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Lionfish on the loose: *Pterois* invade shallow habitats in the tropical southwestern Atlantic

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Lionfish (*Pterois* spp.) evolved in the Indo-Pacific with predators and prey and invaded regions (e.g., the Caribbean Sea and Mediterranean) where no such balance yet exists. In 2020, four lionfish were recorded on mesophotic reefs of the Amazon offshore Coast and Fernando de Noronha Archipelago. However, until now, there were no records of invasive lionfish in Brazilian nearshore waters or even such a high number of individuals. In this article, we report the continuing invasion process along the Brazilian Province by multiple sightings (72) of lionfish from March to May 2022 in estuaries, seagrass beds, and artificial and natural reefs across 240 km of the Brazilian coast. These are the first records of lionfish in coastal northeast Brazil and the shallowest records (1–16 m) from South Atlantic tropical waters. The largest simultaneous records of lionfish in breakwaters, fishing weirs, and *marambaias* (artificial reefs used as fishing grounds) on the Brazilian Northeastern coast indicate that these man-made structures are suitable habitats for this species. Most of the lionfish (58%) were recorded in artificial reefs and fishing weirs. Moreover, the detection of invasions in marginal reefs, estuaries, and two marine protected areas characterized by moderately turbid water and high sedimentation rates highlights the adaptability of the lionfish, making it extremely difficult for divers and fishers to capture them. We call for an urgent management plan considering that the invaded tropical region hosts a high level of endemism, and rare and/or cryptic taxa, which increases the risk of impacts since these are primary lionfish prey.

KEYWORDS

coral reefs, Brazil, endemism, biological invasions, reef fish, Alien species, Non-indigenous species, Brazilian northeastern coast

Introduction

Invasive species are one of the main drivers of species extinction worldwide and can lead to severe ecological and socioeconomic impacts (Simberloff et al., 2013; Haubrock et al., 2022). The invasion of *Pterois volitans* (Linnaeus, 1758) and *Pterois miles* (Bennett, 1828) (hereafter collectively referred to as "lionfish") is potentially harmful and the most damaging marine fish invasion globally to date (Rocha et al., 2015; Hixon et al., 2016). The invasion success and establishment of lionfish are attributable to its dispersal mode, high reproductive rates, rapid growth, lack of natural predators in invaded areas, defensive venomous spines, cryptic habits, color and behavior, habitat generality, high competitive ability, low parasite load, and efficient predation (Albins and Hixon, 2013). These biological and ecological attributes allowed the rapid geographic spread of this species in new environments, causing ecological impacts with multiple detrimental effects on native populations, threatening local biodiversity and some economically important species (Côté and Smith, 2018).

Lionfish evolved in the Indo-Pacific with predators and prey and invaded the northwestern Atlantic and the Mediterranean (Phillips and Kotrschal, 2021), where no such balance yet exists. Its distribution range rapidly increased to the eastern coast of the USA, Bermuda, the entire Caribbean region, the Gulf of Mexico (Schofield, 2010; Johnston and Purkis, 2011), and, more recently, the Southwest Atlantic Ocean (Luiz et al., 2021; U.S. Geological Survey, 2022) and has become a major concern in the western Atlantic and the Caribbean (Hixon et al., 2016).

In Brazil, two individuals had been recorded on the subtropical coast (Rio de Janeiro state) in 2014 and again in 2016 (Luiz et al., 2021). However, since then, no other individuals have been recorded in the region, and the species has not formed an established population in this area (Ferreira et al., 2015). These records are also too distant (approximately 5,500 km) and isolated to be considered a dispersal event from the Caribbean (Figure 1) and were suggested to be related to secondary aquarium releases. In 2020, three new records of lionfish were detected on tropical mesophotic reefs (30–100 m) on the offshore coast of the Amazon and in the Fernando de Noronha Archipelago (Luiz et al., 2021) (Figure 1). Since then, more than 30 individuals of different sizes, including some already mature specimens, have been found in the Fernando de Noronha Archipelago (Pereira, PHC, pers. com.), which suggests an already established population in the tropical Southwestern Atlantic.

The tropical Southwestern Atlantic is home to a diverse morphology of shallow (Leão et al., 2016) and mesophotic reefs (Soares et al., 2019). Brazilian reefs are unique because of a combination of high endemism, low richness of coral species, high sedimentation rates, and moderate turbidity (Castro and Pires, 2001; Leão et al., 2016; Cruz et al., 2018; Soares et al., 2021). It is a unique reef habitat for marine biodiversity in the world's oceans (Leão et al., 2019; Araújo et al., 2020).

Lionfish were first officially recorded in the Western Atlantic in 1985. After reaching Venezuela in 2010, it took 10 years for the lionfish to overcome the Amazon–Orinoco barrier (Schofield, 2010), which consists of a tremendous freshwater and sediment discharge, influencing an area of 2,300 km along the north platform of South America (Rocha, 2003; Floeter et al., 2008). With the North Brazil Current flowing toward the Caribbean, the lionfish as foreseen (Luiz et al., 2013) successfully transposed that barrier through the mesophotic reef corridor (Moura et al., 2016; Francini-Filho et al., 2018). However, until recently, there were no records of lionfish in Brazilian shallow nearshore waters.

In this study, we report the first multiple records of lionfish off the Brazilian coast (Ceará and Piauí states) in shallow-water estuaries and artificial and natural reefs. This is the largest simultaneous (72 records) and first detection of the species on the Brazilian northeastern coast, an important track of the expected invasion down to the Brazilian province. This research provides new information for immediate science-based action for the control and prevention of invasive species in multiple habitats, as well as management actions for the monitoring and protection of native biodiversity.

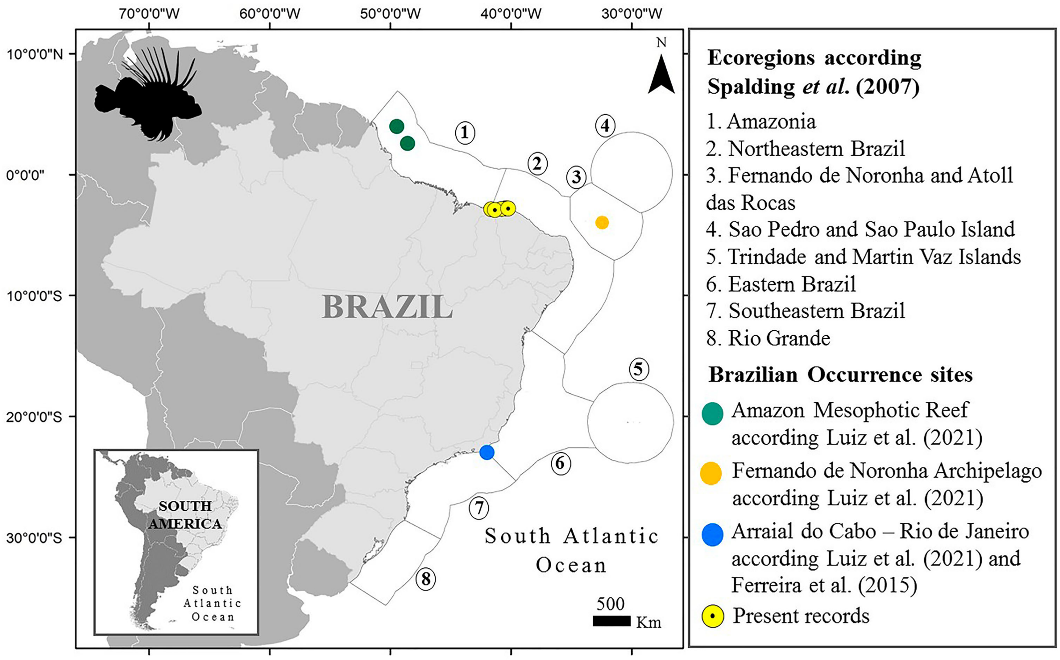

FIGURE 1
Study area along the Brazilian tropical coast, highlighting the ecoregions according to Spalding et al. (2007). The map also shows the previous lionfish records (Amazonia, Fernando de Noronha Archipelago, and Rio de Janeiro) and the current ones (Northeastern Brazil) described in this article.

Material and methods

The Brazilian northeast ecoregion (*sensu* Spalding et al., 2007) (Figure 1) is characterized by a diversity of tropical coastal and marine ecosystems, including seagrass and rhodolith beds, mangroves, intertidal sandstone reefs, and shallow-water coral reefs (Irion et al., 2012; Soares et al., 2017; Costa et al., 2020; Carneiro et al., 2021; Carneiro et al., 2022). The Brazilian semiarid coast is a scarcely known region of great ecological and socioeconomic importance. This equatorial zone extends for approximately 1,000 km, from the Piauí state through the Ceará state up to Cape Calcanhar on the coast of Rio Grande do Norte (Morais et al., 2019; Soares et al., 2021). This region has unique environmental characteristics, such as a rainy season from January to May (Dias et al., 2016) and a strong influence from trade winds, mainly in the second semester (5–7 $m \cdot s^{-1}$) (Soares et al., 2019). Sea surface temperatures are commonly high and stable (26°C–30°C) because of their equatorial position (Teixeira and Machado, 2013).

The strong incidence of trade winds, in combination with intense coastal currents and consistently high swell and semidiurnal mesotides, leads to an intense hydrodynamic regime with frequent sediment resuspension and moderate turbidity in the coastal region (Teixeira and Machado, 2013; Dias et al., 2016). Despite these suboptimal carbonate reef growth characteristics, the region has rhodolith beds (Carneiro et al., 2021) and marginal reefs in the intertidal, shallow, and mesophotic zones (Soares et al., 2019; Carneiro et al., 2022). The mesophotic reefs on the Brazilian semiarid coast have a semi-continuous alignment (Soares et al., 2019) with the Amazon Reef (Rocha, 2003; Moura et al., 2016; Francini-Filho et al., 2018), where lionfish have been previously recorded (Luiz et al., 2021). In the study area, we also find artificial reefs, regionally called *marambaia*, which are man-made fishing structures composed of wood branches, car and truck tires, discarded cans, old cars, and refrigerators, which are sunken on the nearshore seafloor to attract fish and lobsters (*Panulirus* spp.). After colonization, these artificial structures become important fishing grounds in shallow waters (<15 m).

Spatial data were collected in March, April, and May 2022 in the municipalities of Luis Correia, Barra Grande, and Cajueiro da Praia (Piauí state) and Bitupitá, Camocim, Jijoca de Jericoacoara, Cruz, Acaraú, and Itarema (Ceará state) (Figure 1). The lionfish surveys on the Brazilian semiarid coast were conducted between March and May 2022 due to the water transparency during this period, which allows diving activities and detection. During the rest of the year, turbidity is moderate to high because of increased wind speeds (Soares et al., 2017). The specimens were identified in the field or the laboratory by researchers trained in lionfish morphology or by confirming their identity by showing a lionfish photo during an interview with the fishers who spotted it. Lionfish were identified as *Pterois* spp. using the usual approach in the literature (Luiz et al., 2021). The coastal occurrence areas were mapped through field and boat surveys together with fishers on intertidal sandstone reefs and shallow water habitats (1–16m depth). The occurrences were georeferenced and analyzed using geographic information systems (GISs). The QGIS Desktop 3.4.4 software was used to verify if the occurrence of lionfish overlapped with coastal and marine protected areas (MPAs) (Magris et al., 2020).

The captured individuals were kept on ice in the field and frozen in the laboratories of the Institute of Marine Sciences (LABOMAR) of the Federal University of Ceará (UFC), the Federal University of Parnaíba River Delta (UFDPAR), and the Federal Institute of Education, Science, and Technology of Ceará (IFCE). In addition, 60 voucher specimens collected by fishers (50) or scientists (10) were deposited in the Dias da Rocha ichthyological collection of LABOMAR-UFC or local collections of IFCE and UFDPAR.

Results and discussion

We identified multiple records of lionfish (*Pterois* spp.) (Figure 2) distributed at 14 sites along 240 km of the Brazilian semiarid coast (Ceará and Piauí states). A total of 72 individuals were spotted, 60 of which were captured with total lengths between 12 and 18 cm (Figure 2; Table S1). All the sites were in shallow waters (1–16-m depth) and included estuaries, seagrass beds, fishing weirs, and artificial and natural reefs (Figure 3; Supplementary Material).

This is the first record of lionfish in the northeastern Brazil ecoregion (*sensu* Spalding et al., 2007) and the shallowest occurrence recorded in Brazilian tropical waters (Figure 3; Table S1). The specimens were found mainly in 1) shallow sandstone reefs (1–5-m depth at low tide), 2) the breakwater of a harbor area, 3) artificial reefs, and 4) fishing weirs (Figure 3). Some of these habitats were near or inside estuaries such as in the Igaraçu and Timonha rivers, and at least one sighting event occurred adjacent to a large seagrass bed (in the cove of Cajueiro da Praia municipality). Fishing weirs are relatively common on intertidal sandbanks or hard bottoms in this low-latitude region (Carneiro et al., 2022) and comprise fixed enclosure-type traps, usually made of rods and wires, and are traditionally distributed along the beach and estuaries (Lucena et al., 2013) (Figure 3D).

Most of the lionfish (58%) were recorded in artificial reefs and fishing weirs in sandbanks (Figure 3G). This contrasts with previous records of lionfish in Brazil, which have only been recorded in natural environments (Ferreira et al., 2015; Luiz et al., 2021). However, this species has high habitat plasticity (Cure et al., 2014) and also inhabits artificial reefs in other areas

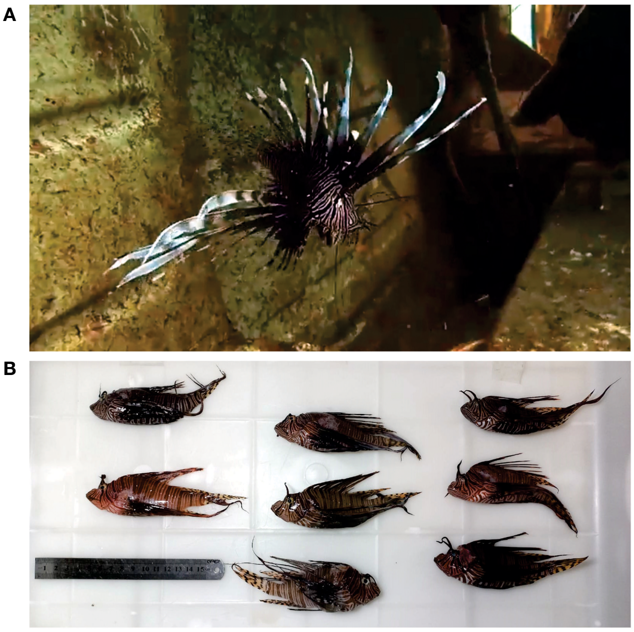

FIGURE 2
Lionfish (*Pterois* spp.) collected on the Brazilian semiarid coast, NE Brazil. **(A)** Lionfish photographed during scientific diving on an artificial reef (an old sunken car acting as a *marambaia*) in Jericoacoara (coast of Ceará, Brazil). **(B)** Eight juvenile lionfish specimens collected off the coast of Ceará (NE Brazil) with total lengths of 12–14 cm.

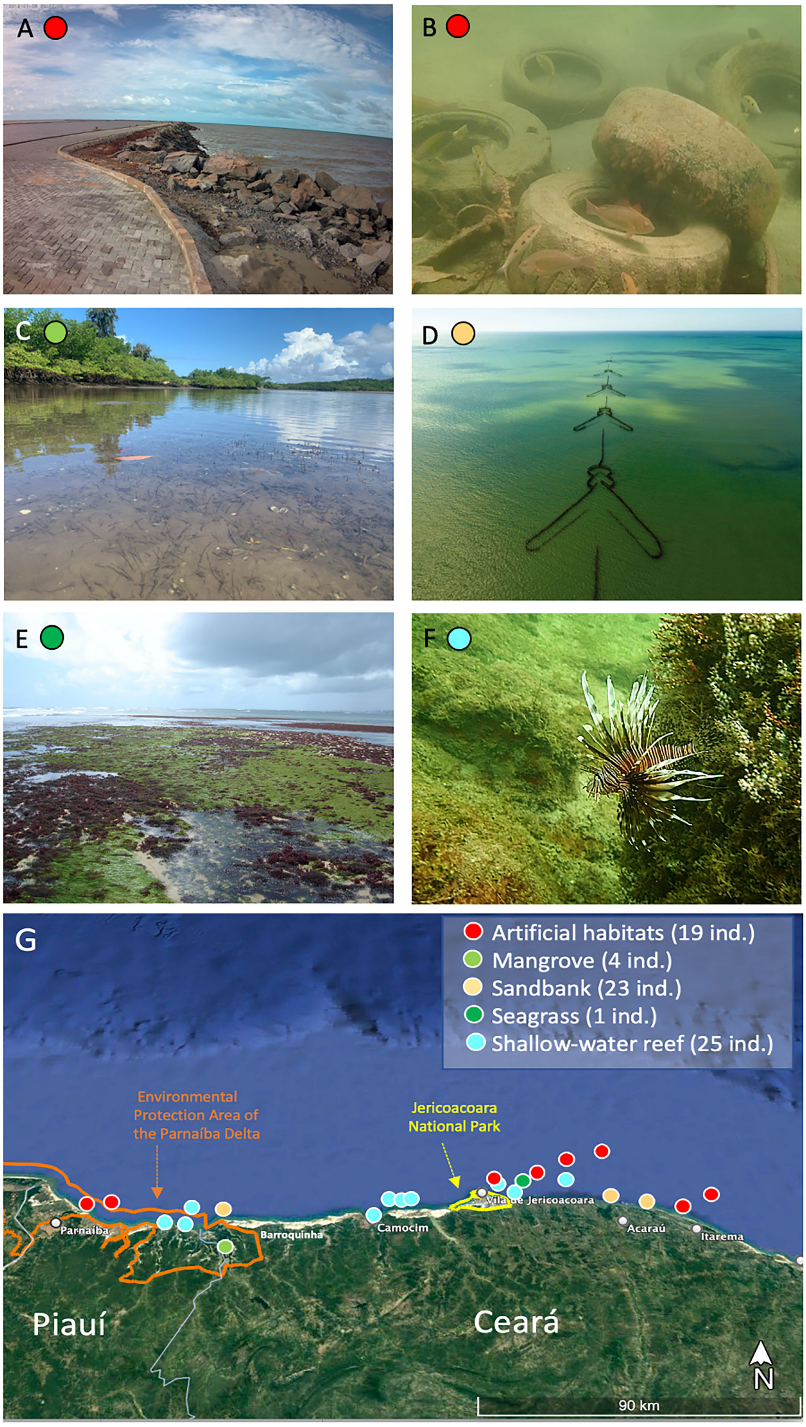

FIGURE 3
Multiple natural and artificial habitats where lionfish (*Pterois* spp.) have been found in the coastal waters of northeastern Brazil. **(A)** the breakwater of a harbor area in Luis Correia (Piauí state). **(B)** *Marambaia*; man-made fishing ground made by car tires, in Jericoacoara (Ceará coast). **(C)** Estuarine mangrove environment (Bitupitá, Brazil). **(D)** Fishing weirs in Bitupitá (Bitupitá, Ceará coast). **(E)** Seagrass bed. **(F)** Lionfish in a shallow sandstone reef on the Ceará coast. **(G)** Locations where lionfish (*Pterois* spp.) were collected in the shallow waters of northeastern Brazil (tropical Southwestern Atlantic) overlaying coastal and marine protected areas (MPAs) (Environmental Protection Area of the Parnaíba Delta on the left and Jericoacoara National Park on the right). Details are provided in Table S1 (Supplementary Material).

(Dahl and Patterson, 2014; Savva et al., 2020). Containers and tens of thousands of tires have been used as artificial reefs to increase artisanal fishing productivity in the Ceará state (Conceição, 2003; Conceição et al., 2007). The widespread and unregulated usage of *marambaias* has also intensified along the coast over the last decade (Aragão, 2013; Aragão and Cintra, 2018). In artisanal fishing communities, each fisher usually has their own *marambaia*, and only they or their family members know where the structure has been sunk (Feitosa, CV, personal communication). Although the placement of artificial reefs is prohibited in Brazil when it does not follow the appropriate licensing process, it is a great challenge for enforcement authorities to either find *marambaias* or identify their owners. The present study suggests that these artificial habitats are likely to play an important role in the dispersion of lionfish populations along the Southwestern Atlantic coast.

Since some shallow regions of the Ceará and Piauí states do not have hard bottoms but a soft seabed composed of submarine dunes and carbonate substrate associated with the *Halimeda* algae plains, fishers build *marambaias* (Supplementary Material Videos 1 and 2) in those areas to attract small reef fish species, which they use as bait to catch economically important pelagic species in the region, such as king mackerel (*Scomberomorus cavalla*) and serra Spanish mackerel (*Scomberomorus brasiliensis*) (Feitosa, CV, personal communication). However, these structures also provide shelter for a broad range of fish and invertebrates preyed on by predatory fish (Eddy et al., 2016; Côté and Smith, 2018). Once "the table is set" and considering the extensive use of *marambaias* throughout the Ceará state coastal waters, the patchy distribution of these artificial reefs can play a key role in the expanding range of lionfish, including the colonization of shallow environments (Supplementary Material Videos 1 and 2). This also demonstrates the negative role of artificial structures in facilitating species invasion along the northeastern Brazil Ecoregion, a previously highlighted problem for invasive corals (Soares et al., 2020; Braga et al., 2021).

Lionfish were recorded in two important MPAs: the Jericoacoara National Park (Parna de Jericoacoara) and the Environmental Protection Area of the Parnaíba Delta (APA Delta do Parnaíba) (Figure 3). The occurrence of lionfish in MPAs should be closely monitored because 1) MPAs exist to protect biodiversity, and lionfish can be a threat; 2) the MPAs can help to control lionfish spread by increasing biotic resistance, given that they can conserve and foster potential natural predators of this invader, such as large groupers and sharks (Albins and Hixon, 2013; Ferreira et al., 2022). The occurrence of lionfish in the shallow waters of Jericoacoara is also a threat to the native reef fish fauna (Machado et al., 2015). The occurrence of lionfish in natural reefs and estuaries (Figure 3, Supplementary Material Video 3) of the APA Delta do Parnaíba is a matter of special concern because this protected area harbors a nursery habitat for many species and the largest deltaic formation, preserving extensive mangrove forests, seagrass beds, and unique fish diversity (Silva et al., 2018; Guimarães-Costa et al., 2019).

Lionfish can colonize and feed in clear-water mangrove habitats, such as those found in the Bahamas (Barbour et al., 2010), but they are likely unable to colonize turbid-water mangroves, similar to those found in the study area (Lacerda et al., 2021) under substantial hypoxia levels (Hasenei et al., 2020). However, some of these shallow habitats were near the mouths of mangrove-lined estuaries, and at least one sighting occurred adjacent to a large seagrass bed and inside the estuary. Considering the new records of lionfish in areas with suboptimal conditions and successful invasion in turbid water environments (Cure et al., 2014) including estuaries (Whitaker et al., 2021), this invasive species must be carefully monitored inside MPAs and in adjacent areas and habitats, including coral reefs, seagrass beds, and low-inflow estuaries on the Brazilian semiarid coast.

The multiple records in estuaries, seagrass beds, natural reefs, and artificial habitats (Figure 3) indicate the fast invasion and pervasive presence of lionfish in shallow waters in the tropical South Atlantic, suggesting the invasion progress is more rapid than was expected, with effects on coastal biodiversity, human safety, and artisanal fisheries yet to be studied. Along the semiarid coast of Brazil, shelf currents flow steadily to the northwest (Teixeira and Machado, 2013; Dias et al., 2016), restricting the dispersal of eggs and larvae southward from the Caribbean across the Brazilian equatorial coast (Luiz et al., 2013). Thus, the semiarid coast is an important recruitment area for species that spawn in the SW Atlantic islands, such as the Fernando de Noronha archipelago and the eastern Brazilian coast (Endo et al., 2019). Because of that, the lionfish individuals recently recorded in the SW Atlantic islands (Luiz et al., 2021) may be acting as a source of individuals for the semiarid coast population. The main direction of coastal currents, which flow mainly to North Brazil, does not prevent the movement of adult individuals from one reef to the next in a stepping-stone pattern using both the natural and artificial reefs recorded here (Figure 3). Therefore, the lionfish range extension to the Brazilian equatorial coast is a result of dispersal mechanisms mainly based on demersal adult movement through mesophotic reefs (Luiz et al., 2021), which naturally occur in the study area (Soares et al., 2019), and now *via* the shallow-water natural and artificial reefs described here.

We hypothesize that the lionfish invasion on the continental shelf of the Ceará and Piauí probably occurred before reaching the Fernando de Noronha Archipelago. This process must have occurred within the last 2 years (2020–2022). However, Fernando de Noronha has clear ocean waters and many recreational and touristic diving activities that help citizens rapidly detect lionfish. This is not the case for the nearshore waters of the Ceará and Piauí coasts. Also, the reduction of scientific activities in the course of COVID-19 pandemic and the turbid waters during most of the year did not allow this detection before. This is also the case with Parcel Manuel Luis reefs. These reefs are unique shallow habitats, part of the northern Amazon reefs. However, these reefs are the least dived and surveyed in Brazil due to the turbulent sea, macrotides, and long distance from the coast. It is logical to affirm that lionfish were probably already established there, as these reefs are part of the expected migration route down to the Brazil hump until Ceará.

Although during this survey lionfish specimens were only collected in coastal waters (1–16 m), it is expected that lionfish populations are already established in deeper waters (30–100 m) in the region, as found in Fernando de Noronha (CELF, per. obs.), as well as in the entire Caribbean (Andradi-Brown et al., 2017). This is likely due to the extensive mesophotic reef ecosystems in this low-latitude region and its alignment with the Amazon reef (Soares et al., 2019), providing a biogeographic corridor for the dispersal of species (Rocha, 2003; Moura et al., 2016; Francini-Filho et al., 2018), including the invasive lionfish (Luiz et al., 2013; Luiz et al., 2021). Moreover, the Brazilian equatorial margin (Ceará coast) has extensive seamounts with minimum depths of 12–30 m. This is the largest cluster of seamounts in the Equatorial SW Atlantic and the closest plateau to the continent (Jovane et al., 2016), which form part of the volcanic mountain chain of the Fernando de Noronha Archipelago, providing extensive mesophotic and shallow reef habitats for lionfish establishment. Since the establishment of lionfish in this oceanic archipelago (Luiz et al., 2021), they are also likely established in mesophotic reefs and seamounts from the equatorial Southwestern Atlantic (Ceará Plateau).

Marginal tropical reef assemblages from northeastern Brazil are characterized by low coral species richness and high endemism (Castro and Pires, 2001; Floeter et al., 2008; Pinheiro et al., 2018). The equatorial coast of Brazil has a higher number of cryptic and endemic fish species (Araújo et al., 2020) compared to the Caribbean region (Linardich et al., 2021), and further impacts need to be studied. A recent trait-based vulnerability approach detected 29 fish species endemic (e.g., *Entomacrodus vomerinus* and *Haemulon squamipinna*) to Brazil and are vulnerable to lionfish impacts (Linardich et al., 2021). If the lionfish populate these natural and artificial reefs at the same densities that they have reached in the Caribbean, local population reductions are a possibility among some endemics (e.g., *H. squamipinna*, *Scarus trispinosus*, and *Sparisoma frondosum*) (Araújo et al., 2020; Luiz et al., 2021). The Brazilian northeastern small-scale artisanal fisheries may also be highly impacted (Haubrock et al., 2022), with possible harm to human safety due to physical contact with lionfish in fishing weirs and artificial reefs.

The coastal region of Northeast Brazil has considerable artisanal fishing activity, which is fundamental for food security (Frédou et al., 2009; Freire et al., 2015) in an area with substantial social inequality (Sathler, 2021). Models suggest a high probability of considerable impacts from lionfish on native reef fish in Brazil, including some of the socioeconomic importance, such as snappers and groupers (Bumbeer et al., 2018). Therefore, impacts on marine biodiversity, public health, and artisanal fisheries in northeastern Brazil must be urgently prevented and mitigated.

Conclusions

Our detection of the lionfish invasion in a marginal reef environment and estuaries characterized by moderately turbid water and high sedimentation rates highlights the adaptability of this species and the difficulty of detecting and managing this species with the use of spearguns compared to what is performed in the Caribbean clear-water coral reefs. The discovery of multiple simultaneous records of lionfish on the Brazilian semiarid coast between March and May 2022 is related to the water transparency during this period, which allows diving activities and detection. During the rest of the year, turbidity is moderate to high because of increased wind speeds (Soares et al., 2017). This means that, in this region, detection and management can be challenging and should concentrate on this short time window. For the rest of the year, complementary strategies, such as surveillance and monitoring using environmental DNA and fishing monitoring, are viable options. The results represent the expected invasion progress of the lionfish bioinvasion along the Brazilian coast after previous records on offshore sites and call for an urgent integrated regional and science-based management plan, considering all ecological and economic impacts that were evidenced herein and those already discussed for the Great Caribbean and Mediterranean.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the animal study because the ethics committee is not required for environmental research involving invasive species records. Collections were allowed according to the environmental agencies of Brazil (IBAMA and ICMBIO) with the permits already registered.

Author contributions

MOS, TG, and CVF contributed to conception and design of the study. TG, CVF, TMG, KC, BV, SVP, OD, LMDG, GS, RCM, DMP, PBMC, EC, AA, CLLS, CELF, PHCP, LAR, TCL, and MOS organized the database. MOS, TG, SVP, TCLT, and PHCP performed the statistical and map analysis. MOS wrote the first draft of the manuscript. MOS, LAR, CVF, LG, CELF, TCLT and TG wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article (including videos and tables) can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.956848/full#supplementary-material

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