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INVASION NOTE

Multiple lionfish (*Pterois* spp.) new occurrences along the Brazilian coast confirm the invasion pathway into the Southwestern Atlantic

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Abstract The invasion of the northwestern Atlantic by the Indo-Pacific lionfish has developed extraordinarily fast. In less than 30 years, lionfish have dramatically expanded their distribution range to an area encompassing the eastern coast of the USA, Bermuda, the entire Caribbean region and the Gulf of Mexico. Until now, just a single sighting had been reported in the South Atlantic and it was questionable whether lionfish would invade this region like it has in the northwestern Atlantic. Here we report four new records of lionfish for the Brazilian coast, in the southwestern Atlantic. Two individuals were captured in mesophotic reefs underneath the Amazon river plume, one in an oceanic archipelago distant 350 km from Brazil's tropical continental coast, and the fourth in the subtropical coast. The records in the Amazon and in the oceanic regions support previous inferences of lionfish invasion routes into the south Atlantic. The subtropical record, despite being considered too far away for a single larval dispersal event from the

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Caribbean, is recurrent and could be a result of aquarium releases.

Keywords Amazon barrier · Exotic species · Fernando de noronha archipelago · Marine invasion · New record · Reef fish

Introduction

The invasion of the northwestern Atlantic by the Indo-Pacific lionfishes *Pterois volitans* and *P. miles* (hereafter referred to as lionfish), is the most studied and best-documented marine fish invasion to date (Côté and Smith 2018). The establishment and expansion of the lionfish across their non-native range have progressed extraordinarily fast: their distribution in the northwestern Atlantic expanded to an area of roughly 7.3 million km^2 in less than 30 years (Schofield 2010). The first Atlantic lionfish was reported off the coast of Florida, U.S., in 1985 (Schofield 2010), likely a result of aquarium releases (Whitfield et al. 2002). By 2000, lionfish were common along the U.S. east coast (Whitfield et al. 2002) and were first recorded in the remote island of Bermuda (Schofield 2010). In 2004, lionfish reached the Bahamas and by 2010, they had become established all across the Caribbean Sea, as well as in the eastern portion of the Gulf of Mexico (Schofield 2010). This is a remarkable case of wide geographical spread and establishment, with a speed never documented before in marine systems (Rojas-Velez et al. 2019). The lionfish success as an invasive species is likely due to its broad dietary breadth, predation efficiency, high fecundity, fast growth, resistance to parasites, and lack of predators (Côté and Smith 2018). The recent discovery that all Atlantic lionfish likely have a hybrid origin (Wilcox et al. 2018) suggests that heterosis (i.e. 'hybrid vigour') may also play a role in their success in the invaded range. However, despite its demonstrated capacity for fast dispersal and range expansion, the lionfish is yet to establish a resident population in the southwestern Atlantic.

The Amazon Barrier—a major marine biogeographic break formed by the combined freshwater discharge of the Amazon and Orinoco Rivers, separates the Caribbean and Brazilian provinces, in the northwestern and southwestern Atlantic respectively (Rocha 2003; Floeter et al. 2008). This barrier is formed by the world's largest freshwater and sediment discharges, and extends over 2300 km of the northeast coast of South America, producing dramatic changes in the physical and chemical properties of coastal waters in the area (Luiz et al. 2012). A thick (approx. 30 m deep) turbid, low-salinity layer at the surface effectively reduces connectivity of northern and southern populations of many coastal marine organisms (Rocha 2003). Characteristically, it is an inshore barrier which contains habitat for species that are tolerant to reduced salinities and high turbidity (Luiz et al. 2012). However, mesophotic reefs under the barrier sustain oceanographic conditions (clear, warm, normal salinity water; Francini-Filho et al. 2018) that provide some reef organisms connectivity between north and south Atlantic via a deep and long corridor underneath the freshwater plume (Rocha et al. 2002; Rocha 2003).

Lionfish have broad tolerance to low salinities and are known to be abundant in clear water Caribbean mangroves (Barbour et al. 2010), but are unlikely to survive in high sediment mangroves along the Amazon mouth. However, they thrive in mesophotic reefs (Andradi-Brown et al. 2017; Rocha et al. 2018), which potentially allows them to disperse south under the Amazon plume. Despite the lionfish ability to survive under the river plume conditions, they have been surprisingly absent south of the Amazon barrier. During the past 10 years since lionfish reached the southern Caribbean, only a single individual has been reported for the Brazilian coast (Ferreira et al. 2015), and because this individual was observed far from the Amazon barrier, it is uncertain if it is either the result of an extremely long distance dispersal event or a secondary aquarium release in Brazil (Ferreira et al. 2015). The apparent delay of lionfish range expansion towards the southwestern Atlantic is attributed to the direction of ocean currents in the Amazon Barrier region, which flow predominantly towards the Caribbean (Luiz et al. 2013), slowing down the movement of floating eggs and larvae southwards. Here we report four new observations of lionfishes in the Southwestern Atlantic, and discuss their biogeographical implications, potential impacts and perspectives for management. Collected individuals were deposited as voucher specimens in the fish collection of the Federal University of the Espírito Santo State, Brazil

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Occurrence sites

Amazon mesophotic reef

Two adult lionfish individuals were collected by local fishers in Northern Brazil, offshore under the Amazon plume on hard bottom with sponges and corals (Lat 3.975, Lon-49.475 and Lat 2.571, Lon-48.567; Fig. 1b). The first individual (20 cm TL; Fig. 2a) was collected on September 16, 2020, using a fishing trap traditionally known as '*manzuá*' at approximately 100 m depth, during commercial fishery aimed at snappers (*Lutjanus* spp.). The second individual was collected with a lobster net at an unknown depth (likely about 70 m, which is the depth where lobster are targeted in the region) and was not photographed. We confirmed its identity by showing a lionfish picture during an interview with the fisherman that collected it. Lionfish has an unique appearance, which is very distinct from any other marine fish in the region, and the fisherman readily identified the fish in the picture as the same species that he collected.

Fernando de Noronha Archipelago

One adult lionfish (21 cm TL; Fig. 2b) was observed, filmed and later collected with a spear in Fernando de Noronha, an oceanic Archipelago located 345 km off the northeastern Brazilian coast (Lat-3.833, Lon-32.423; Fig. 1c) on December 21, 2020. It was captured at 28 m depth in the north (leeward) side of the archipelago's main island, in a reef called '*Laje dos Cabos*' by the staff of a local scuba dive tourism operator (Sea Paradise) and researchers. Accession number: CIUFES 4187.

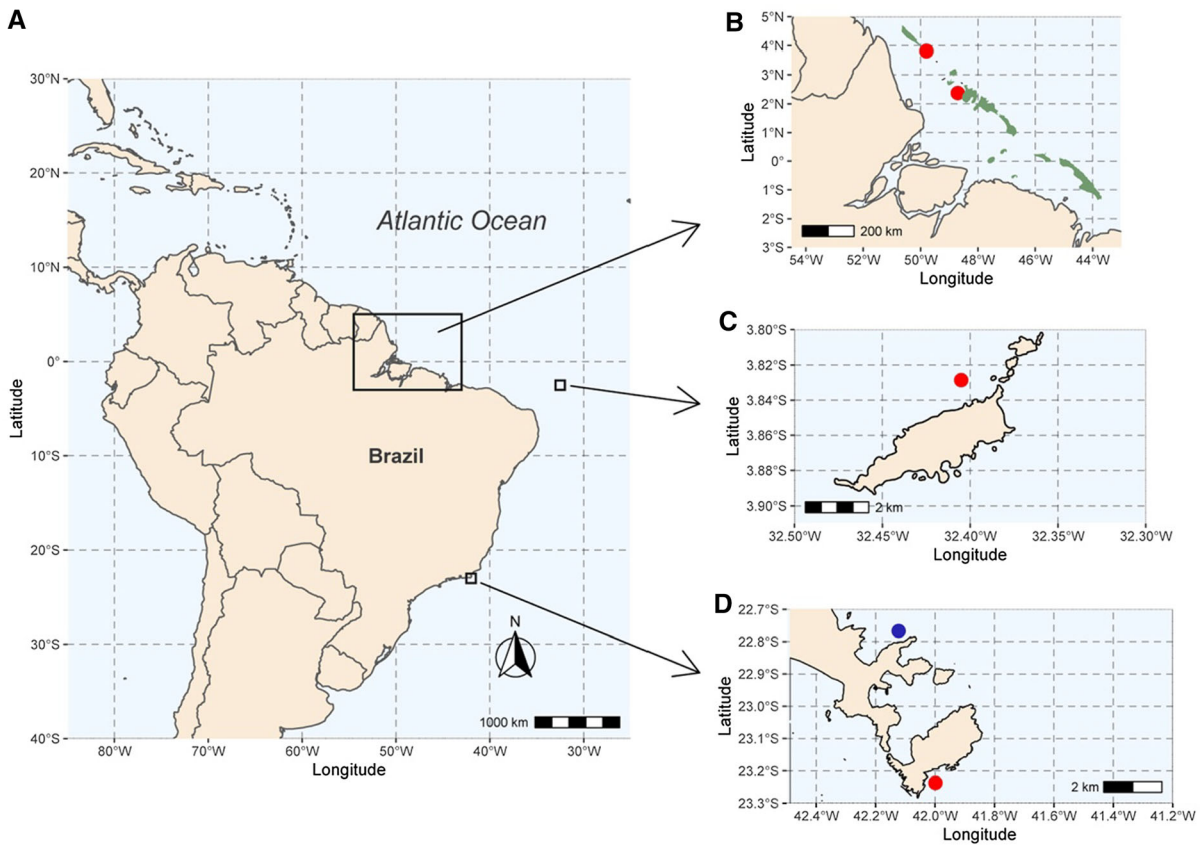

Fig. 1 (**a**) South Atlantic records of lionfish (red dots) in the (**b**) Amazon Reef System (green patch)—2020, (**c**) Fernando de Noronha archipelago—2020, and (**d**) Arraial do Cabo—2016, also showing the location of the previous individual collected (blue dot—2015)

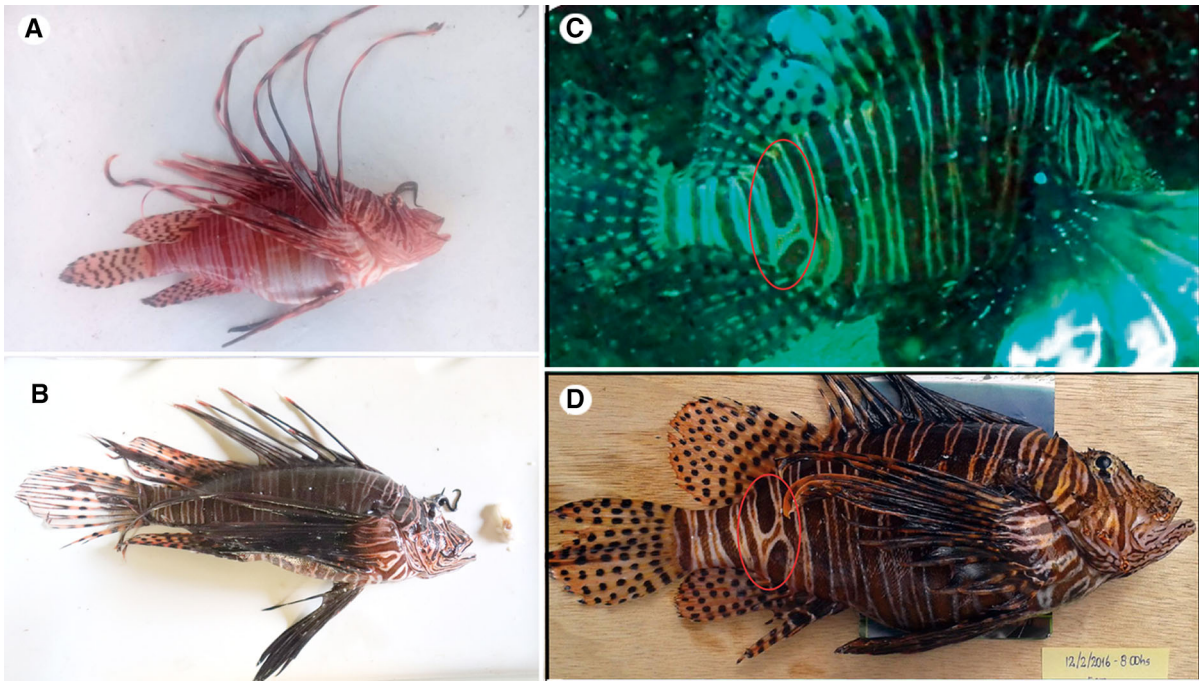

Fig. 2 Lionfish individuals collected in the Amazon reef system (**a**), Fernando de Noronha (**b**), and Arraial do Cabo (same individual; **c**, photographed underwater in march 2015 and D, captured in February of 2016)

Arraial do Cabo

A second record of a lionfish in Arraial do Cabo, southeastern subtropical coast of Brazil, occurred in March 01, 2015, just 14 months after a first report for the region and the first for the South Atlantic (Ferreira et al., 2015). The fish (25 cm TL; Fig. 2c) was photographed by a local dive operator staff (Queiroz Divers) in a site called *Anequim* at the windward shores of the Cabo Frio Island (Fig. 1d; Lat-22.980, Lon-41.984) at a depth of 10 m. Despite an effort to locate and collect the fish the next day, it was not found. Only eleven months later, on February 11, 2016, the fish was again detected by a local spearfisherman 5 km away from the first sight, in the same island (Site *Saco das Neves*; Lat-23.015, Lon-41.999). The fish was collected the next day, at the same spot, by researchers using a spear. The specimen collected was confirmed to be the same individual previously observed by comparing its natural marks on photographs (Fig. 2c and d). Accession number: CIUFES 4188.

Invasion delay and predicted pathway into the SW Atlantic

Despite the relatively close distance, there is a 10-year gap between the first lionfish observations in Trinidad and Tobago—the southernmost record of a lionfish in the Caribbean Province—and these records in the Amazon reef. The speed of the lionfish spread in the northwestern Atlantic were likely assisted by pelagic transport (Johnston and Purkis 2011). Female lionfish produce buoyant, mucous-encapsulated eggs that hatch into pelagic larvae and spend on average 26 days in the plankton before settling to the benthos (Ahrenholz and Morris 2010). We argue that the direction of the surface flow of the North Brazil Current, which varies seasonally in strength, but flows steadily northwards restricts the dispersal of eggs and larvae southward across the Amazon Barrier (Luiz et al. 2013). However, the direction of currents does not prevent the movement of adult individuals from one reef to the next in a stepping-stone fashion. Therefore, we suggest that the slow pace of lionfish range extension to Brazil is a result of dispersal mechanisms relying mostly on demersal adult

movement through mesophotic reefs under the Amazon plume.

Fernando de Noronha is an oceanic archipelago with no aquarium stores or any aquarium fish commerce, so that individual must have reached the area as a pelagic larva. This is not surprising, as there is previous evidence that Fernando de Noronha has strong links to the Caribbean province, sometimes bypassing the Brazilian mainland (Rocha et al. 2005). In fact, Luiz et al. (2013) predicted that Fernando de Noronha would be one of the first places in the south Atlantic to receive lionfish migrants from the Caribbean. Because Fernando de Noronha is a natural connectivity node between the Caribbean and Brazilian provinces, it is a strategic place to concentrate efforts to curb the lionfish invasion into the SW Atlantic.

The North coast of Brazil is one of the world´s most important shrimp fishery grounds, which extends from the border of French Guiana to the state line of Maranhão and Piauí, with a total area of 223,000 km^2. The bottom substrate is a mixture of mud and sand, but also includes rocky substrates (Marceniuk et al. 2019). The two lionfish were detected approximately 200 km from the coast of Amapá state or 500 km from the city of Belém, in a region where no aquarium trade for marine fishes exists. The detection of invasive lionfish in this region is also made very difficult by the fact that there is no recreational diving anywhere in the area.

The mode of transport of the second lionfish record in the subtropical Arraial do Cabo, at 23 degrees of latitude south, is still unknown. That is the same location where the first lionfish in Brazil appeared in 2014 (Ferreira et al. 2015), despite being too far away for a single long-dispersal event from the Caribbean Province. Arraial do Cabo is a popular holiday destination located just 120 km from Rio de Janeiro, one of the most populated cities in Brazil. Therefore we cannot rule out the possibility that these two records are the result of secondary aquarium releases. However, mitochondrial DNA of both individuals match of the Caribbean invasive population, so if it was an aquarium release, that specimen must have entered the aquarium trade via the Caribbean.

Brazilian endemic species and sensitivity to impacts

The lionfish invasion in the NW Atlantic has been heralded as one of the most damaging marine fish invasions to date globally (Hixon et al. 2016). Invasive lionfish are voracious generalist predators that not only prey on a broad range of native fish species (Côté and Smith 2018), but also do it with great efficiency. Compared to native mesopredators, lionfish present novel locomotion and morphological traits that perform a previously inexistent ecological function in the Atlantic (Rojas-Velez et al. 2019), eliciting low avoidance responses by prey exposed to the novel predator (Sih et al. 2010). Lionfish are responsible for significant reductions in native species abundance (Albins and Hixon 2013), including local extinctions (Ingeman 2016).

While Caribbean native species might not be at great risk of global extinction because of their broad distribution across the NW Atlantic (see Rocha et al. 2015 for an exception), the same cannot be said for the unique restricted-range endemic species in Brazilian oceanic islands. One-third of all SW Atlantic endemics have their distributions restricted to small remote oceanic islands (Pinheiro et al. 2018), including Fernando de Noronha Archipelago. Some, like the small and remote St. Peter and St. Paul's Archipelago, have such a limited shallow reef area that local reef fish endemics are considered to have the smallest geographic range known for marine fish species (Luiz et al. 2007; Pinheiro et al. 2020). If the lionfish gets to populate these islands at the same population densities they have reached in the Caribbean, global extinctions are a possibility among some of the most unique endemic Brazilian reef fauna.

Extinctions are less likely to happen along the contiguous Brazilian continental coast because coastal endemics usually have much broader distributions (and consequently bigger populations) than island endemics (Pinheiro et al. 2018). Ecopath-with-Ecosim models assuming the presence of lionfish in Brazilian coastal waters predicted impacts on the local trophic web similar to the impacts reported for the NW Atlantic (Bumbeer et al. 2018). That includes reduction of prey populations with a consequent reduction of food for native predators, cascading trophic effects, and decline of many commercially important fishery

species both through direct predation and competition (Bumbeer et al. 2018).

Management perspectives

The invasive lionfish was highlighted in 2010 as a major issue on the global conservation horizon (Côté and Smith 2018), because they are generalist predators of ecologically and economically important native species on Atlantic coral reefs. Culling programs by spearfishing on scuba are the most common form of lionfish control (Malpica-Cruz et al. 2016). However, due to the lionfish high fecundity and abundance in depths beyond scuba safe limits (Andradi-Brown et al. 2017), complete eradication of the species is thought to be unachievable (Côté and Smith 2018). A more realistic strategy is to reduce lionfish populations below levels that cause unacceptable ecological effects (functional eradication; Green and Grosholz 2020).

The best time for conservation managers in Brazil to act is now. Biological invasions are best controlled at the beginning of the invasion curve, when the invader population is in the phase of slow increase in abundance (Roman and Darling 2007). The ability to make decisions and act quickly on evidence of environmental threat greatly influences the outcome of conservation measures. A rapid attempt at population control is more effective, less costly, and less risky than later interventions when the invaders are established and interacting with the native community (Simberloff et al. 2013). At this stage we are unaware of any established reproducing population in Brazil. Therefore, we recommend that the best management action should be the removal of every individual found. In addition, in areas that have been identified as recruitment areas, a surveillance plan should be established for: (1) continuous monitoring, (2) regular assessment of genetic diversity, and (3) early detection using eDNA. However, since lionfish has already been detected in areas with no diving operations (i.e. the Amazon reefs), fishing operations can be used as monitoring tools, with fishermen properly educated for visual identification. Time will tell if a full Caribbean-like invasion will unfold along the Brazilian coast, with lionfish becoming part of the Brazilian fauna as much as they are in the Caribbean.

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Authors' contribution All authors contributed to the study conception and design. Specimens collection were performed by Wagner Santos, Clara Buck, Alexandre Marceniuk, and Alex Klautau. The first draft of the manuscript was written by Osmar Luiz, Carlos Ferreira, Sergio Floeter and Luiz Rocha and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Conflicts of interest None.

Consent to participate All authors consent in participate in this manuscript.

Consent for publication All authors consent in publishing this manuscript.

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