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Research Article

Non-native marine sessile benthic species from the coastal upwelling ecosystem of Arraial do Cabo, Brazil

Luciana Vieira Granthom-Costa[1], Luciana V. Resende de Messano[1], Luciana Altvater[1], Paula Spotorno[1,2], Ricardo Coutinho[1]

1 Instituto de Estudos do Mar Almirante Paulo Moreira – IEAPM-Departamento de Biotecnologia Marinha, Rua Kioto, 253 - Praia dos Anjos, Arraial do Cabo, RJ, Brazil

2 Centro de Ciências Computacionais, Universidade Federal do Rio Grande – FURG, Av. Itália Km 8, Rio Grande, RS, Brazil

Corresponding author: Luciana Vieira Granthom-Costa (lu.granthom@gmail.com)

Abstract

Marine bioinvasions are human-mediated events that have modified landscapes and altered the composition and structure of native communities. Arraial do Cabo is an Extractive Marine Protected Area located on the Southeastern Brazilian Coast with unique environmental features due to the influence of a coastal upwelling phenomenon. The presence of a small port complex probably facilitated the introduction of non-native species (NNS). This study compiled a list of NNS from Arraial do Cabo based on published and unpublished studies. Our findings compiled 45 non-native benthic species belonging to eight taxonomic groups: Rhodophyta (3); Porifera: Calcarea (3); Anthozoa (4); Serpulidae (2); Mollusca: Bivalvia (5) and Gastropoda (2); Cirripedia (4); Bryozoa (6) and Ascidiacea (16). Three of which occurred exclusively in Arraial do Cabo – *Didemnum* sp. carpet, *Thylaeodus* sp., and *Tubastraea* sp. – and 13 were re-examined and are now categorized as NNS. Since the distribution is based on environmental conditions of water, forty-four NNS were found in warmer waters and only one was exclusively recorded in sites exposed to the cold waters – the red algae *Pyropia suborbiculata*. Based on those results, we updated the list of NNS on the Brazilian coast from 77 to 99 benthic sessile NNS. Our results also provide a tool for a connected environmental network for private and public sectors in order to mitigate impacts in a high-value conservation area that can be considered a relevant NNS hotspot of the southeastern Brazilian coast.

Key words: Biofouling, exotic species, invasive species, marine bioinvasion, southeastern Brazilian coast, southwestern Atlantic Ocean

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Introduction

Human-mediated marine bioinvasions have modified landscapes in communities throughout the world and threatened biodiversity (Pyšek et al. 2020). This biological event caused by the transference of species has left traces on ecological and evolutionary responses in native populations (Geller et al. 2010; Montefalcone et al. 2015; Oyarzun et al. 2016). Marine bioinvasions result from multiple pathways but are strongly related to coastal infrastructures, specifically marinas and

harbors, which are considered the gateway to the arrival of benthic non-native species (NNS) worldwide (Seebens et al. 2013). Marine fouling species could be transferred across oceans, seas, and bays attached on ships, platforms, or buoys (Ruiz et al. 2011). Such transport has enabled their spreading beyond their natural capacity for dispersion (Castro et al. 2022; Carlton and Schmidt 2024).

A species classified as non-native to an area does not imply a successful establishment in a new region. Especially for sessile species, the success and failure of such establishment in the surrounding consolidated substrates depends on propagule pressure (Simberloff 2009). Therefore, it is not only associated with similar environmental conditions between donor and receptor areas (Keller et al. 2011) but also with the reproductive capacity of species (Jänes et al. 2015). Usually, NNS have an opportunistic reproductive dynamic, using strategies of rapid growth and expansion in their surroundings (Quell et al. 2021). Once attached to natural substrates, non-native species might compete for resources, change trophic levels in food chains, introduce new diseases or spread toxic substances, overgrow, and sometimes replace native species (Carlton 2001; Ojaveer et al. 2018). Their presence might compromise biodiversity, cause environmental losses, decrease functional diversity, and promote the homogenization of fauna in coastal habitats (Olden et al. 2004; Tsirintanis et al. 2022).

The Southwestern Atlantic Ocean is one of the longest coastlines, encompassing several biogeographical provinces that sustain an outstanding marine biodiversity (Spalding et al. 2007). The Brazilian coast extends for about 8.000 km (4°N–34°S) and is the largest and most expressive coastal area in the Atlantic Ocean, with a high number of endemic species (Ferreira et al. 2008). As observed worldwide, coastal areas have been transformed because of the increasing demand for coastal facilities, and as a consequence, they are susceptible to biological invasions. The Brazilian coast holds 35 ports in strategic positions relative to domestic seafaring and/or international distribution routes (ANTAQ 2023), which pose imminent risk of bioinvasion. The first comprehensive marine species survey published by the Brazilian governmental agencies categorized 32 sessile organisms as detected, established, and invasive (Lopes et al. 2009) but the records of NNS occurrence have been constantly updated for different locations along the coast (Rocha et al. 2013; Bumbeer and Rocha 2016). The most recent list for non-native marine benthic sessile species, totaled 77 records of occurrence in natural and artificial hard substrates along the Brazilian coast (Teixeira and Creed 2020).

Arraial do Cabo, southeastern of Brazilian coast (22°44'S, 42°00'W) is considered a central point of the coastal upwelling phenomenon that occurs in the Southwestern Atlantic due to its coastal geomorphology associated to the wind patterns (Valentin 1994; Coelho-Souza et al. 2012). Besides being a multi-use Marine Protected Area and being considered a biodiversity hotspot, it also holds a small port, mainly for domestic commercial vessels, that occasionally intercepted offshore vessels in the beginning of the 2000's (Ferreira et al. 2006). Therefore, the purpose of this study is to compile a list of non-native benthic sessile species from consolidated substrates in Arraial do Cabo from a local perspective and also, to contribute from a broader perspective with new records of the NNS to the list of Brazilian coast.

Materials and methods

Study area

Arraial do Cabo is a marine protected area surrounded by shallow and transparent waters, officially designated as the 'National Capital of Diving' by a federal decree (Law no.14.716/2023). Recently, it has been ranked at the highest aesthetically valuable area in southeastern Brazil due to its seascapes and remarkable biodiversity

in comparison to other nine sites along the coast (Waechter et al. 2023). The region forms a "bottle-shaped" embayment due to the position of Cabo Frio and Porcos islands, named here as Arraial do Cabo Bay (ACB). The inner and outer areas of ACB have distinct environmental characteristics: 1) ACB inner area covers Anjos and Forno Inlets, Porcos and Pontal Islands and surroundings, with sheltered rocky shores and shallow waters (up to 16 m) and seawater temperature between 20–23 °C. There is a small commercial port (Port of Forno) in the bottom of the Anjos Inlet with fishery and a small recreational boating facility, in addition to a few domestic commercial vessels (ANTAQ 2023). Furthermore, there is also a breakwater (around 250 meters long) that was built in the 50s to reduce the impact of waves on the docking area; and 2) the outer area that shows a distinct environment from ACB inner area: larger boulders, lower seawater temperatures (<18 °C), deeper waters (>20 m) and higher hydrodynamics (Ferreira et al. 2001; Rogers et al. 2014; Granthom-Costa et al. 2016; Batista et al. 2017) (Figure 1).

Figure 1. Map of Brazilian coast illustrating the southeastern Brazilian region – Arraial do Cabo. Highlights include Arraial do Cabo Bay and the Port of Forno. Key symbols: domestic pier pillars (gray square, asterisk), port pillars (white line, asterisk), breakwater (black line). Minus (-) symbols indicate outer area (open ocean), and plus (+) symbols mark inner area (ACB).

During the last decades, studies have shown that benthic marine distribution responds to these environmental conditions and geomorphological features (Castro et al. 1995; Brasileiro et al. 2009; Granthom-Costa et al. 2016), and so does the distribution of NNS. One of the first studies that revealed this pattern was of Laborel (1970), who called ACB the "coralline oasis" due to the unexpected presence of reef coral communities. In fact, this region is considered the southern limit of the distribution of many benthic species along the Brazilian coast (Castro and Pires 2001; Lima and Coutinho 2016).

Data survey

The literature published up to June/2024 and unpublished data (thesis, dissertations, and reports) were reviewed and compiled. The following databases and literature sources were searched: the World Register of Introduced Marine Species (http://www.marinespecies.org/introduced), the Scientific Electronic Library Online (http://www.scielo.org/php/index.php) and AlgaeBase (http://www.algaebase.org/). The taxonomic nomenclature was updated in accordance with the World Register of Marine Species (Worms Editorial Board 2024). The NNS were classified using the criteria adopted by the Ministry of the Environment of Brazil (Lopes and Villac 2009) (Table 1).

Table 1. Categories of non-native species according to MMA (1998) and Teixeira and Creed (2020).

Status	Definition
Established	when NNS have been detected on a recurrent basis, with its full life cycle in nature and evidence of population increase over time in a restricted or broad region but without apparent ecological or socioeconomic impacts;
Invasive	when NNS have an abundance or geographic dispersion that interfere with the survival capacity of other species in a broad geographic region or even in a specific area, or when the established species causes measurable impacts on socio-economic activities or human health;
Contained	when the presence of NNS has only been detected in controlled artificial environments, totally or partially isolated from the natural environment;
Detected	when the presence of NNS was detected in the natural environment but with no subsequent increase in its abundance and/or its dispersion (considering the time horizon of research or surveys); or, alternatively, without further information on species population (e.g., an isolated record).

All specimen vouchers are available at the following institutions for further consultation: the Scientific Collection of the Almirante Paulo Moreira Marine Research Institute (IEAPM), the National Museum in Rio de Janeiro, Department of Zoology (UFPR), the Department of Zoology (UFPE), and the Oceanographic Museum Prof. Eliézer de Carvalho Rios (MORG-FURG) (Suppl. material 1: table S1).

Results

Arraial do Cabo as NNS hotspot

This review compiled a total of 45 non-native sessile species (Table 2; Figure 2; Suppl. material 1: table S2) occurring in Arraial do Cabo, belonging to eight taxonomic groups: Rhodophyta (n = 3); Porifera, Calcarea (n = 3); Cnidaria, Anthozoa (n = 4); Polychaeta, Serpulidae (n = 2); Mollusca, Bivalvia (n = 5) and Gastropoda (n = 2); Crustacea, Cirripedia (n = 4); Bryozoa (n = 6); and Tunicata, Ascidiacea (n = 16). Among them, seven species were absent from the most recent NNS survey of the Brazilian coast (Teixeira and Creed 2020): the sponges *Heteropia glomerosa* (Bowerbank, 1873) and *Sycettusa hastifera* (Row, 1909), the scleractinian coral *Tubastraea* sp., the bivalve *Perna viridis* (Linnaeus, 1758), the gastropod *Thylaeodus* sp., the co-

lonial ascidian *Didemnum* sp. carpet, and the bryozoan *Scruparia ambigua* (d'Orbigny, 1841). In total, three of those records occurred exclusively in Arraial do Cabo and nowhere else along the Brazilian coast up to this day: *Didemnum* sp. carpet, *Thylaeodus* sp., and *Tubastraea* sp. The barnacle *Tetraclitella divisa* (Nilsson-Cantell, 1921) and the solitary ascidian *Cnemidocarpa irene* (Hartmeyer, 1906) distribution records in Brazil were extended from the last checklist.

Table 2. Sessile benthic non-native species of hard substrates in Arraial do Cabo, Southeast Brazil considering environmental affinities (W = warmer, C = cold waters); Status (DET = detected, EST = established, CONT = contained, INV = invasive); Substrate (N = natural, A = artificial), origin and references.

Taxa	Affinities	Status	Substrate	Origin	References
PLANTAE: RHODOPHYTA					
Pyropia acanthophora (E.C.Oliveira & Coll) M.C.Oliveira, D.Milstein & E.C.Oliveira, 2011	W	EST	N	unknown	1
Pyropia suborbiculata (Kjellman) J.E.Sutherland, H.G.Choi, M.S. Hwang & W.A.Nelson, 2011	C	EST	N	Japan Sea	2
Dasya brasiliensis E.C.Oliveira Filho & Y.Y.Braga, 1971 *	W	EST	N	Western Atlantic Ocean	3
PORIFERA: CALCAREA					
Heteropia glomerosa (Bowerbank, 1873) [NR]	W	EST	N	Indo-Pacific	4
Sycettusa hastifera (Row, 1909) [EXC]	W	DET	N	Red Sea	5
Paraleucilla magna Klautau, Monteiro & Borojevic, 2004	W/C	EST	N/A	Mediterranean Sea	6
ANNELIDA: POLYCHAETA					
Branchiomma luctuosum (Grube, 1870)	W	EST	N/A	Red Sea	7
Spirobranchus tetraceros (Schamarda, 1861)	W	CONT	A	Australia	7, 8
CNIDARIA: ANTHOZOA					
Chromonephthea braziliensis van Ofwegen, 2005	W	EST	N	Indo-Pacific	9
Carijoa riisei (Duchassaing & Michelotti, 1860)	W	EST	N/A	Indo-Pacific	10
Tubastraea coccinea Lesson, 1830	W	INV	N/A	East Pacific	11, 12
Tubastraea sp. n.i. [EXC]	W	INV	N/A	unknown	12
MOLLUSCA: BIVALVIA					
Isognomon bicolor (C.B.Adams, 1845)	W/C	INV	N/A	Caribbean Sea	13
Leiosolenus aristatus (Dillwyn, 1817)	W/C	EST	N/A	Caribbean Sea	14
Saccostrea cucullata (Born, 1778)	W	EST	N/A	Indo-West Pacific	15, 16
Magallana gigas (Thunberg, 1793) *	W	CONT	A	Japan, Pacific Ocean	17
Perna viridis (Linnaeus, 1758)	W	CONT	A	Eastern and Western Indian Ocean	18, 19
MOLLUSCA: GASTROPODA					
Eualetes tullipa (Rousseau in Chenu, 1843)	W	EST	N/A	Panama (Pacific coast)	20
Thylaeodus sp. [EXC]	W	DET	N/A	unknown	21
CRUSTACEA: CIRRIPEDIA					
Amphibalanus amphitrite (Darwin, 1854)	W	EST	N/A	unknown	22
Balanus trigonus Darwin, 1854	W	EST	N/A	unknown	23
Megabalanus coccopoma (Darwin, 1854)	W/C	EST	N/A	unknown	22
Tetraclitella divisa (Nilsson-Cantell, 1921)	W	CONT	A	Indo-Pacific	24
BRYOZOA					
Amathia verticillata (Delle Chiaje, 1822)	W	CONT	A	Mediterranean Sea	25, 28
Hippopodina tahitiensis (Leca & d'Hondt, 1993) *	W	CONT	A	Pacific Ocean	26
Bugula neritina (Linnaeus, 1758)	W	EST	N/A	North East Pacific	26, 27
Bugulina stolonifera (Ryland, 1960)	W	CONT	A	Great British	27

Taxa	Affinities	Status	Substrate	Origin	References
Schizoporella errata (Waters, 1878) *	W	EST	N/A	Mediterranean Sea	26, 27
Scruparia ambigua (d'Orbigny, 1841) EXC	W	DET	A	unknown	28
TUNICATA: ASCIDIACEA					
Clavelina oblonga Herdman, 1880	W	EST	N/A	Bermudas	29
Didemnum perlucidum Monniot F., 1983	W	EST	N/A	Caribbean Sea	30
Didemnum sp. carpet EXC	W	CONT	A	unknown	31, 32
Styela plicata (Lesueur, 1823)	W	CONT	A	West Pacific	31
Styela canopus (Savigny, 1816)	W	CONT	A	North Atlantic Ocean	31
Eusysntyela sp. *	W	EST	N	unknown	29
Botrylloides giganteus (Pérès, 1949) *	W	CONT	A	Eastern Atlantic Ocean	29
Polyandrocarpa anguinea (Sluiter, 1898) *	W	EST	N	unknown	29
Ascidia sydneiensis Stimpson, 1855	W	DET	N	Indo-Pacific	29
Ascidia curvata (Traustedt, 1882)	W	EST	N/A	Caribbean Sea	31
Phallusia nigra (Savigny, 1816) *	W	EST	N/A	Red Sea	29
Ciona robusta Hoshino & Tokioka, 1967 NR	W	EST	N/A	Japan	31
Rhodosoma turcicum (Savigny, 1816)	W	EST	N/A	Red Sea	25
Cnemidocarpa irene (Hartmeyer, 1906) NR	W	CONT	A	Japan	31
Herdmania pallida (Heller, 1878) *	W	EST	N/A	unknown	29
Microcosmus exasperatus Heller, 1878 *	W	EST	N/A	unknown	29

* Preterit record but now categorized as NNS in ACB; NR = new record at ACB; EXC = exclusively in Arraial do Cabo.
1 Yoneshigue-Valentin et al. 2020; 2 Yoneshigue 1985; 3 Yoneshigue 1985; 4 Klautau et al. 2020; 5 Batista et al. 2020b; 6 Klautau et al. 2004; 7 Ruta et al. 2020; 8 Skinner et al. 2012; 9 van Ofwegen 2005; 10 Altvater and Lima 2020; 11 Ferreira 2003; 12 Bastos et al. 2022; 13 López et al. 2010; 14 Ignacio et al. 2012; 15 Amaral et al. 2020; 16 Brahim et al. 2024; 17 Muniz et al. 1986; 18 Santos et al. 2023; 19 Beltrão et al. 2024; 20 Spotorno et al. 2018; 21 Monteiro et al. 2020; 22 Messano et al. 2014; 23 Messano et al. 2009; 24 Naval-Xavier 2018; 25 Granthom-Costa 2012; 26 Ramalho 2006; 27 Ramalho 2020; 28 Xavier et al. 2021; 29 Rocha and Granthom-Costa 2005; 30 Granthom-Costa et al. 2016; 31 Granthom-Costa 2017; 32 Granthom-Costa et al. 2023.

Overall, 11 species had already been registered to Arraial do Cabo but their status were reviewed and are now categorized as NNS based on recent publications: *Dasya brasiliensis* (E.C.Oliveira-Filho and Y. Yoneshigue-Braga, 1971); *Paraleucilla magna* Klautau, Monteiro & Borojevic, 2004); *Hippopodina tahitiensis* (Leca and d'Hondt, 1993); *Magallana gigas* (Thunberg, 1793); *Schizoporella errata* (Waters, 1878); *Eusysntyela* sp., *Phallusia nigra* (Savigny, 1816); *Polyandrocarpa anguinea* (Sluiter, 1898); *Herdmania pallida* (Heller, 1878); *Botrylloides giganteus* (Pérès, 1949); and *Microcosmus exasperatus* (Heller, 1878). Moreover, we considered that one species was misidentified: *Spirobranchus tetraceros* (Schamarda, 1861) (referred to as *S. giganteus*). Also, the algae *Porphyra leucosticta* (Kjellman) (Yendo, 1916) was synonymized to *Pyropia suborbiculata* (Kjellman) (J.E.Sutherland, H'.G.Choi, M.S. Hwang and W.A. Nelson, 2011).

Considering the status of introduction from a local perspective – namely the status of introduction in Arraial do Cabo – 10 NNS could be considered contained in the port complex (pillars of the domestic pier, port pillars, and breakwater): *S. tetraceros*; *T. divisa* and *Hippopodina tahitiensis* (Leca and d'Hondt, 1993); *Amathia verticillata* (Delle Chiaje, 1822); *Bugulina stolonifera* (Ryland, 1960); *Didemnum* sp. carpet, *B. giganteus*, and *Styela canopus* (Savigny, 1816); *Styela plicata* (Lesueur, 1823); and *C. irene*. Two other species – the oyster *M. gigas* and the bivalve *P. viridis* – should also be categorized as contained since both can be found exclusively in the mussel farm in Forno Inlet (near the Port of Forno). Moreover, four species were categorized as detected: the calcareous sponge *S. hastifera*, the solitary ascidian *Ascidia sydneiensis*

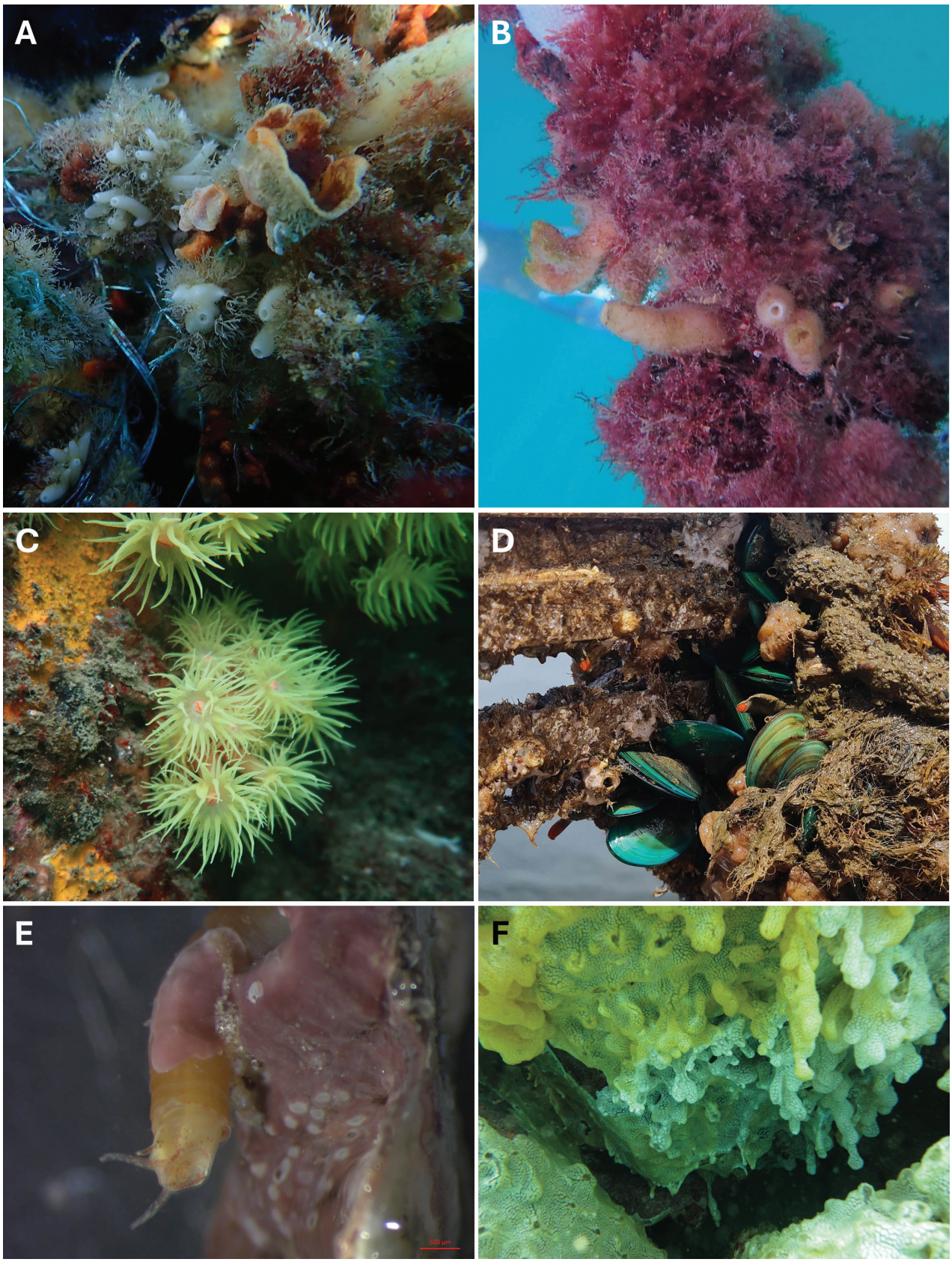

Figure 2. Plate of the recent new records of non-native sessile benthic species in Arraial do Cabo. **A.** *Heteropia glomerosa*; **B.** *Sycettusa hastifera*; **C.** *Tubastraea* sp.; **D.** *Perna viridis*; **E.** *Thylaeodus* sp.; **F.** *Didemnum* sp. carpet. Photos: A, B. Matheus Vieira Lopes; **C, D.** Luciana Altvater; **E.** Paula Spotorno; and **F.** Hector Fabian Messano.

(Stimpson, 1855), the gastropod *Thylaeodus* sp. and the bryozoan *S. ambigua*. Three species were categorized as invasive: *Tubastraea coccinea*, *Tubastraea* sp. and *I. bicolor*. The other 26 species were categorized as established in Arraial do Cabo.

Concerning environmental affinities, four species – the sponge *P. magna*, the bivalves *Isognomon bicolor* (C.B.Adams, 1845) and *Leiosolenus aristatus* (Dillwyn, 1817), and the barnacle *Megabalanus coccopoma* (Darwin, 1854) – were found in both warm and cold waters conditions. While, *P. suborbiculata* was the only NNS exclusively attached to rocky shores exposed to cold waters. Therefore, it was found in the inner area of the embayment, 44 non-native species attached on both natural and artificial substrates.

The Brazilian coast and Arraial do Cabo

The latest version of the Brazilian marine non-native species list registered 77 sessile benthic species distributed in 10 taxonomic groups. Since then, other authors have gathered new records of NNS besides those found in the present study, totaling 99 species to the Brazilian coast up to today (Suppl. material 1: table S3). The most expressive taxonomic groups for the Brazilian coast is Ascidiacea (n = 33); followed by Bryozoa (n = 16); Anthozoa (n = 11); Rodophyta (n = 9); Cirripedia and Bivalvia (n = 8) and Polychaeta (n = 4). The least represented groups include Porifera and Hydrozoa (n = 3), followed by Gastropoda (n = 2) and Chlorophyta (n = 1). The scenario considering ACB was not different: Ascidiacea (n = 16) and Bryozoa (n = 6) were the richest group of non-native species, followed by Bivalvia (n = 5), Cirripedia and Anthozoa (n = 4), Porifera and Rhodophyta (n = 3), Polychaeta and Gastropoda (n = 2) (Figure 3).

As a result of the compilation data, we also added new records of occurrences of sessile NNS which were absent from the last Brazilian list, considering geographic distribution locations apart from those registered to Arraial do Cabo based on last publications. They included three coral species – *Briareum hamrum* (Gohar, 1948), *Sarcothelia* sp., and *Sansibia* sp. – the barnacle *Megabalanus vinaceus* (Darwin, 1854); two bryozoans – *Conopeum reticulum* (Linnaeus, 1767) and *Buskia socialis* Hincks, 1886 and four species of ascidians – *Didemnum psammatodes* (Sluiter, 1895), *Microcosmus helleri* Herdman, 1881, *P. vittata*, and *Polycarpa tumida* Heller, 1878 (Figure 4) (Suppl. material 1: table S3).

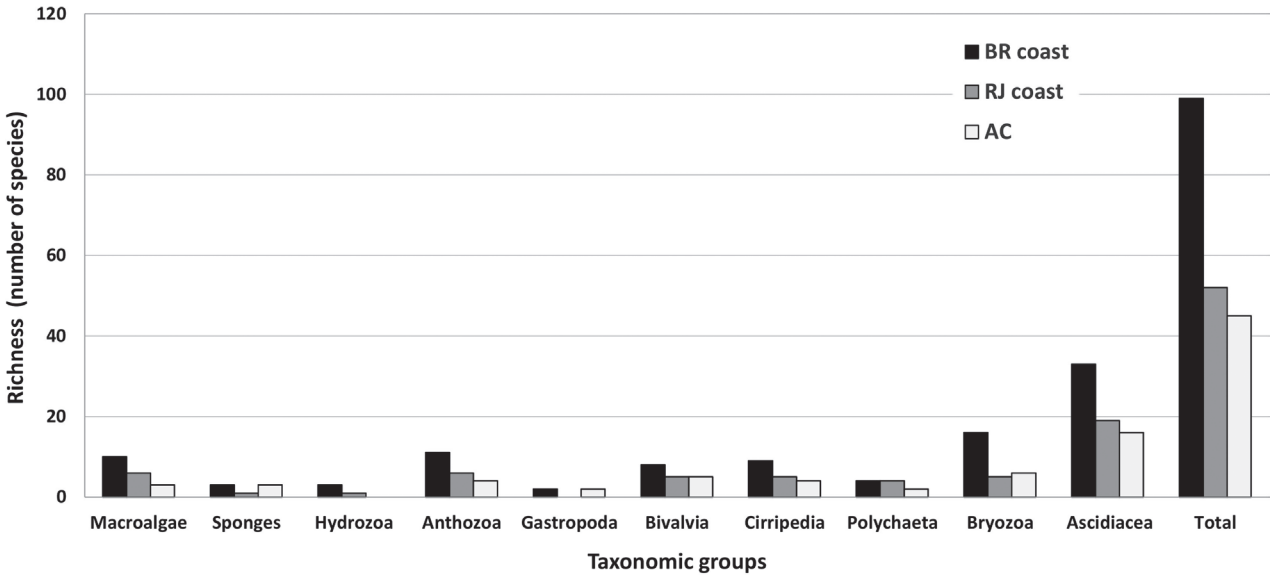

Figure 3. Richness of taxonomic groups of non-native sessile benthic species registered in the Brazilian coast (BR coast), compared to Rio de Janeiro State (RJ Coast) and Arraial do Cabo (AC).

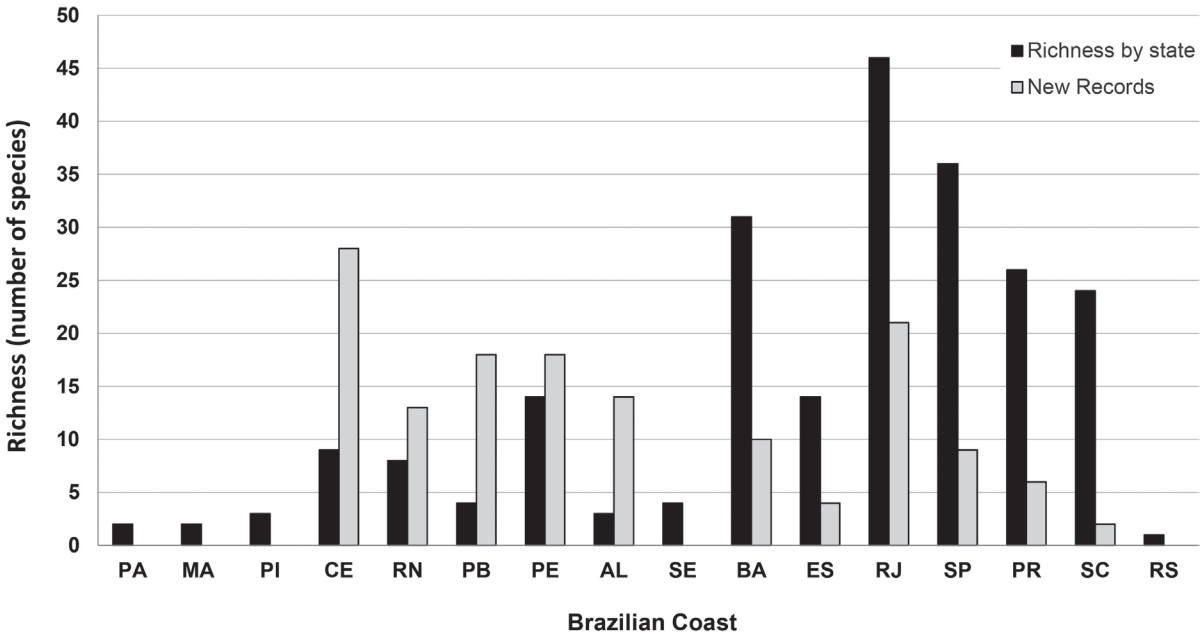

Figure 4. Richness of non-native sessile benthic species and the new records registered in the Brazilian coast in each State (AP = Amapá, PA = Pará, MA = Maranhão, PI = Piauí, CE = Ceará, RN = Rio Grande do Norte, PB = Paraíba, PE = Pernambuco, AL = Alagoas, SE = Sergipe, BA = Bahia, ES = Espírito Santo, RJ = Rio de Janeiro, SP = São Paulo, PR = Paraná, SC = Santa Catarina, RS = Rio Grande do Sul.

Discussion

Our study showed that with the exception of one macroalgae species, all the NNS were registered in the inner area of ACB (n = 44), while four species occurred in both areas. The taxonomic group with the biggest number of NNS in Arraial do Cabo is Ascidiacea, with 16 species. The first "inventory" for the region was published as findings of the oceanographic expedition organized by Oxford University in the late 1970's (Whittle 1979). At least 11 species were identified as "ascidians species" (collected inner and outer ACB). After that, unpublished experimental research registered the occurrence of several species but just in the 2000's was published the first list of species from Arraial do Cabo (Rocha and Granthom-Costa 2005). However, the status of introduction of the species was only considered in the last years (Granthom-Costa 2012; Granthom-Costa et al. 2016). Currently, the ACB and its surroundings have 37 described species, of which 16 are categorized as NNS and three as cryptogenic (Granthom-Costa et al. 2020). NNS attach to artificial and natural substrates around the Anjos and Forno Inlets, especially *Didemnum* sp. carpet, *D. perlucidum*, *S. canopus*, *R. turcicum*, *C. irene*, and *B. giganteus*, whereas *P. nigra*, *H. pallida*, and *S. plicata* have spread to the rocky shores in ACB. The solitary *C. robusta* occurs rarely in ACB, preferring to attach to dark areas protected against predation (Marins et al. 2009; Granthom-Costa 2017). *Didemnum* sp. carpet was registered eight years ago, and it fails to match any other *Didemnum* species worldwide. It is important to note that *Didemnum* sp. carpet shares similar external morphology characteristics with *Didemnum vexillum* Kott, 2002, such as color, tunic surface consistency, organizational system and overgrowth strategies. It also seems to show a similar behavior to *D. vexillum*, a unique species categorized as an aggressive competitor (Lambert 2009). *Didemnum* sp. probably configures another detected carpet ascidian that is neither *D. vexillum* nor *D. pseudovexillum*—confined at Port of Forno surroundings (Granthom-Costa et al. 2023).

The Port of Forno was built in Arraial do Cabo in the 1920s and has mainly served as a regional distribution center for coarse salt for local companies and

continues to operate in this trade to this day (Melo et al. 2009). From the late 1990s to early 2000s, it served as a support base for offshore operations (Ferreira et al. 2006), activities which were forbidden years later. From 2008 to 2013, transshipped cargoes mainly included malt and barley, which were sent to other South American countries (Chile, Argentina, and Uruguay). The port ceased its activities for two years and currently hosts a minimal cargo movement of coarse salt to domestic destinations—around 30 thousand tons (Port Authority, personal communication) (Suppl. material 1: figure S1). This represents 0.0001% of the total cargo movement in Brazilian ports, which handled 10 billion tons of cargo in the last decade (ANTAQ 2023). The Port of Forno and its coastal facilities (pillars, decks and breakwater) have provided a recipient area that can be easily used as a stepping-stone by NNS (Airoldi et al. 2015; Schaefer et al. 2023).

Throughout the period in which the port served as a hub for offshore support, Ferreira et al. (2006) conducted a survey of biofouling attached to drill ships and oil platforms that anchored in the area at that time. The authors reported 98 sessile benthic species (in eight taxonomic groups). Among them, 22 non-native species were registered but only seven were new records for the Brazilian coast. Overall, five species of non-native sponges and one of barnacle featured in that list and were neither detected nor even cited in the gray literature for Arraial do Cabo after that time. These findings corroborate the fact that several incursions of NNS might result in failed introductions, isolated occurrences, and/or cases in which NNS can be considered well-established since impacts have never been detected or quantified for most (Ferreira et al. 2008; Teixeira and Creed 2020).

Three invasive sessile NNS have drawn attention due to their intense spread after their first records: *I. bicolor* and two species of the *Tubastraea* genus. The bivalve *I. bicolor* is native to the Caribbean which was probably introduced between the 1970s and 1980s in the southeastern and southern regions of Brazil but it was only registered northward after the 2000's (Dias et al. 2013). The dispersion of this species with the expansion of the geographical distribution and high colonization on the rocky shores occurred in the 1990's, including Arraial do Cabo (López et al. 2014). However, a mass mortality event of *I. bicolor* occurred along the coast of Rio de Janeiro in 2006 and in other localities (López et al. 2010; Breves and Junqueira 2017). After that event, *I. bicolor* never recovered its former densities but the species narrowly escaped extinction, and populations were observed in 80 localities in southeastern Brazil (including ACB) (López et al. 2015). The extinction and replacement of the commercial species of mussel *Perna perna* (Linnaeus, 1758) were the main concerns of the scientific community and environmental agencies at first but it was not confirmed. Instead, the findings of López et al. (2014) on rocky shores communities before and after the invasion of *I. bicolor* in Arraial do Cabo showed that the most affected was the native population of the barnacle *Tetraclita stalactifera*, rather than *P. perna*, despite the high densities of *I. bicolor* at the intertidal zone.

On the other hand, the scleractinian corals *Tubastraea* spp. – *Tubastraea coccinea* (Lesson, 1830) and *Tubastraea tagusensis* Wells, 1982 – offer the most emblematic cases of marine bioinvasion in Brazil. Commonly called sun corals, they are typically native to tropical areas. Their reproductive characteristics (high fecundity and rapid settlement) contribute to their colonization and dispersal potential (Glynn et al. 2008) and their wide tolerance to environmental variables ensures their success in the invasion process. Records on natural and artificial substrates have been reported in the states of Santa Catarina, São Paulo, Rio de Janeiro, and Espírito Santo, as well as two northeastern states, Bahia and Ceará (Creed et al. 2017a; Soares et al. 2018). Besides, the sun coral species has also been found in the state of Sergipe in association with oil platforms and more recently on shipwrecks in

the states of Pernambuco and Rio Grande do Norte (Coelho et al. 2022). Arraial do Cabo is one of the first sites in which the invasion occurred since Ferreira (2003) reported a few colonies around 25 years ago. Since then, the sun coral has expanded its distribution but mostly in the warmer areas, with rare occurrences in the outer areas exposed to cold upwelling waters (Batista et al. 2017; Santos et al. 2019). *T. coccinea* is a species typical of tropical areas (Creed et al. 2017b) – as are several other NNS that can also be found in the bay. Nevertheless, Bastos et al. (2022) brought to light the fact that Arraial do Cabo included a misidentification of *T. tagusensis*. The species that occurs in the region has not been identified to date, but molecular analysis indicated that the coral also belongs to the *Tubastraea* genus (named here as *Tubastraea* sp.).

Another cnidarian, the soft-coral *Chromonephthea braziliensis* van Ofwegen, 2005 was first registered in Arraial do Cabo in the 1990s and since then has been reported as an invasive species. For many years, this species exclusively colonized the rocky shores of Cardeiros Cave, a small inlet inner area of ACB (Ferreira 2003). More recently, this species has also been found at islands in neighboring localities – Cabo Frio (Ilha dos Papagaios) and Armação dos Búzios (Ilha de Âncora) – both in Rio de Janeiro 7.3 and 30 km away from Arraial do Cabo, respectively (Kassuga et al. 2023). Similarly to ACB, both populations are also confined to small areas. Although the species has been found in areas other than its initial point of introduction, its scattered and restricted distribution suggests that this species was deliberately transplanted to create an attraction for recreational divers, since scuba diving is an economically important activity in the region (Giglio et al. 2017). Marine recreational traffic constitutes another pathway that plays an important role in spreading NNS (López-Legentil et al. 2015; Ashton et al. 2022). As previously described, Arraial do Cabo is a Marine Protected Area with intense touristic nautical activities that significantly increases during the summer season. However, to our knowledge, this pathway has not yet contributed to secondary introductions into the area. Further studies are needed to assess the impact of recreational boating in the region.

The most recent NNS record included the marine bivalve *P. viridis*, native to the western Indo-Pacific region, a species considered a high-risk invader and worldwide threat (Dias et al. 2018). Overall, new records have been reported in Brazil in the last six years, most recently on natural rocky shores, indicating that *P. viridis* spreading is an on-going process (Messano et al. 2019; Machado et al. 2023). In Arraial do Cabo, Santos et al. (2023) reported the occurrence of *P. viridis* in a mussel farm system. Aquaculture is an important pathway to consider, and has historically proven to be a potential vector for marine NNS introduction. Literature often described bivalve transfers for cultivation as means for unintentional "hitchhiking" assemblage vectors (Williams et al. 2013). In the 70's, Arraial do Cabo received shipments of *M. gigas*, the Pacific oyster, from the United States and the United Kingdom to test the commercial feasibility of cultivating this species (ultimately deemed unviable) (Muniz et al. 1986). These stocks of *M. gigas* resulted in notorious invasive events worldwide but not in Arraial do Cabo (Padilla 2010), in which it remains contained to mussel farms at the Forno Inlet (this study).

As to the status of introduction, it is important to note that some NNS have a different status in Arraial do Cabo from their status in Brazil (Suppl. material 1: table S4). For instance, the oyster *M. gigas* and the bivalve *P. viridis* are categorized as invasive for Brazil, but in Arraial do Cabo these bivalves can be found exclusively in the mussel farms in Forno Inlet and thus were categorized as contained in that area. There is also a divergence regarding the octocoral *C. braziliensis*. It has

been classified as invasive in several previous studies (Ferreira 2003; Ferreira et al. 2008; Lopes et al. 2009; Rocha et al. 2013; Teixeira and Creed 2020), however, for decades it has only been found attached to the rocky shores at the Cardeiros Cove. Based on this, and to the best of our knowledge, we recommend changing its status to "established" for the Brazilian Coast.

Despite the presence of a marine research institution generating a significant amount of knowledge about the benthic community in Arraial do Cabo (Batista et al. 2020a), there is no guarantee of continuous investigation. The implementation of a connected network of environmental sectors to promote the monitoring and mapping of NNS is crucial for mitigating impacts in this high-value conservation area (Carlton et al. 2019). All these steps are useful tools to assist stakeholders and policymakers prioritizing measures. The elaboration of protocols, reports, and environmental education actions based on collaborations with the local population, researchers, and institutions located in Arraial do Cabo will guide the unfolding of the bioinvasion process and help with the search for effective strategies.

Authors contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Luciana Vieira Granthom Costa, and Luciana Vicente de Messano, Paula Spotorno and Luciana Altvater. The first draft of the manuscript was written by Luciana Vieira Granthom Costa with the contributions of Luciana Vicente Resende de Messano, Luciana Altvater and Paula Spotorno supervised by Ricardo Coutinho. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Ethics and permits

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Availability of data and material

All zoological material used in morphological studies are deposited in the Scientific Collection of Almirante Paulo Moreira Marine Research Institute (IEAPM), the National Museum at Rio de Janeiro, Department of Zoology (UFPR), Department of Zoology (UFPE) and Oceanographic Museum Prof. Eliézer de Carvalho Rios (MORG-FURG).

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Supplementary material 1

Non-native marine sessile benthic species from Arraial do Cabo and Brazilian coast: worldwide distribution, updated records in Brazil by state and the status of introduction

Authors: Luciana Vieira Granthom-Costa, Luciana V. Resende de Messano, Luciana Altvater, Paula Spotorno, Ricardo Coutinho

Data type: xlsx

Explanation note: **table S1:** Number of the vouchers in the respective institution and references; **table S2:** Biogeographic distribution of marine non-native species registered in hard substrates of Arraial do Cabo, southeastern Brazilian coast; **table S3:** Distribution of non native sessile benthic species by state of Brazilian coast and references; **table S4:** Non native species status in the Brazilian coast based on the last survey (Teixeira and Creed 2020) and the changes proposed in this study; **figure S1:** Total cargo movement in Port of Forno over the last 36 years (Source: Antaq 2023).

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