Marine Pollution Bulletin 174 (2022) 113250

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Baseline

Alien hotspot: Benthic marine species introduced in the Brazilian semiarid coast

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A R T I C L E I N F O

Keywords:
Non-indigenous species
Corals
Ascidians
Bryozoans
Biofouling
Ballast water

A B S T R A C T

In this study, we provide a baseline assessment of introduced marine species along the extensive (~600 km) Brazilian semiarid coast. We reported 27 introduced and 26 cryptogenic species. Moreover, the main vectors of introduction were ballast water, shipping lines, oil and gas activities, biofouling, and rafting on plastic debris. The taxa were Ascidiacea (17 species) and Bryozoa (17), followed by Crustacea (6), Mollusca (6), Cnidaria (3), Echinodermata (3), and Porifera (1). Among these invertebrates, some species are recognized as drivers of impacts such as the invasive corals (*Tubastraea tagusensis* and *Tubastraea coccinea*), the bivalves *Isognomom bicolor* and *Perna viridis*, the crab *Charybdis hellerii*, the brittle star *Ophiothela mirabilis*, and, finally, the bryozoan *Membraniporopsis tubigera*. These species threaten the biodiversity of unique ecosystems such as intertidal sandstone reefs, shallow-water coral reefs, and mesophotic ecosystems. Moreover, the up-to-date results highlight that this region is a hotspot of bioinvasion in the tropical South Atlantic.

Non-indigenous species (NIS), also known as exotic, alien, or allochthonous species, are those species that have been introduced outside their natural range, with said introduction, intentionally or not, resulting from human activities (Ojaveer et al., 2014; Gracia and Rangel-Buitrago, 2020). Human activities are the major driver of the introduction of marine species worldwide, through processes associated mainly with floating materials (e.g., wood and marine litter), shipping lines, oil and gas platforms, biofouling, and ballast water (Castro et al., 2017, 2018; Mantelatto et al., 2020). Globalization, provided by technological advances in maritime transport, has intensified the dispersal of NIS through ballast water and biofouling (Ferreira et al., 2009). In addition to port activity, which acts as an open gate for the entrance of NIS, the oil and gas industry, along with aquaculture are also reported as important vectors for introduction (Farrapeira et al., 2011; Creed et al., 2017).

In the tropical southwestern Atlantic, the search for introduced species was recently initiated at the beginning of the XXI century (Farrapeira et al., 2011; Rocha et al., 2013; Teixeira and Creed, 2020; Soares et al., 2020; Thé et al., 2021). This undesirable spread is acknowledged as a major threat because a subset of NIS (i.e., invasive species) can have serious negative impacts on tropical marine biodiversity and ecosystem services (Firn et al., 2015; Galil et al., 2016), especially in poorly studied marine habitats such as intertidal sandstone reefs, marginal shallow-water coral reefs, the Amazon Reef System, and octocoral forests (Francini-Filho et al., 2018; Soares et al., 2018, 2020).

Drastic changes caused by bioinvasions have grown considerably in

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https://doi.org/10.1016/j.marpolbul.2021.113250
Received 12 February 2021; Received in revised form 30 November 2021; Accepted 5 December 2021
Available online 16 December 2021

recent years, generating concern in the scientific community, including in the South Atlantic Ocean (Ferreira et al., 2009; Rocha et al., 2013; Creed et al., 2017; Teixeira and Creed, 2020). However, knowledge about marine NIS occurring on the Brazilian semiarid coast (Equatorial SW Atlantic) is scarce (Soares et al., 2020; Teixeira and Creed, 2020). Thus, a baseline assessment study compiling information from different taxonomic groups can be used to create a list of marine NIS. Finding hotspots of NIS (high concentration in a geographical region) is a key strategy to establishing prevention and control strategies in the marine environment. Moreover, they would provide a more integrated and the most up-to-date knowledge of NIS occurring in this relevant tropical area. The aim of this baseline study is to survey the literature, as well as scientific data collections, to provide an assessment of the benthic marine invertebrates introduced in the Brazilian semiarid coast, and in addition, to indicate their current introduction status and highlight the specific places where species were recorded.

The study area is located on the Brazilian semiarid coast, specifically in its largest portion (578 km) (Fig. 1). The continental shelf of Ceará state (NE Brazil) has an average width of 63 km and can be divided into an internal platform, 0 to 20 m deep, and an external, ranging from the 20 m isobath to the continental shelf break, which occurs at an average depth of 60 m (Morais et al., 2018). This region is submitted to a tropical semiarid climate with low intra-and interannual variation of sea surface temperature (26 to 30 °C), lower annual precipitation (< 1000 mm year^{-1}), strong swell waves and higher wind speed (6 to 11 m s^{-1}) during most of the year (Soares et al., 2021). Moreover, two main harbors (Mucuripe and Pecém), nine oil and gas fields, and a dense shipping traffic (connection between the Caribbean Sea, Gulf of Mexico, South America, and Africa) are found in this low-latitude region (Soares et al., 2018, 2020).

We compiled a list of benthic marine introduced and cryptogenic species and the main vectors on the Brazilian semiarid coast (Fig. 1) from secondary sources (literature and scientific collections). We did not consider plankton, nekton or estuarine species (e.g., mangrove) in this baseline assessment. Our methodology focused on gathering information from marine environments. Therefore, the focus of this article is on benthic marine species that occur in artificial (e.g., ports, marinas, oil and gas fields, shipwrecks, and plastic debris) or natural habitats (e.g., reefs and sandy beaches). For data collection, a bibliographic review was performed based on records from a scientific literature survey of Science Direct (http://www.sciencedirect.com), Scielo (http://www.scielo.org/php/index.php), and Web of Science (https://www.webofknowledge.com), as well as gray literature, books, and scientific collections of Universidade Federal do Ceará (UFC, Brazil). In our search, we included studies published from 1950 onwards, published in English, Portuguese, and Spanish. We used keywords that included the following terms: non-indigenous species, exotic, invasive, introduced, marine macrofauna, marine invertebrates, Ceará, Northeast Brazil, and Southwestern Atlantic, in addition to taxonomic and popular names of the main marine invertebrate groups.

The marine species highlighted by this process were then searched for in the World Register of Marine Species (WoRMS) (http://www.marinespecies.org/index.php) to increase the information available on Ascidiacea, Bryozoa, Crustacea, Mollusca, Cnidaria, Porifera, and Echinodermata. The nomenclature (introduced and cryptogenic) was used based on previously proposed criteria (Carlton, 1996; Rocha et al., 2013; Castro et al., 2017; Miranda et al., 2018). Introduced species are those in which their natural range distribution does not include Northeast Brazil (Tropical SW Atlantic) and cryptogenic species are those in which the biogeographic information and origin are uncertain, that is, when there is no clear evidence that the benthic marine species is native or introduced.

After the literature search, the data regarding the marine NIS were organized in a list containing the following information (when available in the literature): name of the species and taxa to which it belongs, introduction status (introduced or cryptogenic) and origin (when the species was categorized as introduced), locations where the organisms were recorded, and record source (study or scientific collection). Only organisms with confirmed identification at the species level were included in our study to generate the maps in ArcGis 9.2.

We reported 53 non-native benthic marine invertebrate species on the Brazilian semiarid coast (Supplementary Material, Table S1), with 27 species categorized as introduced and 26 species as included in the cryptogenic category. The introduced species are represented by one (1) species of Porifera, 2 Echinodermata (Ophiuroidea), 2 Bryozoa (Gymnolaemata), 3 Cnidaria (2 Anthozoa and 1 Hydrozoa), 4 Mollusca (3 Bivalvia and 1 Gastropoda), 5 Crustacea (Decapoda), and 10 Tunicata (Ascidiacea). Cryptogenic species included 1 Crustacea (Maxillopoda), 1

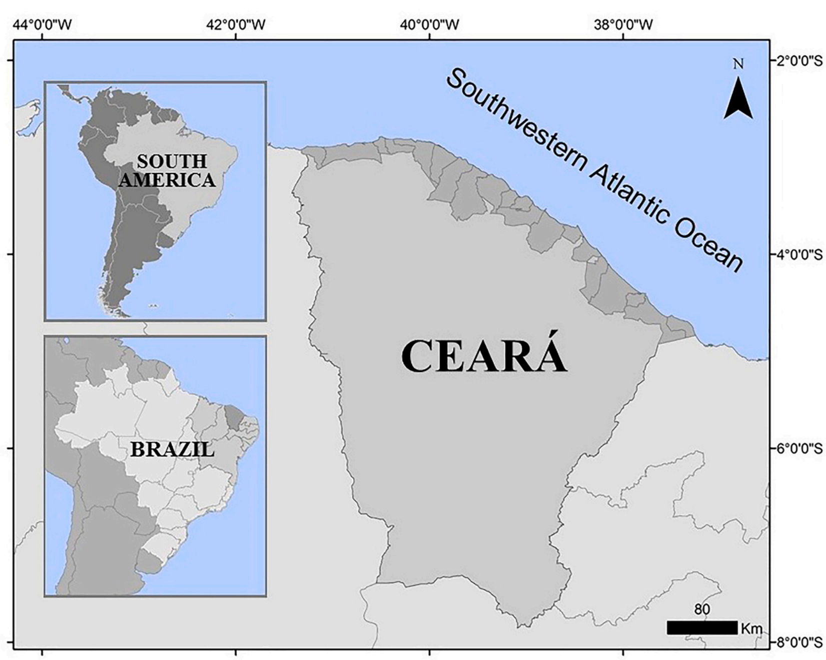

Fig. 1. Study area (Brazilian semiarid coast, Ceará state, Equatorial Southwestern Atlantic).

Echinodermata (Crinoidea), 2 Mollusca (Bivalvia), 7 Tunicata (Ascidiacea), and 15 Bryozoa (Gymnolaemata). In this way, ascidians (17) and bryozoans (17), typical fouling organisms, ranked among the most common NIS (64%) found in this tropical region (Supplementary Material, Table S1).

Although the introduction mode of some of these organisms is still unknown (38%), ballast water and biofouling together form the main vectors of species introduction (54% of the total), followed by oil and gas platforms and shipwrecks (4%), shrimp farms (2%), and rafting on plastic debris (2%) (Fig. 2). Regarding the marine habitat where the species were found (Figs. 3 and 4), 63% were close or directly associated with harbor areas, followed by sandstone reefs (19%), coastal marina (13%), associated with shipwrecks (3%), and rafting in plastic debris (2%).

These baseline results can provide support for an official list of NIS in the region, as well as public policies of monitoring and mitigation of impacts on this scarcely studied Equatorial semiarid coast. The total number of NIS listed in this study was higher than that found in an earlier study (Miranda et al., 2013), which indicated the presence of only seven non-indigenous species. Moreover, our results are also higher than those of a recent paper (Teixeira and Creed, 2020) that pointed to 18 species. Furthermore, Miranda et al. (2013) mentioned two species that were not included in the current study. The first is the polychaete *Phragmatopoma caudata*, which, recent research confirming its natural occurrence along the western Atlantic coast, from Florida to South Brazil, indicates that this species is able to disperse naturally along the entire coast of Brazil (Nunes et al., 2017). The second one is the gastropod mollusk *Lamellaria mopsicolor*, not included in the current study due to doubts about its taxonomic identification.

The highest number of NIS was Tunicata (Ascidiacea) and Bryozoa. The high tolerance of ascidians and bryozoans to environmental changes, resistance to pollutants, host-specific symbionts, their high reproductive and growth rates, and the ability to produce metabolites that are often harmful to predators, gives them a high invasive potential (Zhan et al., 2015; Evans et al., 2017; Miranda et al., 2018). These organisms constitute a group of sessile fouling species commonly found associated with harbors and marinas worldwide (Zhan et al., 2015; Miranda et al., 2018). Nevertheless, it is important to highlight that the high number of ascidians and bryozoan species presented here is the result of efforts focused on the groups (Oliveira-Filho and Lotufo, 2010; Xavier et al., 2021).

In recent years, the main studies carried out with ascidians along this tropical coast have been conducted in shallow waters (Oliveira-Filho and Lotufo, 2010; Paiva, 2013), with subtidal and deeper areas being under-explored. The fact that several species of ascidians occur only in submerged areas probably leads to an underestimation of the number of NIS occurring on this coast. Recently, however, a study carried out in three sites of the tropical coast have reported new records of bryozoans (Xavier et al., 2021), indicating further surveys in harbors, as well as neighboring shallow-water reefs and deep areas (e.g., mesophotic coral ecosystems) (Soares et al., 2019) may increase the number of ascidian species and will allow for tracking the spread of invasive species.

Regarding the form of introduction, ballast water was identified as the main vector of species entry, followed by biofouling. Since many of the species used these two vectors, we chose to represent them together, thus totaling 54% of the introduction methods (Fig. 2). This result is compatible with that found in other studies, which indicate that ballast water is one of the most important vectors of species introduction (Farrapeira et al., 2011; Castro et al., 2017; Teixeira and Creed, 2020). The vast majority of bryozoan and ascidian species reported here lack data on the mode of introduction, however ship hulls and sea chests likely represent major vectors of long-distance dispersal (Coutts and Dodgshun, 2007; Coutts et al., 2010; Miranda et al., 2018).

In addition, 63% of the species identified were found close or directly associated with the Pecém and Mucuripe Ports, two important harbors in this area that receive an important flux of cargo vessels and tankers mainly departing to Europe and Africa (Figs. 3 and 4), reinforcing the role of maritime transportation in the introduction of NIS. In this way, Huang et al. (2017) detected genetic patterns that pointed to commercial shipping transportation as responsible for the long-distance dispersal of invasive species. Moreover, Castro et al. (2017) pointed out the Southwestern Atlantic, including Brazilian waters, as an area of high risk for entry of NIS, since they participate intensively in international trade, receiving large volumes of ballast water from several localities around the globe.

The Brazilian semiarid coast is an important convergence point for vessels coming from the Caribbean and the Gulf of Mexico that are heading to Europe and Africa (Fig. 4). This may reflect distinct exotic fauna assemblies when compared with other areas in the SW Atlantic, as recently reported for NIS of bryozoans (Xavier et al., 2021).

Recent data on international trade indicate that 80% of this, in terms of volume, occurs through marine transport (Unctad, 2014), which implies that a large volume of ballast water is transported far away from its source (Castro et al., 2018), carrying with it a large number of larvae and juvenile forms of many species. Indirect development and the presence of planktonic larvae are common among the benthic NIS

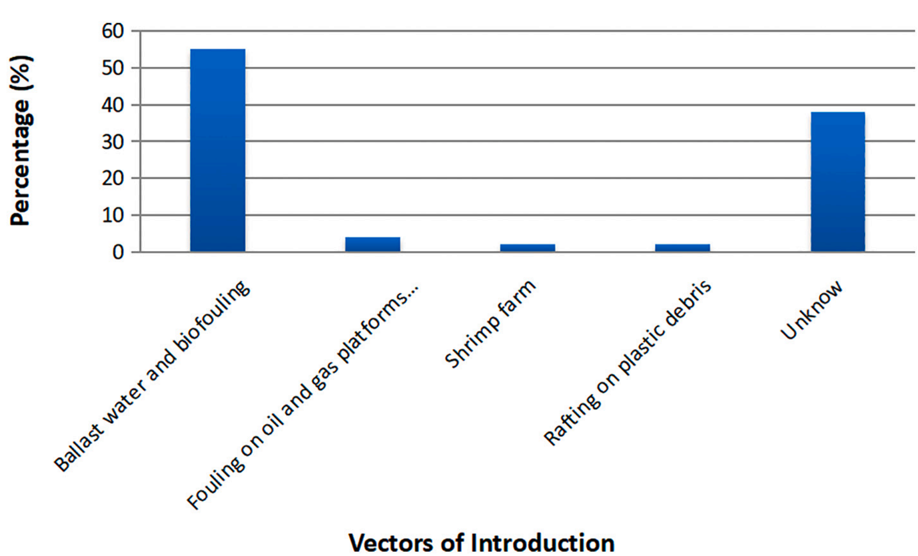

Fig. 2. Vectors used for introduction by non-indigenous species (Brazilian semiarid coast, Equatorial Southwestern Atlantic).

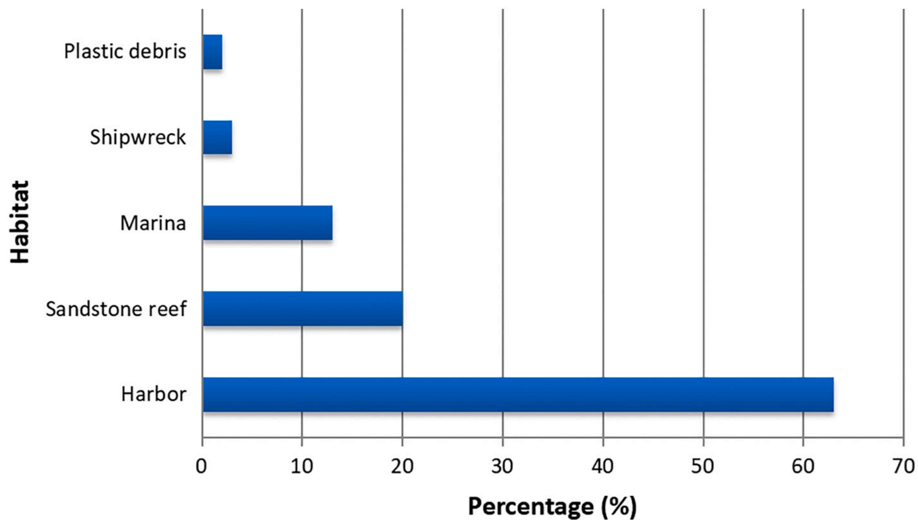

Fig. 3. Percentage of the natural (sandstone reef) and artificial (plastic debris, shipwreck, marina, and harbors) habitats where the non-indigenous species were identified (Brazilian semiarid coast, Equatorial SW Atlantic).

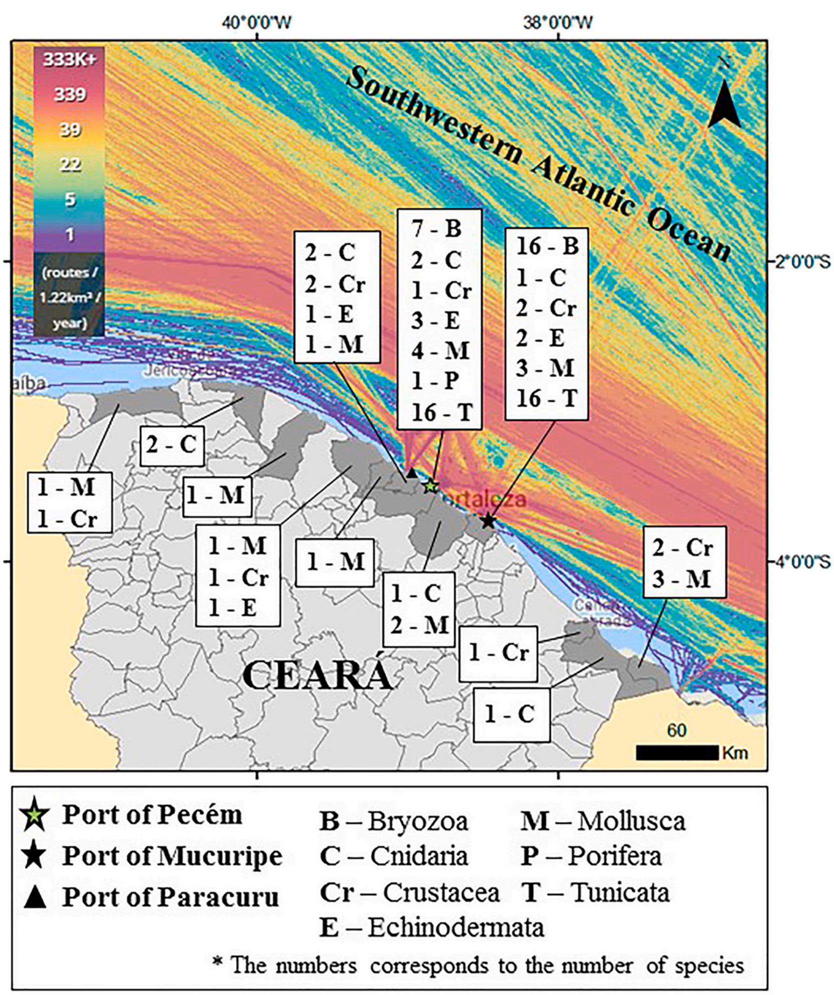

Fig. 4. Distribution of the benthic marine macrofauna introduced along the Brazilian semiarid coast (Equatorial Southwestern Atlantic) and shipping lines in the region. The colors represent the number of ships travelling in this area; the color red indicates the highest density of routes per area and year (see the legend on the top left side of the figure). The numbers before the letters indicate the quantity of non-indigenous species on in taxonomic group (e.g., 16 - T = 16 species of Tunicata). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) (Marine Traffic: Global Ship Tracking, n.d.).

identified (Supplementary Material Table S1), which facilitates their transport by ballast water. In addition, the fact that many of them have a sessile and fouling lifestyle at some stage of their ontogenetic development allows them to be transported over long distances attached to the hulls of vessels.

Of the total recorded forms of introduction, ~ 50% were categorized as unknown, a reflection of the high number of species categorized as cryptogenic (half of the species) (Supplementary Material, Table S1). Since it is not possible to state whether or not these species have a natural distribution for the region, it is also not possible to argue their mode of introduction in the studied area. These data indicate precarious knowledge about the species richness and natural distribution of the benthic macrofauna in the Equatorial Atlantic coast. Studies on introduced species in this low-latitude region, besides being recent, are scarce. Notably, as in many other places in developing countries worldwide, this lack of knowledge is due to the lack of specialists dedicated to taxonomy of groups known for their invasive potential, such as Polychaeta.

Among the species recorded in the current study, some are known to cause ecological and economic damage in coastal zones, such as the swimming crab *Charybdis hellerii*, the bivalves *Isognomon bicolor* and *Perna viridis*, the bryozoan *Membraniporopsis tubigera*, and the invasive corals *Tubastraea tagusensis* and *Tubastraea coccinea* (Bezerra and Almeida, 2005; Santos et al., 2011; Klôh et al., 2013; Creed et al., 2017; Castro et al., 2017; Miranda et al., 2018; Soares et al., 2020). *Charybdis hellerii* is a well-established species in Brazil, introduced by the transport of larval forms through ballast water (Loebmann et al., 2010; Silva and Barros, 2011). This species is a potential competitor for space and food with native species of the genus *Callinectes* in estuaries and shallow-water coastal areas, including tropical reefs (Bezerra and Almeida, 2005).

Isognomon bicolor is a Caribbean species recorded on the Brazilian coast since 1994 (Loebmann et al., 2010). It is a species with a high invasive potential and dispersal ability, which has been reported to have caused damage to native communities (e.g., intertidal sandstone reefs) and marine activities (Castro et al., 2017). *Perna viridis*, in turn, is a native bivalve species of the Indo-Pacific Ocean, well established in the Caribbean (Trinidad and northeastern Venezuela) as well as the North Atlantic (Florida), where it is considered an invasive species due to its interference in clam production, displacement of oyster reefs, and competition with native species (Dias et al., 2018; Rajagopal et al., 2006). De Messano et al. (2019) recorded, for the first time, specimens of *P. viridis* in the South Atlantic (found on experimental plates installed at Guanabara Bay, Rio de Janeiro, Brazil). Similarly, the present study records this species for the first time for the northeastern region of Brazil (more than 3000 km north of Rio de Janeiro), where specimens were found on recruitment plates placed in an area under the influence of the port of Mucuripe (Fortaleza, Ceará) (Regis et al., 2021).

The bryozoan *Membraniporopsis tubigera* is known to cause blooms, resulting in economic impacts in the Southern Hemisphere (Brazil and New Zealand) due to the decrease in recreational use of beaches and the blocking of fishing nets (Miranda et al., 2018). Despite the presence of this species in floating plastic debris, there is no record, to date, of blooms of this species in the equatorial Atlantic waters.

The phylum Echinodermata was represented by two exotic brittlestars, *Ophiothela mirabilis* and *Ophiactis savignyi*, and one cryptogenic crinoid, *Tropiometra carinata*. *Ophiothela mirabilis* is a species from the Pacific Ocean (Mantelatto et al., 2016) and was recorded on the Ceará coast near the port area (Supplementary Material, Table S1), threatening native octocoral forests (Derviche et al., 2021; Glynn et al., 2021) in this semi-arid coast (Araújo et al., 2018) and also the Amazon Reef System (Francini-Filho et al., 2018). *Ophiactis savignyi*, first described in the Red Sea, is the smallest tropical ophiactid brittlestar, once suggested to be the most common brittlestar in the world (Roy and Sponer, 2002).

According to Roy and Sponer (2002), the introduction of *O. savignyi* into the Atlantic Ocean occurred before the nineteenth century. This species has been recorded in natural habitats, including a marine protected area (Pedra da Risca do Meio Marine State Park), and port areas on the Ceará coast, being a common species throughout the Brazilian coast, well adapted to this coastal environment, whose impacts have not yet been detected (Farrapeira et al., 2011; Rocha et al., 2013; Teixeira and Creed, 2020). A common characteristic shared between *O. mirabilis* and *O. savignyi* is that they are fissiparous species (Tavares et al., 2019). In this way, they are widespread brittle stars, such as *Ophiactis lymani*, which may facilitate their establishment in the region studied (Alitto et al., 2020). The shallow water crinoid *T. carinata* is known to have a wide geographic distribution, being native to both the Indian and Atlantic Oceans (Torrence et al., 2012). However, there is no evidence of its origin or its dispersal, and impacts have not been reported (Torrence et al., 2012). One suggestion for this transoceanic distribution is that its larval phase is prolonged (Meyer et al., 1978). This species was recorded in port areas and tourist beaches on the Ceará coast (Martins and Martins De Queiroz, 2006).

Finally, the invasive corals *T. tagusensis* and *T. coccinea* are azooxanthellate organisms known for their invasion capability and multiple impacts on marine ecosystems (Creed et al., 2017). Previously for the Northeast region of Brazil, both species had their most northward record in the state of Sergipe, approximately 1200 km away from the Ceará coast (Soares et al., 2018, 2020), which shows that they continued their fast invasion process throughout the Brazilian coast over the last 40 years (Creed et al., 2017), mainly due to oil and gas activities such as monobuoys, drillships, and platform movement (Creed et al., 2017). Recently, they have been found in wood and plastic debris, which represent a secondary and recent vector mode of introduction (Mantelatto et al., 2020). In the Brazilian semiarid coast (Ceará state), they were found in two shipwrecks from World War II (Soares et al., 2018, 2020) and one oil and gas platform (Braga et al., 2021), which indicates that these artificial habitats constitute a network of stepping-stone habitats for range expansion of these invasive corals.

The number of introduced species on the Brazilian semiarid coast is probably underestimated, and regular assessments, especially in relation to other poorly studied taxa (e.g., Nematoda, Nemertinea, and Polychaeta) and habitats (e.g., mesophotic ecosystems), is essential. Our research does not include estuarine NIS, which have also been recorded in this region, such as the upside-down jellyfish *Cassiopea andromeda* (Thé et al., 2021) and the black tiger shrimp *Penaeus monodon* (Teixeira and Creed, 2020). Both, among others, are generally found in the shallow-water estuaries in this drought-prone compartment of the Brazilian coast (Soares et al., 2021).

In conclusion, the current database provides spatial information about introduction vectors, introduced or cryptogenic species, spatial location and type of habitat (natural or artificial) where the species occurs. This allows the basis for prevention and control actions against the NIS species. The high number of introduced benthic marine species identified near harbor areas reinforces them as important localities for the reception of non-indigenous species. This is corroborated by the fact that ballast water and biofouling were the main forms of species introduction in this area, vectors highly connected to vessel transportation. These results indicate the need for more effective environmental laws and stricter supervision for this type of activity, as well as long-term monitoring programs worldwide and in the Brazilian semiarid coast.

Several NIS known to cause ecological and socioeconomic losses in marine habitats are present in this poorly studied region. Although taxonomy and systematics are used as the main tools for identifying invasive organisms, the knowledge gaps in invasion routes, development of local adaptations, and colonization histories can be solved using genetic techniques (Ojaveer et al., 2014; Marie et al., 2017). These future studies will enable a better understanding of how these tropical semiarid marine ecosystems are changing (Soares et al., 2021) and what impacts they are undergoing, besides providing support for the coastal management and protection measures.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.113250.

CRediT authorship contribution statement

MOS: Conceptualization, Writing - Original Draft, Writing - Review & Editing, Methodology, Formal analysis. **FRLX**: Writing - Original Draft, Writing - Review & Editing, Formal analysis. **NMD**: Writing - Original Draft, Writing - Review & Editing, Formal analysis. **MQMS**: Writing - Original Draft, Writing - Review & Editing, Formal analysis. **JPL**: Writing - Original Draft, Writing - Review & Editing, Formal analysis. **CXB**: Writing - Original Draft, Writing - Review & Editing, Formal analysis. **LMV**: Writing - Original Draft, Writing - Review & Editing, Formal analysis. **SVP**: Writing - Original Draft, Writing - Review & Editing, Formal analysis. **HMC**: Writing - Original Draft, Writing - Review & Editing, Formal analysis. **LEAB**: Writing - Original Draft, Writing - Review & Editing, Formal analysis. **RROF**: Writing - Original Draft, Writing - Review & Editing, Formal analysis. **SL**: Writing - Original Draft, Writing - Review & Editing, Formal analysis. **EVPB**: Writing - Original Draft, Writing - Review & Editing, Formal analysis. All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (Research Productivity Fellowship Nos. 307061/2017-5, 308768/2018-3, 310165/2020-2 and 313518/2020-3), PELD Costa Semiárida do Brasil CSB (No. 442337/2020-5), Marine Animal Forest of the World (COST ACTION - CA 20102), CAPES-PRINT, CAPES-AVH (Alexander Von Humboldt Foundation), and Fundação Cearense de Apoio ao Desenvolvimento Científico e Tecnológico (Chief Scientist Program) for their financial support.

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