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From virus to igapó forest: a systematic review of 35 years monitoring of an Amazonian Lake impacted by bauxite tailings (Batata Lake)

Do vírus à floresta do igapó: uma revisão sistemática de 35 anos de monitoramento de um Lago Amazônico impactado por rejeitos de bauxita (Lago Batata)

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Abstract: Aim: Long-term ecological research often integrates many research groups and subjects in one or few sites sampled systematically along the time. In the Amazon, there is a tradition of long-term research in terrestrial habitats, but this has been less common in floodplain lakes. This study systematically reviews 35 years of research (1988-2022) in Batata Lake, a clear water flood plain lake impacted by bauxite mining tailings for ten years (1979-1989) and discuss some research opportunities and challenges for the future. **Methods:** The review covered 99 scientific reports (78 papers and 21 book chapters) comprising a large spectrum of data from snapshot observations and experiments to enduring quarterly observational and hypothesis-testing studies. Soil, sediments, and the water column were consistently sampled in natural and impacted areas. **Results:** Research topics were quite diverse and covered biological communities from aquatic virus to igapó flooded forests and provided an overview of ecological processes such as primary and secondary production. Ecological variables monitored along the project were constrained by a strong seasonality of the flood pulse and the effect of sampling areas (natural and impacted), which was performed by very connected research groups. **Conclusions:** Despite the extensive information, long-term ecosystem function trends are still incomplete.

Keywords: Amazon; Batata Lake; environmental mining impacts; floodplain lake; freshwater; long-term ecological project.

Resumo: Objetivo: Pesquisas ecológicas de longa duração geralmente integram muitos grupos de pesquisa e assuntos variados. Essas pesquisas concentram-se em amostrar sistematicamente ao longo do tempo um ou poucos locais. Na Amazônia, muitas iniciativas foram realizadas para melhor entender as dinâmicas da floresta, mas poucos estudos de longa duração se dedicaram a compreender os lagos de inundação em escala de longo prazo. Neste estudo trazemos informações de pesquisas realizadas durante 35 anos (1988-2022) no Lago Batata, um lago amazônico de águas claras impactado por rejeitos de mineração de bauxita durante dez anos (1979-1989). **Métodos:** Usando a abordagem de uma revisão sistemática da literatura 99 trabalhos (78 artigos e 21 capítulos de livros), nós encontramos que durante os anos de monitoramento, os esforços de amostragem variaram de algumas observações e experimentos pontuais a estudos trimestrais de observação e teste de hipóteses duradouros. Solo, sedimentos e coluna d'água foram amostrados consistentemente no lago como um todo e comparadas às áreas natural e impactada por rejeito de mineração. **Resultados:** Os tópicos de pesquisa foram bastante diversos e abrangeram comunidades biológicas desde vírus aquáticos à floresta de igapó, os quais forneceram uma visão geral dos processos ecológicos locais como produção primária e produção secundária planctônica. A maioria das variáveis ecológicas monitoradas ao longo do projeto foram reguladas por uma forte sazonalidade exercida pelo pulso de inundação e pelos efeitos das áreas de amostragem (natural e impactada), e foram amostradas por grupos de pesquisa muito conectados. **Conclusões:** Apesar da extensa informação sobre a estrutura e função do Lago Batata, tendências gerais sobre suas funções ecossistêmicas permanecem ainda incompletas.

Palavras-chave: Amazônia; Lago Batata; impactos ambientais de mineração; lago de inundação; água doce; projeto ecológico de longa duração.

1. Introduction

Restoration of freshwater ecosystems is a complex environmental challenge and a matter of high priority regionally (Bozelli, 2019) and globally (Harper et al., 2021). The unsustainable use of freshwater resources worldwide is growing and is likely to intensify with human activities and climate change in the coming years (Bernauer & Böhmelt, 2020). Policies and management decisions should be science-based to address global and local environmental issues and to improve ecological integrity and human well-being (Cadotte et al., 2017).

The Long-Term Ecological Research (LTER) studies have provided a robust framework to predict ecosystem changes in the face of environmental impacts (Likens et al., 2001; Likens, 2004). LTER studies play a disproportionately positive scientific role in forecasting system dynamics, detecting causality between variables, and forewarning impending tipping points (Hughes et al., 2017). More importantly, the LTER studies bring essential insights into managing complex environmental issues and improve our understanding of the ecosystem structure and function (Lindenmayer & Likens, 2009). However, there are important constraints for the establishment of a LTER approach in developing countries, often due to limited funding and infrastructure, and/or political issues (Haase et al., 2018; Bozelli, 2019).

In Brazil, the Batata Lake, an Amazonian Lake impacted by bauxite tailings, represents a good example of a LTER study. After 35 years, the lake and its marginal vegetation undergo both natural and implemented restoration (Scarano et al., 2018). It is to date the only long-term project in Brazil exploring the effects of mining tailings in freshwater ecosystems (Bozelli, 2019). In the last few years, this project has become even more critical, given the unprecedented mining disasters faced in Brazil (Carmo et al., 2017; Rotta et al., 2020). Furthermore, mining remains a major economic activity in Amazon, and there is reason to be concerned about the perspective of expansion (Martins et al., 2022), and consequent socioecological risks (Carmo et al., 2020).

The environmental damages caused by mining highlight the necessity of ecological restoration actions under multiple methodologies (Martins et al., 2022). The long-term monitoring of restoration efforts is critical to identify the effectiveness of recovery actions and management strategies (Hassett et al., 2005; Tango & Batiuk, 2016). In this study we make a systematic review of the literature about the Batata Lake over 35 years. We synthesize information about the limnological characteristic of the lake over the time based on the primary studies. In addition, we explore the main research topics covered by the primary studies and bring information about the co-author's interaction network. All things considered, we briefly discuss the legacy of the research made in the Batata Lake while also highlighting some research opportunities and challenges for the future of the monitoring program.

2. Material and Methods

2.1. Study area

Batata Lake (1°25´- 1°35´ S; 56°15´ - 56°25´ W) is a clear-water Amazonian Lake connected to the right bank of Trombetas River, located at Porto Trombetas, municipality of Oriximiná, state of Pará, Brazil (Figure 1). It ranges between 12 m depth and 31 km^2 surface area in the high-water and 2 m depth and 18 km^2 area in the low-water. For almost ten years (1979 to 1989), it received approximately 24 million tons of bauxite tailings in the north, which covered 30% of the total lake area in the high-water (Lapa & Cardoso, 1988; Roland & Esteves, 1993; Lapa, 2000). It directly impacted the lake water and damaged the surrounding soil and igapó vegetation. After the bauxite tailings discharge ceased, it was possible to identify two different regions in the lake: the impacted area, with the deposition of bauxite tailings, and the natural area, where tailings did not reach. Late in 1987, a monitoring and restoration program was implemented to understand the effects of bauxite on aquatic communities and to restore the surrounding igapó forest in the impacted area. By the time the igapó vegetation was planted on the impacted area of the lake, which later became a terrestrial compartment. The monitoring program is still ongoing and uninterrupted for almost 35 years.

2.2. Systematic review

To provide an overview of the studies performed in the Batata Lake during the 35 years of monitoring, we performed a systematic literature review considering both paper and book chapters published until February 2022. The review followed the PRISMA (Preferred Reporting Items for Systematic

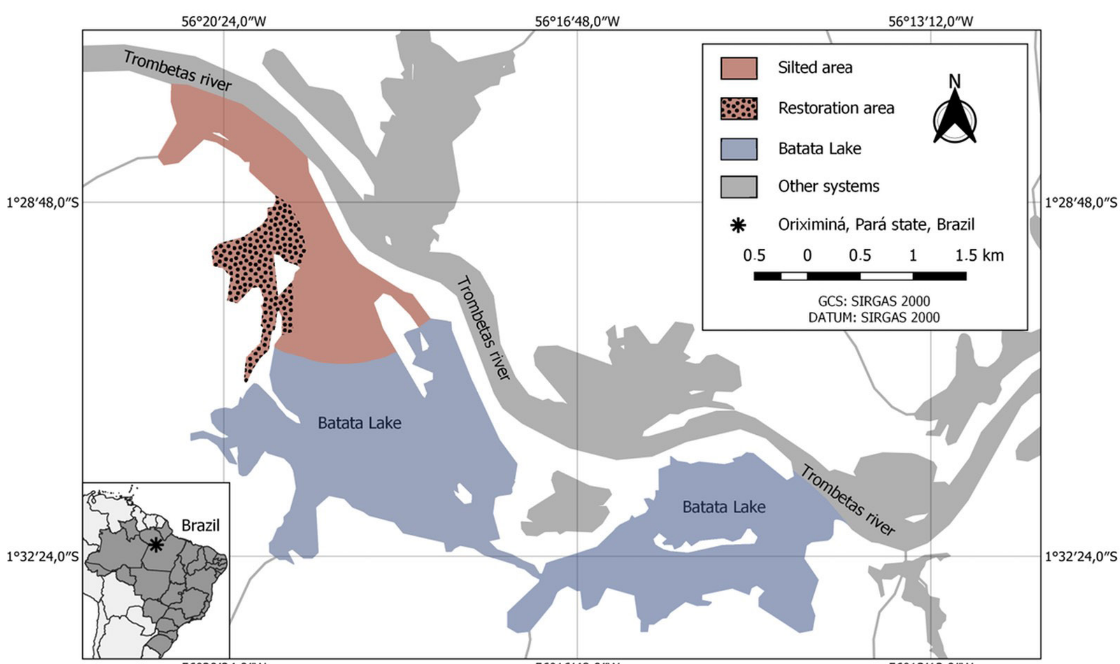

Figure 1. Map of the Lake Batata connected to the right bank of the Trombetas River. The impacted area, where bauxite tailing was discharged is shown in red. The limit of the igapó forest, where the restoration project is ongoing, is shown in the red dotted area.

Review and Meta-Analyses) methodology using the Web of Science Core Collection (WoS), Scopus, Scielo, and PUBMED as databases. The search also included the references within the papers selected and the online curriculum (Plataforma Lattes, 2022) of the principal researchers co-authoring the papers. In the databases, the search was done based on the combination of the following terms: TS = ((lake OR lago OR river OR rio OR lagoon OR lagoa) AND (Trombetas OR Oriximiná OR Mussurá OR Amazôni* OR Amazon*) AND Batata).

Papers and book chapters included in the systematic review were those (i) published in English or Portuguese and (ii) performed in Batata Lake or based on samples gathered in the Lake or surrounding area (*i.e.,* soil and vegetation around the lake).

After duplicates removal, we carefully screened all papers and book chapters retrieved. From each paper and chapter retrieved we gathered the following information: (i) year of publication; (ii) journal where it was published; (iii) authors' names; (iv) keywords; (v) study type (classified as case study, causal-comparative, correlational, descriptive, ethnographic or experimental); (vi) study area (*i.e.* whole lake, natural, transition or impacted areas); (vii) the environment sampled (*i.e.* water column, sediment, or surrounding soil); (viii) period of flood pulse (*i.e.* rising, high-water, falling or low-water); (ix) research topic, (x) study object, (xi) sampling frequency (classified as: snapshot, daily, weekly, fortnightly, quarterly, annually, biannually, or historic - long-term monitoring), (xii) limnological characteristics (classified as: species richness; aquatic communities - bacterioplankton abundance, virioplankton abundance, heterotrophic flagellates abundance, phytoplankton abundance or biomass, zooplankton abundance, macroinvertebrates abundance, fish abundance; metabolism - bacterial production rate, primary production rate, nitrogen fixation; chlorophyll a concentration; turbidity; suspended solids; total nitrogen; total phosphorus; dissolved organic carbon).

All statistical and graphical explorations were made through R Statistical Software version 4.1.1 (R Core Team, 2021).

To check the most frequent keywords described in the papers and book chapters included in the systematic review, we performed a word cloud analysis using the packages "tidyverse" (Wickham et al., 2019), "wordcloud" (Fellows, 2018), "wordcloud2" (Lang & Chien, 2018), "ggplot2" (Wickham, 2016), "RColorBrewer" (Neuwirth, 2014) and "tm" (Feinerer & Hornik, 2020).

To understand the stratification and grouping characteristics of the authorship of the studies, we performed a network analysis. We considered the list of all authors available in papers and book chapters. The network was built using the packages "scholar" (Keirstead, 2016), "networkDynamic" (Butts et al., 2021), "ndtv" (Bender-deMoll, 2021), "igraph" (Csardi & Nepusz, 2006), "statnet" (Handcock et al., 2019), "intergraph" (Bojanowski, 2015), "visNetwork" (Almende et al., 2021), "dplyr" (Wickham et al., 2021) and "stringr" (Wickham, 2019). The network connectance was calculated using the function networklevel and the package "bipartite" (Dormann et al., 2009).

To check if there was any distribution trend in the limnological characteristics reported for Batata Lakewe made a Multiple Correspondence Analysis (MCA). MCA is an extension of the Simple Correspondence Analysis (CA), which helps draw and spatially visualize the correlation between two or more categorical variables. The continuous limnological data were categorized as l - low and h – high for each variable considered. The MCA plots were sorted according to the categorical variables area (natural and impacted) and flood pulse phase (rising, high-water, falling, and low-water). The MCA was performed using the packages "ggplot2" (Wickham, 2016), "FactoMineR" (Lê et al., 2008), "factoextra" (Kassambara & Mundt, 2020).

Related data used in the analysis is available in Cardoso et al. (2023).

3. Results

After duplicates removal, a total of 102 records were identified through the data base searching (SI1). However, after the screening process, 3 records were excluded. This was the case when they did not bring clear information about the Batata Lake (Lopes et al., 2011; Bozelli, 2019) or was an extended abstract (Vidal & Roland, 2005). After all the selection process, 99 studies were included in qualitative synthesis, where 78 were scientific papers and the other 21 were book chapters (SI1). A description of the primary studies and their main outcomes can be found in the SI2. The papers and book chapters were published in 31 different journals, where the most frequent were Hydrobiologia (n = 16, 20.5%), Amazoniana (n = 15, 19.2%) and Acta Limnologica Brasiliensia (n = 7, 8.9%). The period with the greater number of publications was from 1996 to 2006 (Figure 2A). In 2000, a book dedicated to the monitoring project was published. The book consisted of 18 chapters. It brought information about the local people and the landscape and summarized the main research developed in Batata Lake to date.

Most of the studies retrieved from the systematic review were descriptive (37.4%), causal-comparative (22.2%), or experimental (21.2%) (Figure 2B). The studies were developed in the four main periods of the flood pulse (*i.e.,* rising, high-water, falling, and low-water; Figure 2C). The sampling frequency in the lake described in the studies was primarily quarterly (40%) and snapshots (26%) (Figure 2D). The studies mainly targeted the water column and sediments (Figure 2E) in natural and impacted areas (Figure 2F).

The most frequent keywords reported by the papers and book chapters were "Bauxite tailing" (4.6%), "Amazonian Lake" (4.4%), "Amazon" (4.2%), "Floodplain Lake" (2.8%), and "Amazonia" (2.5%) (Figure 3). The studies covered various research topics, such as descriptive abiotic data, species richness, composition, metabolism, and gas fluxes (Figure 4A). Among the most frequent research objects were the lake abiotic conditions (23.6%), aquatic organisms such as phytoplankton (8.9%), zooplankton (8.9%), benthos in general (6.1%), and macroinvertebrates alone (5.7%), nutrients such as nitrogen (2.8%) and ecosystem dynamics such as gas fluxes (0.8%) (Figure 4B).

The most frequent first authors in the papers and book chapters were R.L. Bozelli, A. Enrich-Prast, J. Leal, F. Roland, V.L.M Huszar, and F.A. Esteves (Figure 5). Fonseca J.J.L. and Leal J.J.F. refer to the same author but were considered separately as cited in the original studies to avoid further confusion. The author F. Esteves was present in most publications and was depicted as the central node in the co-authors network (Figure 6). Other authors such as A. Enrich-Prast, F. Barbosa, M. Callisto, J. J. Leal, E. P. Caramaschi, F. R. Scarano, V.L.M. Huszar, V. Farjalla, M.P. Figueiredo-Barros, F. Roland and R.L. Bozelli had high co-authorship among the published papers and book chapters (> 5). Besides, they contributed to increasing the network complexity (Figure 6).

The MCA model, based on the limnological characteristics of Batata Lake along the 35 years of the monitoring program, explained 41.9% of data

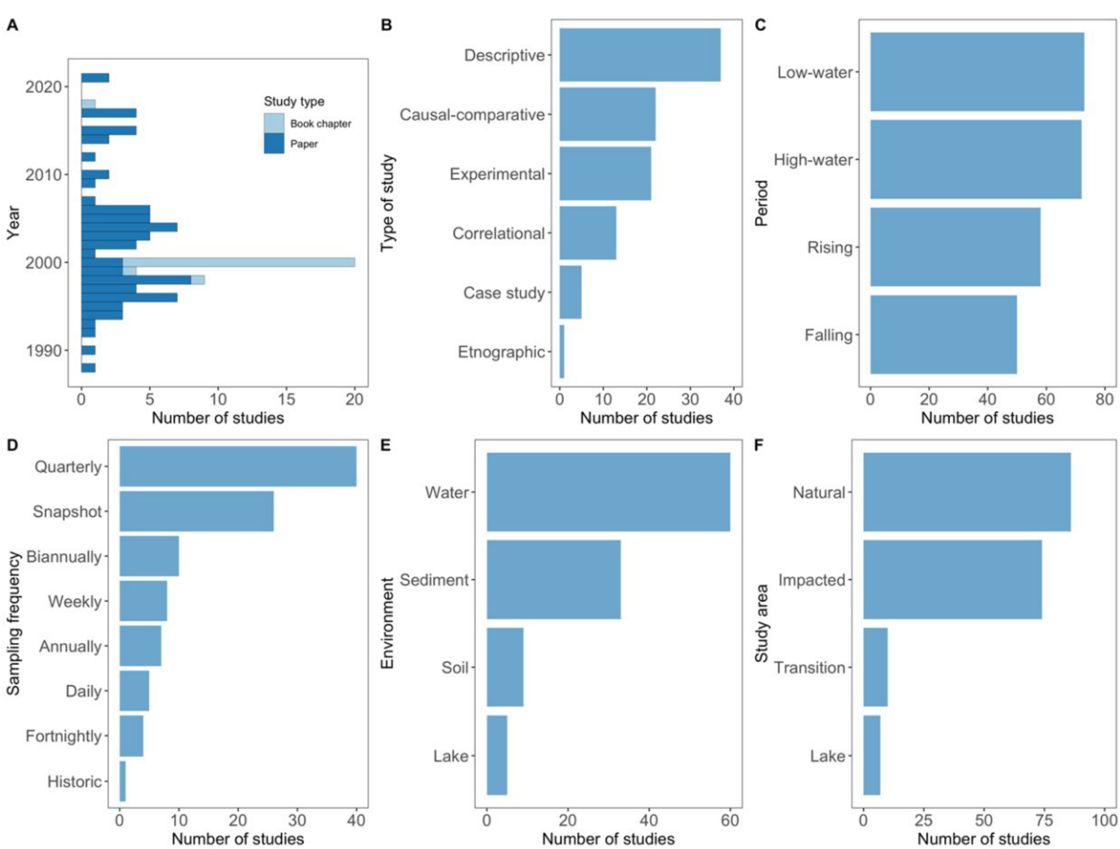

Figure 2. Number of studies published according to (A) Year of the project, (B) Study type, (C) Hydrological period, (D) Sampling frequency, (E) Environment sampled, and (F) Study area.

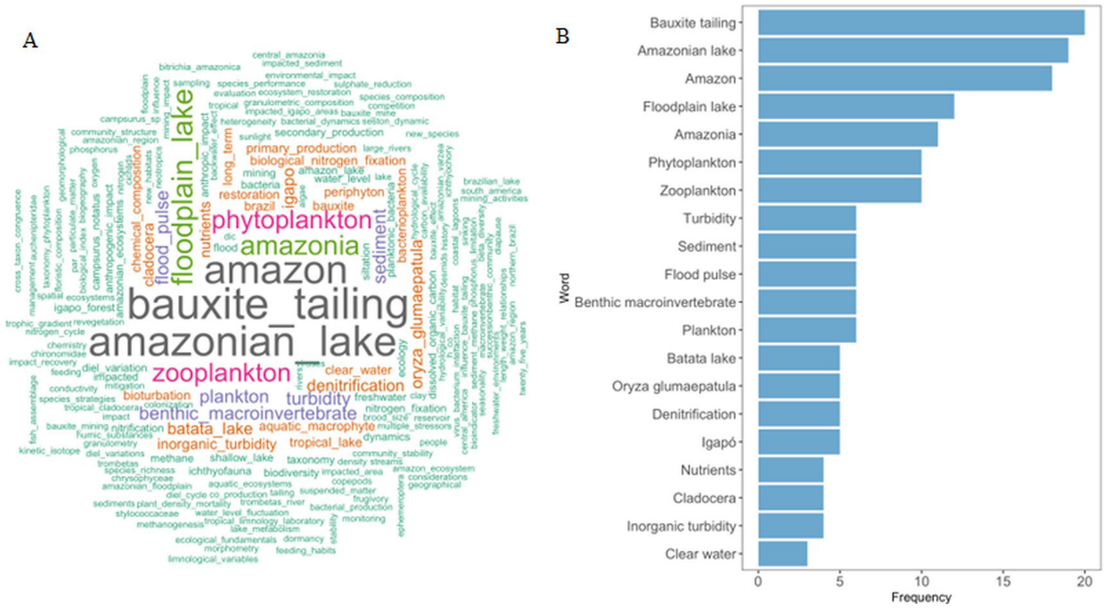

Figure 3. Word cloud representing (A) The keywords described in the papers included in the systematic review, where the font size represents the frequency of citations, and (B) Histogram with the top 20 most cited keywords.

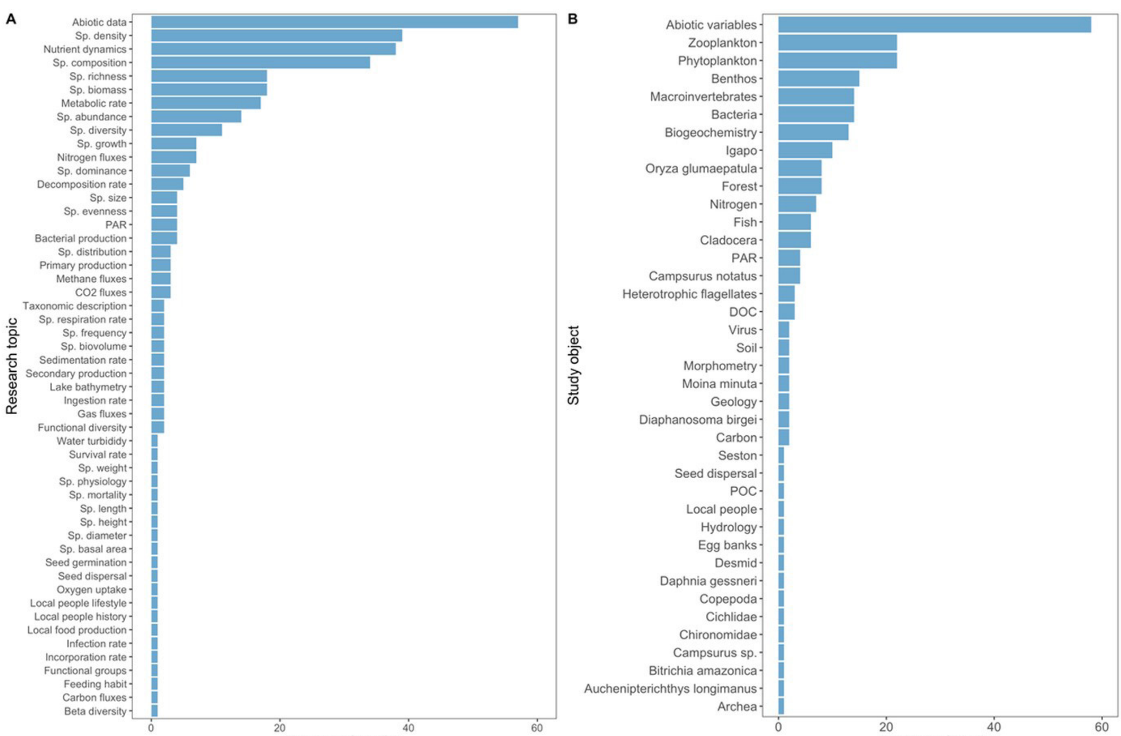

Figure 4. Histogram of the most (A) Research topics and (B) Study objects described in the published papers and book chapters included in the systematic review. Acronyms are Sp. = Species, PAR = Photosynthetically active radiation, DOC = dissolved organic carbon, POC = particulate organic carbon.

distribution (Figure 7A). The MCA first dimension (Dim 1, 25.5%) was mainly driven by the lake areas (natural and impacted) (Figure 7B). In contrast, the second dimension (Dim 2, 16.5%) depicted a gradient of the main periods of the flood pulse (*i.e.,* rising, high-water, falling, and low-water) (Figure 7B). The variables that most contributed to the MCA first dimension were high phytoplankton

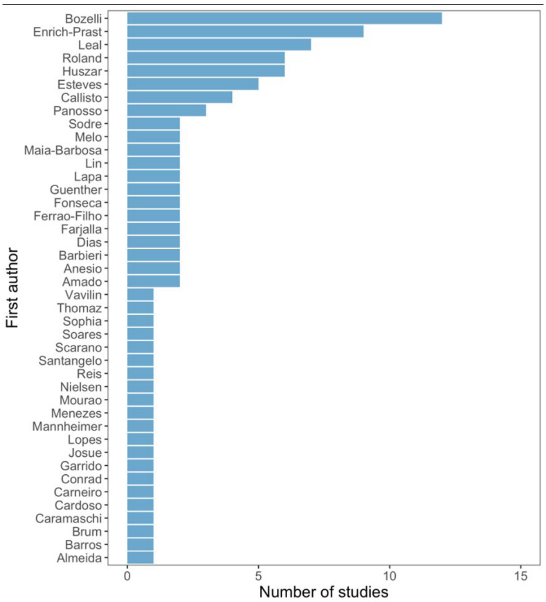

Figure 5. List of the first authors and number of the published papers and book chapters included in the systematic review.

densities or biovolume (Phyto_h and Phyto_l) and high rates of nitrogen fixation (NF_h and NF_l), followed by total phosphorus concentration (TP_h and TP_l). When considering the MCA second dimension, the variables that most contributed were virioplankton densities (Virus_h and Virus_l), dissolved organic carbon concentrations (DOC_h and DOC-l), bacterial production (BP_h and BP_l), and chlorophyll a concentration (Chlor_h, Chlor_l). Variables with less contribution to both dimensions were those located at the center of the graph, mainly zooplankton densities (Zoo_h and Zoo_l), suspended solids (SS_h, SS_l), and species richness in general (SR_h, SR_l).

4. Discussion

4.1. Major findings and trends over time

The ecological monitoring carried out in Batata Lake since 1987 has provided essential knowledge regarding the dynamics of an Amazon floodplain

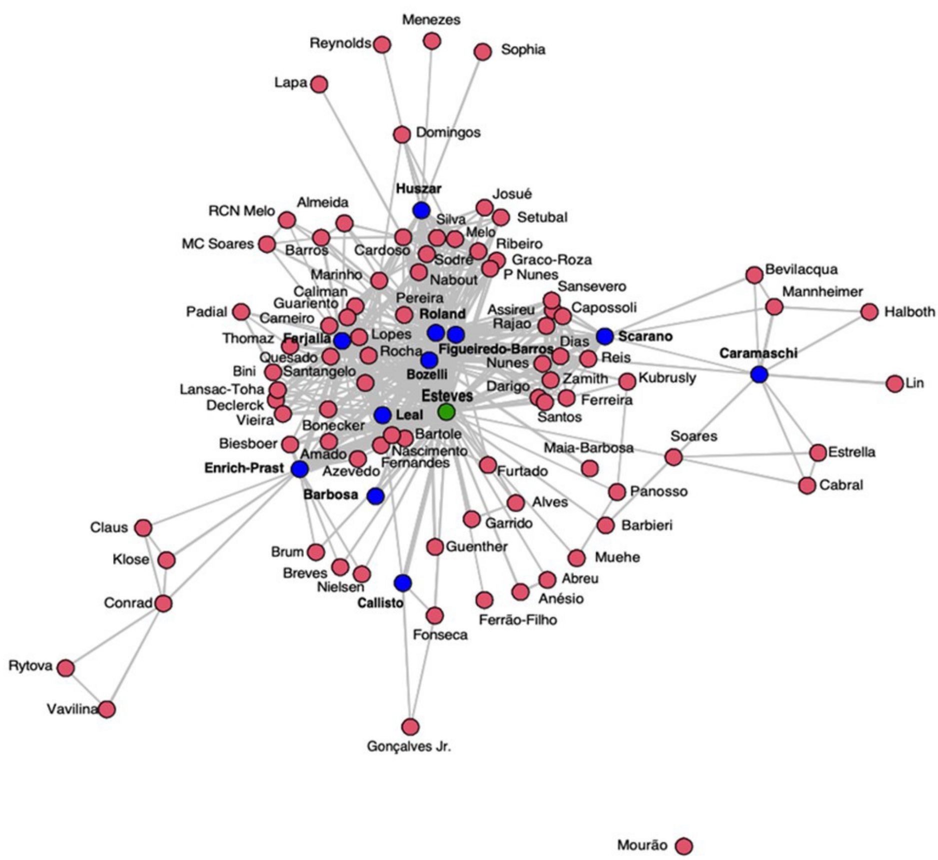

Figure 6. Co-authors network based on the list of co-authors of the publications included in the systematic review. Fonseca and Leal refer to the same author, but were consider separately as cited in the original studies in order to avoid further confusions. In the network, each node represents a co-author. The green node represents the centrality of the network, where the author is present in the majority of publications (n > 50), and the blue nodes are the most frequent co-authors (n > 5). $N_{vertices}$ = 94, $N_{total\ edges}$ = 460, connectance = 0.1147578.

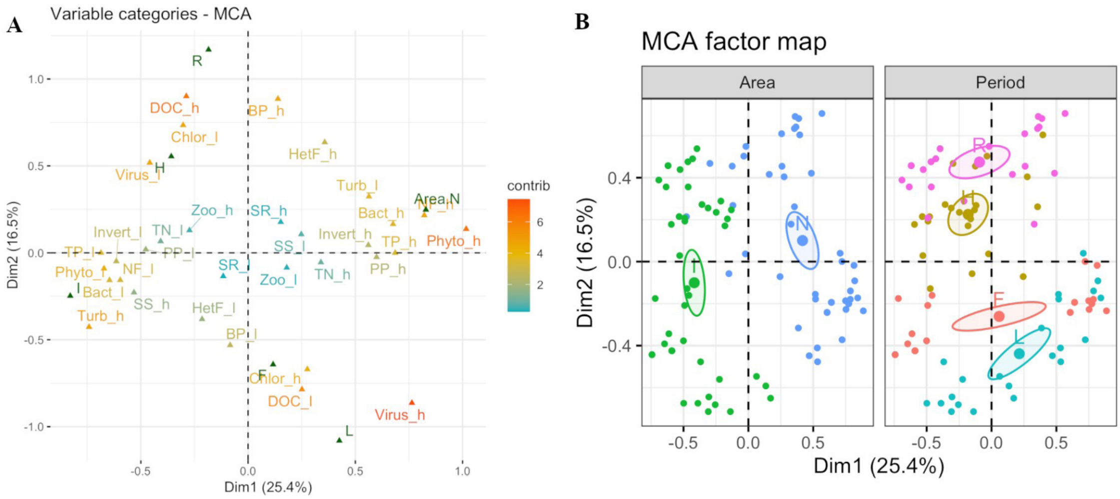

Figure 7. Multiple correspondence analysis (MCA) of limnological characteristics of Batata Lake along with the monitoring program. (A) MCA plot. Limnological characteristics were categorized as l - low and h – high. Dark green symbols represent Area: N = natural area, I – impacted area, and Flood pulse phase: H – high-water, F – falling water, L – low-water, R – rising water. Colored symbols are Bact – bacterioplankton abundance; Virus – viroplankton abundance; HF – heterotrophic flagellates abundance; Phyto – phytoplankton abundance; Zoo – zooplankton abundance; Invert – macroinvertebrates abundance; Fish – fish abundance; Igapo – igapó forest abundance; BP – bacterial production rate; PP – primary production rate; Chlor – Chlorophyll a concentration in the water; Turb – turbidity; SS – suspended solids; SR – species richness; TN – total nitrogen; TP – total phosphorus; DOC – dissolved organic carbon; NF – nitrogen fixation. The letters l and h stand for l -low and h – high. (B) MCA data is sorted according to the categorical variables Area (N – natural, I – impacted) and Flood pulse phase (H – R – rising water, high-water, F – falling water, L – low-water).

lake and the long-term effects of mining tailing in both aquatic and terrestrial environments. During the bauxite tailing was discharged into the lake and until its interruption, the tailing covered 30% of the lake's area giving it a new substrate. After so, many observational studies began aiming to compare the "natural" and "impacted" areas of the lake over the time (Esteves et al., 1990; Esteves, 2000). Even after 35 years, the impact of bauxite tailing in Batata Lake is still present.

Most of studies showing the primary effects of bauxite tailing in the Batata Lake were associated with inorganic particles deposition in the aquatic sediments (Roland & Esteves, 1993; Roland et al., 2002) and increased water turbidity (Bozelli, 2000; Bozelli & Esteves, 2000a; Bozelli & Garrido, 2000b; Callisto & Esteves 1995; Guenther & Bozelli 2004a, b), which in turn impacted water transparency (Roland et al., 1997; Roland & Esteves, 1998; Panosso & Kubrusly, 2000), nutrient cycling (Esteves et al., 1994; Enrich-Prast & Esteves, 1996; Esteves & Enrich-Prast, 1998; Roland et al., 2000; Enrich-Prast, 2002; Nielsen et al., 2004), sediment granulometry (Callisto & Esteves, 1996a; Callisto, 2000), seston composition (Ferrão-Filho & Esteves, 1994; Ferrão-Filho, 2000) and aquatic communities such as virus (Barros et al., 2010), bacteria (Thomaz et al., 1998; Farjalla et al., 2002; 2006), heterotrophic flagellates (Anesio, 2000), phytoplankton (Roland, 2000; Huszar, 2000, 1996a, b; Menezes & Huszar, 1997; Huszar et al., 1998, 2022; Melo & Huszar, 2000), zooplankton (Bozelli, 1992; Carneiro et al., 2003; Garrido et al., 2003; Maia-Barbosa & Bozelli, 2005, 2006; Bozelli et al., 2009; Santangelo et al., 2015; Josué et al., 2021), macroinvertebrates (Callisto & Esteves, 1995; Callisto & Esteves, 1996b; Fonseca et al., 1998; Fonseca & Esteves, 1999; Leal & Esteves, 1999, 2000; Leal et al., 2004, 2005; Bozelli et al., 2009) and fish (Reis & Caramaschi, 1999; Caramaschi et al., 2000; Lin & Caramaschi, 2005a, b). Tailing deposition in the sediments also damaged the surrounding igapó forest causing deforestation of native species (Barbieri et al., 2000a; Dias et al., 2012, 2014; Scarano et al., 2018).

Besides the research demonstrating differences between the natural and the impacted areas of Batata Lake, many others focused on detangling the contribution of hydrological connectivity (Lopes et al., 2014; Almeida et al., 2015; Sodré et al., 2015), seasonality (Sodré et al., 2017) and other environmental variables (*e.g.,* nutrients and euphotic zone depth) (Cardoso et al., 2017) on the aquatic communities' diversity and distribution (see SI2).

Further, other discoveries from the long-term research of Batata Lake have revealed the recovery capacity of the igapó forest after revegetation interventions (Barbieri et al., 2000b; Esteves, 2000; Scarano et al., 2018) and the role of the wild rice *Oryza glumaepatula* in reestablishing local communities due to increasing organic matter and nutrient concentrations in the impacted sediments (Enrich-Prast, 1998; Enrich-Prast et al., 1999), and the accumulation of detritus over the sediment avoiding the resuspension of the bauxite tailings (Enrich-Prast & Esteves, 2005). Studies on the omnivorous catfish *Auchenipterichthys longimanus* indicated a potential disperser of forest seeds with distinct germination and dormancy patterns in the lake (Mannheimer et al., 2003). Since this opportunistic fruit-eater is the most abundant fish species in the silted area, the authors considered that this catfish has also been playing a role in the regeneration process of the igapó forest (Soares et al., 2017).

Benthic macroinvertebrate species, especially *Campsurus notatus,* also figured in many critical studies encompassing *in situ* measurements and laboratory experiments. They revealed successful adaptation of *C. notatus* to the conditions imposed by the bauxite tailings due to their high relative density and biomass in the impacted areas (Callisto, 2000; Leal et al., 2003, 2004). *C. notatus* was also linked to a significant role in gas flux (CH_4 and CO_2) from sediment to the water column and oxygen consumption, influencing the carbon cycle in Batata Lake (Leal et al., 2007).

Nitrogen and carbon cycling also received substantial attention during the monitoring project of Batata Lake. The former was mainly explored regarding nitrogen fixation (Enrich-Prast et al., 1999, 2002; Enrich-Prast & Esteves, 1996, 1998; Esteves & Enrich-Prast, 1998, Esteves et al., 2001; Nielsen et al., 2004), and the latter considering particulate organic carbon incorporation by organisms (Bozelli, 1998a, b), dissolved organic carbon (DOC) quality, origin, and photo-oxidation (Amado et al., 2003, 2006; Farjalla et al., 2006), and recently CH_4 production (Conrad et al., 2010; Vavilin et al., 2017).

Beyond comparing natural and impacted areas, the Batata Lake monitoring project also better understood how Amazonian floods and seasonality shape local environmental conditions and aquatic communities. For instance, floods revealed to be an essential factor controlling the lake limnological features (Panosso et al., 1995; Panosso & Kubrusly, 2000; Panosso, 2000), nitrogen and phosphorus concentrations in the water (Roland & Esteves, 1993; Esteves et al., 2001; Farjalla et al., 2002, 2006), both virus and bacteria abundance (Barros et al., 2010; Almeida et al., 2015), bacteria abundance (Anesio et al., 1997), bacterial metabolism (Amado et al., 2006), and bacterial association with detritus from *O. glumaepatula* (Enrich-Prast et al., 2004), zooplankton abundance and composition (Bozelli, 1994, 1996; Bozelli & Esteves, 1995; Carneiro et al., 2003; Bozelli et al., 2015, Sodré et al., 2015, 2017), benthic macroinvertebrates metabolism, abundance and composition (Callisto & Esteves, 1995), phytoplankton abundance, biovolume and composition (Sophia & Huszar, 1996; Huszar & Reynolds, 1997; Melo & Huszar, 2000; Melo et al., 2004), and functional diversity (Cardoso et al., 2017), seston quality (Ferrão-Filho, 2000), wild-rice (*O. glumaepatula*) growth and abundance (Enrich-Prast & Esteves, 2005; Enrich-Prast et al., 2006; Brum et al., 2006), and plant community composition (Barbieri et al., 2000a).

4.2. Data collection, methods, and ecological descriptors

The ecological monitoring of Batata Lake in its initial decade generated primarily descriptive studies. Environmental conditions and aquatic and benthic communities' structure and function from natural and impacted areas were the focus of investigations. During the second decade, studies aiming to explain causal relationships and those bringing experimental design in both *in situ* and laboratory conditions became more common. After that, studies based on correlational hypotheses became a crescent in the project. Many of the hypotheses were related to ecosystems and communities' resilience to bauxite tailings and periodic floods but not limited to those. This trend of progressively changing from an observational to a hypothesis-oriented study was also the case in many other LTER studies. Some examples are (i) the Upper Paraná River floodplain, Brazil (Bonecker et al., 2020); (ii) Chesapeake Bay, USA, where research was linked to local regulatory programs (Hassett et al., 2005; Tango & Batiuk, 2016); monitoring program in the Hubbard Brook Experimental Forest (HBEF), USA (Likens, 2004); Danube River Restoration

Project, Austria (Schiemer, 1999; Schiemer et al., 1999), and Moreton Bay Waterways and Catchment Partnership in southeast Queensland, Australia (Ecosystem Health Monitoring Program, 2008).

Along with the Batata Lake monitoring, there was a predominance of seasonal studies (quarterly observations) - covering the four periods of the regional flood pulse (rising, high-water, falling, and low-water) - and snapshot studies, where conditions and communities were sampled only once. Both natural and impacted areas were consistently sampled, compared to the transition areas and the lake (*i.e.,* the ecosystem as a whole), which were only sporadically sampled. In general, monitoring programs rely on both sampling designs, which are necessary to understand changes along the time scale, while also offering the opportunity to test simple observational or experimental hypotheses (Walters & Holling, 1990; Schiemer et al., 1999).

By considering the keywords described by the primary studies, after "Bauxite tailing," most of them included "Amazonian lake", "Amazon", "Floodplain lake", and "Amazonia" among their keywords, which highlights the intrinsic dynamics of floods as an essential driving factor for both limnological conditions and communities. However, except for the studies of Dias et al. (2012, 2014), none of them addressed specifically management-oriented questions or related ecosystems services, which configures a vital research gap under the perspective of a more holistic indicator of ecosystem conditions (Erős et al., 2019).

Most of the research topics described by the primary studies and their research objects included benthic and aquatic organisms, their diversity, metabolism, and function in the different compartments of Batata Lake. The most cited communities were zooplankton, phytoplankton, benthic invertebrates, and *O. glumaepatula*. The research groups themselves may bias such predominance of selected research topics and objects. Most researchers have those topics and organisms among their specialties, which can be seen through the clusters formed in the co-author's network (Figure 6). However, long-term projects usually target some "indicator species". They can provide an effective strategy to obtain meaningful ecological results (Lindenmayer & Likens, 2009) when correctly assigned (*i.e.,* a credible relationship between a surrogate and the investigated identity/species).

Figuring the list of authors described in the primary studies, Bozelli, the first author, and Esteves, the last author, were the most frequent. Besides the dominance of some authors in the prior publications (Figure 6, blue nodes), the co-author's interaction was quite large and diverse, with 94 vertices and 460 edges. Mourão (2000) was the most distant and disconected author of the net. This was probably because it was the only reference discussing historical and social aspects of the local community living arround the Batata Lake. Esteves figured out the centrality of the network once he cooperated in almost all publications. This was expected since he was the Principal Investigator (PI) of the monitoring program and supervised many of the students, who later became researchers in the project, a relevant aspect of the Batata Lake monitoring. Solid and enduring leadership has been described as one of the main factors making successful examples of long-term monitoring (Lindenmayer & Likens, 2009).

4.3. Research gaps and perspectives

When summarizing the multiple outcomes of primary studies (Figure 7), a clear trend reveals the effect of bauxite tailings when comparing natural and impacted areas and the driving force of the flood pulse on shaping both limnological conditions and aquatic communities of Batata Lake. The complexity of the ecosystem dynamics makes it a unique example of how managing impacted aquatic ecosystems in the Amazon may be challenging. Further, the retrospective about the Batata Lake research project comes when aquatic environments, especially those in Amazon, are under unprecedented threat due to fast-increasing mining activities, the weakening of environmental law and the lack of governmental protection (Fearnside, 2016; El Bizri et al., 2016; Bozelli, 2019).

The scientific understanding of the Batata Lake dynamics still needs conceptual models summarizing the interactions between water, sediment, and biota interactions in a time series perspective. Significant ecosystem responses may be revealed by linking historical data sets with current data collected in the lake and surrounding areas, especially considering the management actions and ongoing climate changes. Further, better achievements can be gathered in the Batata Lake monitoring if it evolves toward "adaptative monitoring", as suggested by Lindenmayer and Likens (Lindenmayer & Likens, 2009). Paradigms are driven by more tractable questions, rigorous statistical design, and better conceptual models ranging from ecosystems to their components (*i.e.,* populations of individual species) evolving in response to new information and research questions (Lindenmayer & Likens, 2009).

Despite the extensive information on the effects of bauxite tailings on the Batata ecosystem structure and function, the long-term quantification trends remain incomplete (Soares et al., 2017; Sodré et al., 2017, Huszar et al. 2022). Many questions were raised throughout the research project and are still under investigation. For instance, would the recovery/restoration wheel, a new methodology from the Society for Ecological Restoration (Bozelli et al., 2000b; Bozelli, 2019), be a possible strategy to restore the igapó forest damaged by tailings? How do the terrestrial-aquatic connectivity and interactions contribute to reestablishing Batata Lake's resilience and biodiversity? How have aquatic trophic interactions changed in both natural and impacted areas along the time? Would the tailing impact open the window for new no-native species in planting areas (*e.g.,* epiphytes)? Would the ecosystem impact change the carbon budget in the lake and the surrounding areas?

Those questions and so many others are good examples of how investing in a long-term research project can engage scientists and make significant scientific contributions to society. It is essential to highlight the studies sustained over decades. The monitoring of Batata Lake helps document gradual changes and long-term variability that often cannot be revealed by short-term studies. Such understanding provides essential information for science and water and land management. It supports stakeholders, legislators, and decision-makers to make responsible policies and regulatory assessments. More importantly, a greater understanding of the Batata Lake dynamics can help forecasting and ecosystem recovery actions in Amazon and other aquatic ecosystems impacted by mining tailings and that are also under the effect of hydrological dynamics.

Long-term studies require continued financial support, which is scarce, especially in developing countries like Brazil. In the case of Batata Lake, it was only possible through a partnership program between public universities and the mining company Mineração Rio do Norte. However, it is not the case in many other ecosystems. A multi-agency partnership is still required by involving local, state, regional, and federal agencies, other academic institutions, and non-governmental organizations.

We believe the Batata Lake study illustrates the response of a floodplain system to long-term siltation caused by bauxite tailings in a sensitive area such as the Amazon. The monitoring program represents a valuable resource for future environmental models in Amazon and for supporting collaborative science and decision-making.

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Supplementary Material

Supplementary material accompanies this paper.

Supplementary Information - SI1: Prisma flowchart shows the selection process for studies on the systematic review. Adapted from PRISMA (Moher et al., 2009).

Supplementary Information - SI2: Main outcomes of studies selected in the systematic review. Outcomes are depicted by the natural and impacted areas and the whole lake as study area.

This material is available as part of the online article available at Dataverse: https://data.scielo.org/dataset.xhtml?persistentId=doi:10.48331/scielodata.1UCLWP