundant in the Silted area and other species were more abundant in the Non-Silted area. Caramaschi *et al.* (2000) already observed similar richness among areas in the first decade of monitoring, except by a heightening of the richness in the Silted area in the filling period due to the attraction of expanded areas provided by inundation, but this difference is not a temporal trend in Batata Lake. In addition, Lin & Caramaschi (2005b) also did not observe differences in the fish diversity between the two areas in the first years of monitoring.

Mining does not exhibit a clear trend over taxonomic structure of fish communities; some areas display biodiversity loss (Kimmel & Argent 2009, Melcher *et al.* 2012), but others do not (Brosse *et al.* 2011). Direct comparisons should not be made, since cases are submitted to different mining pressures and are distributed over different ecosystems. Bauxite tailings are chemically inactive and have a physical effect in the ecosystem, translated in a constant suspension and sedimentation process. Besides that, Batata Lake has a complex dynamic due to the annual variation in rainfall, which affects its size, as well as its connectivity with Trombetas River and the

surrounding Igapó Forest. In the case of Batata Lake, the hydrological period we analyzed (filling period) comprises a season with a strong flooding pulse that diminishes the limnological effects of the tailings over the Silted area and also promotes weaker biological stress from siltation (Bozelli *et al.* 2009). Even with the attenuating effect of the filling period, the siltation provided distinct environmental filters in different areas. In general, it was registered a loss in the depth of the water column, higher turbidity, lower primary production and lower densities of benthic macroinvertebrate fauna (Table 2).

Fish communities may response to environmental changes caused by human impacts through changes in its functional structure and composition, primarily due to abundance responses to temporal and spatial variation (Winemiller *et al.* 2008). Indeed, Brosse *et al.* (2011) observed that stream fish communities have functional responses to mining activities, which favor smaller and habitat-generalist fishes over larger and habitat-specialist species. In Batata Lake, changes in ichthyofauna did not occur by species loss, but by small changes in species' abundance due to habitat preferences, as discussed below. The response based on differences in species' relative abundance may be caused by strong lateral movement of the fishes that inhabit the lake, which may also attenuate the differences between the two areas.

When it comes to fish composition, siluriforms were most abundant in the Silted area. Siluriforms are primarily nocturne and exhibit morphological adaptation to use turbid environments (Brejão *et al.* 2013), which partially explains their success in low-light environments in Amazon basin (Rodríguez & Lewis 1997, Galacatos *et al.* 2004) and in the Silted area of Batata Lake (*e.g.*, *A. longimanus* and *Astrodoras asterifrons*).

Curimata vittata, a detritivorous characiform, was more abundant in the Silted area of Batata Lake, which can be a consequence of the ecosystem role of the highly dominant ephemeropteran *C. notatus* in the Silted area through bioturbation. *C. notatus* nymphs build burrows up to 13 cm that allow water flow within it, which expanded the aerobic layer that led to higher bacterial production in the in the Silted area (Leal *et al.* 2003, 2005). The expansion of the bacterial production within the sediment of the Silted area can enhance decomposition process

(Santana *et al.* 2015), which would favor the occurrence of *C. vittata* in the Silted area.

Hemiodontids did not exhibit a clear trend: some hemiodontids were more abundant in the Silted area and *H. immaculatus* was more abundant in the Non-Silted area. Species that used primarily the Silted area exhibited a tendency to herbivory, using predominantly algae, while *H. immaculatus* consumes predominantly autochthonous invertebrates (M. F. O. Pinto, unpublished data). These patterns are in accordance with benthonic macroinvertebrates, which exhibit lower densities in the Silted area (Callisto 2000), and also with the greater amount of algae in the substrate due to algal sinking from algae-clay aggregation (Guenther & Bozelli 2004) or with the greater algae development on detritus due to low depths that allow the euphotic zone to reach the bottom of the lake in the Silted area, as suggested by Lin & Caramaschi (2005b). Thus, the distribution of Hemiodontids within the lake seems related to the spatial distribution of their food items (aquatic macroinvertebrates and algae) in response to siltation.

Piscivorous species also did not exhibit a clear trend of habitat occupancy toward Silted or Non-Silted area in Batata Lake. Given that, the higher turbidity in the Silted area during the filling period must not be a crucial factor in their distribution within the lake. As suggested by Lin & Caramaschi (2005b), the turbidity in the filling period may not have reached critical levels to inhibit these species occurrence. The habitat preferences of these species may be related to depth preferences, as shown by Layman & Winemiller (2005); pirañas from the genus *Serrasalmus* and peacock basses (*Cichla*) are more abundant in deep waters, while the spotted pike-characin (*Boulengerella*) used predominantly sand banks.

Therefore, the bauxite waste impact in Batata Lake did not express itself in the loss of fish richness, but in the same way that happened for the invertebrate fauna: in a reconfiguration of the community structure. These changes in fauna composition are one of the main patterns of current defaunation worldwide, and may have consequences for both ecosystem functioning and evolutionary processes (Dirzo *et al.* 2014). This looks even more concerning when composition changes in response to anthropic impacts persist through time, as it happen in Batata Lake.

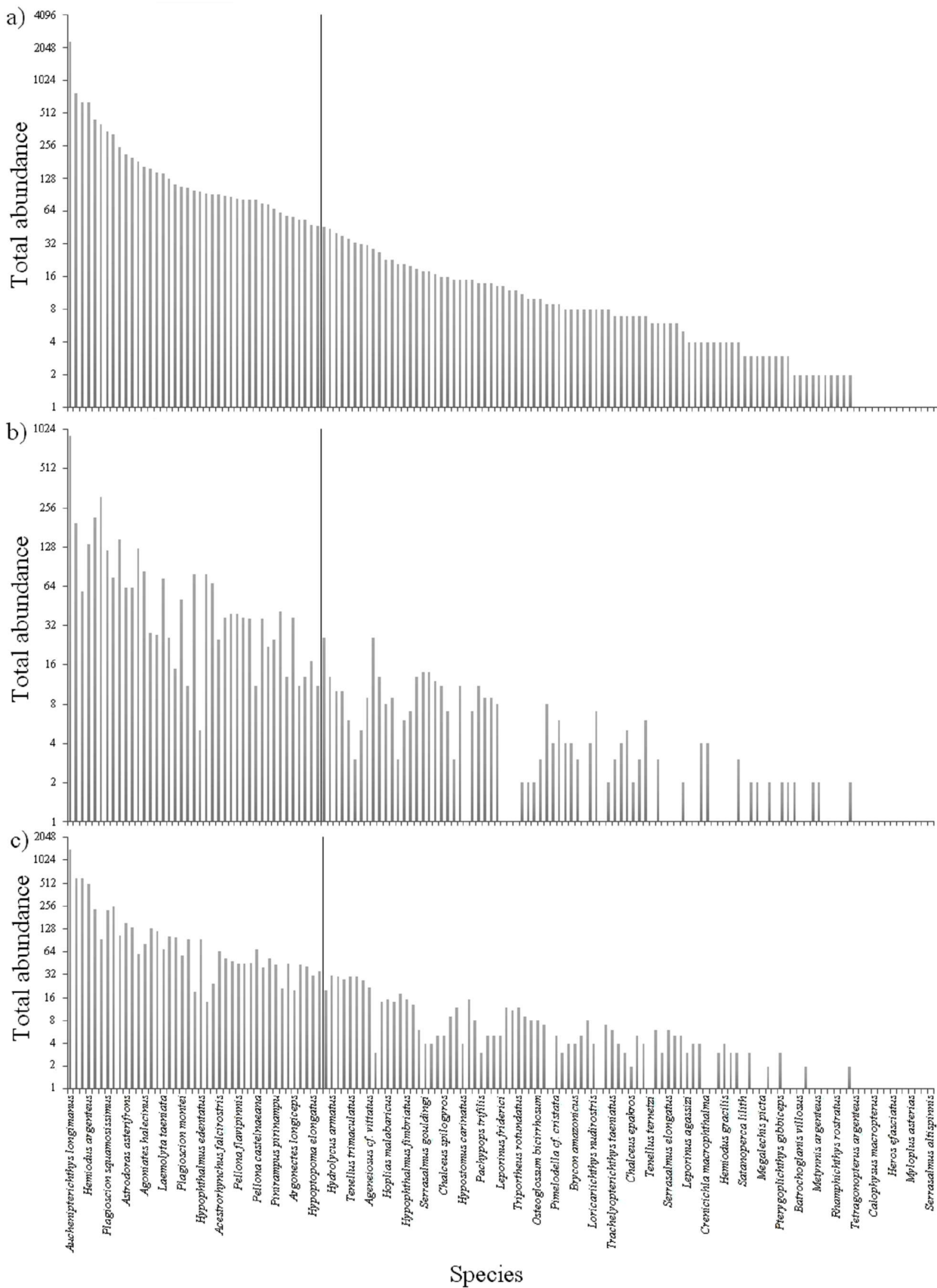


Figure 2. Total abundance of all species captured in all lake (a), only in the Non-Silted area (b) and only in the Non-Silted area (c) of Batata Lake, Pará State, Brazil. Y axes are shown in logarithmic scale. Dominant species are in the left of the black lines.

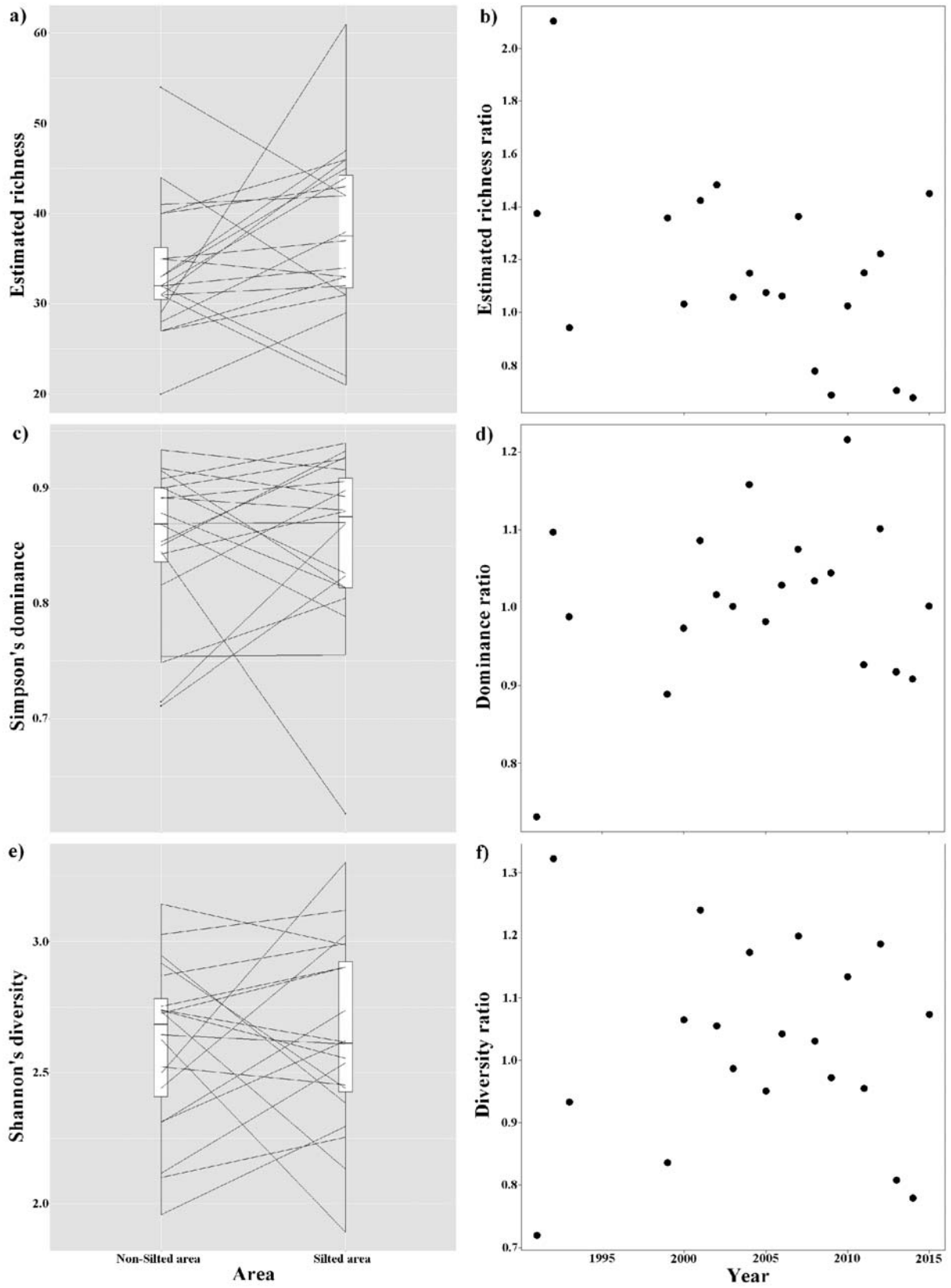


Figure 3. Profile plots comparing estimated richness (a), Simpson’s dominance (c) and Shannon’s diversity (e) of Silted and Non-Silted areas in the same year, and the temporal pattern of the ratio between Silted and Non-Silted area of estimated richness (b), Simpson’s dominance (d) and Shannon’s diversity (e) for the fish community sampled between 1991 and 2015 in Batata Lake, Pará State, Brazil. Lines in the profile plots refer to samples within same year, and profile plots show median, standard error and minimum and maximum values.

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Appendix 1. List of species and respective voucher numbers of the 41 most dominant species in the Batata Lake, Pará, Brazil. Specimens were deposited in the ichthyological collection of the Fish Ecology Lab (DEPRJ) of the Federal University of Rio de Janeiro (UFRJ).

Order/Family/Species	Voucher number
Characiformes	
Serrasalminae	
<i>Myloplus lobatus</i> (Valenciennes, 1850)	DEPRJ 8415
<i>Serrasalmus rhombeus</i> (Linnaeus, 1766)	DEPRJ 8334
Hemiodontidae	
<i>Argonectes longiceps</i> (Kner, 1858)	DEPRJ 8337
<i>Hemiodus argenteus</i> Pellegrin, 1909	DEPRJ 8407
<i>Hemiodus immaculatus</i> Kner, 1858	DEPRJ 8340
<i>Hemiodus unimaculatus</i> (Bloch, 1794)	DEPRJ 8338
<i>Micromischodus sugillatus</i> Roberts, 1971	DEPRJ 8414
Anostomidae	
<i>Laemolyta taeniata</i> (Kner, 1858)	DEPRJ 8412
<i>Leporinus fasciatus</i> (Bloch, 1794)	DEPRJ 8413
Chilodontidae	
<i>Caenotropus labyrinthicus</i> (Kner, 1858)	DEPRJ 8315
Curimatidae	
<i>Curimata vittata</i> (Kner, 1858)	DEPRJ 8389
<i>Curimata roseni</i> Vari, 1989	DEPRJ 8325
<i>Curimata ocellata</i> Eigenmann & Eigenmann, 1889	DEPRJ 8333
<i>Cyphocharax abramoides</i> (Kner, 1858)	DEPRJ 8405
<i>Cyphocharax festivus</i> Vari, 1992	DEPRJ 8406
Ctenoluciidae	
<i>Boulengerella cuvieri</i> (Cuvier, 1816)	DEPRJ 8403
<i>Boulengerella lucius</i> (Valenciennes, 1850)	DEPRJ 8404
Triporthidae	
<i>Agoniatas halecinus</i> Müller & Troschel, 1845	DEPRJ 8382
<i>Triporthus albus</i> Cope, 1872	DEPRJ 8420
Iguanodectidae	
<i>Bryconops alburnoides</i> Kner, 1858	DEPRJ 8375
Acestrorhynchidae	
<i>Acestrorhynchus falcistrostris</i> (Cuvier, 1819)	DEPRJ 8373
<i>Acestrorhynchus microlepis</i> (Jardine, 1841)	DEPRJ 8374
Siluriformes	
Auchenipteridae	
<i>Ageneiosus ucayalensis</i> Castelnau, 1855	DEPRJ 8400
<i>Auchenipterichthys longimanus</i> (Günther, 1864)	DEPRJ 8398
<i>Auchenipterus nuchalis</i> (Spix & Agassiz, 1829)	DEPRJ 8402

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Order/Family/Species	Voucher number
Siluriformes	
Doradidae	
<i>Astrodoras asterifrons</i> (Kner, 1853)	DEPRJ 8401
<i>Hassar orestis</i> (Steindachner, 1875)	DEPRJ 8377
<i>Trachydoras brevis</i> (Kner, 1853)	DEPRJ 8419
Loricariidae	
<i>Hypoptopoma elongatum</i> Aquino & Schaefer, 2010	DEPRJ 8410
<i>Loricariichthys acutus</i> (Valenciennes, 1840)	DEPRJ 8379
Pimelodidae	
<i>Hypophthalmus edentatus</i> Spix & Agassiz, 1829	DEPRJ 8408
<i>Hypophthalmus marginatus</i> Valenciennes, 1840	DEPRJ 8409
<i>Pinirampus pirinampu</i> (Spix & Agassiz, 1829)	DEPRJ 8418
Perciformes	
Cichlidae	
<i>Cichla vazzoleri</i> Kullander & Ferreira, 2006	DEPRJ 8320
<i>Geophagus altifrons</i> Heckel, 1840	DEPRJ 8322
Sciaenidae	
<i>Plagioscion montei</i> Soares & Casatti, 2000	DEPRJ 8321
<i>Plagioscion squamosissimus</i> (Castelnau, 1855)	DEPRJ 8327
Clupeiformes	
Engraulidae	
<i>Lycengraulis batesii</i> (Günther, 1868)	DEPRJ 8332
Pristigasteridae	
<i>Ilisha amazonica</i> (Miranda-Ribeiro, 1920)	DEPRJ 8411
<i>Pellona castelnaeana</i> Valenciennes, 1847	DEPRJ 8416
<i>Pellona flavipinnis</i> (Valenciennes, 1837)	DEPRJ 8417