Aquat Ecol (2024) 58:47–55
https://doi.org/10.1007/s10452-023-10069-z

Tilapia venturing into high-salinity environments: A cause for concern?

Ana Clara Sampaio Franco · Valter M. Azevedo-Santos · Marluce Aparecida Mattos de Paula Nogueira · Tommaso Giarrizzo · Rachel Ann Hauser-Davis · Erick Cristofore Guimarães · Roger Henrique Dalcin · Marcelo Soeth · Matheus Oliveira Freitas · Áthila A. Bertoncini · Vinícius Abilhoa · Almir Manoel Cunico · Johnatas Adelir-Alves · Bianca Bentes · José Luís Costa Novaes · Mauricio Hostim-Silva · Jonas Rodrigues Leite · Vagner Leonardo Macêdo dos Santos · Jean Ricardo Simões Vitule

Received: 7 March 2023 / Accepted: 30 September 2023 / Published online: 18 October 2023
© The Author(s) 2024, corrected publication 2024

Abstract Invasive species are continuously introduced in several ecosystems from human activities. Aquaculture activities are noteworthy among the many different species introduction vectors currently in place, generating a pattern of constant, frequent or massive release of propagules into aquatic ecosystems, increasing species establishment success rates. Reported cases in marine or brackish ecosystems, however, are still scarce. As aquaculture constantly generate propagules with the ability to employ these facilities as corridors to further spread to interconnected brackish and freshwater ecosystems, colonising high salinity systems, this study aimed to compile evidence of Tilapiines detected in Brazilian coastal marine and brackish ecosystems. Nineteen records were obtained, with the presence of this invader suggested as higher following rainfall

---

Communicated by Lorena Silva Nascimento.

A. C. S. Franco (✉)
Laboratório de Ictiologia Teórica e Aplicada, Universidade Federal do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
e-mail: anaclara306@gmail.com

A. C. S. Franco
Institute of Aquatic Ecology, University of Girona, Catalonia, Spain

V. M. Azevedo-Santos
Faculdade Eduvale de Avaré, Avaré, São Paulo, Brazil

V. M. Azevedo-Santos
Programa de Pós-Graduação em Biodiversidade, Ecologia e Conservação, Universidade Federal do Tocantins, Porto Nacional, Tocantins, Brazil

V. M. Azevedo-Santos
Grupo de Ecologia Aquática, Universidade Federal do Pará, Belém, Pará, Brazil

M. A. M. d. Nogueira
Programa de Pós-Graduação em Ecologia, Universidade Federal de São João Del Rei, São João del Rei, Minas Gerais, Brazil

T. Giarrizzo
Instituto de Ciências do Mar, Universidade Federal do Ceará, Fortaleza, Ceará, Brazil

R. A. Hauser-Davis
Laboratório de Avaliação e Promoção da Saúde Ambiental, Instituto Oswaldo Cruz, Fundação Oswaldo Cruz, Rio de Janeiro, Brazil

E. C. Guimarães
Programa de Pós-Graduação Sociedade Natureza e Desenvolvimento, Instituto de Ciências da Educação, Universidade Federal do Oeste do Pará, Santarém, Pará, Brazil

R. H. Dalcin · V. Abilhoa
Programa de Pós-Graduação em Zoologia, Universidade Federal do Paraná, Curitiba, Brazil

M. Soeth
Programa de Pós-Graduação em Sistemas Costeiros e Oceânicos, Universidade Federal do Paraná, Pontal do Paraná, Paraná, Brazil

seasons. The widespread distribution of Tilapiines is relatively well-known in Brazilian freshwater ecosystems but, up to now, its potential to use brackish and marine ecosystems as ecological corridors has been described only experimentally. Our findings highlight the potential for a typically freshwater invader to spread through marine ecosystems, raising concerns regarding the licensing of aquaculture projects within rivers and estuaries, as tilapia may significantly affect native Brazilian biota.

Keywords Cichlid · Estuaries · Invasiveness · Invasive species · Tilapiine

Introduction

Invasive species are recognised as one of the leading causes of biodiversity and ecosystem services losses (Cucherousset and Olden 2011; Bellard et al. 2022; Hogue and Breon 2022). These impacts are often closely associated with other human stressors, e.g., climate change (Fischer et al. 2021; Rahel and Olden 2008). The interactions between these events and the impacts caused by aquatic IAS are, however, still poorly understood, particularly in South America (Lowry et al. 2013). In this regard, increased establishment rates and more widespread distribution of non-native species can be expected due to climate-driven environmental changes (Rahel and Olden 2008). In this context, to better understand invasions and their effects, it is crucial to understand how these interactions can change from simple additives to more extensive synergistic effects (Blois et al. 2013).

Economically important species, such as those employed in aquaculture, sport fisheries and stocking, exhibit distribution patterns closely related to other sources of human impacts (Leprieur et al. 2008). These activities increase local propagule pressures, consequently increasing ecosystem vulnerability to invasions at a regional level (Azevedo-Santos et al. 2011; Forneck et al. 2021). Although harbouring a lower number of non-native fish species, marine and brackish systems are often interconnected to richer freshwater ecosystems that act as propagule sources. Salinity-tolerant species (*e.g.*, some cichlids, such as tilapias) are often introduced into freshwater systems and may survive and colonise brackish and marine ecosystems (Gutierre et al. 2014; Schofield et al. 2011).

Tilapias are representatives of the Cichlidae family, subfamily Pseudocrenilabrinae and tribe Tilapiini, which naturally occur in the African continent. They are widespread throughout Brazil, mainly in freshwater systems, in aquaculture production, representing 63.5% of all farmed fish in Brazil (Peixe 2022). Although the Brazilian government has not conducted an official fishery monitoring program since 2012, the Brazilian Fish Farming Association reports production of around 534 tons of tilapia in 2021, a 9.8% increase from 2020 (Peixe 2022). The expansion of aquaculture production based on non-native species is linked to several national regulations that aim to promote the installation of new facilities and protect those species from extermination

---

M. Soeth · M. Hostim-Silva
Laboratório de Ecologia de Peixes Marinhos, Centro Universitário Norte do Espírito Santo, Universidade Federal Do Espírito Santo, São Mateus, Espírito Santo, Brazil

M. O. Freitas · Á. A. Bertoncini · J. Adelir-Alves · J. R. Leite
Instituto Meros do Brasil, Rua Benjamin Constant, 67, Centro, Curitiba, Paraná, Brazil

V. Abilhoa
Museu de História Natural Capão da Imbuia, MAPCF/PMC, Curitiba, Paraná, Brazil

A. M. Cunico
Laboratório de Ecologia, Pesca e Ictiologia, Departamento de Biodiversidade, Setor Palotina, Universidade Federal do Paraná, Palotina, Paraná, Brazil

B. Bentes
Laboratório de Biologia Pesqueira e Manejo de Recursos Aquáticos, Núcleo de Ecologia Aquática e Pesca da Amazônia, Universidade Federal do Pará, Belém, Pará, Brazil

J. L. C. Novaes
Departamento de Biociências, Universidade Federal Rural do Semi-Árido, Mossoró, Rio Grande do Norte, Brazil

V. L. M. dos Santos
Laboratório de Ecologia de Peixes, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

J. R. S. Vitule
Laboratório de Ecologia e Conservação, Departamento de Engenharia Ambiental, Setor de Tecnologia, Universidade Federal do Paraná, Centro Politécnico, Curitiba, Paraná, Brazil

(Charvet et al. 2021; Pelicice et al. 2013). These protective measures are misleading and completely disregard the numerous negative effects related to the presence of non-native tilapias in aquatic ecosystems (Occhi et al. 2021). Constant propagule pressure (*e.g.,* the number and frequency of individuals/units introduced into a new environment; sensu Lockwood et al. 2009) may promote adaptation to novel conditions and create new lineages with even greater invasive potential due to expanded environmental tolerance, with unknown impacts on marine ecosystems. This artificial selection pressure of non-native species is even more concerning considering the ongoing expansion of tilapia farming to brackish ecosystems (Setyawan et al. 2022). Considering the potential for adaptation to high salinity and increased distribution of tilapia species (Cassemiro et al. 2018; Gutierre et al. 2014; Schofield et al. 2011), this study describes records of tilapias found in coastal ecosystems from Brazil, also discussing the potential use of marine ecosystems as corridors for *Tilapiine* dispersal.

Methods

Data regarding tilapia records in coastal marine ecosystems in Brazil were obtained from aquatic ecology experts, online databases (*e.g.,* the Information System on Brazilian Biodiversity, SiBBr) and social media platforms. The use of publicly available digital information followed the ethics of using social media by Monkman et al. (2018) and Di Minin et al. (2021). A map was built using Quantum GIS (QGIS Development Team 2023) based on the coordinates of the records gathered and also on GBIF occurrence (GBIF 2023) data for *Oreochromis niloticus* (species that accounted for most of the records) in order to provide further evidence on the potential propagule pressure on upstream basins. To characterise the abiotic conditions of the systems where the Tilapiine individuals were observed, we extracted data on salinity (minimum, mean and range) from the Bio-Oracle database (Tyberghein et al. 2012; Assis et al. 2017).

Table 1 Locations with the reported occurrence of Tilapiines in Brazilian brackish and marine ecosystems. Photographs and videos are openly available and linked below

N	Locality	Lat/Long	Data source
1	Praia Grande, Arraial do Cabo, RJ	−22.976/−42.033	YouTube video 1
2	Praia Vermelha, Rio de Janeiro, RJ	−22.955/−43.16	Figure 2D; Franco et al. (2023)
3	Praia da Vila, Saquarema, RJ	−22.934/−42.512	Figure 2A; Franco et al. (2023)
4	Praia da Reserva, Rio de Janeiro, RJ	−23.014/−43.394	Franco et al. (2023)
5	Praia de Ponta Negra, Maricá, RJ	−22.958/−42.696	Franco et al. (2023)
6	Prainha, Arraial do Cabo, RJ	−22.956/−42.022	Franco et al. (2023)
7	Jericoacoara National Park, Ceará	−2.804/−40.454	GEA 5502[a]
8	Guanabara bay, Rio de Janeiro, RJ	−22.802/−43.133	LBP 21417[b]
9	Itanhaém, São Paulo, SP	−24.193/−46.781	YouTube Video 2
10	São Luís, MA	−2.477/−44.235	Franco et al. (2023)
11	Rodrigo de Freitas Lagoon, Rio de Janeiro, RJ	−22.973/−43.211	Hauser-Davis et al. (2010)
12	Lençóis Maranhenses National Park, MA	−2.43629/−43.068	CIUEMA2800[c]
13	Jacarepaguá Lagoon, Rio de Janeiro, RJ	−22.986 /−43.399	Hauser-Davis et al. (2015)
14	Jaguarema river estuary, Maranhão, MA	−2.4739/−44.21624	CIUEMA2801[c]
15	Apodi-Mossoró river estuary, RN	−4.9387/−37.1533	UFRN3469/UFRN3632[d]
16	Canal do Linguado, Balneário Barra do Sul, SC	−26.4569/−48.6109	Franco et al. (2023)
17	Maricá lagoon, Maricá, RJ	−22.9486/−42.8223	Franco et al. (2022)
18	Cricaré river estuary, Conceição da Barra, ES	−18.599/−39.7323	Franco et al. (2023)
19	São José lagoon, Saquarema, RJ	−22.9496/−42.8755	Franco et al. (2023)

[a] Grupo de Ecologia Aquática—GEA, Núcleo de Ecologia Aquática e Pesca da Amazônia—NEAP, Universidade Federal do Pará

[b] Laboratório de Biologia e Genética de Peixes—LBP, Universidade Estadual Paulista—campus Botucatu

[c] Coleção Ictiológica da Universidade Estadual do Maranhão

[d] Fish collection of the Universidade Federal do Rio Grande do Norte

Results

A total of 19 video, photographic, museum records and personal communications from researchers (as listed in Table 1) were obtained reporting the presence of *Tilapiines* in sandy beaches and coastal lagoons from northern to southeastern Brazil (Fig. 1). Two of the records were from the Arraial do Cabo municipality, located in a typical marine region with a well-studied upwelling system. Three reports indicated numerous shoals (approximately 30 individuals) at the surf-zone of sandy beaches and near docks. One of the seven records for Saquarema was an individual captured with hook and marine shrimp as bait in the surf zone (Fig. 2). Brackish and marine ecosystems where the Tilapiine individuals were recorded had minimum salinities varying from 34.5 to 36.3, mean temperatures between 21.64 and 28.04 °C and mean dissolved oxygen between 200.64 and 231.34 μmol/m^3 (Table 2).

Discussion

Our findings are indicative of two alternative, albeit non-mutually exclusive hypotheses, that the tilapia individuals detected in brackish and marine ecosystems are, in fact, (i) part of established populations due to chronic propagule pressure that exported individuals to these systems, or (ii) originated from acute propagule pressure from nearby aquaculture facilities, probably due to stochastic climatic events, such as tank flooding (Fig. 3; and as also described by Woodford et al. 2013). Even though we cannot discard any of these hypotheses based on our data, further genetic studies would be able to disclose the origin of the

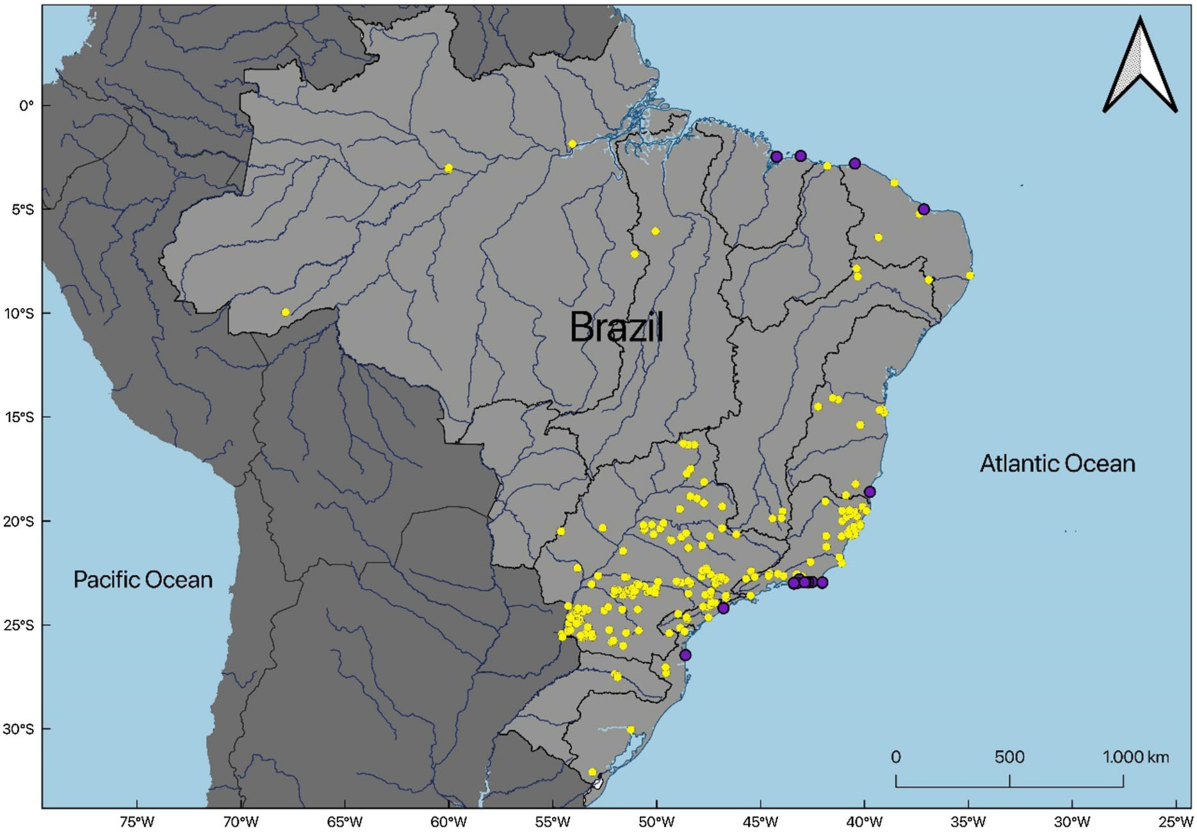

Fig. 1 Map depicting the distribution of tilapias: (i) recorded in brackish and marine environments throughout the Brazilian coast (in purple); and (ii) throughout Brazilian freshwater ecosystems according to the data available in GBIF for *Oreochromis niloticus* ($N=273$ records in yellow). See Table 1 and Methods section for further details. Grey lines represent major rivers and black lines delimit Brazilian hydrographic basins

observed individuals. Nevertheless, the presence of these individuals and the new environmental licences for aquaculture in brackish waters in Brazil highlights the potential for the further spread of tilapias to marine ecosystems and also to freshwater systems interconnected to them [as described by Brown et al. (2007) for other fish species]. In fact, none of this is surprising, given that marine and freshwater ecosystems are separated in rather artificial ways and are largely connected and interdependent on each other.

Euryhaline fishes demonstrate a remarkable ability to adapt to opposing osmotic challenges, from hypoosmotic surroundings in freshwater to hyperosmotic surroundings in seawater (Laverty and Skadhauge 2012). Such facts are more acute when we know that tilapias are fish of primary marine origin, and therefore, extremely euryhaline and robust to different environmental conditions. Although the establishment of a sustainable population may be unlikely, although not impossible, in the long term, the constant propagule pressure imposed by aquaculture facilities and stocking programs creates a chronic impact due to the continuous arrival of novel individuals (Woodford et al. 2013). Studies have been demonstrating the key role played by anthropogenic disturbances (e.g., climate change, salinisation processes, canals construction and hydrological regulation) in favouring the invasion process of non-native fish in coastal ecosystems since these systems are constantly subjected to several human activities creating acute and chronic disturbances and increasing the propagule pressure, allowing several freshwater species to establish (Woodford et al. 2013; Moyle and Stompe 2022).

Furthermore, brackish and estuarine ecosystems are already known for harbouring a large number of non-native fish species that are primarily freshwater, which colonise upper to middle portions of these systems, despite salinity conditions (Moyle and Stompe 2022). This highlights the potential use of these systems as stepping-stones or ecological corridors (or "salty bridges" sensu Gutierre et al. 2017) for further spread through other basins by species that can endure moderate to high salinities (e.g., *Pterygoplichthys*, Capps et al. 2011; swamp eels, Schofiel and Nico 2009; and also, the peacock bass *Cichla kelberi*, Catelani et al. 2021). The colonisation by a group of individuals, even though increasing through *per capita* effect, is per se a source of many negative effects through feeding and transference of parasites for

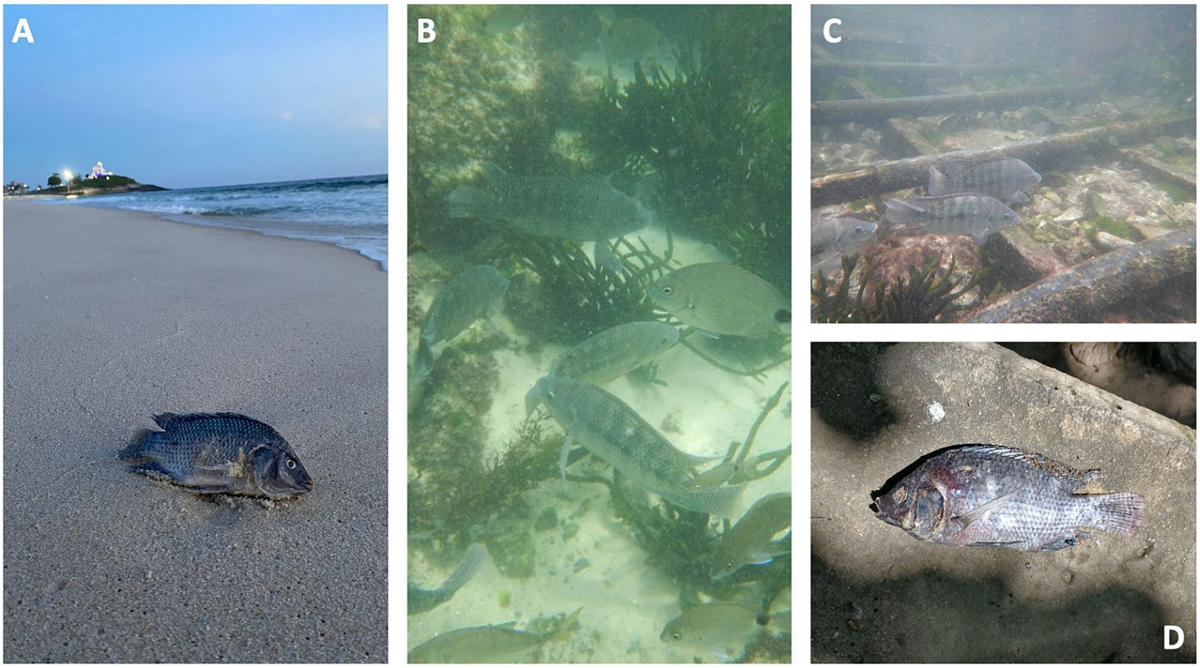

Fig. 2 Photographic records of the tilapias in: **A**—Saquarema, Rio de Janeiro; **B** and **C**—Arraial do Cabo, Rio de Janeiro, and **D**—Praia Vermelha, Rio de Janeiro

Table 2 Abiotic variables of the Brazilian coastal ecosystems where *Tilapiine* individuals were detected as available in the BioOracle database (Tyberghein et al. 2012; Assis et al. 2017)

N	Locality	Salinity			Temperature (°C)			Dissolved oxygen (μmol/m^3)		
		Minimum	Mean	Range	Minimum	Mean	Range	Minimum	Mean	Range
1	Praia Grande, Arraial do Cabo, RJ	36.33	36.57	0.48	20.87	23.65	5.79	204.63	215.60	26.26
2	Praia Vermelha, Rio de Janeiro, RJ	35.98	36.22	0.47	20.43	23.52	6.91	207.45	218.90	24.78
3	Praia da Vila, Saquarema, RJ	36.30	36.55	0.52	19.64	22.20	5.43	207.42	216.92	18.91
4	Praia da Reserva, Rio de Janeiro, RJ	36.00	36.32	0.64	18.84	21.64	5.94	205.92	216.60	22.56
5	Praia de Ponta Negra, Maricá, RJ	36.11	36.42	0.43	20.83	23.76	6.27	204.68	215.60	26.26
6	Prainha, Arraial do Cabo, RJ	36.33	36.57	0.48	20.87	23.65	5.79	204.63	215.60	26.26
7	Jericoacoara National Park, Ceará	35.58	36.09	0.88	26.28	27.61	2.93	196.43	201.17	9.92
8	Guanabara bay, Rio de Janeiro, RJ	36.06	36.34	0.63	20.31	23.43	6.77	210.28	221.35	23.28
9	Itanhaém, São Paulo, SP	35.36	35.95	0.94	17.58	22.08	8.31	213.53	231.34	42.97
10	São Luís, MA	34.98	36.19	2.09	26.99	28.04	2.37	196.27	201.72	15.91
11	Rodrigo de Freitas Lagoon, Rio de Janeiro, RJ	35.94	36.19	0.47	20.59	23.66	6.85	206.95	218.32	25.20
12	Lençóis Maranhenses National Park, MA	34.81	35.96	1.58	26.75	27.87	2.59	196.42	200.64	8.90
13	Jacarepaguá Lagoon, Rio de Janeiro, RJ									
14	Jaguarema river estuary, Maranhão, MA	34.98	36.19	2.09	27.00	28.04	2.37	196.27	201.72	15.91
15	Apodi-Mossoró river estuary, RN	35.71	36.21	0.85	25.95	27.65	3.48	195.81	201.13	11.07
16	Canal do Linguado, Balneário Barra do Sul, SC	34.50	35.54	1.41	16.19	22.48	12.02	203.02	221.37	52.05
17	Maricá lagoon, Maricá, RJ	36.10	36.33	0.45	20.58	23.58	6.47	206.04	217.04	24.71
18	Cricaré river estuary, Conceição da Barra, ES	36.79	37.22	0.75	23.40	25.91	4.97	198.90	206.17	18.27
19	São José lagoon, Saquarema, RJ	36.10	36.33	0.45	20.58	23.58	6.47	206.04	217.04	24.71

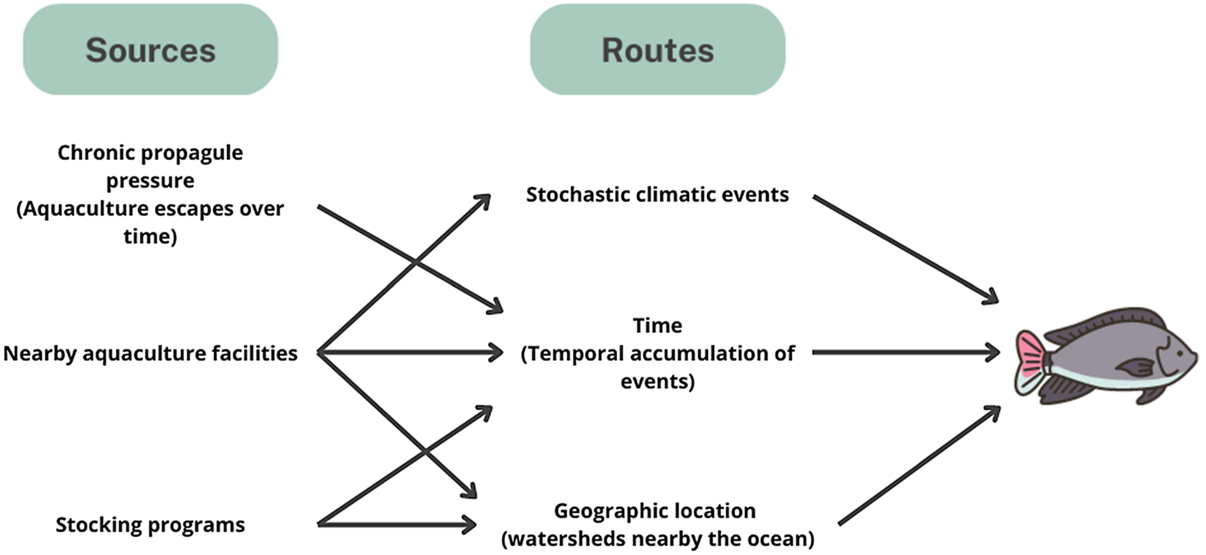

Fig. 3 Theoretical framework on the sources and routes taken by *Tilapiines* introduced into marine and brackish Brazilian ecosystems

native species (Canonico et al. 2005; Starling et al. 2002). If we consider that a higher salinity does not act as a barrier to their spread, then the potential for the spread of an individual should be evaluated at a regional scale, considering the use of brackish and marine systems as corridors.

Tilapias have become widespread due to their use as a food resource in aquaculture (Naylor et al. 2000), often inside natural environments. Escapes are frequent, and established populations have been related to increased eutrophication and habitat modification. Even though their impacts are already known, tilapia farms are now being constructed in brackish conditions inside estuaries in Brazil (Tilápias Mangaratiba 2023). Considering the frequency of escapes from these facilities and their ability to tolerate salinities close to that of the sea (~30; Gutierre et al. 2014), it is likely that wild populations are already established around these systems (see Leal-Flórez 2007; Peterson et al. 2005 for examples of tilapia populations in estuarine-marine conditions). Moreover, tilapias are recognised for their rusticity and ability to tolerate harsh conditions, such as polluted environments, which can enhance their invasive potential.

Brazilian authorities promote tilapia farming as an important activity to ensure the protein intake for the population (Naylor et al. 2000), regardless of the risks and the enormous potential of the great number of native fish species that have already been proven as farmable. Furthermore, novel structures have been installed in brackish regions with massive production and a greenwashing that says they have a "sustainable" production system with tilapias farmed free within cages. At the same time that the largest tilapia producer in the world, China, is turning on an alert and seeking to map and study the impacts of invaders to improve its legislation and reduce impacts (Xiong et al. 2023), Brazil, through governmental proposals attempted to naturalise tilapias by decree (Pelicice et al. 2013), so the environmental laws that regulate the spread of non-native species would not apply to them anymore. Finally, we highlight that our findings show a factual potential for a freshwater IAS to spread in marine ecosystems using freshwater facilities. These results add to the reality that new introductions are inevitable (Xiong et al. 2023), bring light to the urgent need for control and containment methods program for the species in natural environments and raise concerns regarding the licensing of running and new aquaculture projects inside rivers and estuaries.

Author's contribution ACSF and JRSV contributed to the study's conception and design. Data collection was performed by all authors. The first draft of the manuscript was written by ACSF. English review was performed by RAH-D. All authors read and approved the final version of the manuscript.

Funding This study was supported by the Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, Brazil (postdoctoral fellowship to ACSF, E-26/202.423/2019) and National Council for Scientific and Technological Development (research grant to JRSV 302367/2018-7). MOF, AAB, and JRL thank the Meros do Brasil Project, sponsored by Petrobras.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this paper.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visithttp://creativecommons.org/licenses/by-nc-nd/4.0/.

References

Assis J, Tyberghein L, Bosh S, Verbruggen H, Serrão EA, De Clerck O (2017) Bio-ORACLE v2.0: extending marine data layers for bioclimatic modelling. Global Ecol Biogeogr 27:277–284. https://doi.org/10.1111/geb.12693

Azevedo-Santos VM, Rigolin-Sá O, Pelicice FM (2011) Growing, losing or introducing? Cage aquaculture as a vector for the introduction of non-native fish in Furnas Reservoir, Minas Gerais, Brazil. Neotrop Ichthyol. https://doi.org/10.1590/S1679-62252011000400024

Bellard C, Marino C, Courchamp F (2022) Ranking threats to biodiversity and why it doesn't matter. Nat Commun 13:2616. https://doi.org/10.1038/s41467-022-30339-y

Blois JL, Zarnetske PL, Fitzpatrick MC, Finnegan S (2013) Climate change and the past, present, and future of biotic interactions. Science 341:499–504. https://doi.org/10.1126/science.1237184

Brown JA, Scott DM, Wilson RW (2007) Do estuaries act as saline bridges to allow invasion of new freshwater systems by non-indigenous fish species? In: Gherardi F (ed) Biological invaders in inland waters: Profiles, distribution, and threats. Springer, pp 401–414. https://doi.org/10.1007/978-1-4020-6029-8_21

Canonico GC, Arthington A, McCrary JK, Thieme ML (2005) The effects of introduced tilapias on native biodiversity. Aquat Conserv 15:463–483. https://doi.org/10.1002/aqc.699

Capps KA, Nico LG, Mendoza-Carranza M, Arévalo-Frías W, Ropicki AJ, Heilpern SA, Rodiles-Hernández R (2011) Salinity tolerance of non-native suckermouth armoured catfish (Loricariidae: Pterygoplichthys) in south-eastern Mexico: implications for invasion and dispersal. Aq Conserv Mar Fresh Ecosyst 21:528–540. https://doi.org/10.1002/aqc.1210

Cassemiro FAS, Bailly D, da Graça WJ et al (2018) The invasive potential of tilapias (Osteichthyes, Cichlidae) in the Americas. Hydrobiol 817:133–154. https://doi.org/10.1007/s10750-017-3471-1

Catelani PA, Petry AC, Pelicice FM, García-Berthou E (2021) When a freshwater invader meets the estuary: the peacock bass and fish assemblages in the São João River, Brazil. Biol Invasions 23:167–179. https://doi.org/10.1007/s10530-020-02363-w

Charvet P, Occhi TVT, Faria L, Carvalho B, Pedroso CR, Carneiro L, Freitas M, Petrere-Junior M, Vitule JRS (2021) Tilapia farming threatens Brazil's waters. Science. https://doi.org/10.1126/science.abg1346

Cucherousset J, Olden JD (2011) Ecological impacts of non-native freshwater fishes. Fisheries 36:215–230. https://doi.org/10.1080/03632415.2011.574578

Di Minin E, Fink C, Hausmann A, Kremer J, Kulkarni R (2021) How to address data privacy concerns when using social media data in conservation science. Conserv Biol 35:437–446. https://doi.org/10.1111/cobi.13708

Fischer EM, Sippel S, Knutti R (2021) Increasing probability of record-shattering climate extremes. Nat Clim Chang 11:689–695. https://doi.org/10.1038/s41558-021-01092-9

Forneck SC, Dutra FM, de Camargo MP et al (2021) Aquaculture facilities drive the introduction and establishment of non-native *Oreochromis niloticus* populations in Neotropical streams. Hydrobiol 848:1955–1966. https://doi.org/10.1007/s10750-020-04430-8

Franco ACS, Araújo FG, dos Santos AFGN et al (2022) From meso to hyperhaline: the importance of Neotropical coastal lagoons in supporting the functional fish diversity at regional scale. Hydrobiologia 849:4101–4118. https://doi.org/10.1007/s10750-021-04683-x

Franco ACS, Azevedo-Santos VM, Nogueira MAMP, Giarrizzo T, Hauser-Davis RA, Guimarães EC, Dalcin RH, Soeth M, Freitas MO, Bertoncini AA, Abilhoa V, Cunico AM, Bentes B, Novaes JLC, Hostim-Silva M, Leite JR, Santos VLM, Adelir-Alves J, Vitule JRS (2023) Records of Tilapiines in Brazilian brackish and marine ecosystems. figshare Data Repository. https://doi.org/10.6084/m9.figshare.23977137

GBIF.org (2023) GBIF Occurrence Download. https://doi.org/10.15468/dl.ps9mbv

Gutierre SMM, Vitule JRS, Freire CA, Prodocimo V (2014) Physiological tools to predict invasiveness and spread via estuarine bridges: tolerance of Brazilian native and worldwide introduced freshwater fishes to increased salinity. Mar Freshw Res 65:425–436. https://doi.org/10.1071/MF13161

Gutierre SMM, Schulte JM, Schofield PJ, Prodocimo V (2017) Osmoregulation and muscle water control of the Amazon fish Oscar *Astronotus ocellatus* (Cichlidae) when facing salinity stress. Mar Fresh Behav Physiol 50:303–311. https://doi.org/10.1080/10236244.2017.1387480

Hauser-Davis RA, Oliveira TF, Silveira AM, Silva TB, Ziolli RL (2010) Case study: comparing the use of nonlinear discriminating analysis and Artificial Neural Networks in the classification of three fish species: acaras (*Geophagus brasiliensis*), tilapias (*Tilapia rendalli*) and mullets (Mugil liza). Ecol Inf 5:474–478

Hauser-Davis RA, Lavradas RT, Lavandier RC, Rojas EG, Guarino AW, Ziolli RL (2015) Accumulation and toxic effects of microcystin in tilapia (*Oreochromis niloticus*) from an eutrophic Brazilian lagoon. Ecotoxicol Environ Saf 112:132–136. https://doi.org/10.1016/j.ecoenv.2014.10.036

Hogue AS, Breon K (2022a) The greatest threats to species. Conserv Sci Pract. https://doi.org/10.1111/csp2.12670

Laverty G, Skadhauge E (2012) Adaptation of teleosts to very high salinity. Comp Bioch Physiol 163:1–6

Leal-Flórez J (2007) Impacts of non-native fishes on the fish community and the fishery of the Ciénaga Grande de Santa Marta estuary, northern Colombia. PhD Thesis, University of Bremen, Bremem, Germany, pp 153

Leprieur F, Beauchard O, Blanchet S, Oberdorff T, Brosse S (2008) Fish invasions in the world's river systems: when natural processes are blurred by human activities. PLoS Biol 6:e28. https://doi.org/10.1371/journal.pbio.0060028

Lockwood JL, Cassey P, Blackburn T (2009) The more you introduce the more you get: the role of colonization pressure and propagule pressure in invasion ecology. Div Distrib 15:904–910. https://doi.org/10.1111/j.1472-4642.2009.00594.x

Lowry E, Rollinson EJ, Laybourn AJ et al (2013) Biological invasions: a field synopsis, systematic review, and database of the literature. Ecol Evol 3:182–196. https://doi.org/10.1002/ece3.431

Monkman GG, Kaiser M, Hyder K (2018) The ethics of using social media in fisheries research. Rev Fish Sci Aqua 26:235–242. https://doi.org/10.1080/23308249.2017.1389854

Moyle PB, Stompe DK (2022) Non-native fishes in estuaries. In: Whitfield AK, Able KW, Blaber SJM, Elliott M (eds) Fish and fisheries in estuaries: a global perspective. Wiley, pp 684–705

Naylor RL, Goldburg RJ, Primavera JH et al (2000) Effect of aquaculture on world fish supplies. Nature 405:1017–1024. https://doi.org/10.1038/35016500

Occhi TV, Carneiro L, Faria L, Miiller NOR, Vitule JRS (2021) Nile Tilapia impacts reference list LEC-UFPR. figshare. Dataset. https://doi.org/10.6084/m9.figshare.14551275.v9

Peixe BR (2022) Anuário 2022 Peixe BR da Piscicultura. Associação Brasileira de Piscicultura, 79p. Available at: https://www.peixebr.com.br/anuario2022/

Pelicice FM, Vitule JRS, Lima Junior DP, Orsi ML, Agostinho AA (2013) A serious new threat to Brazilian freshwater ecosystems: the naturalization of nonnative fish by decree. Conserv Lett 7:55–60. https://doi.org/10.1111/conl.12029

Peterson MS, Slack WT, Woodley CM (2005) The occurrence of non-indigenous Nile tilapia, *Oreochromis niloticus* (Linnaeus) in coastal Mississippi, USA: ties to aquaculture and thermal effluent. Wetlands 25:112–121. https://doi.org/10.1672/0277-5212

QGIS.org (2023) QGIS Geographic Information System. QGIS Association. http://www.qgis.org

Rahel FJ, Olden JD (2008) Assessing the effects of climate change on aquatic invasive species. Conserv Biol 22:521–533

Schofield PJ, Nico LG (2009) Salinity tolerance of non-native Asian swamp eels (Teleostei: Synbranchidae) in Florida, USA: comparison of three populations and implications for dispersal. Environ Biol Fish 85:51–59. https://doi.org/10.1007/s10641-009-9456-9

Schofield PJ, Peterson MS, Lowe MR, Brown-Peterson NJ, Slack WT (2011) Survival, growth and reproduction of non-indigenous Nile tilapia, *Oreochromis niloticus* (Linnaeus 1758). I. Physiological capabilities in various temperatures and salinities. Mar Freshw Res 62:1–11. https://doi.org/10.1071/MF10207

Setyawan P, Imron I, Gunadi B, van den Burg S, Komen H, Camara M (2022) Current status, trends, and future prospects for combining salinity tolerant tilapia and shrimp farming in Indonesia. Aquac 561:738658. https://doi.org/10.1016/j.aquaculture.2022.738658

Starling F, Lazzaro X, Cavalcanti C, Moreira R (2002) Contribution of omnivorous tilapia to eutrophication of a shallow tropical reservoir: evidence from a fish kill. Freshw Biol 47:2443–2452. https://doi.org/10.1046/j.1365-2427.2002.01013.x

Tilápias Mangaratiba (2023) Available at https://www.flowcode.com/page/tilapias.mangaratiba. Access on 10 Jan 2023

Tyberghein L, Verbruggen H, Pauly K, Troupin C, Mineur F, De Clerck O (2012) Bio-ORACLE: a global environmental dataset for marine species distribution modelling. Global Ecol Biogeogr 21:272–281. https://doi.org/10.1111/j.1466-8238.2011.00656.x

Woodford DJ, Hui C, Richardson DM, Weyl OLF (2013) Propagule pressure drives establishment of introduced freshwater fish: quantitative evidence from an irrigation network. Ecol Appl 23:1926–1937

Xiong W, Guo C, Gozlan RE, Liu J (2023) Tilapia introduction in China: economic boom in aquaculture versus ecological threats to ecosystems. Rev Aquac. https://doi.org/10.1111/raq.12710

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.