Acta Limnologica Brasiliensia

Publication of the Brazilian Association of Limnology

Original Article
Acta Limnologica Brasiliensia, 2024, vol. 36, e19
https://doi.org/10.1590/S2179-975X6423
ISSN 2179-975X on-line version

Assessing the occurrence of alien species on Brazilian freshwater ecosystems: insights from a comprehensive survey

Avaliando a ocorrência de espécies exóticas nos ecossistemas de água doce brasileiros: percepções de uma pesquisa abrangente

Anderson Oliveira Latini[1], Daniela Chaves Resende[1], Daniel Paiva Silva[2] and Dilermando Pereira Lima-Junior[3*]

[1]Laboratório de Ecologia Aplicada, Departamento de Ciências Exatas e Biológicas, Universidade Federal de São João del-Rei – UFSJ, Rodovia MG 424, Km 47, CEP: 35701-970, Caixa Postal: 56, S CEP 35701-970, Sete Lagoas, MG, Brasil

[2]COBIMA Lab, Instituto Federal Goiano – IF Goiano, Rod. Geraldo Silva Nascimento, Km-2,5 - Zona Rural, CEP 75790-000, Urutaí, GO, Brasil

[3]Laboratório de Ecologia e Conservação de Ecossistemas Aquáticos, Universidade Federal de Mato Grosso – UFMT, Av. Valdon Varjão, CEP 78600-000, Barra do Garças, MT, Brasil

*e-mail: dilermando.junior@ufmt.br

Cite as: Latini, A.O. et al. Assessing the occurrence of alien species on Brazilian freshwater ecosystems: insights from a comprehensive survey. *Acta Limnologica Brasiliensia*, 2024, vol. 36, e19. https://doi.org/10.1590/S2179-975X6423

Abstract: Aim: Assessing the damage caused to natural environments and native biodiversity by alien species is challenging. We tested whether the number of detections of alien species is affected by total alien or total invader alien species richness, considering the importance of predicting which species are more probable future invaders. **Methods:** We summarized a research information survey conducted on alien amphibians, annelids, aquatic macrophytes, cnidarians, crustaceans, fish, microorganisms, mollusks, nemathelminths, platyhelminths, and reptiles, and for Brazilian watersheds. We used linear regressions between detections and total alien species richness and between detections and invader species richness. **Results:** We obtained 1,896 alien detections of 183 aquatic species in Brazil. Fish and mollusk species were the commonest invaders due to their detections being more frequent than expected by chance, considering all the alien species occurring in Brazilian freshwater ecosystems. We also found positive and robust linear relationships between alien species detections and alien species richness. **Conclusions:** Our results illustrate how Brazilian freshwater systems are fragile to alien invasions and highlight the need for effective action to address this question. Scientific uncertainty in Brazil regarding the status of some alien species and their potential harm is high, highlighting the need for a cautionary overview of invaders. Despite this scenario, new policies create opportunities for aquatic parks with exotic organisms to spread further in Brazil, which, in actual Brazilian conditions, is likely to increase the pressure on natural ecosystems and native species. This reinforces the already expressed need by the scientific community for greater attention to the issue.

Keywords: biological conservation; exotic species; inland waters; watersheds

Resumo: Objetivo: Inventariar os danos causados aos ambientes naturais ou à biodiversidade nativa por por espécies exóticas é desafiador. Nós testamos se o número de detecções de espécies exóticas é afetado pelo número total de espécies exóticas ou pela riqueza de exóticas invasoras, com o intuito de predizer que grupos de espécies são mais prováveis futuros invasores. **Métodos:** Nós apresentamos informações obtidas de um senso nacional conduzido sobre organismos exóticos anelídeos, anfíbios, cnidários, crustáceos, macrófitas aquáticas, microrganismos, moluscos, nematelmintos, peixes, platelmintos e répteis para todas as bacias hidrográficas do país. Utilizamos o número de detecções como variável dependente da riqueza de espécies exóticas, por grupo taxonômico e da riqueza de espécies exóticas invasoras. **Resultados:** Nós obtivemos 1.896 detecções de diferentes 183 espécies aquáticas. Peixes e moluscos foram os invasores comuns já que suas detecções são mais frequentes do que o esperado ao acaso, considerando todas as espécies ocorrendo nos ecossistemas de água doce do país. Nós também encontramos relações positivas e robustas entre as detecções por grupo taxonômico e a riqueza em espécies por grupo. **Conclusões:** Os resultados ilustram como o ambiente de água doce brasileiro é frágil a invasões biológicas e destacam a necessidade de ações efetivas direcionadas à questão. A incerteza científica a respeito do status de espécies exóticas e seu podencial invasor é grande, o que leva à necessidade de precaução a respeito destas espécies. Apesar do cenário atual, novas políticas abrem opotunidades para que parques aquáticos com organismos exóticos se dispersem mais no Brasil o que deve aumentar ainda mais a pressão sobre ecossistemas naturais e espécies nativas, reforçando a necessidade já manifestada pela comunidade científica, de maior atenção ao tema.

Palavras-chave: conservação da biodiversidade; espécies exóticas; ecossistemas continentais de água doce; bacias hidrográficas.

1. Introduction

Over the last few decades, alien species dispersal has allowed economic benefits and extensive damage to biodiversity and society worldwide (Boddy et al., 2012; Jacobs & Keller, 2017; Vitule et al., 2019; Muñoz-Mas & García-Berthou, 2020). After many studies on alien species (Elton, 1958; Vellend et al., 2007; Richardson, 2011), knowledge regarding their dispersal, range, and damage to biodiversity and society is still inconclusive (Chivers et al., 2017). Some studies have indicated the contribution of alien species (Gozlan, 2008; Sax et al., 2022), while others reinforced the negative impacts of these species in natural ecosystems (Vitule et al., 2019; Magalhães et al., 2020; Magalhães et al., 2021) and on the worldwide economy (Diagne et al., 2021). Short surveys for early detection and procedures on alien species dispersal are recognized as an opportunity to prevent social, economic, and environmental damage, especially in large areas (Beric & MacIsaac, 2015; Early et al., 2016; Latini and Petrere Junior, 2018; Anastácio et al., 2019; Hughes et al., 2020). However, climate, environmental impacts, fisheries, and inadequate environmental policies may also increase threats to biodiversity (Gonçalves et al., 2020; Charvet et al., 2021; Latini et al., 2021).

Many Brazilian basins and wetlands surround one of the most diverse freshwater aquatic communities worldwide (Richards et al., 2015). However, this also makes it extraordinarily complicated to know which species are near to invade or occur there. Furthermore, escaping alien species from aquaculture and damaging freshwaters threaten Brazilian international compromises, as established in the Conference of the Parties of the Convention on Biological Diversity (Lima-Junior et al., 2018; Latini et al., 2021).

Considering the extensive network of hydrographic basins in Brazil, many aquatic species, and the risk that alien invasions represent to biodiversity and society, this work aimed to summarize and analyze the results of the first Brazilian survey on alien species in freshwater ecosystems. Judging the importance of predicting which species are more probable future invaders (Fournier et al., 2019), the inventory data were useful for testing whether the number of detections of alien amphibians, annelids, aquatic macrophytes, cnidarians, crustaceans, fish, microorganisms, mollusks, nemathelminths, platyhelminths, and reptiles species groups is affected by alien or invasive alien species richness.

2. Material and Methods

A survey was conducted physically and digitally using a questionnaire that addressed questions on alien amphibians, annelids, aquatic macrophytes, cnidarians, crustaceans, fish, microorganisms, mollusks, nemathelminths, platyhelminths, and reptile species for Brazilian watersheds from 2006 to 2012. We communicated with researchers via mail and gathered information on alien species residing in inland waters by utilizing the Plataforma Lattes (CNPq, 2023; Lane, 2010), a comprehensive researcher catalog containing the credentials of approximately 200,000 Brazilian researchers. The researchers were chosen based on their scientific productivity, as documented by Plataforma Lattes, and their affiliation with the investigated taxonomic group. In addition, we sent a questionnaire to governmental and private institutions with a significant economic, social, or academic impact. These institutions were selected based on a combination of formal and informal databases, including commercial and government sources. For illustration, we obtained a list of hydroelectric plants from the websites of the Agência Nacional das Águas e Saneamento Básico (ANA) and Agência Nacional de Energia Elétrica (ANEEL), and we collected data related to aquatic organism breeders from the website of the Ministério de Aquacultura e Pesca. At some level, all these were related or potentially related to any alien species in continental aquatic ecosystems, and all of them were informed about the possibility of answering the survey by an internet link where some additional questions related to the biome and the basin were requested.

The questionnaire, sent by mail to 6,000 recipients, requested the name of the person responsible for filling them out (optional), the completion date, and responses to the following questions: a) Do you know of any exotic species?, b) What is the name of the species (common or scientific or both), c) How do you believe the species reached the location?, d) Is the organism contained in some artificial place or the natural environment?, e) Do you know why the species reached the region?, f) Could you describe the type of environment?, g) Do you have any measure of counting of the organism?, h) How do you describe the organism?, i) What is the exact location of occurrence?, j) Are you able to identify some economic importance?, k) Are there visible consequences?, l) Do you know any control methods?, m) Do you work with the organism?, and n) Do you know any publication about it?

The survey also used a bibliographic revision done in databases and digital libraries. The Web of Science (Clarivate, 2023), the Scopus Preview (Elsevier, 2023), the SciELO (SciELO, 2023), and the thesis database from the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES, 2023) were used searching for publications about alien species incidence. We also searched for alien species in aquatic environments in published books, nonindexed journals, technical reports, regional species datasets, scientific meeting proceedings, and gray literature, such as journal articles or books. All data were used to build a dataset with freshwater alien species occurrence in Brazil.

After concluding the survey, the Plataforma Lattes was used again to invite some of the leading Brazilian specialists and was carefully chosen by the importance of their scientific production. Two specialists were invited for each surveyed taxonomic group. The specialists could check the data for failures and help improve the final dataset in an in-person workshop.

Alien species occurrences were obtained, and a list of alien species of amphibians, annelids, aquatic macrophytes, cnidarians, crustaceans, fish, microorganisms, mollusks, nemathelminths, platyhelminths, and reptile groups was achieved. The species were classified into one of the categories: i) isolated alien species (IAS) – species confined in artificial environments; ii) detected alien species (DAS) – who were just detected in natural environments; iii) established alien species (EAS) – species with all life stages in natural environments, but without recognized impacts on the environment; and iv) invasive alien species (InAS) – established species, with at least one scientifically proven damage to a native species, native community, or aquatic environment. Sometimes it was impossible to discern whether a given species was a native species with high growth rates or an alien species when it was associated with preexisting impacts in the aquatic environment. Therefore, this last situation classified the species as cryptic (CRY).

Linear regressions between detections and total alien species richness and between detections and invader species richness (InAS) were performed by considering the number of alien species as a surrogate of their dispersal potential and discussing this result regarding Brazilian inland waters. We used Statistica v.13 (StatSoft; license: 201804-41993) for these analyses.

3. Results

In total, 1,148 Brazilian institutions were contacted to obtain information on alien species, of which 52 were companies responsible for hydroelectric power generation, 657 non-governmental organizations related to environmental issues, 205 colleges and universities with professionals potentially involved with alien species, and 234 governmental (e.g., federal, state, and municipal) autarchies. Additionally, we obtained the collaboration of 333 researchers and managers involved in environmental issues and some influence of alien species in Brazilian inland waters.

The survey detected 1,896 occurrences of 183 alien species in Brazilian inland waters (Table 1). Of these, 40 (21.86%) cause social, economic, or environmental problems, allowing us to characterize them as *invasive alien species* (InAS) (ISSG, 2018). Among all the invasive taxonomic groups found, there was one nemathelminth, one annelid, two reptiles, two platyhelminthes, two cnidarians, four amphibians, seven mollusks, 11 crustaceans, 12 aquatic macrophytes, 12 microorganisms (including microcrustacean) and 1,029 fish (Table 2). A large number of the alien species in Brazilian freshwater ecosystems (e.g., 58% for aquatic macrophytes, 36% for crustaceans, and 57% for fishes) are translocated and are primarily related to aquaculture use (Table 3 and Table 1).

Table 1. Taxonomic group, species name, native range, and classification of alien species in Brazilian inland waters. The classification refers to origin (another country or translocated) and invasion categories (IAS, isolated alien species; DAS - detected alien species; EAS, established alien species; InAS, invasive alien species, and CRY, cryptic species).

Taxonomic group in this study	Species name	Native range	From another country	Translocated domestic species	Species classification				
					IAS	DAS	EAS	InAS	CRY
Annelid	*Barbronia weberi* (Blanchard, 1897)	Asia	■			■			
Anuran	*Bufo schneideri* Werner, 1894	South America		■			■		
Anuran	*Lithobates catesbeianus* (Shaw, 1802)	North America	■					■	
Anuran	*Scinax ruber* (Laurenti, 1768)	South America		■			■		
Anuran	*Xenopus laevis* (Daudin, 1802)	Africa	■		■				
Aquatic macrophyte	*Ceratophyllum demersum*	South America		■				■	
Aquatic macrophyte	*Echinochloa polystachya* (Kunth) A.S. Hitchc.	South America		■				■	
Aquatic macrophyte	*Egeria densa* Planch.	South America		■				■	
Aquatic macrophyte	*Egeria najas* Planch.	South America		■				■	
Aquatic macrophyte	*Eichhornia crassipes* (Mart.) Solms.	South America		■				■	
Aquatic macrophyte	*Hedichyum coronarium* J. König	Asia	■					■	
Aquatic macrophyte	*Hydrilla verticillata* (L. f.) Royle	Asia	■					■	
Aquatic macrophyte	*Pistia stratiotes* L.	uncertain	n.i.	n.i.				■	
Aquatic macrophyte	*Salvinia auriculata* (Micheli) Adans	South America		■				■	
Aquatic macrophyte	*Salvinia biloba* Raddi emend. de la Sota	South America		■				■	
Aquatic macrophyte	*Urochloa arrecta* (Hack. ex T. Durand & Schinz) Morrone & Zuloaga	Africa	■					■	
Aquatic macrophyte	*Urochloa mutica* (Forssk.) T.Q. Nguyen	Africa	■					■	
Cnidarian	*Cordylophora caspia* (Pallas,1771)	Asia	■					■	
Cnidarian	*Craspedacusta swerbyi* Lankester, 1880	Asia	■					■	
Crustacean	*Daphnia lumholtzi* (Sars, 1885)	Africa, Australia, Asia	■			■			
Crustacean	*Daphnia magna* (Straus, 1820)	China	■		■				
Crustacean	*Daphnia similis* (Claus, 1876)	China	■		■				
Crustacean	*Dendrocephalus brasiliensis* (Pesta, 1921)	South America		■	■				
Crustacean	*Dilocarcinus pagei* (Stimpson, 1861)	South America		■	■				
Crustacean	*Lernaea cyprinacea* (Linnaeus, 1758)	Asia	■					■	
Crustacean	*Macrobrachium amazonicum* Heller, 1862	South America		■		■			
Crustacean	*Macrobrachium jelskii* (Miers, 1877)	South America		■				■	
Crustacean	*Macrobrachium rosenbergii* (De Man, 1879)	Asia, Australia	■			■			
Crustacean	*Mesocyclops ogunnus* Onabamiro, 1957	Africa, Asia	■					■	
Crustacean	*Procambarus clarkii* (Girard, 1852)	North America	■					■	
Fish	*Ageneiosus ucayalensis* Castelnau, 1855	South America		■		■			
Fish	*Amatitlania nigrofasciata* (Günther, 1867)	Central America	■			■			
Fish	*Arapaima gigas* (Schinz, 1822)	South America		■	■				

Table 1. Continued...

Taxonomic group in this study	Species name	Native range	From another country	Translocated domestic species	Species classification				
					IAS	DAS	EAS	InAS	CRY
Fish	*Astronotus ocellatus* (Agassiz, 1831)	South America		■		■			
Fish	*Auchenipterus osteomystax* (Miranda Ribeiro, 1918)	South America		■		■			
Fish	*Australoheros facetus* (Jenyns, 1842)	South America		■		■			
Fish	*Betta splendens* Regan, 1910	Southeast Asia	■			■			
Fish	*Brycon cephalus* (Günther, 1869)	South America		■		■			
Fish	*Brycon hilarii* (Valenciennes, 1850)	South America		■	■				
Fish	*Callichthys callichthys* (Linnaeus, 1758)	South America		■		■			
Fish	*Carassius auratus auratus* (Linnaeus, 1758)	Asia	■			■			
Fish	*Cichla intermedia* Machado-Allison, 1971	South America		■				■	
Fish	*Cichla kelberi* Kullander & Ferreira, 2006	South America		■				■	
Fish	*Cichla monoculus* Spix and Agassiz, 1831	South America		■				■	
Fish	*Cichla ocellaris* Bloch & Schneider, 1801	South America		■				■	
Fish	*Cichla orinocensis* Humboldt, 1821	South America		■				■	
Fish	*Cichla temensis* Humboldt, 1821	South America		■				■	
Fish	*Clarias gariepinus* (Burchell, 1822)	Africa		■				■	
Fish	*Colisa lalia* (Hamilton, 1822)	Asia	■			■			
Fish	*Colossoma macropomum* (Cuvier, 1816)	South America		■		■			
Fish	*Corydoras undulatus* Regan, 1912	South America		■		■			
Fish	*Crenicichla macrophthalma* Heckel, 1840	South America		■		■			
Fish	*Ctenopharyngodon idella* (Valenciennes, 1844)	Asia	■			■			
Fish	*Cyprinus carpio carpio* Linnaeus, 1758	Asia	■			■			
Fish	*Danio rerio* (Hamilton, 1822)	South Asia	■			■			
Fish	*Devario malabaricus* (Jerdon, 1849)	South Asia	■			■			
Fish	*Franciscodoras marmoratus* (Lütken, 1874)	South America		■		■			
Fish	*Geophagus proximus* (Castelnau, 1855)	South America		■				■	
Fish	*Geophagus surinamensis* (Bloch, 1791)	South America		■		■			
Fish	*Gymnocorymbus ternetzi* (Boulenger, 1895)	South America		■		■			
Fish	*Helostoma temminkii* Cuvier, 1829	Asia	■			■			
Fish	*Hemichromis bimaculatus* Gill, 1862	Africa	■			■			
Fish	*Hoplerythrinus unitaeniatus* (Spix & Agassiz, 1829)	South America		■		■			
Fish	*Hoplias lacerdae* Miranda Ribeiro, 1908	South America		■		■			
Fish	*Hoplosternum littorale* (Hancock, 1828)	South America		■		■			
Fish	*Hyphessobrycon eques* (Steindachner, 1882)	South America		■		■			

Table 1. Continued...

Taxonomic group in this study	Species name	Native range	From another country	Translocated domestic species	Species classification				
					IAS	DAS	EAS	InAS	CRY
Fish	*Hypophthalmichthys molitrix* Valenciennes, 1844	Asia	■			■			
Fish	*Hypophthalmichthys nobilis* (Richardson, 1845)	Asia	■			■			
Fish	*Hypophthalmus edentatus* Spix & Agassiz, 1829	South America		■				■	
Fish	*Ictalurus punctatus* (Rafinesque, 1818)	North America	■			■			
Fish	*Laetacara curviceps* (Ahl, 1923)	South America		■		■			
Fish	*Lepomis gibbosus* (Linnaeus, 1758)	North America	■			■			
Fish	*Lepomis macrochirus* Rafinesque, 1819	North America	■			■			
Fish	*Leporinus elongatus* Valenciennes, 1850	South America		■		■			
Fish	*Leporinus friderici* (Block, 1794)	South America		■		■			
Fish	*Leporinus macrocephalus* Garavello & Britski, 1988	South America		■		■			
Fish	*Lophiosilurus alexandri* Steindachner, 1876	South America		■		■			
Fish	*Loricariichthys platymetopon* Isbrücker & Nijssen, 1979	South America		■		■			
Fish	*Macropodus opercularis* (Linnaeus, 1758)	Eastern Asia	■			■			
Fish	*Metynnis maculatus* (Kner, 1858)	South America		■		■			
Fish	*Micropterus salmoides* (Lacepède, 1802)	North America	■			■			
Fish	*Mikrogeophagus altispinosus* (Haseman, 1911)	South America	■			■			
Fish	*Mikrogeophagus ramirezi* (Myers & Harry, 1948)	South America		■		■			
Fish	*Misgurnus anguillicaudatus* (Cantor, 1842)	East Asia	■			■			
Fish	*Mylossoma duriventre* (Cuvier, 1818)	South America		■		■			
Fish	*Nannostomus beckfordi* Günther, 1872	South America		■		■			
Fish	*Odontesthes bonariensis* (Valenciennes, 1835)	South America	■			■			
Fish	*Oncorhynchus mykiss* (Walbaum, 1792)	North America	■					■	
Fish	*Oreochromis macrochir* (Boulenger, 1912)	Africa	■			■			
Fish	*Oreochromis niloticus niloticus* (Linnaeus, 1758)	Africa	■					■	
Fish	*Oreochromis urolepis hornorum* (Trewavas, 1966)	Africa	■			■			
Fish	*Pachyurus bonariensis* Steindachner, 1879	South America		■			■		
Fish	*Parachromis managuensis* (Günther, 1867)	Central America	■			■			
Fish	*Pelvicachromis pulcher* (Boulenger, 1901)	Africa	■			■			
Fish	*Piaractus brachypomus* (Cuvier, 1818)	South America		■		■			
Fish	*Piaractus mesopotamicus* (Holmberg, 1887)	South America		■		■			
Fish	*Plagioscion squamosissimus* (Heckel, 1840)	South America		■		■			

Table 1. Continued...

Taxonomic group in this study	Species name	Native range	From another country	Translocated domestic species	Species classification				
					IAS	DAS	EAS	InAS	CRY
Fish	*Plagioscion surinamensis* (Bleeker, 1873)	South America		■		■			
Fish	*Poecilia latipinna* (Lesueur, 1821)	North America	■			■			
Fish	*Poecilia reticulata* Peters, 1859	South America		■		■			
Fish	*Poecilia sphenops* Valenciennes, 1846	South America	■			■			
Fish	*Poecilia velifera* (Regan, 1914)	Central America	■				■		
Fish	*Polycentrus schomburgkii* Müller & Troschel, 1848	South America		■			■		
Fish	*Prochilodus argenteus* Spix & Agassiz, 1829	South America		■		■			
Fish	*Prochilodus costatus* Valenciennes, 1850	South America		■		■			
Fish	*Prochilodus lineatus* (Valenciennes, 1837)	South America		■			■		
Fish	*Pseudoplatystoma fasciatum* (Linnaeus, 1766)	South America		■			■		
Fish	*Pterodoras granulosus* (Valenciennes, 1821)	South America		■		■			
Fish	*Pterophyllum scalare* (Schultze, 1823)	South America		■		■			
Fish	*Puntius arulius* (Jerdon, 1849)	Asia	■				■		
Fish	*Puntius conchonius* (Hamilton, 1822)	Asia	■			■			
Fish	*Puntius nigrofasciatus* (Günther, 1868)	Asia	■			■			
Fish	*Puntius oligolepis* (Bleeker, 1853)	Asia	■				■		
Fish	*Puntius sachsii* (Ahl, 1923)	Asia	■			■			
Fish	*Puntius semifasciolatus* (Günther, 1868)	Asia	■			■			
Fish	*Puntius tetrazona* Bleeker, 1860	Asia	■				■		
Fish	*Puntius ticto* (Hamilton, 1822)	Asia	■				■		
Fish	*Puntius titteya* Deraniyagala, 1929	Asia	■			■			
Fish	*Pygocentrus nattereri* Kner, 1858	South America		■				■	
Fish	*Pygocentrus piraya* (Cuvier, 1819)	South America		■			■		
Fish	*Salminus brasiliensis* (Cuvier, 1816)	South America		■		■			
Fish	*Satanoperca jurupari* (Heckel, 1840)	South America		■		■			
Fish	*Satanoperca pappaterra* (Heckel, 1840)	South America		■			■		
Fish	*Serrasalmus brandtii* Lütken, 1875	South America		■			■		
Fish	*Serrasalmus marginatus* Valenciennes, 1837	South America		■				■	
Fish	*Serrasalmus spilopleura* Kner, 1858	South America		■			■		
Fish	*Steindachnerina brevipinna* (Eigenmann & Eigenmann, 1889)	South America		■			■		
Fish	*Tanichthys albonubes* Lin, 1932	Asia	■			■			
Fish	*Tilapia rendalli* (Boulenger, 1897)	Africa	■					■	

Table 1. Continued...

Taxonomic group in this study	Species name	Native range	From another country	Translocated domestic species	Species classification				
					IAS	DAS	EAS	InAS	CRY
Fish	*Trachelyopterus galeatus* (Linnaeus, 1766)	South America		■		■			
Fish	*Trachydoras paraguayensis* (Eigenmann & Ward, 1907)	South America		■		■			
Fish	*Trichogaster chuna* (Hamilton, 1822)	Asia	■			■			
Fish	*Trichogaster leerii* (Bleeker, 1852)	Asia, Australia	■			■			
Fish	*Trichogaster pectoralis* (Regan, 1910)	Asia	■			■			
Fish	*Trichogaster trichopterus* (Pallas, 1770)	Asia	■				■		
Fish	*Triportheus angulatus* (Spix & Agassiz, 1829)	South America		■			■		
Fish	*Xiphophorus hellerii* Heckel, 1848	North America	■				■		
Fish	*Xiphophorus maculatus* (Günther, 1866)	North America	■				■		
Fish	*Xiphophorus variatus* (Meek, 1904)	North and Central America	■			■			
Microorganism	*Anabaena circinalis* Rabenhorst, 1852	uncertain	n.i.	n.i.					■
Microorganism	*Anabaena planctonica* Brunnthaler, 190	uncertain	n.i.	n.i.					■
Microorganism	*Anabaena spiroides* Klebahn, 1895	uncertain	n.i.	n.i.					■
Microorganism	*Ceratium furcoides* (Levander) Langhans, 1925	Europe	■			■			
Microorganism	*Cylindrospermopsis raciborskii* (Woloszynska) Seenaya & Subba Raju	Java	■					■	
Microorganism	*Kellicottia bostoniensis* (Rousselet 1908)	North America	■					■	
Microorganism	*Microcystis aeruginosa* (Kützing) Kützing 1846	uncertain	n.i.	n.i.					■
Microorganism	*Microcystis botrys* Teiling, 1942	uncertain	n.i.	n.i.					■
Microorganism	*Microcystis protocystis* Crow 1923	uncertain	n.i.	n.i.					■
Microorganism	*Microcystis viridis* Lemmermann, 1903	uncertain	n.i.	n.i.					■
Microorganism	*Planktothrix mougeotii* (Bory ex Gomont) Anagnostidis & Komárek	uncertain	n.i.	n.i.					■
Microorganism	*Synechocystis aquatilis* Sauvageau 1892	uncertain	n.i.	n.i.					■
Mollusk	*Corbicula fluminalis* (Müller, 1774)	Asia	■				■		
Mollusk	*Corbicula fluminea* (Müller, 1774)	Asia	■					■	
Mollusk	*Corbicula largillierti* (Philippi, 1844)	China	■					■	
Mollusk	*Helisoma duryi* (Wetherby, 1879)	North America	■			■			
Mollusk	*Limnoperna fortunei* (Dunker, 1857)	Southeast Asia	■					■	
Mollusk	*Melanoides tuberculatus* (Müller, 1774)	Africa, Asia, Australia	■					■	
Mollusk	*Physa acuta* Draparnaud, 1805	Europe	■					■	
Nemathelminth	*Camallanus cotti* Fugita, 1927	Asia	■		■				
Platyhelminth	*Bothriocephalus acheilognathi* Yamaguti, 1934	Asia	■		■				
Platyhelminth	*Diphyllobothrium latum* (Linnaeus, 1758)	Aisa, Europe	■		■				

Table 1. Continued...

Taxonomic group in this study	Species name	Native range	From another country	Translocated domestic species	Species classification				
					IAS	DAS	EAS	InAS	CRY
Reptilian	*Trachemys dorbigni* (Duméril e Bibron, 1835)	South America		■			■		
Reptilian	*Trachemys scripta elegans* (Wied-Neuwied, 1839)	North America	■				■		

Table 2. The number of detected species by category of alien species in Brazilian inland waters. The richness of alien species and the number of cases by group of species. Codes indicate: IAS, isolated alien species; DAS - detected alien species; EAS, established alien species; InAS, invasive alien species, and CRY, cryptic species.

Group of Species	Category of alien species					Alien species richness	Number of cases
	IAS	DAS	EAS	CRY	InAS		
Annelida	0	1	0	0	0	1	2
Anurans	1	0	2	0	1	4	27
Aquatic macrophytes	0	0	0	0	12	12	172
Crustaceans	3	4	0	0	4	11	124
Cnidarians	0	0	0	0	2	2	13
Fishes	9	87	19	0	14	109	1,098
Microorganisms	0	2	0	8	2	12	99
Mollusks	0	1	1	0	5	7	335
Nemathelminthes	1	0	0	0	0	1	2
Platyhelminthes	2	0	0	0	0	2	2
Reptilians	0	0	2	0	0	2	22
Total	**16**	**95**	**24**	**8**	**40**	**183**	**1,896**

Table 3. The number of alien species in Brazilian inland waters originated from another country or as translocated domestic species. The 'n.i.' (not identified) status was assigned for species with no confirmed origin.

Taxonomic group	Origin from another country	Translocated domestic species	n.i.	Species richness
Annelida	1	0	0	1
Anurans	2	2	0	4
Aquatic macrophytes	4	7	1	12
Crustaceans	7	4	0	11
Cnidarians	2	0	0	2
Fishes	47	62	0	109
Microorganisms	3	0	9	12
Mollusks	7	0	0	7
Nemathelminthes	1	0	0	1
Platyhelminthes	2	0	0	2
Reptilians	1	1	0	2
Total	**77**	**76**	**10**	**163**

Fish species were in the group with the highest number of occurrences of introduced species and InAS in Brazilian inland waters. Despite the few introduced species of aquatic macrophytes and mollusks, they also reached many species classified as InAS: 100% and 71%, respectively. By considering the number of alien species detections as a surrogate of their dispersal potential, we found positive and robust linear relationships between alien species detections and alien species richness (Figure 1; R^2 = 80%) and with InAS richness (Figure 2; R^2 = 60%).

4. Discussion

Despite the time of the survey (data was gathered only until 2012), alien species richness in Brazilian freshwater environments (N=183) is important in establishing an essential measure for subsequent comparisons. The same consideration may be made for the number of confirmed cases (1,896). According to the results for the species groups, the detections of microorganisms, mollusks, and fish outperform the alien species pool, which

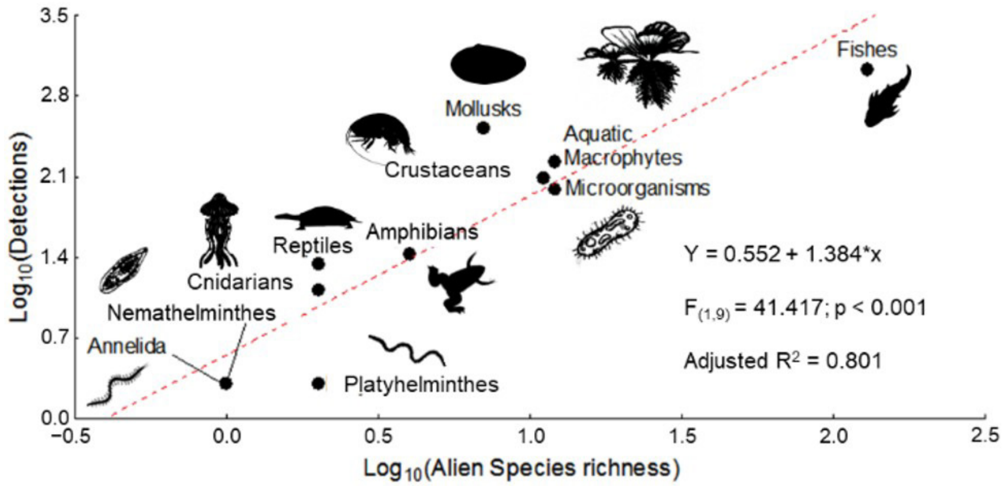

Figure 1. Relationship between the richness of alien species and detections for each alien species group in Brazilian inland waters.

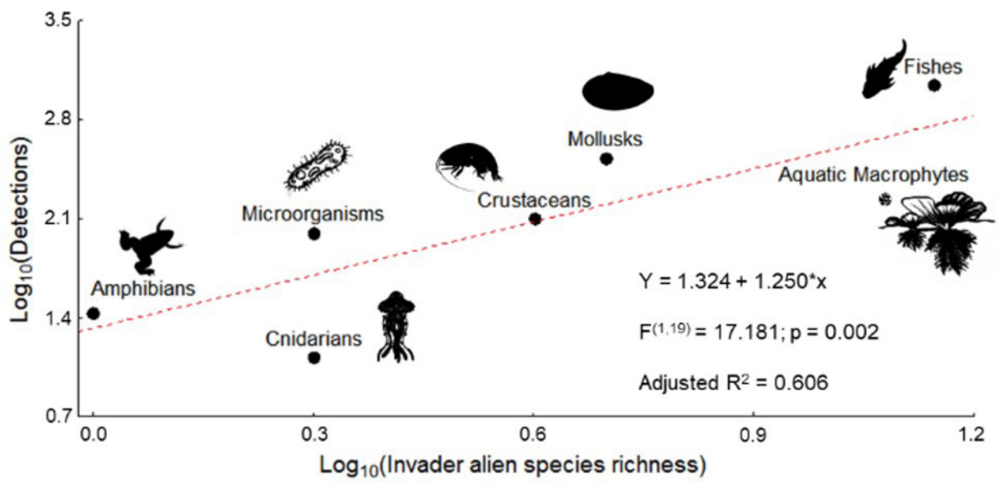

Figure 2. Relationship between the invaders of alien species richness and detections for each group of alien species in Brazilian inland waters.

can be visualized both in the relationship between detections and the richness of alien species (Figure 1) and in the relationship between detections and the richness of alien invasive species (Figure 2).

Some features may favor these groups: pollution primarily benefits microorganisms (e.g., cyanobacterial species), commonly associated with decreasing water quality (Crooks et al., 2010), but also benefits fish species, such as the guppy *Poecilia reticulata* (Peters, 1859) that assimilate carbon directly from sewage (Carvalho et al., 2019). Mollusks, such as *Limnoperna fortunei* (Dunker 1857), have improved dispersal abilities since fixing on boats and have long-term survival out of the water (Oliveira et al., 2010). Fish have dispersal potentialized by fishing (Daga et al., 2016), inland aquaculture (Lima-Junior et al., 2018; Forneck et al., 2020), and ornamental cultivation and dumping in natural habitats (Magalhães et al., 2017, 2021). Explanations came from a bibliographic review and were corroborated by the invited specialists who validated the survey.

A recent and significant publication on alien species provided a systematic discussion of the vectors influencing the introduction, establishment, and spread of alien species in Brazil (Bergallo et al., 2024). The changes in aquatic ecosystems, organism trade, and navigation are considered some of the most important direct vectors. There is evidence of organism trade benefiting fish (e.g., Magalhães & Jacobi, 2017), environmental impacts benefiting microorganisms (e.g., Saulino & Trivinho-Strixino, 2017), and navigation benefiting mollusks (e.g., Hermes-Silva et al., 2021). These vectors are likely responsible for the response that these taxa, fish, microorganisms, and mollusks have, allowing us to identify, among them, an average response superior to the expected in our models.

In addition to constituting a dangerous scenario, alien species in Brazilian inland waters may be a surrogate vision of what has occurred, since they represent specialists and documented alien species occurrence in Brazilian watersheds. It helps to show how fragile and threatened these freshwater ecosystems are, given the pervasive effects on biodiversity loss worldwide (Bellard et al., 2016), mainly in megadiverse countries such as Brazil (Pelicice et al., 2017). However, the survey also represents a primordial step to knowing about the establishment of alien species.

It is essential to note that a large number of the alien species in Brazilian freshwater ecosystems (e.g., 58% for aquatic macrophytes, 36% for crustaceans, and 57% for fishes) are translocated (i.e., species introduced from another river basin or freshwater ecoregion within Brazil) and are primarily related to aquaculture use (Tables 1, 2) what corroborates with previous studies that showed that aquaculture is the leading vector or pathway of introduced species in Brazil (Ortega et al., 2015), China (Kang et al., 2023) and in the world (Casal, 2006). Therefore, this scenario is worrisome once it is difficult to control the transport and introduction of species among the national river basin. A direct consequence is the increasing number of alien species in freshwater ecosystems in Brazil (Magalhães et al., 2021; Rocha et al., 2023), including pristine regions like the Amazon River basin (Doria et al., 2021). An emblematic example is the invasion of giant arapaima *Arapaima gigas* (Schinz, 1822). This species was introduced in the Madeira River (in the Amazon River basin) and Grande River (in the Paraná River basin) due to the escape of aquaculture facilities (Catâneo et al., 2022; Sousa et al., 2022).

Despite the well-known crisis of freshwater ecosystems worldwide (Albert et al., 2021), freshwater biodiversity and its benefits persist in decline. Water supply, wild-caught fishing, recreation, flood control, and gene biodiversity are just examples of the reduced benefits of nature that alien invasions and dispersal can reduce (Flood et al., 2020). Unfortunately, the general opinion of Brazilians about this problem is poor. Changing this scenario is imperative and requires enhancing the quality of environmental regulatory policies and considering a cautionary overview regarding alien species and biodiversity and benefit maintenance.

In Brazil, some other factors worsen alien species. For instance, the Forest Code amendments relax natural area preservation and affect water quality and community stability (Magalhães et al., 2010; Tollefson, 2011). Additionally, the expansion of dams/reservoirs around all river basins impact negatively the integrity of local ecological communities and favors the establishment of alien species (Johnson et al. 2008; Muniz et al. 2021). The aquaculture expansion with alien species, a key introduction vector, spreads across regions (Pelicice et al., 2017; Lima-Junior et al., 2018; Charvet et al., 2021), while the crisis in science investments impacting biodiversity (Overbeck et al., 2018; Escobar, 2019; Gonçalves et al., 2020; Kowaltowski, 2021) and new laws threaten freshwater biodiversity in neighboring countries, promoting alien fish farming (Latini et al., 2021). Like what happens worldwide, scientific uncertainty in Brazil regarding the status of alien species is high and their potential harm, highlighting the need for a cautionary overview of invaders.

Acknowledgements

This work was supported by the Ministério do Meio Ambiente e Mudança do Clima and Projeto de Conservação e Utilização Sustentável da Diversidade Biológica Brasileira – PROBIO (grant number 68.0012/04-4). Thank Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for research grants awarded to D. P. Lima-Junior (Grant Number: 305923/2020-0).

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Received: 01 July 2023
Accepted: 07 May 2024

Associate Editor: Andre Andrian Padial.