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Discussion

Lessons from the invasion front: Integration of research and management of the lionfish invasion in Brazil

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A R T I C L E I N F O

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A B S T R A C T

After successful invasions in the Caribbean and Mediterranean, lionfish (*Pterois* spp.) have recently invaded another important biogeographical region —the Brazilian Province. In this article, we discuss this new invasion, focusing on a roadmap for urgent mitigation of the problem, as well as focused research and management strategies. The invasion in Brazil is already in the consolidation stage, with 352 individuals recorded so far (2020–2023) along 2766 km of coastline. This includes both juveniles and adults, including egg-bearing females, ranging in length from 9.1 to 38.5 cm. Until now, most of the records in the Brazilian coast occurred in the equatorial southwestern Atlantic (99%), mainly on the Amazon mesophotic reefs (15% of the records), north-eastern coast of Brazil (45%), and the Fernando de Noronha Archipelago (41%; an UNESCO World Heritage Site with high endemism rate). These records cover a broad depth range (1–110 m depth), twelve protected areas, eight Brazilian states (Amapá, Pará, Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, and Pernambuco)

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and multiple habitats (i.e., mangrove estuaries, shallow-water and mesophotic reefs, seagrass beds, artificial reefs, and sandbanks), indicating a rapid and successful invasion process in Brazilian waters. In addition, the lack of local knowledge of rare and/or cryptic native species that are potentially vulnerable to lionfish predation raises concerns regarding the potential overlooked ecological impacts. Thus, we call for an urgent integrated approach with multiple stakeholders and solution-based ecological research, real-time inventories, update of environmental and fishery legislation, participatory monitoring supported by citizen science, and a national and unified plan aimed at decreasing the impact of lionfish invasion. The experience acquired by understanding the invasion process in the Caribbean and Mediterranean will help to establish and prioritize goals for Brazil.

1. Introduction

Many invasive fish species have pervasive ecological and socioeconomic effects worldwide (Haubrock et al., 2022). Since the 1960s, invasive fish species have caused financial losses of at least $37.08 billion globally, increasing from less than $0.01 million per annum in the 1960s to approximately $1 billion since 2000, a value that is almost certainly underestimated because of current data gaps (Haubrock et al., 2022). In marine environments, high connectivity between habitats increases the severity of this issue, making it difficult to manage (Albins and Hixon, 2013; Andradi-Brown et al., 2017). The challenge can be greater depending on the invasion area and dispersal capability of the invasive fish species (Haubrock et al., 2022).

Invasive species are one of the main causes of biodiversity loss. Thus, studying and managing such invasive events greatly contributes for "sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans", item 14.2 of UN's sustainable development goal (SDG 14 - Life Underwater). Moreover, the theme of invasive species is also linked to SDG 15 as research on this topic contributes to Target 15.8 "Prevent invasive alien species on land and in water ecosystems". Studying fish bioinvasions is not only fundamental to the aims of the United Nations Ocean Decade but also is in line with the aim of providing ocean knowledge and science for the ocean we need (UN (2022).

The lionfish (*Pterois* spp.) is among the most known invasive fish in marine environments, and its recent invasion has made them the most studied reef fish to date (Côté and Smith, 2018). The ecological impacts of lionfish are well-documented, not only in the Caribbean coral reefs (Côté and Smith, 2018) but also in other tropical ecosystems, such as mangroves and seagrass beds (Claydon et al., 2012; Whitaker et al., 2021). Alarmingly, lionfish may trigger cascading ecological and socioeconomic impacts by disrupting local food webs (Albins and Hixon, 2013) as they may prey on species that are important for fisheries, as well as increase competition for resources, putting native species at a disadvantage (Bumbeer et al., 2018). Moreover, the consumption of herbivorous fish (e.g., the surgeonfish *Acanthurus* spp.) could reduce their functional role in keeping algae in check (Morris, 2012).

Lionfish invasion in the Gulf of Mexico, Caribbean Sea, North Atlantic Ocean, Mediterranean Sea, and, more recently, in the Brazilian coast, has raised widespread concerns because of its impacts on biodiversity and effects on economic sectors such as fisheries (Albins and Hixon, 2013; Côté and Smith, 2018; Soares et al., 2022; Ulman et al., 2022). New locations in the Brazilian coast for lionfish invasion are emerging rapidly and, given the large territorial extension of the country, a comprehensive and objective approach to mitigate the negative impacts of this invasion is needed and should aim to (1) guide decision-making, (2) prioritize and integrate management actions, (3) shorten the response time against the invasive lionfish, and (4) have citizen support and broad participation.

In this article, we discuss the ongoing lionfish invasion in the extensive coast of Brazil and focus on a new roadmap to advance research and management priorities. Moreover, we provide important and novel information about the lionfish invasion in Brazil, such as: a) invaded Brazilian states; b) Brazilian marine protected areas with lionfish occurrence; c) animal size, abundance, lionfish sightings along time (2020–2023), and current bathymetric distribution; and d) Brazilian habitats with lionfish records.

2. The Brazilian coast: historical and ongoing lionfish invasion

The first detection and collection of lionfish occurred in early 2014 in the subtropical region of Arraial do Cabo, off the coast of Rio de Janeiro. In March 2015, there was a new sighting of a lionfish, with its collection taking place 11 months later, in February 2016 (Fig. 1). As only two individuals were found in 2014 and 2015, this observation represented an odd record at that time because, despite being proven to belong to the Caribbean genetic pool, no additional individuals were recorded as expected for the initial phase of the invasion (Ferreira et al., 2015). Indeed, aquarium releases were not discarded as a source at that time (Fig. 1 - D).

Over the past three years (2020–2023), a large number of sightings have been reported from Amazon continental shelf (Amapá and Pará states), northeastern Brazil, and Fernando de Noronha, a UNESCO World Heritage Site, over 5000 km north of Arraial do Cabo (Fig. 1), covering three ecoregions (according to Spalding et al., 2007) (Fig. 2). In the Brazilian province, multiple lionfishes have been recorded from a wide depth range (1–110 m) (Fig. 3). Notably, despite being only ~100 km from Fernando de Noronha, lionfish have not yet been recorded at Rocas Atoll, the only atoll of the South Atlantic, which harbors unique biodiversity.

In order to follow the path of the invasion by lionfish, local research groups, including the authors of this paper and their collaborative networks (e.g., dive centers and fisheries), have been monitoring this region closely and maintaining an updated and curated log of the current situation in the southwestern Atlantic Ocean (Figs. 1 and 2). However, the equatorial southwestern Atlantic is comparatively less surveyed than the Caribbean and lacks high-resolution seabed mapping. This lack of data implies that the areas affected by the lionfish invasion are mostly underestimated. There are several factors that have likely contributed to low surveying rates for lionfish. First, the Brazilian turbid waters make it difficult for scientists, divers and fishers to record the invasive animal. Second, cuts to the Brazilian science budget during 2018–2022 have made field surveys difficult (Kowaltowski et al., 2021). Third, the COVID-19 pandemic that severely affected Brazil reduced field surveys due to lockdowns and social distancing (Magalhães et al., 2021). In the case of the lionfish invasion of the Brazilian coast, after the first records in the Amazon reefs and Fernando de Noronha Archipelago (2020), two years characterized by the SARS-CoV-2 pandemic have passed. During this time, a series of pandemic-related restrictions took place and hindered the monitoring of lionfish occurrences, which were noticed again only in 2022 (northeastern Brazil).

The Brazilian Province has unique reef formations (popularly known as "chapeirões" in the Northeastern coast) and high endemism rates. It harbors rocky or biogenic structures and is the only true coral reef system in the southwestern Atlantic Ocean (Castro et al., 2001; Floeter et al., 2008). The Brazilian coast has contrasting warm currents, upwelling of cold nutrient-rich deep waters, substantial river runoff, and large variability in the width of the continental shelf (Leão et al., 2016; Soares et al., 2021). One particular condition is the moderate turbidity of nearshore waters in many areas throughout most of the year (Dias et al., 2013), which limits the potential for lionfish surveys.

Although a combination of the Amazon-Orinoco estuarine plume and prevailing northward currents off northern Brazil seems to have delayed the arrival of lionfish in Brazil for approximately 10 years (Luiz et al., 2013). The slow pace hitherto observed in the expansion of lionfish into the equatorial southwestern Atlantic (Luiz et al., 2013) is likely caused by the fact that prevailing currents along the Brazilian equatorial coast move in the opposite direction of the present invasion path (Fig. 1). Therefore, the current expansion process seems to be driven by adult movement along mesophotic reefs, and once populations reached shallow waters and artificial reefs (e.g., shipwrecks and *marambaias*) used as fishing grounds, the process accelerated (Soares et al., 2021, 2022).

Over the past three years (2020–2023; till March 2023), we have recorded 352 animals, including juveniles, adults, and egg-bearing females, with body lengths ranging from 9.1 cm to 38.5 cm (Fig. 3), on the Brazilian coast. The lionfish were found in multiple environments, ranging from mangrove estuaries, sandbanks, and seagrass beds to natural (1–110 m depth) and artificial (<16 m depth) reefs (Soares et al., 2022) (Fig. 4).

After being recorded in the coast of northeastern Brazil (Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, and Pernambuco) (Fig. 1 - B), the lionfish is advancing towards the state of Bahia from where it could quickly advance further southwards in the Brazilian coast following the downward Brazilian current (Fig. 1 - blue dots line).

Given the invasion process in the Brazilian coast, the records observed here (Figs. 1 and 2), the risks to native biodiversity (Soares et al., 2022), and the lack of a government policy for the control of invasive species (Miranda et al., 2020), it urgent the implementation of specific management and research initiatives. In this regard, we provide a roadmap (synthesis on Fig. 5) related to management, research, and policy that are discussed in the following sections 3 and 4.

3. Management, research, environmental education, and policy actions

The ongoing, widespread, and fast invasion of Brazilian waters by lionfish requires a set of science- and socioeconomic-based measures, ranging from data collection to urgent management actions and policy

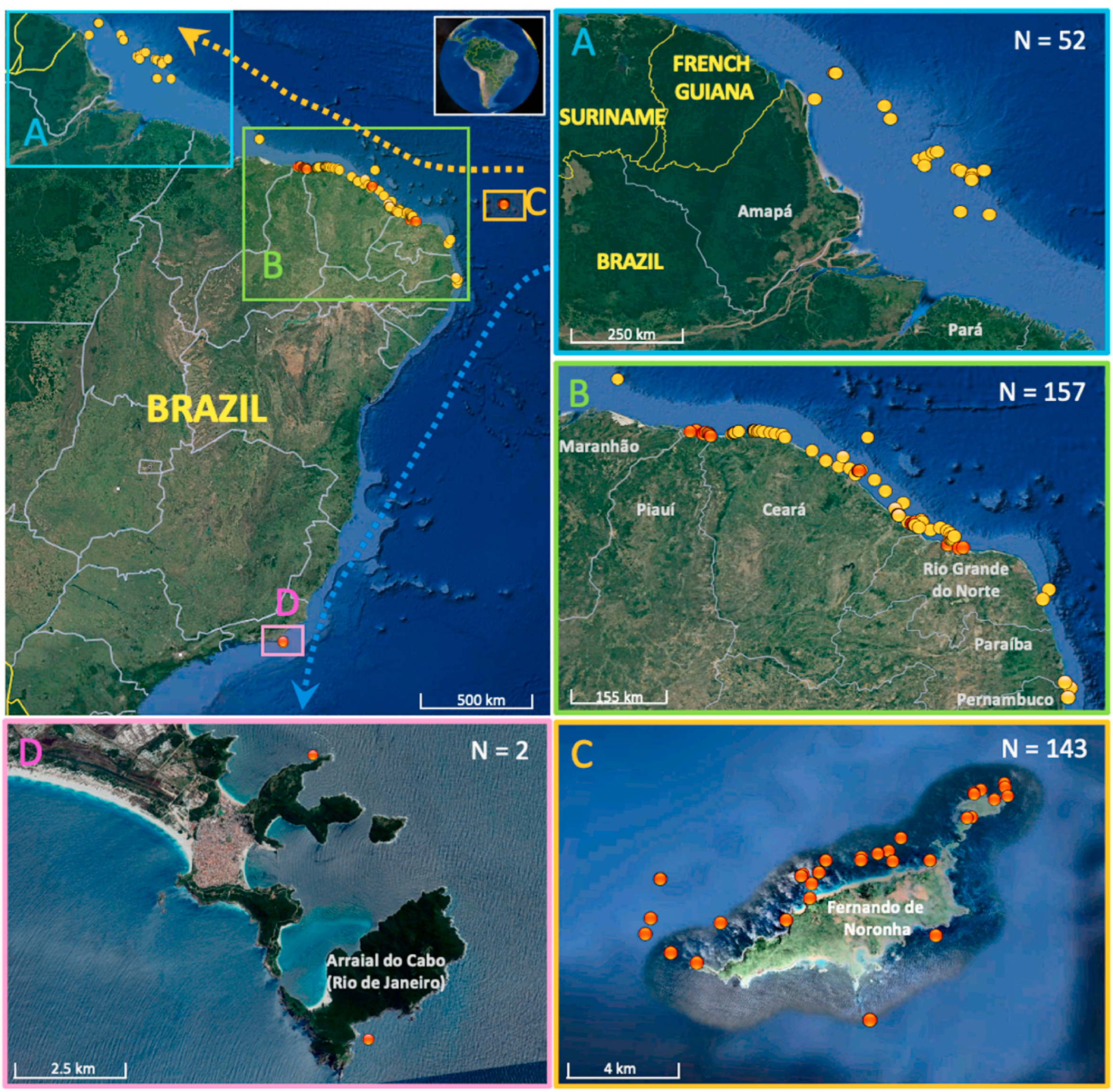

Fig. 1. The current known distribution of the invasive lionfish (*Pterois* spp., 352 records) and main ocean currents (arrows) in the Brazilian coast. Updated on 24/03/2023. Red and yellow dots indicate records inside and outside marine protected areas, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

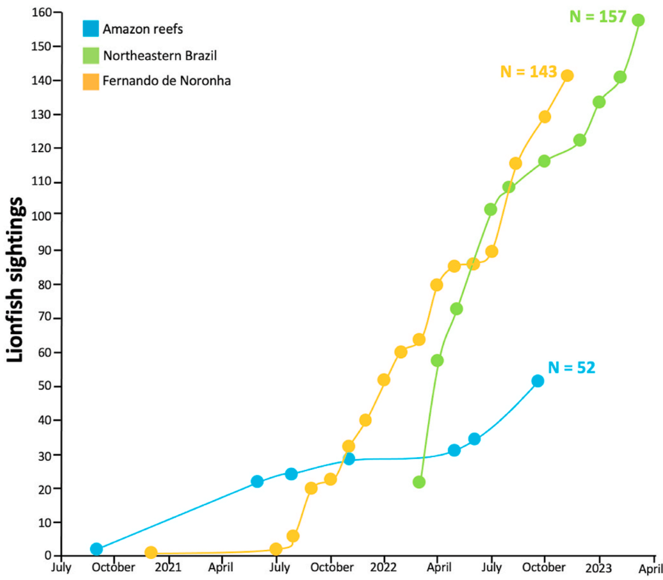

Fig. 2. Timeline showing the cumulative curves of lionfish sightings in the invaded ecoregions (Amazon reefs, northeastern Brazil, and Fernando de Noronha Archipelago) in the equatorial southwestern Atlantic Ocean from August 2020 to March 2023. Ecoregions according to Spalding et al. (2007).

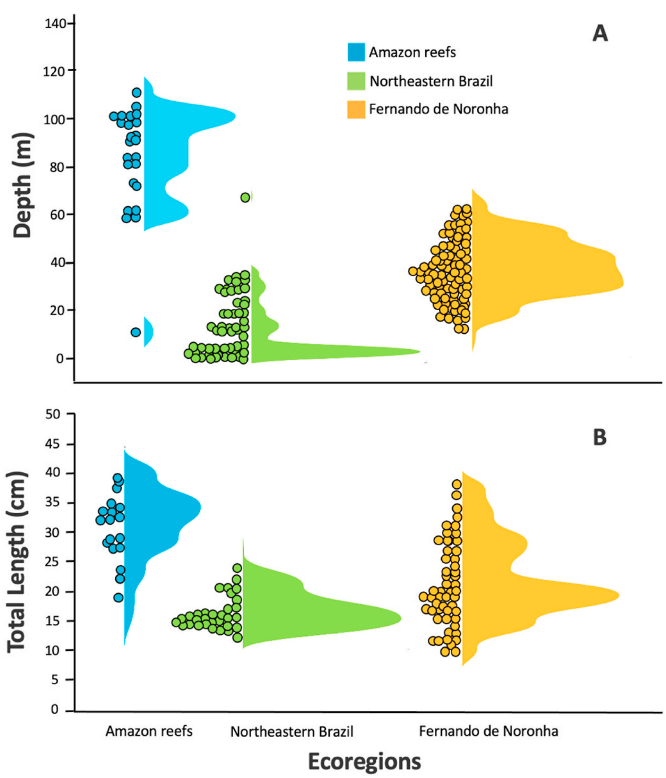

Fig. 3. Jitter and density plots of depth (a) and body size (b) of lionfish captured in Brazil since 2020. The jitter plot is a data visualization chart suitable for plotting the distribution of many individual one-dimensional values, while the density plot visualizes the data distribution over a continuous interval by smoother distributions. The plots are placed side by side to compare the distributions of data points among the invaded ecoregions (Amazon reefs, northeastern Brazil, and Fernando de Noronha Archipelago).

changes (Fig. 5). In this section, we discuss five key measures that must be taken to reduce the ecological and socioeconomic impacts of lionfish invasion: (1) a collaborative network of actions for raising public awareness and developing education programs, (2) ecological research, (3) early detection and control of populations, (4) updating the legal instruments for aquarium trade and fishing at different political levels (municipal, state, and federal), and (5) management in marine protected areas (MPAs) (Fig. 5).

3.1. Collaborative network of actions for raising public awareness and developing education programs

Considering the fast and extensive lionfish invasion of the Brazilian coast (~2766 km of multiple habitats within 3 years) (2020–2023), citizen science and communications technology (ICT) are important approaches in other regions affected by invasive lionfish (Phillips and Kotrschal, 2021). Given the scale of the Brazilian coast, the inaccessibility of many areas, the diversity of habitats known to be occupied, and the scarcity of monitoring programs focused on lionfish, the use of ICT is critical for data collection to manage this invasion. Moreover, there has been no collection of fishing data or national fishing statistics for at least ten years (Gonçalves Neto et al., 2021). In this context, in April 2022, our research group launched an online dashboard (https://monitoramentos.shinyapps.io/LionfishWatch/) , which is continuously updated with data from both scientific surveys and local communities using a self-reporting application or app.

This app can be freely downloaded to a mobile phone (Android or IOS) or computer to upload data on lionfish observations. These records can be made by recreational divers, tourists, fishers, scientists, public agencies, and other citizens and are checked and validated by our research group (https://monitoramentos.shinyapps.io/Peixe-leao/). Data on depth, habitat, and techniques used to capture or record lionfish, together with photographs and information on possible accidents involving lionfish, can be easily inserted into the app. Although this is a scientific initiative, non-governmental organizations (NGOs) and the municipal, state, and federal governments can use the information from the invaded areas to establish management and environmental education strategies, including accident prevention. For example, the Ceará State Health Department in northeastern Brazil established an awareness campaign in response to the recent envenomation of four artisanal fishers by lionfish (CEARÁ. Secretaria de Saude do Governo do Estado do Ceará, 2022; Haddad Jr. et al., 2022).

Environmental education is an extremely important strategy to manage lionfish invasion, especially in countries that have low levels of education (OECD, 2022) and high social inequality, such as Brazil in the most affected regions (North and Northeast Brazil). Through a collaborative network with various environmental agencies, NGOs, social media, and formal and non-formal education institutions, the lionfish invasion issue can be addressed through lectures, workshops, and other events as a form of environmental education to promote regional-scale integration between stakeholders. These activities must be adapted to different Brazilian educational backgrounds, such as fishers who cannot read or write.

The integration of ICT is essential for controlling lionfish in the Brazilian waters. For instance, the records of the first individuals in the field were based on reports by these local stakeholders. The first lionfish detection in Arraial do Cabo and in Fernando de Noronha Archipelago (as most of the records so far) (Luiz et al., 2013) were performed by recreational diving guides, who contacted researchers, protected the area after sighting the fish, and supported the capture of the individual. Additionally, in northern and northeastern Brazil, most records so far have been conducted by local fishers, who once again contacted managers and provided both samples and coordinates of the capture site and supported the invasion control (Luiz et al., 2021; Soares et al., 2022). Thus, citizens can substantially contribute to the detection and monitoring of lionfish, reducing management response time and increasing public support for the implementation of other measures such as public or private investment resources to deal with bioinvasions (Scyphers et al., 2015). However, the participation of fishers, divers, and even tourists must have the support of scientists through citizen science projects and of public authorities through training for capture, awareness of the risks of accidents, environmental education, and providing protective equipment. It must also be considered that, in the SW Atlantic, the intense hydrodynamics (Knoppers et al., 1999), the turbid waters (Soares et al., 2017), and the ample areas of coastal and mesophotic reefs (Moura et al., 2016; Francini-Filho et al., 2018; Soares et al., 2019) represent a challenge for participative management measures by ICT (Soares et al., 2022).

Thus, participatory research based on self-reporting applications, such as the easily accessible online dashboard presented here, will probably be the most effective strategy for low-cost monitoring of the spread of lionfish in Brazilian waters. The gathered data will also be added to the National Invasive Species Information and Management System (SIMAF/IBAMA; https://simaf.ibama.gov.br/). This approach is essential for defining local, regional, and national measures to minimize the impact of this invasion.

3.2. Ecological research

Effective monitoring is a strong tool when dealing with bioinvasions. However, despite punctual research having been conducted with focus on the lionfish problem in the SW Atlantic, Brazil lacks effective monitoring programs for the early detection of invasive marine species. Furthermore, the overall situation has worsened in recent years owing to a paucity of federal funding for science, in general, and environmental research, in particular (Oliveira et al., 2020), combined with flawed policies for the control of invasive species (Miranda et al., 2020).

Long-term monitoring programs and socio-ecological knowledge are essential for immediate and effective responses to fish invasion (Côté and Smith, 2018). Northern and northeastern Brazil, especially the reefs of the Brazilian semi-arid coast (Soares et al., 2017), the Amazon mesophotic reefs, the Fernando de Noronha Archipelago, and the Parnaíba Delta (the largest deltaic formation in the Americas), are critical for mitigating the effects of lionfish on key marine habitats. Therefore, it is essential to increase the financial resources available for solution- and problem-based ecological programs, such as long-term ecological research programs (LTER, also known by the acronym 'PELD' in Brazil) and the National Biodiversity Monitoring Program (*Monitora* Program) in the invaded regions. In this regard, some areas in the invaded states have long-term Brazilian research programs, such as LTERs (PELDs) in the Amazon reefs, semi-arid coast and oceanic islands. However, studied area coverage must be improved, mainly in mesophotic and estuarine environments.

These research programs provide fundamental data on population genetics, density and distribution, trophic ecology, reproduction, and competition, which are essential for the management and control of the invasion. A systematic assessment of the spatial distribution and density of these fish is important for the implementation of mitigatory and preventive measures in the affected areas (Côté and Smith, 2018).

The invasive success of the lionfish is derived from its voracity, as the fish can eat prey that is up to 2/3 its size (Vallejo Velásquez, 2017), a huge predatory potential that may alter the local prey population density (Linardich et al., 2021). Considering the size of an adult lionfish (45 cm), juvenile individuals of many species are part of their diet. However, we do not know yet the impact on Brazilian fauna. Another important factor is their ability to adapt (Arbeláez and Acero, 2011). These species can withstand variations in temperature, pH, depth, and salinity, and

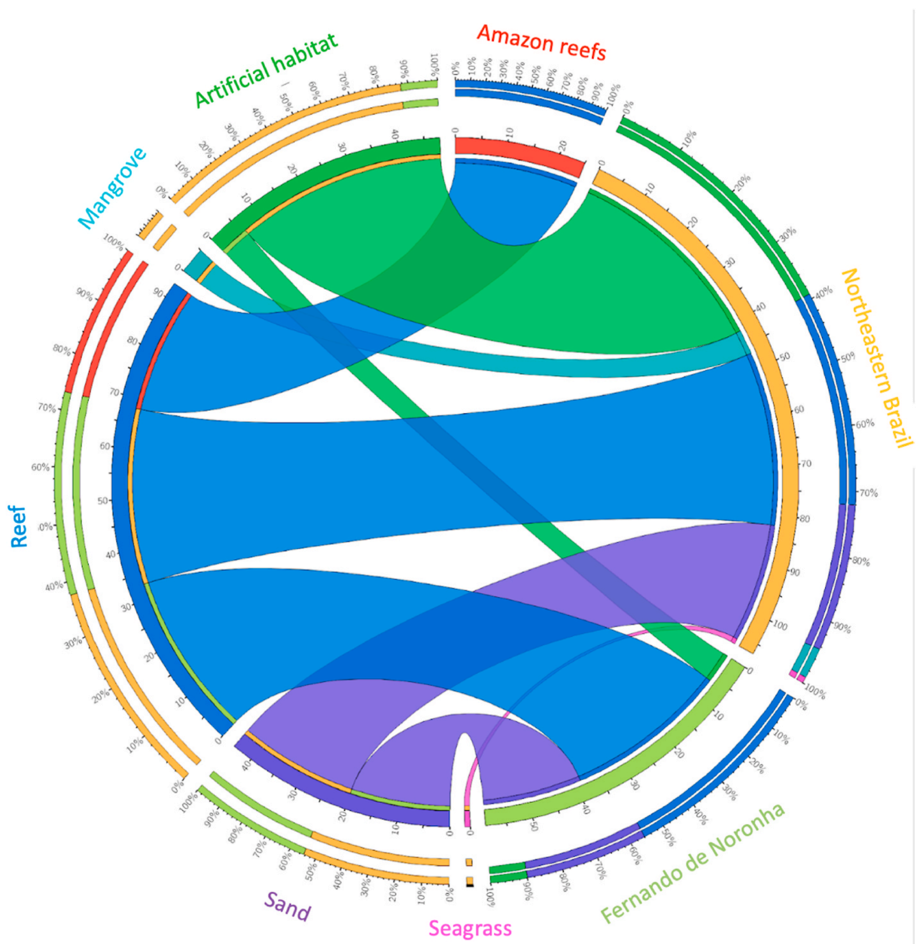

Fig. 4. Chord diagram showing the flows and relationships of the abundance of lionfish recorded between the three ecoregions (*i.e.*, Amazon reefs, Fernando de Noronha, and northeastern Brazil *sensu* Spalding et al., 2007), and environments (*i.e.*, mangrove, artificial habitat, seagrasses, sand, and reef) in the equatorial southwestern Atlantic Ocean. The different nodes (*i.e.*, ecoregions and environments) are arranged along a circle and the size of the arc is proportional to the importance of the flow detached by high-contrast colors. On the outer and inner parts of the circular layout are displayed the relative and absolute abundance of lionfish, respectively, with colors in the right side of the inner circle referring to the studied ecoregion (red: Amazon reefs; orange: Northeastern Brazil; and green: Fernando de Noronha). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

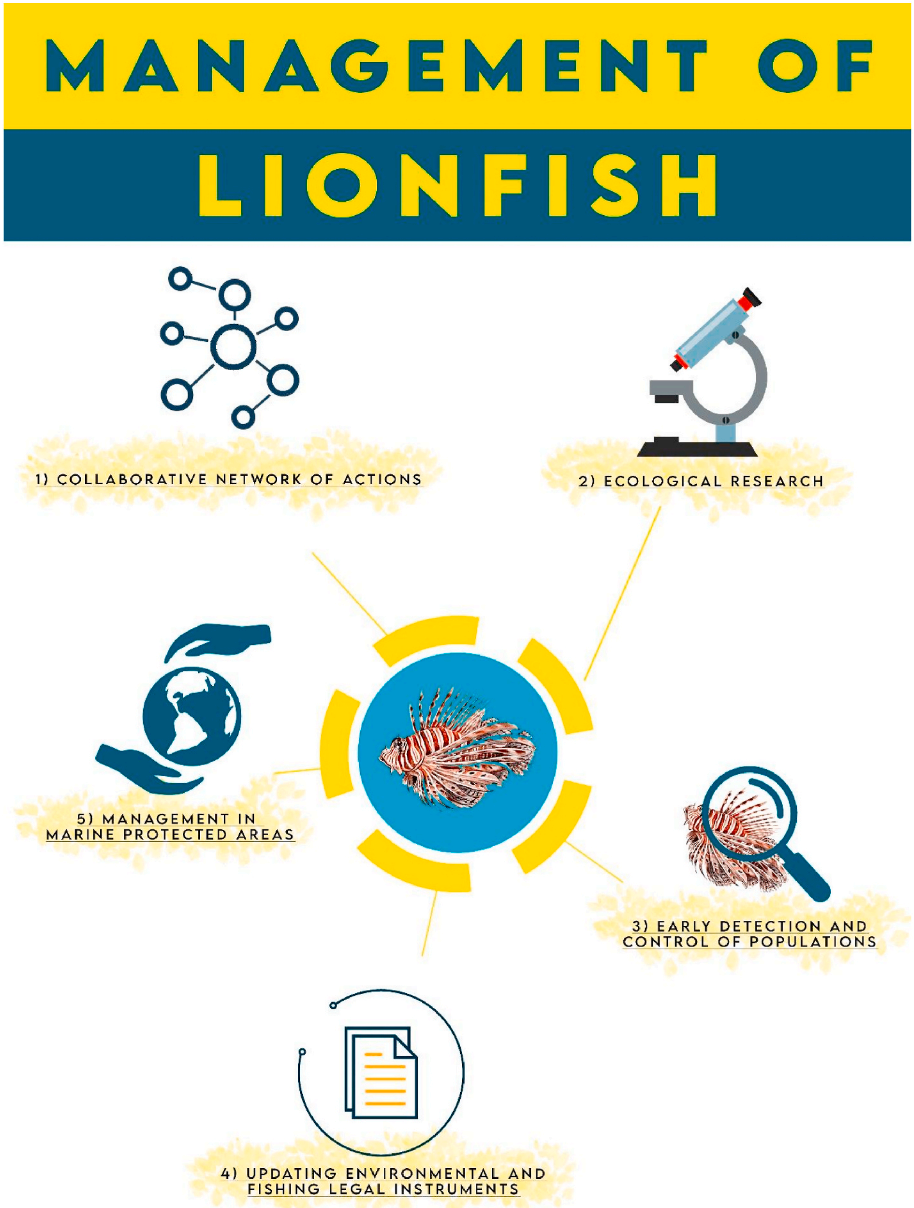

Fig. 5. Five principal measures proposed to manage lionfish (*Pterois* spp.) invasion in the Brazilian coast (southwestern Atlantic Ocean).

they also have a reproductive disposition (Morris et al., 2009; Zelaya, 2012). Another important aspect is the risk of accidents with humans, already reported in the Brazilian semi-arid coast (Haddad et al., 2022).

The impacts are likely especially in the case of the Fernando de Noronha Archipelago, where at least eight native fish species (e.g., *Bathygobius brasiliensis* and *Scartella itajobi*) and rare and cryptic species may be vulnerable to predation by lionfish. Moreover, new records of the poorly surveyed mesophotic ichthyofauna have just begun to be reported (Pimentel et al., 2020). A recent trait-based vulnerability analysis identified 29 endemic and range-restricted fish species that are likely to be highly vulnerable to predation by this invasive species in Brazilian waters (Linardich et al., 2021). The nearshore areas with the largest numbers of these vulnerable species were found in the states of São Paulo and Santa Catarina (nine species/each, although not yet affected by lionfish invasion), followed by six species in the Fernando de Noronha Archipelago and Rocas Atoll, four in the Trindade-Martin Vaz island complex, and two at St. Peter and St. Paul's Rocks (Linardich et al., 2021).

The pursuit of such information can result in further hypothesis-driven or descriptive research and ultimately in novel knowledge of the subject matter itself. For example, stomach content analysis can provide new data on lionfish diet and feeding habits (i.e., problem-based research). Tracking the changes in diet composition can help us understand the level of risk to different Brazilian species and the impacts of lionfish at specific scales (including their impact on endemic, cryptic, and threatened species).

Monitoring lionfish genetic diversity and using environmental DNA (eDNA) for early detection are important aspects of applied research in the affected Brazilian region (subsection 3.3). In addition, metabarcoding along with trophic ecology methodologies (isotopes and stomach content analysis) can be used to assess the most frequent species in the diet of the invader, as performed in the Mexican Caribbean (Valdez-Moreno et al., 2012) and Puerto Rico (Harms-Tuohy et al., 2016).

Direct field observations of the impact on rare or cryptic fish are generally scarce in the Brazilian coast (Araújo et al., 2020). This may result in the lesser-known species being overlooked during conservation decision-making and in the underestimation of the number of fish species that are vulnerable to lionfish invasion, particularly in northern and northeastern Brazil, due to the lack of knowledge (discussed in Section 2). Another relevant theme is the association between individual lionfish and Brazilian benthic substrates. For example, the preference patterns detected by new fish invasions can provide ecosystemic information about which food webs tend to be most impacted by lionfish predation.

In the Caribbean Sea, it has been reported that lionfish management is harpoon-dependent, which is limited by human depth range, as lionfish go to much deeper depths and that traps are not very effective in catching them (Albins and Hixon, 2013; Côté and Smith, 2018 Ulman et al., 2022). In this context, it is fundamental to develop efficient fishing traps for capture in Brazilian deep waters as has been tested by the United States Geological Survey (USGS) in the Caribbean Sea. Furthermore, because the harpoon is effective for capturing adults in diving areas, other methods of handling eggs/larvae/puppies in shallow estuarine areas or turbid areas with low visibility (common on the Brazilian coast) are necessary. In general, the aim is to look for new technologies to diversify and increase the effectiveness of management. Thus, establishing research priorities in more affected areas increases the chance that new approaches will emerge to control lionfish.

3.3. Early detection and control of populations

As discussed throughout this perspective, lionfish invasion into Brazilian waters is a serious problem that tends to get more intense as they spread along such an extensive coast over the next few years, threatening unique ecosystems and marine protected areas in its path. Thus long-term monitoring of lionfish densities is required to construct population growth curves for lionfish across Brazilian regions. However, considering the ongoing invasions and spread to other Brazilian states (nine Brazilian states have not yet been invaded, corresponding to ~4000 km of coastline), visual and/or capture-based monitoring may not be enough. Thus, alternative science-based measures, such as the use of environmental DNA (eDNA) and metabarcoding for early detection, larval collection, and capture (Whitaker et al., 2021) are important and can be implemented through coordinated efforts.

Early detection is essential for the control of the invading lionfish populations and predicting the future paths of the invasion, especially considering that many times there is a normal lag between invasion and first detection. Indeed, the control of marine invaders is a challenging task, however, there are rare cases in which their eradication has been achieved. Those successful cases were characterized by early detection and rapid response besides having occurred in restricted areas (e.g., the eradication of the black-striped mussel *Mytilopsis sallei* in Darwin Harbor, Australia, and of the algae *Caulerpa taxifolia* in Agua Hedionda Lagoon and Huntington Harbor, USA). Early detection also represents saving resources due to faster implementation of preventive measures, as Haubrock et al. (2022) estimated that the expansion of lionfish into non-native ecosystems provokes losses of the order of US$24 million per year, and Ahmed et al. (2022) concluded that a delayed response to an invasive species may cause seven times greater costs than the rapid implementation of preventive measures.

Current records provided by the present study (Figs. 1 and 2) show lionfish sightings in eight Brazilian coastal states (Amapá, Pará, Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, and Pernambuco) between 2020 and 2023. Recent modeling (Loya-Cancino et al., 2023) predicted suitable environments in southern Brazil up to the coast between Brazil and Uruguay. Thus, the remaining Brazilian states (9 states in the Northeast, Southeast and South regions) may be invaded by lionfish in the next years, indicating the importance of early detection and invasion control. Considering the difficulty of reaching deeper lionfish populations (~300 m deep) (Green and Grosholz, 2021), even if a substantial number of lionfish are eliminated from shallow-water habitats (<30 m) with the support of trained divers and fishers, these areas can be recolonized by the populations found in deeper habitats, such as mesophotic reefs (Andradi-Brown et al., 2017). In order to plan controlling measures for this re-colonization dynamics, it is essential to keep an updated record of deep-water lionfish population, which can be achieved by early detection using deep-water eDNA and larval surveys. Early detection is essential to elicit responsiveness and controlling measures timely, which means a lower population to be controlled in a new territory and can increase the success of the controlling measures. For this, a collaboration between different areas of research (fisheries sciences, plankton research, genetics and nautical engineering) is essential to employ different approaches to detect eggs and larvae, as well as eDNA, to monitor the expansion of the lionfish distribution range.

When considering the control of populations, although it is possible to capture lionfish using reef fish traps, which can be employed at up to 170 m depth (Wolff and Chlslett, 1974; Mahon and Hunte, 2001; Harris et al., 2020), in other conditions the use of these tools is rather difficult. In the Caribbean, for instance, lionfish have been extremely difficult to eradicate because of their metapopulation dynamics and deep refuge populations (Andradi-Brown et al., 2017).

This same scenario is likely to be established in the Brazilian coast, as indicated by the progressively deeper records of lionfish off northern Brazil (Figs. 1 and 2). The reefs on the Brazilian equatorial continental shelf have turbid waters that restrict the presence of recreational divers at these depths, which calls for the use of alternative measures for control and detection.

3.4. Updating the legal instruments for aquarium trade and fishing

Since 2008, the import of lionfish by Brazilian aquarium traders had been regulated by the Federal Act (202/2008) established by the Brazilian Institute for the Environment and Renewable Natural Resources Agency (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis – IBAMA). This act permitted the sale of species of the genera *Dendrochirus* (*Dendrochirus barberi, Dendrochirus biocellatus, Dendrochirus brachypterus*, and *Dendrochirus zebra*) and *Pterois* (*Pterois miles, Pterois radiata*, and *Pterois sphex*). Hence, they could have been legally brought into the country in the past. Otherwise, they could be illegally smuggled, in the case of mislabeling (Monteiro-Neto et al., 2003; Rosa et al., 2011; Lyons et al., 2019), i.e., if unlisted lionfish species (e.g., *P. volitans*) were imported under the name of a listed similar congeneric (e.g., *P. miles*).

Nevertheless, shortly after the first lionfish was found in Brazilian waters (Ferreira et al., 2015), possible aquarium releases raised concerns about the risks of bioinvasion associated with this activity (Holmberg et al., 2015), which led IBAMA to revert its previous position and ban all *Pterois* imports. IBAMA act 102/2022 banned the import of five *Pterois* species (*P. antennata, P. miles, P. radiata, P. sphex* and *P. volitans*), still allowing four species of the genus *Dendrochirus* (*D. barberi, D. biocellatus, D. brachypterus* and *D. zebra*) and considering to approve requests to import other members of the subfamily Pteroinae. However, it is noteworthy that some other large bodied invasive congeners (e.g. *P. russelii* and *P. lunulata*), and even dwarf lionfishes (e.g. *D. brachypterus*), may also cause problems as invasive species, which means that risk assessment to improve management actions and guide regulatory measures is necessary (Lyons et al., 2020).

Additionally, IBAMA has worked on new regulations to control the exploitation of wild-caught lionfish in Brazilian waters, in an attempt to slow the spread of the species by means of secondary introductions. In addition, the latterly recreated Ministry of Fisheries and Aquaculture (Decree 11.352/2023) now shares responsibilities with IBAMA regarding regulation and management of fishery resources in Brazil. These two authorities now also have to consider how national rules will impact neighboring countries as lionfish dispersion through the Brazilian coast is expected to reach Uruguay (Schofield, 2010; Evangelista et al., 2016). Thus, there should be international engagements to harmonize regulations with these countries, in order to achieve common goals.

3.5. Management in marine protected areas

Records of lionfish in the Brazilian coast include twelve coastal and marine protected areas (MPAs) in three ecoregions (Table 1). This novel information reinforces the importance of implementing management measures in partnership with the federal agency that manages most of these MPAs, Chico Mendes Institute for Biodiversity Conservation Agency (ICMBio), in addition to state and municipality authorities. Management strategies should primarily focus on the suppression and control of the lionfish in priority hotspots. A rigorous capture system with allocated management resources for this purpose could achieve the status of “functional eradication”, reducing the threat to acceptable levels in terms of its effects on the ecosystem (Green and Grosholz, 2021).

In Brazilian waters not included under MPAs, fishers can remove lionfish, whether encountered as bycatch or intentionally targeted for the culling of populations. However, fishing is prohibited in no-take MPAs, where lionfish populations may find refuge to breed and then recolonize neighboring areas. At the federal level, the ICMBio, which is responsible for the management of the federal MPAs, already has specific regulations for the management of invasive alien species such as lionfish (ICMBio Federal Act 06/2019). Therefore, the control of this species has already been authorized and implemented in the federal PAs. However, the state and municipal MPAs (Table 1) tough to develop specific regulations to enable lionfish culling in these MPAs, which may require modifications to the management plans of no-take MPAs or the elaboration of specific projects and laws (at federal, state, and/or municipal levels) aimed at the control of invasive alien species. These actions must be coordinated by competent authorities involving divers, fishers, and researchers. It’s important that food sector and socioeconomic activities are regulated to avoid unintentionally incentivizing individuals to maintain the lionfish population and perpetuate the invasion for monetary gain.

Actions have been taken in this direction (ICMBIO, 2019; 2020, 2021), mainly stimulated by the invasion scenario in the Fernando de Noronha Archipelago. Adopted as an “emergency strategy,” this work proved to be effective for the adoption of management measures, environment education, and data collection methods. This example shows that adequate management should be encouraged to minimize the adverse effects of this bioinvasion on the integrity of marine ecosystems and, in particular, to protect the most sensitive species. Other MPAs could follow this example and adopt actions in their work, research, and monitoring routines. In August 2022, the ICMBio also conducted a workshop with managers of all federal MPAs to discuss institutional guidelines for combating lionfish. Questions about prevention and control, community involvement, communication, challenges, and future perspectives on lionfish management were discussed and are being implemented in federal MPAs.

3.6. Other actions to assist in the control of lionfish invasion

In some localities where both the pressure of the lionfish and the pressure on fishing resources already exist, such as in the Caribbean Sea, initiatives to reduce negative impacts through population management and the introduction of the species in the local production chain have had positive effects (Ulman et al., 2022). Socioeconomic activities, especially diving tourism and the gastronomic sector, can be an important factor in the success of lionfish management activities. Even handmade products arising from lionfish traits have been explored as an option for the local economy. However, these activities should be regulated to directly concentrate efforts in areas and during periods of greater activity of the species. In addition, they must be properly subjected to environmental control and inspection, conducted together with legislation and specific rules for fishing, accident prevention, and cooking. Moreover, each person interested in using the species in cooking must, for example, be properly regulated as being co-responsible for controlling lionfish and reducing the poaching of native animals.

Studies that evaluate the contamination levels of lionfish should also be taken into account, since, for example, in the state of Ceará, some specimens are found next to *marambaias*. These are artificial reefs used as fishing grounds, sometimes are made of iron drums previously used with hazardous materials (Soares et al., 2022). Thus, if these organisms are contaminated with toxic metals, their consumption must be prohibited. Moreover, its use in gastronomy can also increase the risk of human accidents and create a market value for lionfish in a country characterized by high social inequality, which could undermine voluntary capture actions by fishers. Currently, the lack of science-based information on these concerns highlights the need for caution in adopting this management strategy.

Table 1
Records (2020–2023) of lionfish from eleven Brazilian (federal[1], state [2], and municipal [3]) coastal and marine protected areas, showing the biogeographic province and ecoregions (as defined by Spalding et al., 2007), the timing of the first animal record, and the depth at which the lionfish was observed.

Brazilian state	Marine Protected Area	Province/Ecoregion (as defined by Spalding et al., 2007)	Time of detection (first collected lionfish)	Number of records	Depth
Pernambuco	Fernando de Noronha Environmental Protected Area[1]	Tropical Southwestern Atlantic/Fernando de Noronha	December 2020	78	13–56 m
Pernambuco	Fernando de Noronha Marine National Park[1]	Tropical Southwestern Atlantic/Fernando de Noronha	July 2021	64	10–50 m
Ceará	Jericoacoara National Park[1]	Tropical Southwestern Atlantic/ Northeastern Brazil	March 2022	6	3 m
Ceará and Piauí	Parnaíba River Delta Environmental Protected Area[1]	Tropical Southwestern Atlantic/ Northeastern Brazil	March 2022	17	1–3 m
Ceará	Pedra da Risca do Meio Marine State Park [2]	Tropical Southwestern Atlantic/ Northeastern Brazil	September 2022	6	18–28m
Ceará	Barra Grande Environmental Protected Area [3]	Tropical Southwestern Atlantic/ Northeastern Brazil	July 2022	1	3m
Ceará	Ponta Grossa Environmental Protected Area [3]	Tropical Southwestern Atlantic/ Northeastern Brazil	June 2022	1	8–10m
Ceará	Berçários da Vida Marinha Environmental Protected Area[2]	Tropical Southwestern Atlantic/ Northeastern Brazil	August 2022	4	7–10m
Rio Grande do Norte	Dunas do Rosado Environmental Protected Area [2]	Tropical Southwestern Atlantic/ Northeastern Brazil	August 2022	6	9–28m
Rio Grande do Norte	Ponta do Tubarão Sustainable Development Reserve [2]	Tropical Southwestern Atlantic/ Northeastern Brazil	November 2022	2	2–12m
Paraíba	Naufragio Queimado Environmental Protected Area [2]	Tropical Southwestern Atlantic/ Northeastern Brazil	April 2023	1	18–20m

4. Discussion and summary for policymakers

Overall, the functional eradication of this fish from local ecosystems would appear to be the most effective approach to combat the effects of this invasion (Green and Grosholz, 2021), which could prevent both ongoing and future impacts. Suppressing lionfish populations to acceptable levels may limit ecological impacts (Davis et al., 2021), particularly in high-priority locations such as the Amazon reefs, the coast of northeastern Brazil, and the Fernando de Noronha Archipelago. Attempts to develop lionfish fishery, as an extension of the concept of an ecologically sustainable yield, would require considering the local ecological health when establishing fishery management targets (Bogdanoff et al., 2021) with human communities (Malpica-Cruz et al., 2016) in northern and northeastern Brazil, where invasion is more advanced. Although the socioeconomic impacts of lionfish in the SW Atlantic remain unquantified, they have the potential to be severe in vulnerable sectors, including small-scale fishing and tourism economies, which are critically important to the northeast coast of Brazil.

Considering that lionfish can live off the coasts of western Africa and the Americas, under mild warming scenarios, suitable conditions for lionfish could allow their expansion to higher latitudes due to their high thermal range and salinity tolerance. Thus, the entire Brazilian coast would be occupied by lionfish in the next few years. In this regard, current models predicted that lionfish could reach the coasts of neighboring countries of Brazil such as Uruguay, among other regions (French Guiana), under warmer scenarios (Loya-Cancino et al., 2023).

Since the first records of lionfish in Brazil, our research group has established a multidisciplinary team to deal with this bioinvasion, including environmental, biological, scientific communication, and public health perspectives (Haddad Jr. et al., 2022), to provide a database to support the development of a science-based management program to deal with lionfish invasion (Soares et al., 2022). Based on our overview of the current scenario, we have outlined six priorities for research, monitoring, and management programs that aim to combat the lionfish invasion in Brazil: (1) introducing environmental education programs and management initiatives together with municipal authorities, the managers of MPAs, NGOs, fishers, divers, and state and federal governments to help controlling the spread of lionfish and to educate local residents on proper removal techniques; (2) the implementation of mapping and early detection approaches, such as eDNA, larval detection, and citizen science; (3) the analysis of population structure and the reproductive dynamics of lionfish; (4) genetic surveys of the invader and the identification of the patterns of connectivity among the Brazilian populations, in particular between continental and oceanic island populations, and also with the Caribbean populations; (5) studies in trophic ecology based on the analysis of stomach contents and stable isotopes, to assess the impacts of the lionfish on the native marine biodiversity; and (6) engagement with the international community so that regulations can be incorporated among neighboring countries (e.g., French Guiana and Uruguay) and harmonized.

To date, the Brazilian government has not taken effective steps in response to the ongoing lionfish invasion, as emphasized by the lack of a national action plan or science-based policies to prevent or delay the lionfish expansion. The response has followed the typical pattern of putting out, rather than preventing fires (Escobar, 2018), as observed previously during the most extensive oil spill yet recorded in the tropical oceans (Soares et al., 2020) and the slow, flawed, and denialist measures taken against the coronavirus pandemic (Castro et al., 2021). Between 2019 and 2021, in the last presidential administration there was a reduction in the funding for federal environmental initiatives by 36.7% (Kowaltowski et al., 2021). In addition, the impact of lionfish invasion cannot be considered an isolated impact compared to other human pressures (Magris et al., 2021; Soares et al., 2021). The establishment of this invasive species, together with the other current pressures already detected (e.g., overfishing, climate change, and other invasive species such as *Tubastraea* spp.) (Leão et al., 2016; Francini-Filho et al., 2018), can have a synergistic and cumulative effect, further compromising ocean health. So, we call for efforts to act against those threats and, as discussed, performing local management strategies constitute a good way to inter-institutional action plans and practices.

As lionfish is expected to rapidly invade the remaining 5000 km of the Brazilian coast in the coming months, the costs of the Brazilian government's inaction will multiply quickly, not only for the country's citizens but also for the marine life of one of the world's biodiversity hotspots (South Atlantic Ocean). In this context, it is hoped that this article provides important insights for the development of solid, science-based policies that will turn the tide on the current lack of response on all fronts.

Ethical approval

No animal testing was performed during this study.

Sampling and field studies

The study does not contain sampling material or data from field studies.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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