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Baseline

Marine debris in the Fernando de Noronha Archipelago, a remote oceanic marine protected area in tropical SW Atlantic

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ABSTRACT

Marine debris is widespread worldwide, from coastal areas to remote protected oceanic islands. We assessed marine macro-debris on the shores of Fernando de Noronha, an archipelago 360 km off Brazil that encompasses no-take and multiple-use areas. The windward uninhabited coast, more exposed to oceanic currents and winds and inside a no-take area, presented higher abundance of plastic debris. The leeward coast, within the multiple-use urban area, presented more disposable plastics and cigarette butts. These patterns may be explained by the marine debris transportation by ocean currents to the windward side and by locally generated debris by the high quantity of beach users in the leeward coast. These results indicate that oceanographic characteristics and tourism infrastructure play important roles in the accumulation of marine debris in a protected archipelago. They also serve as a baseline for future monitoring initiatives and to improve strategies to tackle plastic pollution within this remote archipelago.

Oceanic islands, which rise beyond continental shelves, are among remote areas frequently considered as near-pristine environments (Quimbayo et al., 2019). Because of their evolution in isolation, they can harbor unique terrestrial and marine biotas, representing important conservation hotspots. However, some anthropogenic impacts, such as pollution and climate change, respect no boundaries (Halpern et al., 2015), leading to negative impacts on remote and protected locations such as oceanic islands (Barnes, 2005; Lavers and Bond, 2017).

Marine debris found on insular shores originates either locally or are transported from elsewhere by ocean currents. Inhabited islands are sources of marine debris because of human occupation and tourism (Wilson and Verlis, 2017). However, some types of debris, particularly plastics, can be found several kilometers from their original source (Ivar do Sul and Costa, 2007; de Scisciolo et al., 2016). They can be dropped in distant areas or dumped at sea, subsequently accumulating on inhabited and unpopulated remote island's coastlines (Pérez-Venegas et al., 2017; Andrades et al., 2018) by the action of currents and winds (Barnes et al., 2009; Eriksson et al., 2013). Due to this oceanic transport, islands tend to accumulate proportionally more plastic debris than continental sites (Pérez-Venegas et al., 2017). Although marine debris found in islands can be both locally and distantly generated (Carson et al., 2013; de Scisciolo et al., 2016), the later source is more prevalent (Donohue et al., 2001).

Marine debris severely threatens marine wildlife (Sheavly and Register, 2007) as it can entangle and/or be ingested by organisms such as mammals, fish, seabirds, and turtles, affecting their fitness, breeding, and survival (Kühn et al., 2015). There is evidence that even sessile organisms such as corals can ingest microplastic (Hall et al., 2015; Rotjan et al., 2019). Marine debris can also facilitate the dispersal of organisms by rafting, thus promoting the introduction of invasive species (Gregory, 2009; Kiessling et al., 2015). Therefore, regardless of its origin, marine debris negatively affects the local biodiversity of oceanic islands and their conservation (Dias, 2016). In addition, tourism and local economies relying on it can be negatively impacted by the presence of debris (Jang et al., 2014).

The Fernando de Noronha Archipelago (FNA), 360 km off the northeastern coast of Brazil (3°51′ S, 32°25′ W), is formed by the main island of Fernando de Noronha (18 km^2) plus 20 other smaller islands and islets. The FNA comprises two protected areas: a multiple-use Environmental Protection Area, which covers the inhabited part of the main island (~30%) and allows for human occupation and sustainable use of its resources; and a Marine National Park, a no-take area covering

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70% of the main island and all secondary islands. Considered a glamorous national and international destination, the FNA receives an increasing number of tourists each year. In 2018, the number of tourists exceeded 100,000 (ICMBio, 2018). In addition, there are 3000 residents, including permanent residents and temporary workers (IBGE, 2020). The multiple-use area encompasses all the urban facilities, such as streets, guesthouses, restaurants, banks, a hospital, and an airport, as well as historical constructions and beaches with bars. Visitation can thus be done without many restrictions. The remaining 70% of the main island is a no-take area, with more deserted beaches and forest trails that can be accessed only under supervision of a trained guide. Tourists must pay a fee to visit the no-take area and previous scheduling is mandatory to access some of the areas.

The entire coast of the multiple-use area and a part of the no-take area are located on the leeward coast of the archipelago, which faces north and is sheltered from ocean currents and winds. The windward coast of the main island, comprising the no-take area, faces south and is influenced by relatively strong winds (Matheus et al., 2019) and the South Equatorial Current (Lumpkin and Garzoli, 2005). These differences in exposure levels between the leeward and windward sides of the FNA affect the human activities performed on the island, like fishing and diving, and the insular biodiversity (Batistella, 1996; Matheus et al., 2019).

Previous studies on marine debris in Fernando de Noronha have focused mainly on microplastics (<5 mm; Ivar do Sul et al., 2017; Monteiro et al., 2020). Although some have included larger plastic debris (<100 mm; Ivar do Sul et al., 2009), sampling items included mostly fibers and strands (Ivar do Sul et al., 2009; Ivar do Sul et al., 2014). Therefore, the objective of this study was to describe the distribution, composition, and abundance of marine macro-debris, including plastic, paper, glass, and metal, on the sheltered and exposed shores of the FNA. The southern coast of the island is expected to present more marine debris because of its oceanographic characteristics, despite the protection status granted by the Marine National Park. This assessment comparing different types of marine macro-debris among sites complements the knowledge already available on the composition of marine debris, serves as a baseline for future monitoring programs, and may contribute to evaluate and adjust strategies for the management of marine debris in the FNA.

This study was conducted on five no-take sites in the windward coast of the FNA and one site within the leeward multiple-use area. The no-take sites were Abreus (13,000 m^2), Atalaia (10,600 m^2), Alagados da Raquel (30,000 m^2), Leão (22,000 m^2), and Sueste (10,200 m^2), and the multiple use site was Conceição (28,000 m^2) (Fig. 1). Alagados da Raquel is a restricted access shore platform where only researchers can enter with previous authorization. Abreus is another shore platform and Atalaia is a sandy beach with a neighbouring shore platform. The main attraction of Abreus and Atalaia are tide pools in which the number of visitors (tourists and residents) and the time for free dive are limited. Leão is a beach visited by few people due to difficulty in access and Sueste is a highly visited bay with a free diving area. Conceição is an easily accessible beach with bars heavily visited by tourists wishing to

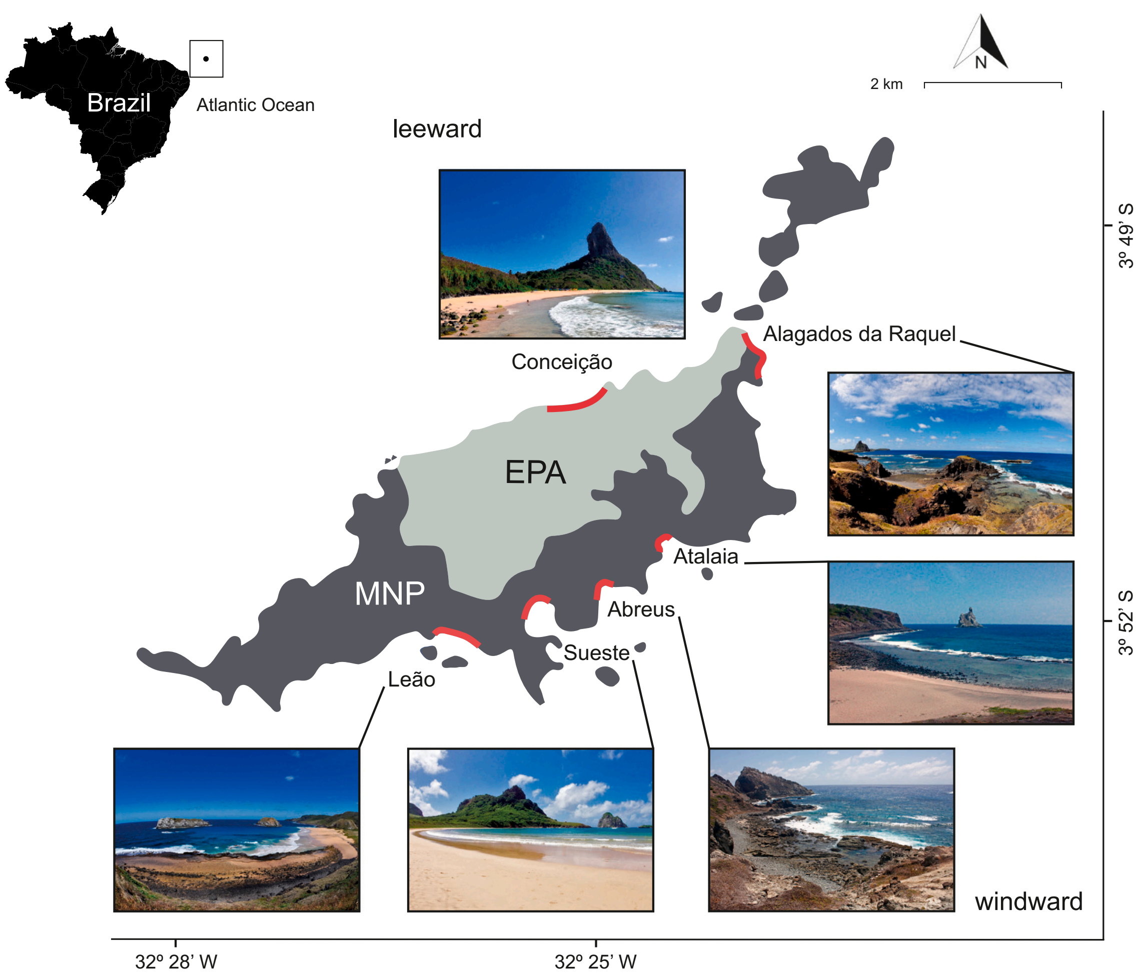

Fig. 1. Study sites in the Fernando de Noronha Archipelago (3°51′ S, 32°25′ W). Protected areas: multiple-use Environmental Protection Area (EPA) and no-take Marine National Park (MNP). Extension of the sampled sites in the leeward and windward coast of the main island (in red). Photos: Grillo, A.C.; Pires, J.M; Teixeira, F.C. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

perform leisure activities.

The sampling sites are enclosed by natural features such as cliffs and dense vegetation, that act as boundaries. The entire area of each sampling site was surveyed from the edge of the water to the beginning of the vegetated area or cliffs during low tide and all marine macro-debris (>2.5 cm) were collected. Samplings were carried out from September 2016 to September 2018. Marine debris was weighted and categorized into four broad groups: plastic, paper, glass, and metal. Plastics were further classified into four subcategories: bottle caps, disposable plastics (cups, cutlery), hospital waste (plastic syringes), and cigarette butts (based on UNEP/IOC marine debris classification, UN Environmental Programme/International Oceanic Commission; Cheshire et al., 2009). For these subcategories, the number of items was counted. Other kinds of plastic objects and fragments were generically classified as "plastic".

Since the area varies among sites, data was standardized by dividing the total weight and the amount of each debris category by the area of each site, resulting in a comparable value by m^2. Kruskal-Wallis tests were used to test for differences on the weight and amount of marine debris categories and subcategories among the sites and between the windward and leeward coasts of the FNA using samples as replicates. A non-metric multidimensional scaling (MDS) ordination was used to summarize spatial similarities (Bray-Curtis) on the composition and abundance of plastic marine debris subcategories, and a separate one-way analysis of similarity (ANOSIM) was used to test for differences according to sampling sites.

In sum, 294.5 kg of plastic, 15.3 kg of glass, 8.2 kg of metal, and 3 kg of paper were collected. Plastic was the most abundant category of marine debris. Plastic weight differed among the sampling sites (Kruskal-Wallis $H = 33.55$, $p < 0.001$), and the sites with higher and lower mean weight of plastics were Atalaia and Conceição, respectively (Fig. 2). The amount of plastic debris subcategories also differed among the sampling sites (Kruskal-Wallis: bottle caps $H = 21.22$, $p < 0.001$; disposable plastics $H = 22.64$, $p < 0.001$; hospital waste $H = 19.94$, $p < 0.01$; cigarette butts $H = 23.98$, $p < 0.001$). Although bottle caps and disposable plastics were collected in all sites, the higher amounts of bottle caps were recorded in Atalaia, Sueste, and Abreus, and disposable plastics were mostly found in Conceição (Table 1, Fig. 3). Hospital waste

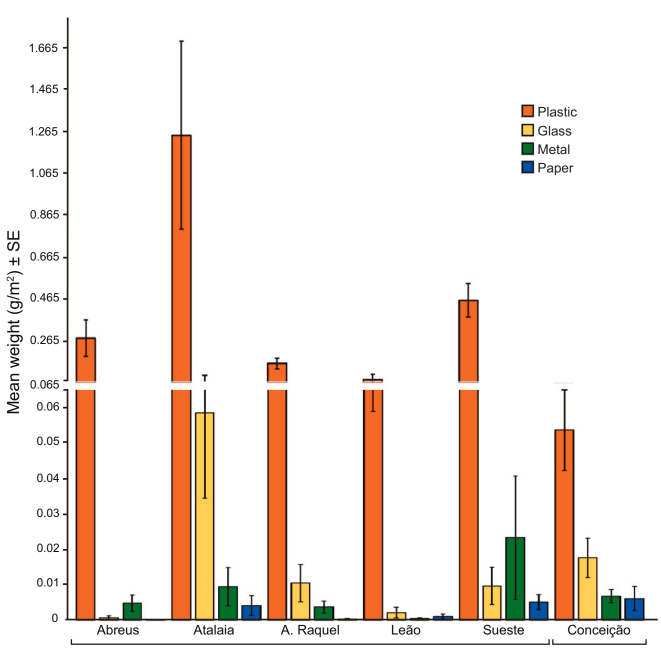

Fig. 2. Weight (mean ± SE) of marine macro-debris categories in the windward no-take Marine National Park (MNP) and leeward multiple-use Environmental Protection Area (EPA) sites.

Table 1
Amount (mean ± SE) of the plastic marine debris subcategories in the windward no-take Marine National Park (MNP) and leeward multiple-use Environmental Protection Area (EPA) sites of Fernando de Noronha.

Plastic debris subcategories	Mean amount (items/m^2) ± SE					
	Windward (MNP)					Leeward (EPA)
	Abreus	Atalaia	A. Raquel	Leão	Sueste	Conceição
Bottle caps	23.67 ± 8.88	51.44 ± 30.47	14.36 ± 2.81	8.02 ± 3.28	39.91 ± 9.49	0.84 ± 0.25
Disposable plastics	0.03 ± 0.03	0.12 ± 0.05	0.03 ± 0.02	0.01 ± 0.01	0.04 ± 0.02	0.20 ± 0.06
Hospital waste	0.03 ± 0.02	0.23 ± 0.14	0.05 ± 0.03	0.08 ± 0.04	0.18 ± 0.05	0
Cigarette butts	0	0	0.01 ± 0.01	0.04 ± 0.02	0.17 ± 0.08	0.73 ± 0.26

was collected in all sites, except in Conceição. Cigarette butts were mostly found in Conceição, and among the other sites, 66% of all cigarette butts belonged to Sueste. The MDS ordination diagram showed a distinction among the sampling sites for the plastic subcategories, with plastic debris of Conceição clustering apart from the remaining sites (Fig. 4; ANOSIM: $R = 0.3$, $p = 0.001$).

The mean weight (g/m^2) of glass (Kruskal-Wallis: $H = 21.63$, $p < 0.001$) and paper (Kruskal-Wallis: $H = 19.96$, $p < 0.01$) was different among the sampled sites, and metal debris did not differ among the sites (Kruskal-Wallis: $H = 5.42$, $p > 0.05$; Fig. 2). Glass was mostly represented by beer and other alcoholic beverage bottles. In Conceição, 80% of the surveys contained paper (napkins and food packages; Fig. 3), followed by Sueste and Atalaia (64% and 57% of the surveys respectively). Metal was represented by beer and soda cans, wires, and bottle caps. Additionally, packages of identifiable brands that are not commercialized in Brazil, in foreign languages (mostly Asiatic languages, but also English and Spanish), were collected only in the windward sites, totalizing 115 items among all samples. They were mostly represented by plastic beverage bottles in a low state of decay, but also included carton packaging and metal bottle caps (Fig. 3).

The mean total weight of marine debris on the windward coast was significantly higher than on the leeward coast (Table 2). Since the sampling effort was higher on the windward coast, the same analyses were done after randomly sampling 1000 times the windward data by bootstrap to obtain equally sized samples in both coasts ($n = 10$) and the pattern remained. The mean weight of plastic debris was significantly higher on the windward than on the leeward coast. Also, the mean debris amount regarding bottle caps and hospital waste was significantly higher on the windward coast. On the leeward coast, mean amounts of disposable plastics and cigarette butts were significantly higher. The mean weight (g/m^2) of glass, paper, and metal debris was not significantly different between the leeward and the windward coasts.

The composition and abundance of marine macro-debris differed according to the distinct characteristics of the sampled sites in the FNA. The windward coast, a no-take Marine National Park, presented higher plastic abundance than the leeward coast, a multiple-use Environmental Protection Area. Plastic bottle caps and hospital waste were collected in higher amounts in the windward sites. Contrarily, the leeward site presented a higher density of disposable plastics and cigarette butts.

Higher abundance of plastic debris on the windward coast may be explained by the transportation of plastic from its origin to the FNA through oceanic forces, such as winds and currents (Barnes et al., 2009). Bottle caps abundance, for example, was more than twenty-fold greater on the windward than on the leeward coast of the FNA, which can be explained by their efficiency in being transported by the ocean

Fig. 3. Marine macro-debris collected on the shores of Fernando de Noronha: windward coast samplings (a, b, d, e); leeward coast sampling (c); hospital waste, including a syringe with a needle (d); packages of products from brands not commercialized in Brazil, in foreign languages (e). Photos: Furlani, F.; Grillo, A.C.; Santana, J.

(Andrady, 2011). Some polymers such as polyethylene and polypropylene, used for making bottle caps, plastic bags, bottles, and straws, are less dense than seawater and therefore float in the ocean until they are washed ashore on beaches, sometimes far away from where they entered the sea (Andrady, 2011). The lightweight, high buoyancy, elevated durability, and super slow environmental degradation of plastic objects (from 58 years for bottles to 1200 years for pipes; Chamas et al., 2020) make them perfect to accumulate in the ocean (Andrady, 2011, 2015).

Moreover, hospital waste was completely absent in leeward surveys. There is only one public hospital on the FNA, which is located in the urban area and closer to the leeward coast, and there are no perennial watercourses on the island, turning less plausible the possibility of debris transportation from the hospital to windward shores. In addition, the fact that one of the sites surveyed in the windward side (Alagados da Raquel) is closed for public use suggests that most of the marine debris on its shores might have come from elsewhere. Finally, the presence of packages with foreign language labels at early decomposition states among the debris collected only in windward sites also points to the hypothesis that some of these objects might have been thrown overboard and then traveled through currents (Duhec et al., 2015). These results agree with a previous study conducted in the FNA (Ivar do Sul et al., 2009), and previous studies of insular shores facing winds and oceanic currents elsewhere, such as in the Seychelles (Duhec et al., 2015), Easter Island and Salas & Gómez, Chile (Miranda-Urbina et al., 2015), Trindade Island, Brazil (Andrades et al., 2018), and Hawaiian Archipelago, USA (McDermid and McMullen, 2004; Ribic et al., 2012), evidencing a higher vulnerability to debris on windward sides of isolated locations.

The marine debris recorded in Conceição beach, on the leeward coast, may have originated from local uses and infrastructure. The higher quantity of disposable plastics, such as single-use cups and cutlery, and cigarette butts suggests that this kind of debris was generated locally by beach users. Similarly, other studies have pointed touristic use of urban beaches as the cause of accumulation of this kind of debris on oceanic and continental islands (Martinez-Ribes et al., 2007; de Scisciolo et al., 2016; Wilson and Verlis, 2017). Together, these results indicate improper disposal of local debris in the FNA and elsewhere.

Cigarette butts are usually one of the top three most abundant items collected in beach surveys and clean-ups on islands (Martinez-Ribes et al., 2007; Pieper et al., 2015; de Scisciolo et al., 2016; Wilson and

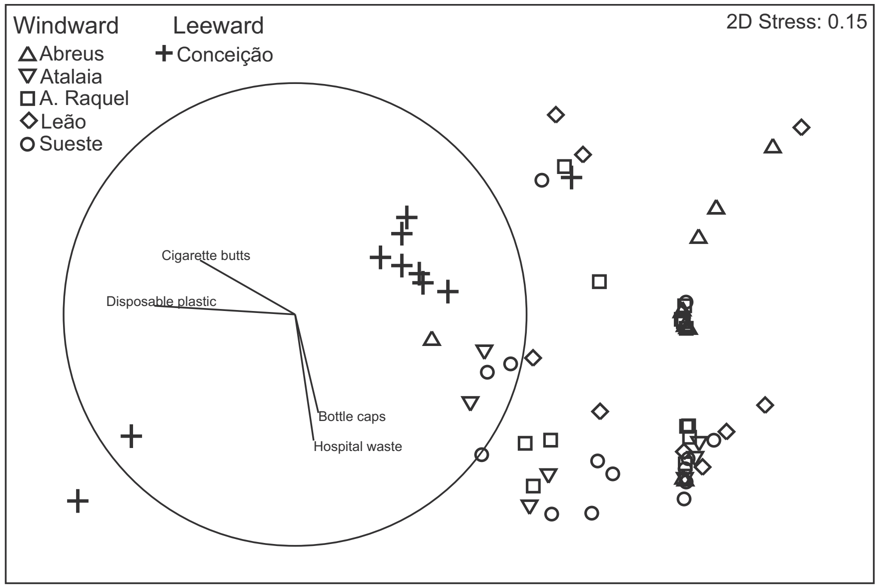

Fig. 4. Multidimensional scaling (MDS) of the composition and abundance of plastic marine debris subcategories between windward and leeward sampling sites of Fernando de Noronha based on Bray-Curtis similarities.

Table 2
Abundance (mean ± SE) of marine macro-debris on the windward no-take Marine National Park (MNP) and leeward multiple-use Environmental Protection Area (EPA) coasts of Fernando de Noronha. Significance differences between windward and leeward coasts, based on Kruskal-Wallis tests, are indicated (*$p < 0.01$, **$p < 0.001$).

Marine debris	Mean abundance ± SE		
	Windward (MNP)	Leeward (EPA)	
Total debris (g/m^2)	0.412 ± 0.078	0.084 ± 0.016	*
Plastic (g/m^2)	0.388 ± 0.077	0.054 ± 0.011	**
Bottle caps (items/m^2)	26.576 ± 5.182	0.843 ± 0.252	**
Disposable plastics (items/m^2)	0.039 ± 0.011	0.196 ± 0.059	**
Hospital waste (items/m^2)	0.104 ± 0.025	0	*
Cigarette butts (items/m^2)	0.052 ± 0.022	0.732 ± 0.256	**
Glass (g/m^2)	0.013 ± 0.004	0.018 ± 0.006	
Metal (g/m^2)	0.009 ± 0.005	0.007 ± 0.002	
Paper (g/m^2)	0.002 ± 0.001	0.006 ± 0.003	

Verlis, 2017). Although in the windward sampling sites of the FNA the abundance of cigarette butts was much lower than in the leeward site, most of them were collected at Sueste, which is explained by the far greater number of visitors compared to other windward sites (Sueste: ~98,000; Atalaia: ~20,000; Abreus ~6000 visitors/year; ICMBio, 2018). Despite Alagados da Raquel being a restricted access site, the presence of cigarette butts suggests that they might have been thrown from a viewpoint located just above the cliff. Installing public ashtrays in the viewpoints and handing out portable ashtrays at the beaches can help diminish the number of cigarette butts littered in inadequate areas and raise smokers' concern about their behavior as polluters (Araújo and Costa, 2019).

Inside the windward no-take area, paper was more frequent in Sueste, represented by food packages, sales receipts, and diving equipment rental receipts. The only marine activity allowed in Sueste is free diving, which explains the high quantity of equipment rent tickets surveyed. Sueste was the only sampling site in the windward coast to bear an Information and Control Point in front of the beach (when the study was conducted), which offers food, bathroom, and store services for visitors. Therefore, these results suggest the role of visitors in the presence and density of marine debris on insular shores. After concluding the samplings, another Control Point was inaugurated in Leão beach, and a viewpoint located in the leeward Boldró beach has been conceded for the construction of a bar. It is important to keep marine debris monitoring in the long term to verify if the installation of these new infrastructures will cause an increase in the amount of debris related to beach users, and take steps to minimize the problem if necessary.

Despite being a no-take and supervised Marine National Park, the high abundance of marine debris on the windward coast of Fernando de Noronha poses negative impacts to marine biodiversity. During this study, a classic example of entanglement was recorded in Atalaia. A plastic debris collar was observed in a reef resident grunt (*Haemulon parra*) for several days, limiting the movements of its pelvic fins (Fig. 5a). This kind of entanglement has already been recorded in other Brazilian locations (Sazima et al., 2002; Nunes et al., 2018), threatening the supposedly protected marine fauna and implying a risk for conservation efforts. Consequently, the protection status of an area does not prevent the ubiquity of marine debris nor protect its inhabitants from the negative effects of this type of pollution (Barnes et al., 2018; Luna-Jorquera et al., 2019).

Another example of inappropriate debris disposal that could affect the marine fauna was documented in Porto beach, located in the leeward multiple-use area, a site highly visited by residents and tourists. This is the only port on the island, where all vessels arrive and depart, and several activities are performed, including scuba diving due to the abundant marine life and to a shallow shipwreck nearby. In 2016 a high quantity of underwater debris was recorded alongside the pier, composed mainly of tires, ropes, plastic big bags, building materials, single-use plastics, and cans (Fig. 5b). This debris points to several anthropogenic in-situ sources, such as island supply (i.e., objects falling from ships while transferred to the island and vice versa), pier construction, and recreational activities by beach users. These examples add information to the managers, citizens, and tourists for an improvement of the waste disposal and accumulation on the island. Moreover, ineffective urban solid waste management is a recurrent environmental problem in the FNA, with a monthly average production of about 300 tons of garbage on the island (Fioravanso, 2017) mainly due to the large number of tourists throughout the year.

Despite being internationally known as a glamorous ecotourism destination, a Protected Area, a UNESCO World Heritage and Ramsar Wetland Site, and having a beach ranked among the most beautiful in the world, Fernando de Noronha suffers from anthropogenic debris on its shores. A large amount of marine debris, especially plastic, was

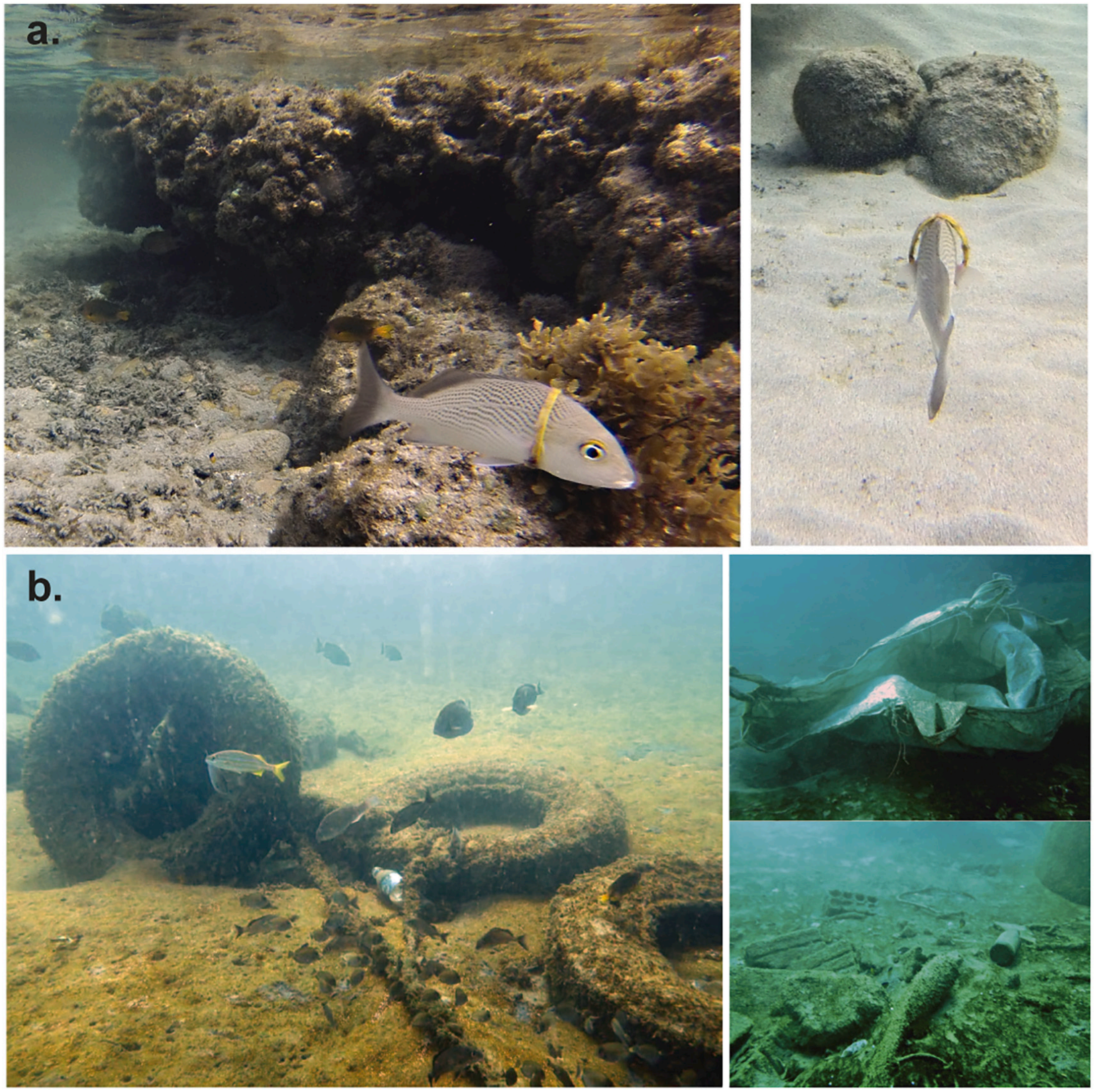

Fig. 5. Sailor's grunt (*Haemulon parra*) with a plastic debris collar in Atalaia's tide pool, in the windward no-take area (a); debris disposal recorded underwater in Porto beach, in the leeward multiple-use area of Fernando de Noronha (b). Photos: Grillo, A.C.; Mello, T.J.

surveyed in all sites. The distinct debris composition and abundance along the coast of Fernando de Noronha could indicate that debris accumulation on its shores is influenced by the exposure to winds and currents and by the increasing number of tourists to the island. It also evidences that distance from the coast and protection status do not prevent pollution by marine debris on oceanic islands. These pollutants present a threat to the entire ecosystem, posing consequences from the marine wildlife to social and economic levels, and also impacting tourism (Cristiano et al., 2020).

In 2018 a decree was published (District Decree no. 002/2018) forbidding the use and commercialization of single-use plastics in the island. Therefore, this study serves as a baseline to evaluate the effectiveness and orient improvements of this and other environmental measures adopted in Noronha to reduce the input of debris to its shores and the sea. Socio-environmental programs, mainly directed to tourists and beach users, international cooperation, enforced supervision, and integrated prevention strategies are urgent and essential to address the marine debris question worldwide and thus reduce its accumulation, production, and impacts on the environment.

CRediT authorship contribution statement

Ana Carolina Grillo and Thayná Jeremias Mello contributed equally in this study, from the conception and methods development to data analyses and manuscript preparation.

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.

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