

Research Article

A decade on: an updated assessment of the status of marine non-indigenous species in Brazil

Larissa Marques Pires Teixeira¹ and Joel Christopher Creed^{2,3,*}

¹Programa de Pós Graduação em Ecologia e Evolução, Universidade do Estado do Rio de Janeiro. Rua Francisco Xavier 524, 20559-900, Rio de Janeiro, RJ, Brazil

²Departamento de Ecologia, Universidade do Estado do Rio de Janeiro, Rua São Francisco Xavier 524, 20550-900, Rio de Janeiro, RJ, Brazil

³Associate Researcher, Coral-Sol Research, Technological Development and Innovation Network, Instituto Brasileiro de Biodiversidade - BrBio, Rua Senador Dantas, 20 grupo 1509 - Centro 20031-205, Centro, Rio de Janeiro, RJ, Brazil

Author e-mails: larissamarques@ymail.com (LMPT), jcreed@uerj.br (JCC)

*Corresponding author

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Abstract

In order to prevent the introduction, control or eradicate non-indigenous species (NIS) which threaten native species, habitats or ecosystems, an essential first step is that countries have and keep up-to-date lists of species non-indigenous to the region. The last list of marine NIS for Brazil was published a decade ago. We compiled an updated list of marine NIS and revised the species' statuses. One-hundred-thirty-eight marine species in 15 classes or functional groups are NIS in Brazil. Brazilian states with greater maritime commerce (greater market share) had more marine NIS. From the period between the 1950s to 2010, the number of NIS at least doubled each decade. We identified a significant mismatch (underestimation) between the previous list and this study, which seemed to be due to improved scientific knowledge and an often considerable lag between first record (detection), identification and communication of new marine NIS. Currently Brazil has 19 invasive, 76 established and 43 detected marine NIS, an increase of 160% in ten years compared to the previous national list. We recommend that Brazil implements a national database as a rapid, appropriate, flexible and cost effective method of monitoring trends in NIS introductions.

Key words: class/functional groups, geographical variation, historical change, invasive, national checklist, non native species

Introduction

The Convention on Biological Diversity (to which Brazil is a party, Brasil 1998) states that consenting parties should prevent the introduction, control or eradicate those alien species which threaten ecosystems, habitats or native species. In Brazil this convention was ratified in 1994, with the Ministry of the Environment being the principal entity responsible for planning and decision making with regard to non-indigenous species (NIS) and biological invasion (Lopes et al. 2009). An essential first step is that countries have and keep up-to-date lists of NIS recorded for their region. According to Sliwa et al. (2009) once lists are adopted into the

management framework, they are often used for long periods without revision. However it is important that these lists are constantly reviewed and updated to incorporate new introductions and changes in species status based on further research (Sliwa et al. 2009). This information may be used to assess management initiatives and targets.

The Brazilian coastline extends for about 8000 km from Cape Orange (4°N) to Chui (34°S) comprising a range of tropical and sub-tropical ecosystems such as sandy beaches, mangrove forests, coral reefs, rocky shores, coastal lagoons, saltmarshes, oceanic islands and sandy to muddy bottoms from the infralittoral realm down to the shelf break (Ferreira et al. 2009). Further offshore the Exclusive Economic Zone of 200 nautical miles and the proposed extension called the *Amazônia Azul*, or “Blue Amazon” (Wiesebron 2013) form a very large oceanic biome. According to Ferreira et al. (2009) this makes the country a major receptor and donor of tropical and subtropical organisms amongst the world’s oceans.

The INFORME/PROBIO Project, which was conducted in 2005, provided the first comprehensive list of non-indigenous species in coastal areas of Brazil (Ferreira et al. 2009). The I National Report on Invasive Exotic Species affecting the marine environment (fauna, flora and micro-organisms) (*I Informe Nacional sobre as Espécies Exóticas Invasoras que afetam o ambiente Marinho (fauna, flora e microrganismos)*) resulting from the study was published in 2009 by Lopes et al. At the time of that study 58 marine NIS were known from Brazil (Lopes et al. 2009); the species that made the most impact were reviewed by Ferreira et al. (2009). In this paper, we compile, update, systematize and synthesize currently available information on marine NIS in Brazil in order to characterize the frequency of introduction events as well as reassess the status of the species a decade on from the INFORME/PROBIO list published in 2009 by Lopes et al.

Materials and methods

Based on the INFORME/PROBIO list and data provided therein (Lopes et al. 2009), we conducted a literature search up to May 2019 for new records and new research regarding the status of marine NIS in Brazil. The following databases and literature sources were consulted: Horus Institute (<http://i3n.institutohorus.org.br/www/>), World Register of Introduced Marine Species (WRIMS) (<http://www.marinespecies.org>), Google Scholar (<https://scholar.google.com/>), Researchgate (<https://www.researchgate.net/>), Scientific Electronic Library Online (<http://www.scielo.org/php/index.php>), FishBase (<http://www.fishbase.org/search.php>), and AlgaeBase (<http://www.algaebase.org/>).

We classified the status of each species by using the same criteria and categories as those described by Lopes and Villac (2009), as these have been adopted by the Brazilian Federal Government. Lopes and Villac (2009) recognized a status hierarchy as the following:

Contained: when the presence of the NIS has only been detected in controlled artificial environments, totally or partially isolated from the natural environment (e.g. commercial aquarium, cultivation for scientific purposes, vessel ballast water tanks, etc.);

Detected: when the presence of the NIS 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 the population situation of the species (e.g. an isolated record);

Established: when the NIS has 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 the NIS has 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 (Elliott 2003), or when the established species causes measurable impacts on socioeconomic activities or human health.

When a species had been assigned different statuses in different studies, we used the classification criteria based on the most recent study available (e.g., compare Farrapeira et al. 2011 and Rocha et al. 2013). Species native to Brazil which demonstrated human-mediated range shift (*sensu* Lonhart 2009) were also included. Furthermore, we noted the occurrence by Brazilian state and the year of first record in the country. This was taken as the year of collection, or record, if reported in the reference(s), or the year of the reference publication when the year of collection or record was not provided. The nomenclature was updated in accordance with the World Register of Marine Species (Worms Editorial Board 2019). Contained or cryptogenic species were not included in the present list of NIS. In order to compare the status of different taxonomic or functional groups, we organized records by functional group, class, order and family. In order to describe temporal changes, we calculated cumulative records and estimated current detection rates. We also compared the status according to Lopes et al. (2009) with the revised status noted here. In order to describe spatial patterns, we also documented species by Brazilian state. As states are of different sizes, we also converted these data to a per km basis using coastline length data obtained from https://pt.wikipedia.org/wiki/Litoral_do_Brasil accessed on 26/12/2018 (Supplementary material Table S1). To test whether the volume of shipping explained the difference in the abundance of NIS between states, we used a simple linear regression between the number of NIS per state and the “Market share” which is the proportion of the national tonnage of shipping (imports + exports) for which each state is responsible (ANTAQ 2018; Table S1).

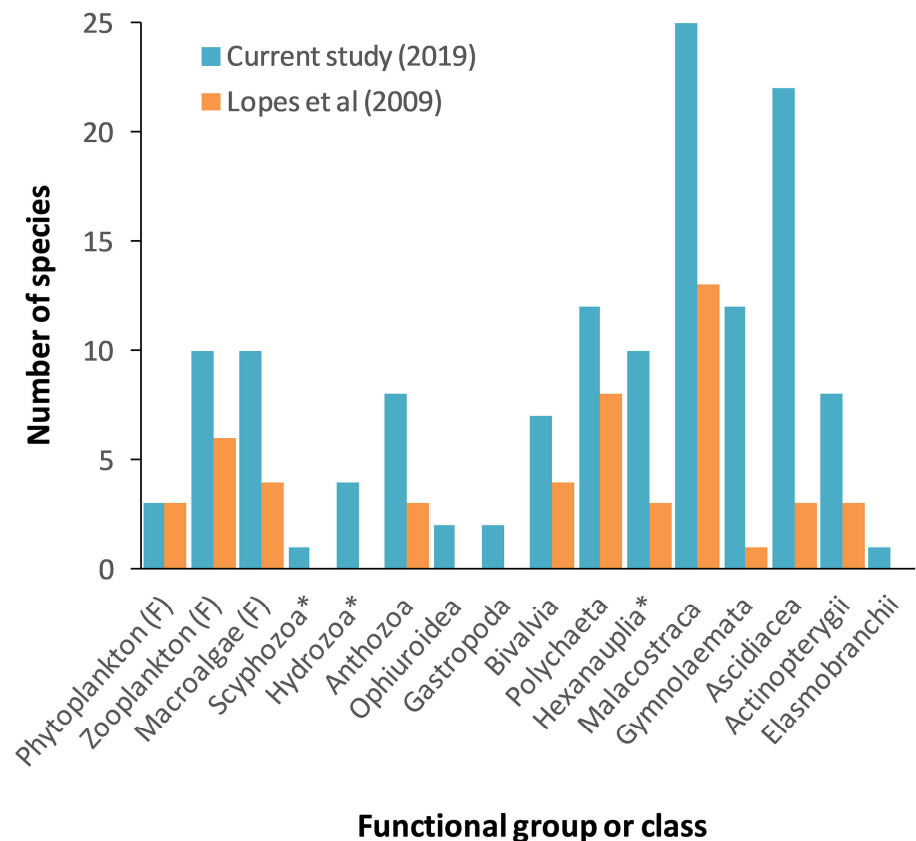


Figure 1. Number of non-indigenous marine species in Brazil by functional group (F) or class in May 2019 and compared to Lopes et al. (2009). Zooplankton category includes all planktonic Hexanauplia, Scyphozoa and Hydrozoa; * = zoobenthic species of these classes.

Results

We compiled information from more than 120 data sources (Table S2). We reviewed all studies and identified and assigned status to 138 marine NIS recorded from Brazil up to May 2019. Contained or cryptogenic species were not included in the list. The updated summary and status list is presented in Table S3. The NIS comprised 15 classes or functional groups (Figure 1); Malacostraca was the class with most NIS ($n = 26$), followed by Ascidacea ($n = 22$), Polychaeta and Gymnolaemata ($n = 12$ each). Elasmobranchii ($n = 1$), Ophiuroidea and Gastropoda ($n = 2$ each) and phytoplankton ($n = 3$) were the groups with the least NIS. The group with the largest number of invasive (sensu Methods) NIS was the Anthozoa ($n = 7$), followed by the phytoplankton and Bivalvia ($n = 3$ each) (Tables S2 and S3).

Distribution in space

Up to May 2019 at least three NIS have been documented in each of the 17 Brazilian coastal states, but most were concentrated in southeast Brazil. The state with the greatest absolute number of NIS was São Paulo with 73 species (52.9% of total), followed by Rio de Janeiro with 69 (50%), Bahia with 45 (32.6%) and Paraná with 43 (31.2%); the state with the lowest number

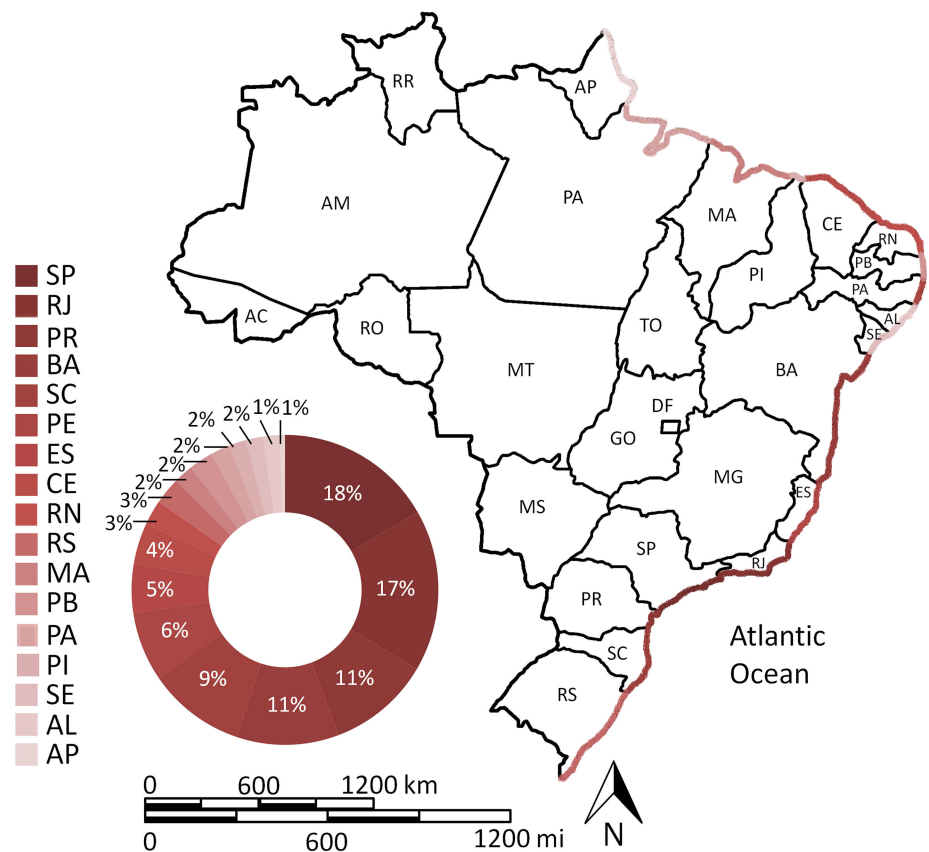


Figure 2. Map of Brazil highlighting the coastal states in which non-indigenous species (NIS) were detected. The color gradation is directly related to the number of NIS, with sites with the highest number of NIS having darker shades. Abbreviations: Amapá (AP), Pará (PA), Maranhão (MA), Piauí (PI), Ceará (CE), Rio Grande do Norte (RN), Paraíba (PB), Pernambuco (PE), Alagoas (AL), Sergipe (SE), Bahia (BA), Espírito Santo (ES), Rio de Janeiro (RJ), São Paulo (SP), Paraná (PR), Santa Catarina (SC), Rio Grande do Sul (RS).

of NIS (three; 2.2%) was Amapá in the far north (Figure 2; Table S2). However, considering and correcting for the significant variation in coastline extension between states on a per km basis (Table S1), there was a trend of increasing numbers of NIS from north to south to Paraná, which although a small state had the highest number of NIS per 100 km of coastline (Figure 3). The states of Piauí and Pernambuco also had a higher number of NIS than expected by the north-south trend (Figure 3).

The most widespread NIS in Brazil is currently the Pacific White Shrimp *Penaeus vannamei* (15 states; Table S2). Other widespread NIS are the Indo-Pacific swimming crab *Charybdis* (*Charybdis*) *hellerii* which occurs in 11 states, the copepod *Temora turbinata* and purse oyster *Isognomon bicolor* in 10 states, the hydroid *Cordylophora caspia*, snowflake coral *Carijoa riisei* and mudsleeper *Butis koilomatodon* in eight states, and the barnacles *Amphibalanus reticulatus* and *Megabalanus coccopoma* and sun corals *Tubastraea coccinea* and *Tubastraea tagusensis* in seven states each (Table S2). Only one species, the macroalga *Caulerpa scalpelliformis*, has a demonstrated human-mediated range shift as its natural southern limit of distribution in Brazil is Espírito Santo state but is invasive in the state of Rio de Janeiro.

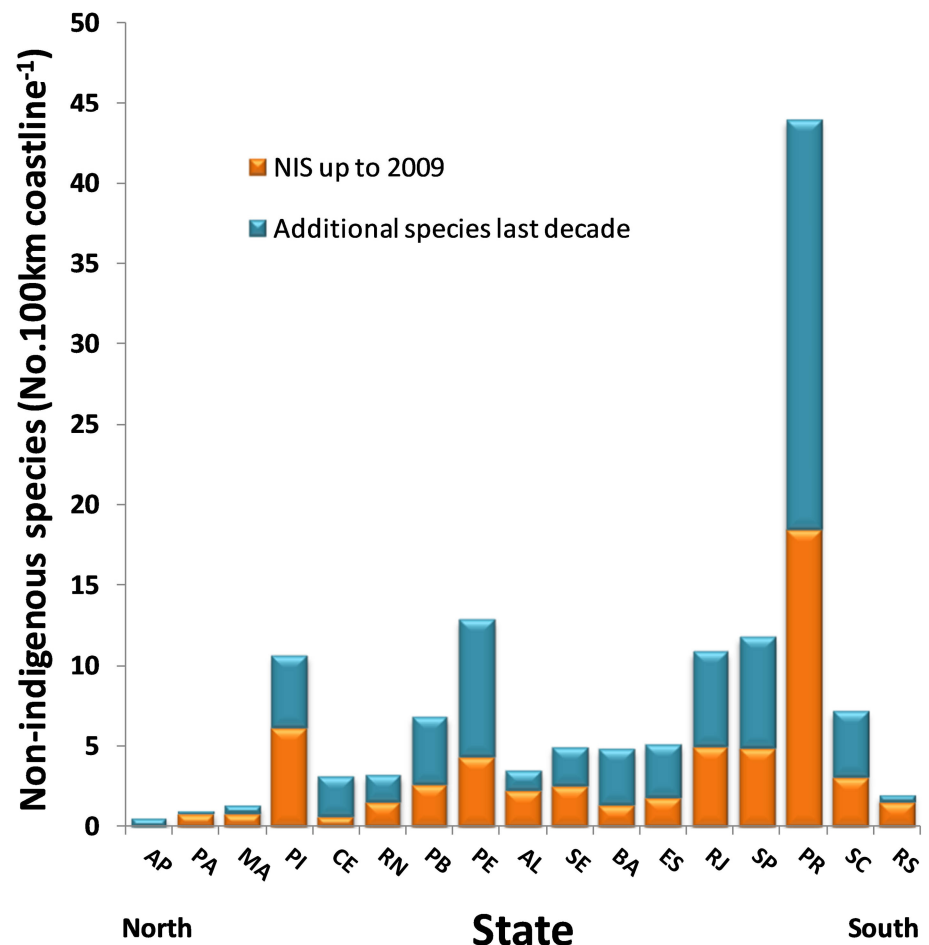


Figure 3. Standardized comparison of non-indigenous marine species per Brazilian state, per 100 km coastline, in May 2019 and those additional species from 2009–2019. Names of the states as in Figure 2.

There were several NIS previously reported in Brazil in 2009 which expanded their ranges into other states over the last 10 years. These species included the mudsleeper *Butis koilomatodon* (into seven additional states), the orange sun coral *Tubastraea coccinea* (six), yellow sun coral *Tubastraea tagusensis* and the muzzled blenny *Omobranchus punctatus* (four each) and the boring bivalve *Leiosolenus aristatus* (three) (Table S2). The alga *Anotrichium yagii*, mussel *Mytilopsis leucophaeata*, sabellid polychaete *Branchiomma luctuosum*, portunid crab *Scylla serrata* and the xanthid crab *Pilumnoides perlatus* also expanded their ranges (one additional state each).

The total number of NIS per 100 km of coastline in each state was dependent on the volume of market share (exports + imports, Table S1); a significant though not a very strong relationship was observed (NIS per 100 km coastline = $1.5748 \times \text{Market share} + 14.383$, Adjusted $R^2 = 0.2494$, $p = 0.01$; Figure 4). However when two outlier states which have exceptionally large exports of specific commodities were removed (Espírito Santo and Maranhão), a stronger relationship was observed (NIS per 100 km coastline = $3.466 \times \text{Market share} + 9.918$; $n = 14$, Adjusted $R^2 = 0.71$, $p \leq 0.001$; Figure 4).

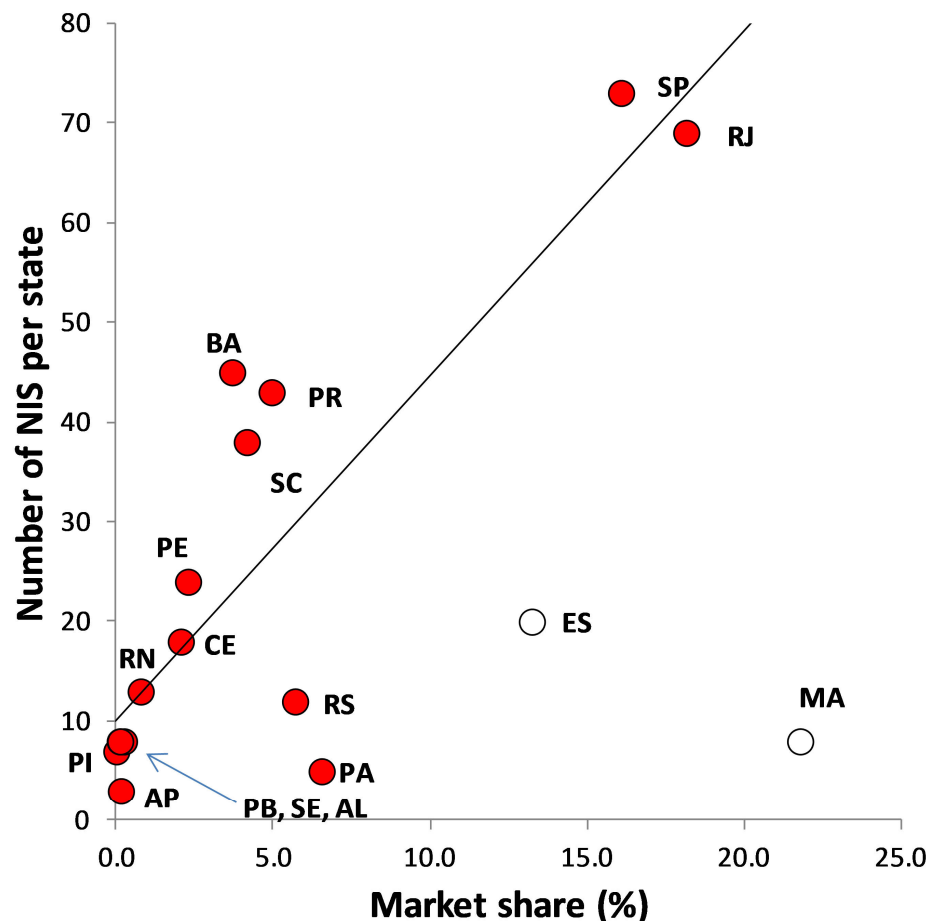


Figure 4. Relationship between market share (%) and number of non-indigenous marine species per Brazilian state. Market share is proportion of total tonnage of Brazilian maritime imports + exports per state in 2018 (ANTAQ 2018). Line fit to filled points (unfilled points were considered outliers). Names of the states as in Figure 2.

Change over time

The first record of a non-indigenous marine species in Brazil was from 1860 (the bryozoan *Amathia verticillata*) (Miranda et al. 2018) followed by the ascidian *Styela plicata* recorded in Rio de Janeiro in 1883 (Lopes et al. 2009) (Figure 5 and Table S2). The third record occurred 40 years later, in 1925 (the ascidian *Clavelina oblonga*) (Rocha et al. 2012). Up through the 1960s additional NIS were sporadically reported, but from 1949 onwards new records of NIS have at least doubled ($\geq 100\%$ increase) every decade up to a total of 99 in 2008 (Figure 5). Over the last decade the number of new records of NIS has increased to 138 which represents a 25% decadal increase according to our dataset. The only group which did not increase in NIS abundance over the last decade was the phytoplankton (Figure 1). The state which exhibited the most substantial increase in NIS over the last decade was Paraná (25.5 species/100 km), then Pernambuco (8.6 species/100 km) while Rio Grande do Sul, Amapá, Pará and Maranhão only increased by < 1 species/100 km (Figure 3).

The current status of marine NIS and the change in status over the last decade as compared to Lopes et al. (2009) is summarized in Table S3. As some

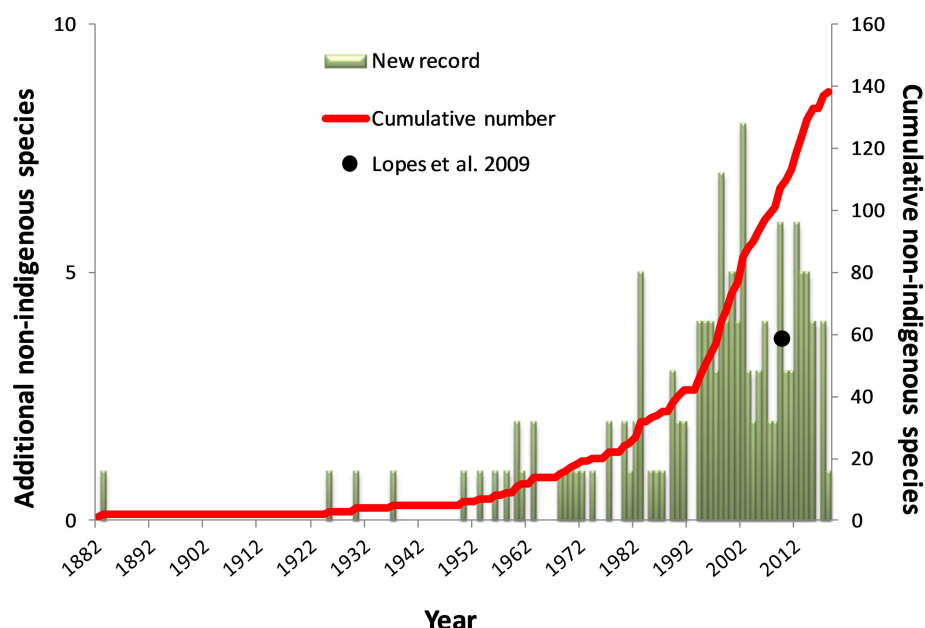


Figure 5. Number of new non-indigenous marine species recorded from Brazil every year from 1883 to 2019, together with the cumulative curve reaching a total of 138 species by May 2019; the total by 2008 as reported in Lopes et al. (2009) is also indicated.

species have changed their status and new species have been detected, we considered 19 species to be invasive, 76 established and 43 detected; in the survey by Lopes et al. (2009) there were 9 invasive, 17 established and 27 detected species (Tables S2, S3). According to this comparison, the number of NIS in Brazil has increased by 160% over the last 10 years. There has been no loss of any marine NIS in Brazil over the last 10 years, except for species that previously had been described as non-indigenous but that are currently considered as cryptogenic or native. Compared to the previous list, there was a 347% increase in the number of established species and a 111% increase in invasive species. The lowest increase was in the number of detected species (59%). Five species previously considered established were considered invasive, and eleven species that were previously considered to be detected were considered established (Table S3).

Discussion

Ten years on from the first national effort to compile a list and define the status of marine species non-indigenous to Brazil, published by the Ministry of the Environment (Lopes et al. 2009), much has changed. The effort by Lopes et al. (2009) was important in providing a first national list as well as focusing on the need for new research on marine NIS, including research on vectors of introduction (Loebmann et al. 2010; Farrapeira et al. 2011; Van Ofwegen and Haddad 2011; Skinner et al. 2013; Castro et al. 2017; Creed et al. 2017; Mantelatto et al. 2018) and quantification of impact and risk (Silva et al. 2010; Carlton et al. 2011; Rocha et al. 2013; Altvater and Coutinho 2015; Bumbeer and Rocha 2016; Miranda et al. 2018) (Table S2). In 2013 the National Biodiversity Targets established that

the National Strategy on Invasive Alien Species should be fully implemented in Brazil by 2020, including the participation and commitment of the states in the formulation of a National Policy. Central to the national strategy is the need to identify and list NIS. The present study clearly demonstrates the need for regularly updating national lists of NIS.

This study is a data compilation, and therefore we compiled previously published information and assigned status according to previously established classification criteria. This must be done in an accurate and responsible way but even so the literature contains controversy regarding NIS statuses. Of the 58 NIS listed by Lopes et al. (2009), eight were not included in the present study. Five of these are now considered cryptogenic and include the sponge *Paraleucilla magna* Klautau, Monteiro and Borojevic, 2004 (Rocha et al. 2013; Cavalcanti et al. 2013) and the bryozoan species complex *Schizoporella errata* (Waters, 1878) (see Rocha et al. 2013; Miranda et al. 2018), both previously considered established, the bryozoans *Licornia diadema* (Busk, 1852) and *Virididentula dentata* (Lamouroux, 1816) (see Miranda et al. 2018) and the ascidian *Bostrichobranchus digonas* Abbott, 1951 (Rocha et al. 2013), all previously considered detected. The isopod *Sphaeroma annandalei* Stebbing, 1911 was described as the new species *Sphaeroma silvai* Khalaji-Pirbalouty and Waegle, 2010, and thus lost its NIS status (Khalaji-Pirbalouty and Waegle 2010). The seaweed *Kappaphycus alvarezii* (Doty) Doty ex P.C. Silva, which was introduced intentionally into Brazil for farming, has not been able to establish itself naturally outside the culture systems (although broken, unfixed fragments are occasionally found on adjacent bottoms), so we considered this to currently be a contained species (Castelar et al. 2009; Lima et al. 2018).

With regard to the eighth species, the mussel *Perna perna* (Linnaeus, 1758), that was initially treated by Lopes et al. (2009) as a NIS, much has been discussed about the origin of this bivalve [see contrasting views of Cunha et al. (2014), Pierri et al. (2016) and Oliveira et al. (2017)]. Based on molecular, ecological and archaeological studies, the species may have been historically transported to Brazil from Africa on slave boats or be native. It is an edible species which is harvested and farmed and is of significant commercial importance; maybe for these reasons it has been termed “naturalized” by Oliveira et al. (2017). We did not include it in the present list as additional molecular, ecological and archaeological studies of different populations are required to better clarify the origin of the species. As it is of uncertain origin, it should be considered cryptogenic (a conservative category of obscure or unknown origin; Carlton 1996). The fact that a number of previously listed species ($n = 6$) have had their status redefined as cryptogenic attests to a more conservative scientific approach as invasion biology matures in Brazil (Carlton 1996).

Both morphological characteristics and molecular studies can aid in determining the invasive status of questionable species. Lopes et al. (2009)

listed the bivalve *Mytilopsis leucophaeata* as a NIS in Pernambuco state but a subsequent molecular study by Fernandes et al. (2018) identified that population as *M. cf. sallei* also a NIS for Brazil; however in the same study they also identified a new population in Rio de Janeiro state as *M. leucophaeata*, so the species maintains its status as NIS for Brazil. In addition to molecular studies, identifying morphological characters is important when determining NIS. The ascidian *Ciona intestinalis*, also known as a complex of two species, was later described in 2015 as *C. intestinalis* and *C. robusta* (Brunetti et al. 2015). Here we conservatively maintained the species as *Ciona intestinalis* until future studies establish which species actually occur in Brazil. Five new taxonomic classes not previously listed as NIS in Brazil were added to the list and include the following: two ophiuroids (*Ophiactis savignyi* and *Ophiothela mirabilis*), two gastropods (*Bulbaeolidia alba* and *Eualetes tulipa*), two Scyphozoa (*Cassiopea andromeda* and *Phyllorhiza punctata*), five hydrozoans (*Podocoryna loyola*, *Cordylophora caspia*, *Blackfordia virginica*, *Cnidostoma fallax* and *Garveia franciscana*) and one Elasmobranchii (the whitetip reef shark *Triaenodon obesus*).

The 11 species which were described as detected in 2009 and are currently considered established changed their classification because they have expanded their ranges and/or have been detected on multiple occasions. The five invasive species that were previously considered established had their status changed because they are now known to cause some type of damage, be it environmental, economic and/or to public health (Table S3). For example in 2009 the muzzled blenny *Omobranchus punctatus* was considered to be established and possibly an invasive species. Currently, this herbivorous fish, which scrapes algae from the bottom, has been described as competing with the native molly miller *Scartella cristata* (Linnaeus, 1758) and thus gained the status of an invasive species (Soares et al. 2011).

The increase in the number of established species and the decrease in detected species demonstrates that we are still ineffective in completely controlling the movement of NIS and that we must focus on management plans to stop NIS increasing their area of coverage and eventually becoming invasive (sensu Methods). Rather than focus exclusively on prevention of introduction, the ideal invasive species policy should also involve a combination of other strategies such as risk assessment, efforts to detect new species and activities to monitor and control existing populations of newly detected species. If an incipient population of a species is detected before establishment and spread, subsequent control costs may be reduced and eradication may be a viable option (Mehta et al. 2007). It is important to remember that so far in Brazil no established or invasive marine NIS has been eradicated after its introduction. That having been said, two species, the lionfish *Pterois volitans* and the octocoral *Clavularia viridis*, were both controlled on detection. They have not since been detected in Brazilian waters (Ferreira et al. 2015; Mantelatto et al. 2018) and may thus be considered eradicated.

Those species which have become widespread use multiple mechanisms of expansion. Some have been introduced multiple times for aquaculture (e.g., Pacific White Shrimp *Penaeus vannamei*, Lopes et al. 2009) or on shipping associated with the offshore oil and gas industry (e.g., sun corals *Tubastraea coccinea* and *Tubastraea tagusensis*, and the associated purse oyster *Isognomon bicolor*; Creed et al. 2017). Others, such as the snowflake coral *Carijoa riisei* and the barnacles *Amphibalanus reticulatus* and *Megabalanus coccopoma*, are commonly found on artificial floating substrates (Ferreira et al. 2006; Carlton et al. 2011). The Indo-Pacific swimming crab *Charybdis* (*Charybdis*) *hellerii*, the copepod *Temora turbinata* and mudsleeper *Butis koilomatodon* were probably spread by currents, swimming and/or larval dispersal (Lopes et al. 2009).

In cases where species are introduced into new habitats for economic benefit or to meet developmental needs, there may be an initial economic gain, but if a species becomes invasive it can cause serious economic and ecological damage (Molnar et al. 2008). These risks of invasion are often not considered during the decision process of whether to introduce a species (Naylor et al. 2001). For example, ten years ago the Pacific oyster *Crassostrea gigas* was considered a contained species because it did not reproduce naturally on the Brazilian coast, and the cultivation of this species depended on the constant imports of seed or reproduction in the laboratory (Lopes et al. 2009). However *C. gigas* has now been found in natural banks on the south coast of Brazil, at a distance of up to 100 km south of the farms where they are cultivated (Melo et al. 2010). For this reason, *C. gigas* is now considered an established NIS.

Our study showed that the states with the greatest number of NIS are also those that have substantial movement of marine commerce. These ports usually also offer services for the off-shore oil industry, including rig harboring, and are important marine navigation hubs. These are three of the most important vectors of introduction of marine species (Ruiz and Carlton 2003; Silva and Souza 2004; Ferreira et al. 2006; Yeo et al. 2009). As outliers, we excluded two states from the analysis, Maranhão (MA) and Espírito Santo (ES), which both export very high tonnages of minerals from the interior of Brazil. We used market tonnage as a proxy for species dispersal as that data were available but frequency with which ports receive vessels and their origin was also important. Furthermore, some states (such as ES) are probably understudied while others (Rio de Janeiro – RJ, São Paulo – SP and Parana – PR) contribute to the bulk of previously published data (Figure 4). Identifying the spatial distribution and most common pathways for the introduction of harmful marine species can help to focus monitoring efforts, provide information for risk assessment and inform and support international policies to prevent such introductions (Molnar et al. 2008). In this respect it would be useful for management if future studies attempt to 1) identify the principal pathways and vectors of

introduction for these NIS, if this information is available; 2) identify which states are most critically threatened by NIS (by analyzing first introductions at the state level).

When we compared the timeline of reports of marine NIS in Brazil over the last 10 years to Lopes et al. (2009), we identified apparently incongruent results. For example we estimated a 160% increase in NIS over the last decade compared to Lopes et al.'s (2009) study but only a 25% decadal increase when comparing our own results. This was because by 2008 there were 99 marine NIS in Brazil compared to only 53 listed by Lopes et al. (2009) (see the point and line indicated in Figure 5). Bearing in mind that we used the year of first record (collection date, record date or publication date, in that priority order) for each new NIS, the reasons for this mismatch are various and could include the following: 1) while Lopes et al. was published in 2009, the data had been collected some time previously; 2) several NIS species included here, which were known in Brazil pre-2009, were not considered to be NIS at that time; 3) novel NIS may take some years to be formally identified, or even described, after first being recorded (but the date remains the same); 4) records of novel NIS may take years to get published. For example the brittlestar *Ophiothela mirabilis* was first detected in 2000 but the first published record was in 2012 by Hendler et al. Similarly, the octocoral *Stragulum bicolor* was first detected in 2002 in Brazil but only described (and as a new species) by Van Ofwegen and Haddad in 2011.

Given the above, it should be recognized that the apparent reduction in the rate of new records of marine NIS this last decade may also simply be an artifact of the lag between new NIS being detected and the community becoming aware through communication or publication of those records. Nevertheless, it may also be the case that the date of first record does not actually reflect the year of introduction, since many species may remain undetected for a while, which generally results in the opposite pattern of an apparent increase in the rate of introductions that is an artifact of increased awareness and sampling effort. These observations further confirm the need for NIS lists to be constantly reviewed and updated to incorporate newly detected NIS and changes in species status based on further research (Sliwa et al. 2009). Brazil has not yet implemented a national database of marine NIS which we consider may be the most appropriate and cost effective method of moving forward in updating and maintaining current the national NIS lists as part of the National Strategy on Invasive Alien Species.

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References

- Altwater L, Coutinho R (2015) Colonisation, competitive ability and influence of *Stragulum bicolor* van Ofwegen and Haddad, 2011 (Cnidaria, Anthozoa) on the fouling community in Paranaguá Bay, Southern Brazil. *Journal of Experimental Marine Biology and Ecology* 462: 55–61, <https://doi.org/10.1016/j.jembe.2014.10.007>
- ANTAQ (2018) Anuário Estatístico Aquaviário - 2018, ANTAQ. <http://web.antaq.gov.br/Anuario/> (accessed 11 July 2019)
- Brasil (1998) Decreto nº 2.519 Promulga a Convenção sobre Diversidade Biológica. http://www.planalto.gov.br/ccivil_03/decreto/D2519.htm (accessed 18 June 2014)
- Brunetti R, Gissi C, Pennati R, Caicci F, Gasparini F, Manni L (2015) Morphological evidence that the molecularly determined *Ciona intestinalis* type A and type B are different species: *Ciona robusta* and *Ciona intestinalis*. *Journal of Zoological Systematics and Evolutionary Research* 53: 186–193, <https://doi.org/10.1111/jzs.12101>
- Bumbeer J, Rocha RMD (2016) Invading the natural marine substrates: a case study with invertebrates in South Brazil. *Zoologia (Curitiba)* 33: e20150211, <https://doi.org/10.1590/S1984-4689zool-20150211>
- Carlton JT (1996) Biological invasions and cryptogenic species. *Ecology* 77: 1653–1655, <https://doi.org/10.2307/2265767>
- Carlton JT, Newman WA, Pitombo FB (2011) Barnacle invasions: introduced, cryptogenic, and range expanding Cirripedia of North and South America. In: Galil BS, Clark PF, Carlton JT (eds), In the Wrong Place-Alien Marine Crustaceans: Distribution, Biology and Impacts. Springer, Dordrecht, pp 159–213, https://doi.org/10.1007/978-94-007-0591-3_5
- Castro MCT, Fileman TW, Hall-Spencer JM (2017) Invasive species in the Northeastern and Southwestern Atlantic Ocean: A review. *Marine Pollution Bulletin* 116: 41–47, <https://doi.org/10.1016/j.marpolbul.2016.12.048>
- Castelar B, Reis RP, Moura AL, Kirk R (2009) Invasive potential of *Kappaphycus alvarezii* off the south coast of Rio de Janeiro state, Brazil: a contribution to environmentally secure cultivation in the tropics. *Botanica Marina* 52: 283–289, <https://doi.org/10.1515/BOT.2009.002>
- Cavalcanti FF, Skinner LF, Klautau M (2013) Population dynamics of cryptogenic calcarean sponges (Porifera, Calcarea) in Southeastern Brazil. *Marine Ecology* 34: 280–288, <https://doi.org/10.1111/maec.12013>
- Creed JC, Fenner D, Sammarco P, Cairns S, Capel K, Junqueira AO, Cruz I, Miranda RJ, Carlos-Junior L, Mantelatto MC (2017). The invasion of the azooxanthellate coral *Tubastraea* (Scleractinia: Dendrophylliidae) throughout the world: history, pathways and vectors. *Biological Invasions* 19: 283–305, <https://doi.org/10.1007/s10530-016-1279-y>
- Cunha RL, Nicastro KR, Costa J, McQuaid CD, Serrão EA, Zardi GI (2014) Wider sampling reveals a non-sister relationship for geographically contiguous lineages of a marine mussel. *Ecology and Evolution* 4: 2070–2081, <https://doi.org/10.1002/ece3.1033>
- Elliott M (2003) Biological pollutants and biological pollution—an increasing cause for concern. *Marine Pollution Bulletin* 46: 275–280, [https://doi.org/10.1016/S0025-326X\(02\)00423-X](https://doi.org/10.1016/S0025-326X(02)00423-X)
- Farrapeira CMR, Oliveira Tenório D, Amaral FD (2011) Vessel biofouling as an inadvertent vector of benthic invertebrates occurring in Brazil. *Marine Pollution Bulletin* 62: 832–839, <https://doi.org/10.1016/j.marpolbul.2010.12.014>
- Fernandes MR, Salgueiro F, Miyahira IC, Caetano CHS (2018) mtDNA analysis of *Mytilopsis* (Bivalvia, Dreissenidae) invasion in Brazil reveals the existence of two species. *Hydrobiologia* 817: 97–110, <https://doi.org/10.1007/s10750-018-3602-3>
- Ferreira CEL, Gonçalves JEA, Coutinho R (2006) Ship hulls and oil platforms as potential vectors to marine species introduction. *Journal of Coastal Research* SI39: 1340–1345
- Ferreira CEL, Junqueira AOR, Villac MC, Lopes RM (2009) Marine bioinvasions in the Brazilian coast: brief report on history of events, vectors, ecology, impacts and management of non-indigenous species. In: Rilov G, Crooks JA (eds), Biological invasions in marine ecosystems. Springer, pp 459–477, https://doi.org/10.1007/978-3-540-79236-9_27
- Ferreira CEL, Luiz OJ, Floeter SR, Lucena MB, Barbosa MC, Rocha CR, Rocha LA (2015) First Record of Invasive Lionfish (*Pterois volitans*) for the Brazilian Coast. *PLoS ONE* 10: e0123002, <https://doi.org/10.1371/journal.pone.0123002>
- Hendler G, Migotto AE, Ventura CRR, Wilk L (2012) Epizoic *Ophiothela* brittle stars have invaded the Atlantic. *Coral Reefs* 31: 1005–1005, <https://doi.org/10.1007/s00338-012-0936-6>
- Khalaji-Pirbalouty V, Waagele J-W (2010) A new record of *Sphaeroma annandalei* Stebbing, 1911 (Crustacea: Isopoda: Sphaeromatidae) from the Persian Gulf, and description of a new related species (*Sphaeroma silvai* nov. sp.) from the South Atlantic Ocean. *Zootaxa* 2508: 30–44, <https://doi.org/10.11646/zootaxa.2508.1.2>
- Lima LB, Oliveira FJM, Giacomini HC, Lima-Junior DP (2018) Expansion of aquaculture parks and the increasing risk of non-native species invasions in Brazil. *Reviews in Aquaculture* 10: 111–122, <https://doi.org/10.1111/raq.12150>
- Loebmann D, Mai ACG, Lee JT (2010) The invasion of five alien species in the Delta do Parnaíba Environmental Protection Area, Northeastern Brazil. *Revista de Biologia Tropical* 58: 909–923, <https://doi.org/10.15517/rbt.v58i2.5254>
- Lonhart SI (2009) Natural and climate change mediated invasions. In: Rilov G, Crooks JA (eds), Biological invasions in marine ecosystems. Springer, pp 57–69, https://doi.org/10.1007/978-3-540-79236-9_3

- Lopes R, Villac M (2009) Métodos. In: Lopes RM, Coradin L, Pombo VB, Cunha DR (eds), Informe sobre as espécies exóticas invasoras marinhas no Brasil. Ministério do Meio Ambiente - Secretaria de Biodiversidade e Florestas, Brasília, pp 19–28
- Lopes RMC, Pombo L, Cunha VB, Rimoldi D (2009) Informe sobre as espécies exóticas invasoras marinhas no Brasil. Ministério do Meio Ambiente - Secretaria de Biodiversidade e Florestas, Brasília, 440 pp
- Mantelatto MC, Silva AG, Louzada TS, McFadden CS, Creed JC (2018) Invasion of aquarium origin soft corals on a tropical rocky reef in the southwest Atlantic, Brazil. *Marine Pollution Bulletin* 130: 84–94, <https://doi.org/10.1016/j.marpolbul.2018.03.014>
- Mehta SV, Haight RG, Homans FR, Polasky S, Venette RC (2007) Optimal detection and control strategies for invasive species management. *Ecological Economics* 61: 237–245, <https://doi.org/10.1016/j.ecolecon.2006.10.024>
- Melo CM, Silva FC, Gomes CHA, Solé-Cava AM, Lazoski C (2010) *Crassostrea gigas* in natural oyster banks in southern Brazil. *Biological Invasions* 12: 441–449, <https://doi.org/10.1007/s10530-009-9475-7>
- Miranda AA, Almeida AC, Vieira LM (2018) Non-native marine bryozoans (Bryozoa: Gymnolaemata) in Brazilian waters: Assessment, dispersal and impacts. *Marine Pollution Bulletin* 130: 184–191, <https://doi.org/10.1016/j.marpolbul.2018.03.023>
- Molnar JL, Gamboa RL, Revenga C, Spalding MD (2008) Assessing the global threat of invasive species to marine biodiversity. *Frontiers in Ecology and the Environment* 6: 485–492, <https://doi.org/10.1890/070064>
- Naylor RL, Williams SL, Strong DR (2001) Aquaculture -A gateway for exotic species. *Science* 294: 1655–1656, <https://doi.org/10.1126/science.1064875>
- Oliveira MJS, Beasley CR, Barros NGV, Socorro Marques-Silva N, Simone LRL, Lima ES, Tagliaro CH (2017) Two African origins of naturalized brown mussel (*Perna perna*) in Brazil: past and present bioinvasions. *Hydrobiologia* 794: 59–72, <https://doi.org/10.1007/s10750-016-3082-2>
- Pierri BS, Fossari T, Magalhães A (2016) The brown mussel *Perna perna* in Brazil: native or exotic? *Arquivo Brasileiro de Medicina Veterinária e Zootecnia* 68: 404–414, <https://doi.org/10.1590/1678-4162-8534>
- Rocha RM, Bonnet NY, Baptista MS, Beltramin FS (2012) Introduced and native Phlebobranch and Stolidobranch solitary ascidians (Tunicata: Ascidiacea) around Salvador, Bahia, Brazil. *Zoologia (Curitiba)* 29: 39–53, <https://doi.org/10.1590/S1984-46702012000100005>
- Rocha RMD, Vieira LM, Migotto AE, Amaral ACZ, Ventura CRR, Serejo CS, Pitombo FB, Santos KC, Lopes RM, Pinheiro U, Marques AC (2013) The need of more rigorous assessments of marine species introductions: a counter example from the Brazilian coast. *Marine Pollution Bulletin* 67: 241–243, <https://doi.org/10.1016/j.marpolbul.2012.12.009>
- Ruiz GM, Carlton JT (2003) Invasion vectors: a conceptual framework for management. In: Ruiz GM, Carlton JT (eds), *Invasive species: vectors and management strategies*. Island Press, London, pp 459–504
- Silva JV, Souza RSCL (2004) Água de Lastro e Bioinvasão. Rio de Janeiro, Brazil, 252 pp
- Silva BNT, Amancio CE, de Oliveira Filho EC (2010) Exotic marine macroalgae on the Brazilian coast: a revision. *Oecologia Australis* 14: 403–414, <https://doi.org/10.4257/oeco.2010.1402.05>
- Skinner LF, Oliveira GCM, Barboza DF, Tenório AA, Soares DC (2013) First record of the Ascidiacea *Rhodosoma turcicum* in the south-west Atlantic Ocean. *Marine Biodiversity Records* 6: E37, <https://doi.org/10.1017/S1755267213000092>
- Sliwa C, Migus S, McEnulty F, Hayes KR (2009) Marine bioinvasions in Australia. In: Rilov G, Crooks JA (eds), *Biological Invasions in Marine Ecosystems*. Springer, pp 425–437, https://doi.org/10.1007/978-3-540-79236-9_25
- Soares BE, Raiol RDO, Montag LDA (2011) Occurrence of the non-native blenny *Omobranchius punctatus* (Valenciennes, 1836) (Perciformes: Blenniidae) in the Amazon coastal zone, Brazil. *Aquatic Invasions* 6: S39–S43, <https://doi.org/10.3391/ai.2011.6.S1.009>
- Van Ofwegen L, Haddad M (2011) A probably invasive new genus and new species of soft coral (Octocorallia: Alcyonacea: Clavulariidae) from Brazil. *Zootaxa* 3107: 38–46, <https://doi.org/10.11646/zootaxa.3107.1.2>
- Wiesebron ML (2013) Blue Amazon: thinking the defense of Brazilian maritime territory. *Austral: Brazilian Journal of Strategy and International Relations* 2: 101–124, <https://doi.org/10.22456/2238-6912.35039>
- WoRMS Editorial Board (2019) World Register of Marine Species. <http://www.marinespecies.org> (accessed 10 May 2019)
- Yeo DC, Ah Yong ST, Lodge DM, Ng PK, Naruse T, Lane DJ (2009) Semisubmersible oil platforms: understudied and potentially major vectors of biofouling-mediated invasions. *Biofouling* 26: 179–186, <https://doi.org/10.1080/08927010903402438>

Supplementary material

The following supplementary material is available for this article:

Table S1. Coastal extension and maritime market share of the Brazilian States.

Table S2. Checklist of marine taxa non-indigenous to Brazil, including date first registered, states of occurrence, status assigned in 2019 and 2009 and sources of information.

Table S3. Summary checklist and current status of marine non-indigenous species in Brazil.

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