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Marine debris provide long-distance pathways for spreading invasive corals

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ABSTRACT

Anthropogenic marine debris and invasive species are pervasive in the ocean. However, research on the mechanisms and dynamics controlling their distribution in marine systems (e.g.; by floating debris acting as vectors for invasive species) is limited. Applying a numerical modeling approach, we demonstrate that rafting invasive corals (*Tubastraea* spp.) can be transported over long distances and reach important tropical receptor regions. In <180 days, buoyant debris can cover distances between 264 and 7170 km moving from the Brazilian semiarid coast to the Amazon coast and reaching eight regions in the Wider Caribbean (mainly the Eastern Caribbean and Greater Antilles). Analyzing 48 simulated scenarios (4 years × 3 depths × 4 months), we demonstrate that in ~86 % of the scenarios the particles are stranded in the Caribbean and in ~71 % they end up in the Amazon coast. Our results showed litter floating trajectories at 0–10 m water depth, transported every year to the Caribbean province. However, in August this transport is frequently blocked by the retroflection of the North Brazil Current adjacent to the Amazon River estuarine plume. Our results indicate routes for fast and long-distance transport of litter-rafting invasive species. We hypothesized a high risk of bioinvasion on important marine ecosystems (e.g., coral reefs) likely becoming increasingly threatened by these invasive species and debris. This highlights the imperative need for an ocean governance shift in prevention, control, and eradication, not only focused on local actions to prevent the spread of invasive species but also a broad international action to decrease and mitigate marine debris pollution globally.

1. Introduction

Anthropogenic marine debris and invasive species are two of the many drivers impacting the oceans health (Creed et al., 2017; Póvoa et al., 2021). They can act individually and synergistically, having compounded negative effects on ecosystems. An understudied phenomena, despite the rising number of concerning cases, is the transport of biofouling invasive species by floating marine debris (Barnes, 2002; Mantellato et al., 2020; Haram et al., 2021). Litter as a floating substratum for colonization and transport by fouling organisms (native and non-native) is known as rafting (Jokiel, 1990). Marine litter such as styrofoam, wood, and rope are generally cited as main transporting vectors for invasive species but plastics are one of the most cited substrates for rafting (Póvoa et al., 2021; Al-Khayat et al., 2021) due to their persistence and increased/widespread distribution (Stubbins et al., 2021).

Most of the studies (~40 %) on marine rafting are focused on the North Pacific Ocean due to the conspicuousness of litter, especially after the Japan Tsunami of 2011, which generated enormous volumes of debris spread throughout North American beaches (Póvoa et al., 2021). A global increase of marine debris in the oceans is predicted in the coming decades (Ostle et al., 2019; Stubbins et al., 2021) with likely increased risks of rafting accelerating the dispersal of invasive benthic species (Rech et al., 2016; Mantellato et al., 2020; Haram et al., 2021).

Certain invasive species are ecosystem engineers and can thus restructure marine ecosystems and their functioning, changing material

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cycling, energy flow, and community structure (Creed et al., 2020). One of the most worrying invasive ecosystem engineer in the Atlantic Ocean are the scleractinian sun corals (*Tubastraea* spp.). These corals are native from the Indo-Pacific Ocean but invasive in the Atlantic (Paula and Creed, 2004, 2005; Creed, 2006). The *Tubastraea* genus was first recorded in the Western Atlantic in Puerto Rico and Curaçao around 1943 (Cairns, 2000). Most recently, (since ~1980), two species (*T. coccinea* Lesson, 1829 and *T. tagusensis* Wells, 1982) demonstrated high invasive potential, especially along an extensive range (~3900 km) on the Brazilian coast (Creed et al., 2017).

The negative ecological impacts of this invasion on marine biodiversity, ecosystem and food web functioning are clear. The establishment and high abundance of invasive *Tubastraea* spp. coral reduces benthic cover of native species (Lages et al., 2011; Miranda et al., 2016), alters native reef fish trophic interactions (Miranda et al., 2018a), increases competition with native scleractinian corals (Creed, 2006; Luz and Kitahara, 2017), increases energy costs on zoantharia (Saá et al., 2020), and changes fish biomass due to modification of seafloor habitat (Mizrahi et al., 2017). Moreover, these invasive corals also decrease the recruitment of native reef-building corals (Miranda et al., 2018b) and help spread other invasive species, such as borer bivalves (Vinagre et al., 2018). These impacts occur due to the success of this invasive species and its ongoing range expansion throughout the Atlantic Ocean (Creed et al., 2017; Coelho et al., 2022).

In the Atlantic Ocean, the invasive *Tubastraea* have been successfully established in different marine systems in the USA (Florida State), Brazil, the Caribbean, the Gulf of Mexico, Gabon (African continent), and Spain (Canary Islands) (Fenner, 2001; Fenner and Banks, 2004; Friedlander et al., 2014; Capel et al., 2019; López et al., 2020), mainly through vectors associated with oil and gas activities (Creed et al., 2017; Coelho et al., 2022). The transport of *Tubastraea* attached to floating plastic, glass, and wood particles has been recently reported, highlighting the potential of rafting as a new vector for secondary introductions (Mantellato et al., 2020). Some of these materials are positively or neutrally buoyant (e.g., styrofoam; Mantellato et al., 2020) allowing their transport in surface ocean layers (e.g., 0 to 10 m water depth).

This dispersal mechanism raises concerns, considering that marine litter is highly frequent in all ocean basins. This is particularly concerning in Brazil, the largest producer of plastics in Latin America and a country with low levels of sanitation and recycling (Videla and Araujo, 2021). Brazil produces 79 million tons of debris per year, of which 6.3 million tons are not collected and part of it is transported to the ocean (ABRELPE, 2019). The rise in economic activities and debris mismanagement favor the increase in the quantity of marine litter, flotsam and jetsam, and thus provides an ever-more-common means of transport for non-indigenous species (such as *Tubastraea* corals), as well as the potential synergy between them (Mantellato et al., 2020). Identifying areas that can act as sources of floating litter and assessing the risk of transport for both floating litter and invasive species is thus particularly urgent.

Litter-biofouling *Tubastraea* spp. can travel over long distances (Faria and Kitahara, 2020; Mantellato et al., 2020). The significance of this phenomenon as a mechanism of range expansion and/or secondary introduction of sun coral species into tropical marine ecosystems requires investigation. In fact, the role of anthropogenic flotsam and jetsam in species introductions and ocean basin spreads should be urgently evaluated globally (Rech et al., 2016). For this purpose, the risk analysis of marine rafting of invasive species using validated numerical models is urgent. However, these studies are currently scarce (Póvoa et al., 2021). Although validated numeric models are important and reliable tools for marine debris dispersal (Lebreton et al., 2012; Critchell et al., 2015; Baudena et al., 2022) and *Tubastraea* larvae dispersal (Coelho et al., 2022), such analysis has not yet been conducted for litter-rafting invasive coral colonies in the SW Atlantic Ocean.

The shelf region in the Brazilian semiarid coast (Fig. 1) is the northernmost record of invasive *Tubastraea* in the Southwestern

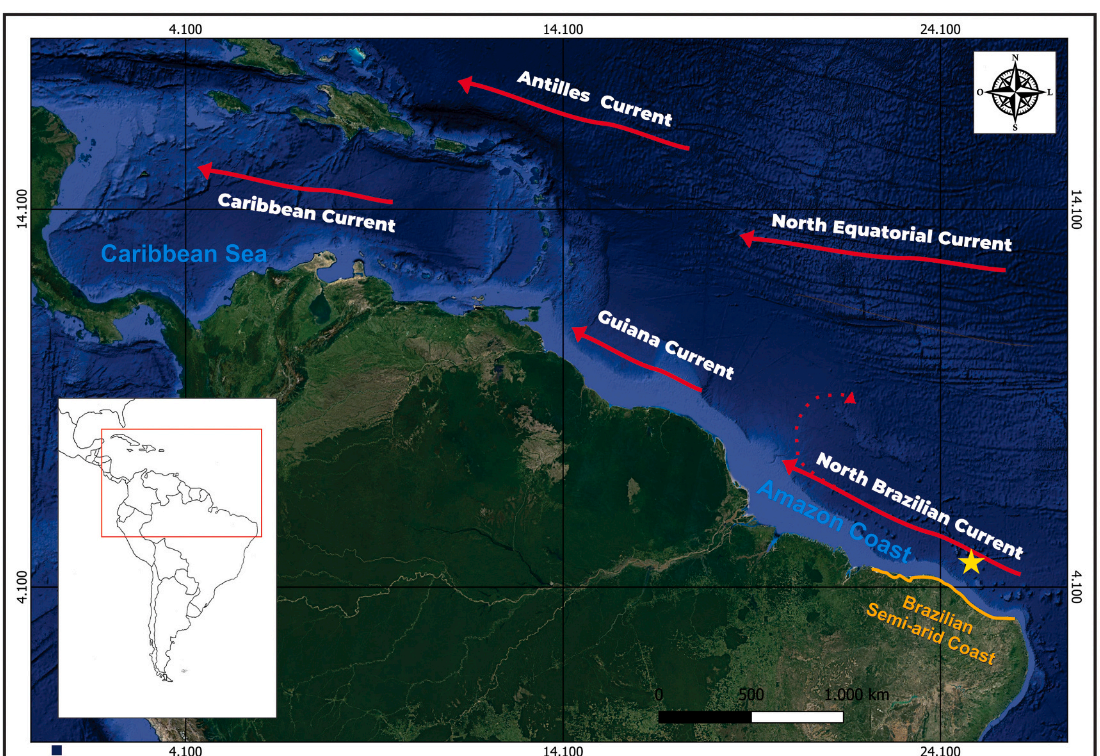

Fig. 1. Study area in the Atlantic Ocean showing the Caribbean Sea, Amazon Coast and Brazilian semi-arid coast. The main surface currents are indicated as red arrows. The dashed red arrows represent the North Brazil Current retroflection that is present during the austral winter and spring. The yellow star represents the northernmost record of *Tubastraea* in Southwestern Atlantic (Brazilian semi-arid coast, Ceará state).

Atlantic. *Tubastraea coccinea* and *Tubastraea tagusensis* were recorded at ~2° S at the continental shelf waters (Creed et al., 2017; Soares et al., 2018, 2020; Braga et al., 2021). Recently, *Tubastraea* spp. were found in two shipwrecks and one oil and gas rig between 15 and 32 m depth (Fig. 2) on artificial habitats (Soares et al., 2018, 2020; Braga et al., 2021). These invaded sites could act as a source/donor area for secondary introductions, especially larval dispersion along the Brazilian coast (Coelho et al., 2022), and unknown northward dispersion by rafting debris (Fig. 1).

These low-latitude invaded sites (Fig. 2) are located on the Brazilian semiarid coast (Jovane et al., 2016), 1000 km and 4000 km far away from the Amazon coast and the Wider Caribbean Region (WCR), respectively (Fig. 1). Moreover, these neighboring regions are connected by the fast northwestward flow of the North Brazil Boundary Current, Guiana Current and Caribbean Current, and also by northwestward subtidal shelf currents (Fig. 1). These currents can transport materials present on the shelf and also on deeper/open sea regions towards the Caribbean and Amazon reefs (Cordeiro et al., 2015; Moura et al., 2016; Francini-Filho et al., 2018; Mahiques et al., 2019), which we hypothesize can act as receptor regions due to the main circulation system (Fig. 1). Here, we carried out a dispersion modeling study for the Western Tropical Atlantic between the WCR and the Brazilian semiarid coast (Fig. 1) to test this proposed hypothesis. To simulate the debris dispersion between the donor region (Brazilian semiarid coast) and two potential receptor regions (Amazon and the WCR) (Fig. 1), we used the Mercator-Ocean system (Lellouche et al., 2018). We use this system as the hydrodynamic source to the OpenDrift dispersion model to conduct computational experiments using virtual particles (e.g., litter-rafting colonies of *Tubastraea coccinea* and *T. tagusensis*). We simulated scenarios at 0, 1, and 10 m depth, and predicted intra-annual (months) and inter-annual variability of stranded particles.

2. Methods

2.1. Study area

The donor area on the Brazilian semiarid coast (Ceará state) has a narrow continental shelf characterized by oligotrophic waters, periodic swell waves, strong winds, and mesotidal regimes. The morphology and sedimentology create a remarkable zonation comprising an inner shelf (<20 m), a middle shelf (20–40 m), and an outer shelf (>40 m to the shelf break, ~60–70 m) (Morais et al., 2019) that is influenced by the North Brazilian Current (NBC). A particular feature in this region is a warm and fast-flowing along-shore shelf current fed by the trade winds and flows mostly to the west in direction to the Amazon coast and the Caribbean Sea (Dias et al., 2018; Teixeira and Machado, 2013) (Fig. 1).

The biofouled shipwrecks (SS Eugene V.R Thayer and SS Baron Dechmont) and oil and gas platforms (PX-1) with *Tubastraea* spp. (Soares et al., 2018, 2020; Braga et al., 2021) are located in the Metropolitan region of Fortaleza (the most densely populated region in North and Northeast Brazil with 4.2 million inhabitants) (Fig. 1) near ports and large cities. This region is one of the top-five largest national producers of marine debris, including plastics (Cavalcante et al., 2020; Garcia et al., 2020). An important characteristic of the Brazilian semiarid coast that makes it a potential donor region of marine debris is the fact that it is an open coastline, without the presence of large bays or inlets. Moreover, the rise in human activities (Soares et al., 2018, 2020) increased the quantity of litter, flotsam and jetsam, and provided additional transport vectors (Mantellato et al., 2020). The absence of marine debris retention structures (e.g., bays) and the proximity of ports, cities, oil and gas platforms (ANP, 2020) makes it potentially a donor area of invasive litter-rafting corals. For this purpose, we considered potential donor areas as regions in which the target invasive species is found (northernmost records) and that has oceanographic and geomorphological features that allow the transportation to other sites (Fig. 1).

The NBC is one of the fastest (~0.9 m/s) western boundary currents in the world (Johns et al., 1998) and flows between the Brazilian equatorial outer shelf and continental slope (Fig. 1). The NBC is originated by the North Brazil Under Current (NBUC) and is fed by the Central South Equatorial Current. During the austral winter and spring the majority of NBC retroflects eastward around 50° W and feeds the North Equatorial Counter-Current. During the austral summer and fall, the NBC shifts from its retroflection mode towards a northwestward current, merging with the North Equatorial Current and feeding the Guiana Current (GC) (Johns et al., 1998; Schott et al., 1998). The GC then enters the Caribbean Sea feeding the Caribbean Current (CC) (Johns et al., 1998; Schott et al., 1998). Due to its mesoscale activity the NBC originates large anticyclonic rings that flow northwestward along the South American continental slope, often reaching the eastern edges of the Lesser Antilles (Schott et al., 1998).

The wide estuarine plume dispersion from the Amazon and Pará rivers, to about 250 km offshore (Prestes et al., 2018), would favor a fast and long distance transport of fluvial materials, such as sediments and debris to the continental slope. Rafting debris in the outer shelf would be readily transported by the NBC, GC and CC to adjacent areas in the WCR (Molleri et al., 2010; Prestes et al., 2018) due to the highly dynamic environment and debris availability, such as microplastics, at the Amazon coast itself (Queiroz et al., 2022). The WCR comprises the insular and coastal States and Territories with coasts on the Caribbean Sea and Gulf of Mexico (Fig. 1), as well as waters of the Atlantic Ocean adjacent to these 28 States and Territories and includes 28 islands and continental countries (UNEP, 2021).

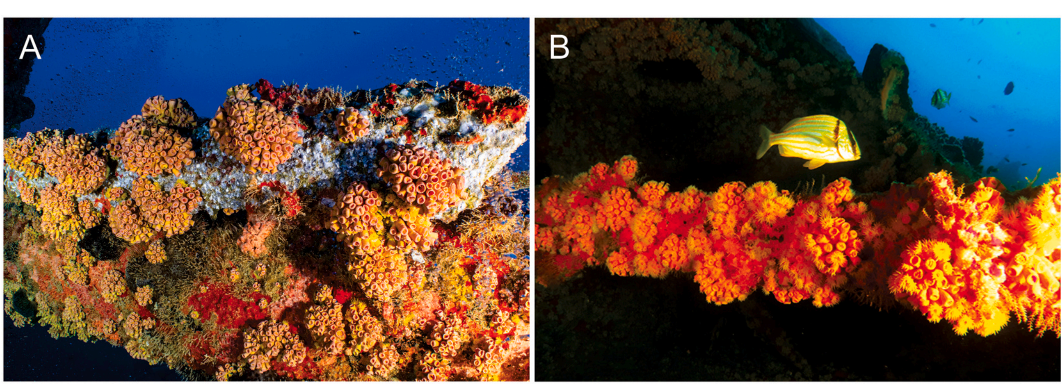

Fig. 2. Presence of the invasive coral *Tubastraea* spp. in the Brazilian semi-arid coast (Ceará coast, Southwest Equatorial Atlantic) that could act as donor/source area for litter-rafting invasive corals. A) Oil and gas rig with *Tubastraea* in 2021 (Paracuru, Brazil). Source: Alexandre Custódio; B) Shipwreck SS Eugene Thayer with *Tubastraea* in 2020 (Acaraú, Brazil). Source: Marcus Davis.

2.2. Numerical experiments (inter-and intra-annual dispersion)

To simulate the debris dispersion between the donor region (~2° S in Brazilian semiarid coast, at the Ceará State continental shelf waters) and two potential receptor regions (Amazon coast and the Wider Caribbean Region) (Fig. 1), we used 1/12° spatial resolution (approx. 8 km), daily mean currents data from the CMEMS PSY4QV3R1 Global Ocean Physics Analysis and Forecast (Mercator) produced by the Mercator-Ocean system (Lellouche et al., 2018) as the hydrodynamic source to the OpenDrift dispersion model. The Mercator model is a 50 vertical level (from 0 to 5500 m) eddy-resolving model that assimilates in situ and satellite observations and is forced by 3-hourly surface data from the ECMWF and climatological values for river discharge. The Mercator Model is widely used and already validated for the Atlantic Ocean (Lellouche et al., 2018; Teixeira et al., 2021; Lessa et al., 2021), which supports their application to test the hypothesis of long-distance pathways for litter-rafting corals. The currents for the first 200 m from surface, have been downloaded from the Copernicus website (https://data.marine.copernicus.eu).

The OpenDrift dispersion model (Dagestad et al., 2018) is a software package for modeling the trajectories and fate of objects or substances (e.g. oil drift and weathering, microplastics, larvae drift, etc) drifting in the ocean. It uses a Runge–Kutta fourth-order time-stepping method whereby particle positions were calculated based on circulation data provided by an ocean model. In our simulations we used the OpenDrift OceanDrift model that would represent neutral buoyancy marine debris. Virtual particles (i.e. marine debris biofouled with *Tubastraea*) were set to be stranded when it reached the continental coastline or islands. The coastline is represented using the Global Self-consistent Hierarchical High-resolution Geography, (GSHHG version 2.3.6) full resolution. We used a 60 min time step with no additional diffusion added to the trajectories. The OpenDrift is open source (available at https://github.com/OpenDrift/opendrift), and is programmed in Python. Neither winds nor waves have been used in the OpenDrift simulations.

Two sets of experiments were performed. In the first set of simulations, 5000 virtual particles representing the debris were released in a 1 km radius around the northernmost site of the invasive coral occurrence in Brazilian semiarid coast - Ceará state (Soares et al., 2018, 2020; Braga et al., 2021). Particles were released in the following 24 h after the 1st of January, March, August and December for 2018, 2019, 2020, and 2021 considering the likely non-existence (or non-reporting) of this coral in this Brazilian equatorial region before these years (Soares et al., 2018; Braga et al., 2021). This set of simulations will cover inter- and intra-annual variability of the circulation in the region in the first and second half of the years. The first half of the year is the rainy period in the region while the second is dry (lower precipitation). We conducted simulations for the months of January (beginning of the rainy season and minimum wind winds), March (peak rainy season), August (beginning of the dry season and high wind speed) and December (end of the dry season) to test different environmental and hydro-oceanic conditions. The trajectories for each particle were followed for 180 days using two hour outputs.

Tubastraea spp. was recently found in distinct types of marine and wood debris in Brazil such as a fishing buoy (expanded polystyrene), styrofoam fragments (expanded polystyrene), rope (nylon), electric cable (nylon), sandal (rubber), tree fragments (wood) and bottle (glass) (Mantellato et al., 2020). Most of these materials drift on the ocean surface between 0 and 1 m. However, due to differences in the debris density and the vertical mixing, the debris can be displaced along the water column. Therefore, three release depths (0, 1, and 10 m deep) were tested and the particle trajectories analyzed for each experiment. The vertical velocity of the particles was set to zero in the simulations and particles were only vertically displaced by the diffusivity, which was set to 1.2e-05 m/s. This will assure the particles will be vertically displaced a few millimeters around the release depths and the trajectories will show the advection at each depth. In total, we had 48 simulations (4 years × 4 months × 3 depths) for the first experiment. From this n (48) we calculated the percentage (%) of scenarios in which the particles stranded on the Amazon coast, in the WCR and in both regions to assess the potential risk of introduction in these marine areas. The number of scenarios in which particles remained only active (e.g., floating debris) and not stranded at any receptor region was also evaluated (n/48).

In the second set of experiments we used a continuous particle emission approach, where 100 particles were released per day at the same invaded site of the first experiment between 1st January 2018 and 31 December 2021 and trajectories followed for the next 180 days. This approach allows the determination of regions of larger transit of particles (i.e., litter-rafting corals) released under the most different oceanographic conditions during the period. The trajectories were gridded onto a 10 × 10 km grid cell to produce density maps. This experiment with a continuous particle emission approach is important since the particle's amount arriving at a location can serve as a *proxy* for propagule pressure. The propagule pressure is a measure of the number of individuals released into a non-native region (Lockwood et al., 2005). These density maps are calculated as the number of particles released during 2018, 2019, 2020, and 2021 passing through each 10 × 10 km grid cell during the 180 days after its release.

2.3. Data analysis

To assess the virtual stranded particles distribution percentage in the Amazon coast and the Wider Caribbean Region across three depth strata, and in 16 time scenarios (4 years × 4 months), a shade plot was produced by clustering the spatial dimension (i.e., region and depth) on the x-axis, with the temporal dimension (i.e., month and year) on the y-axis, based on Bray–Curtis similarity. A similarity profile permutation test (SIMPROF) was applied to determine the significance of the differences between the clusters and to identify groups of scenarios with similar patterns of virtual particles stranded in both temporal and spatial dimensions. These analyses were run in PRIMER version 7.0.11 with the PERMANOVA + add-on (Anderson et al., 2008).

3. Results and discussion

3.1. Models and statistical results

The 48 simulations showed the annual (2018–2021), monthly release, and depth (0, 1 and 10 m) variability in marine debris long-distance trajectories (Figs. 3 to 6). There are numerous cross-shelf and open sea routes of transport from the Brazilian semiarid coast (donor region) to the Amazon coast and the WCR (Figs. 3 to 6). For January (Fig. 3), March (Fig. 4), August (Fig. 5) and December (Fig. 6) we observed the dispersion of virtual particles (5000 initial particles) both towards the Amazon coast and the WCR with a possibility to be stranded or floating in these regions.

In <180 days, particles can cover long-distances ranging between 264 km (in ~8 days) and 7170 km (in ~180 days) from the equatorial SW Atlantic (Brazilian semiarid coast) before they strand on eight tropical receptor (sink/particles stranded on the coast) regions. Important sink regions include the Amazon (e.g., Fig. 3g, j, k), Southwestern Caribbean (e.g., Fig. 6h, k, j), the Western Caribbean (e.g., Fig. 6h, k, j), Florida (e.g., Fig. 6g, h), The Bahamas (e.g., Fig. 6d, g), the Eastern Caribbean (e.g., Fig. 3f, i, l), Southern Caribbean (e.g., Figs. 4h, 6h, k), and Greater Antilles (e.g., Figs. 3b, e, 4e).

Virtual particles released on all months/years at 0 and 1 m depth from the Brazilian semiarid coast reached and stranded on the Wider Caribbean (Figs. 3 to 6), except for three scenarios (e.g., January 2020 on Fig. 3g, h and December 2019 on Fig. 6d) when the particles were stranded in the Amazon coast (Table 1). A clear seasonality was present, with particles released during August, following the NBC retroflection and being transported for a shorter distance westward into the Caribbean Sea compared with the other release periods when the retroflection

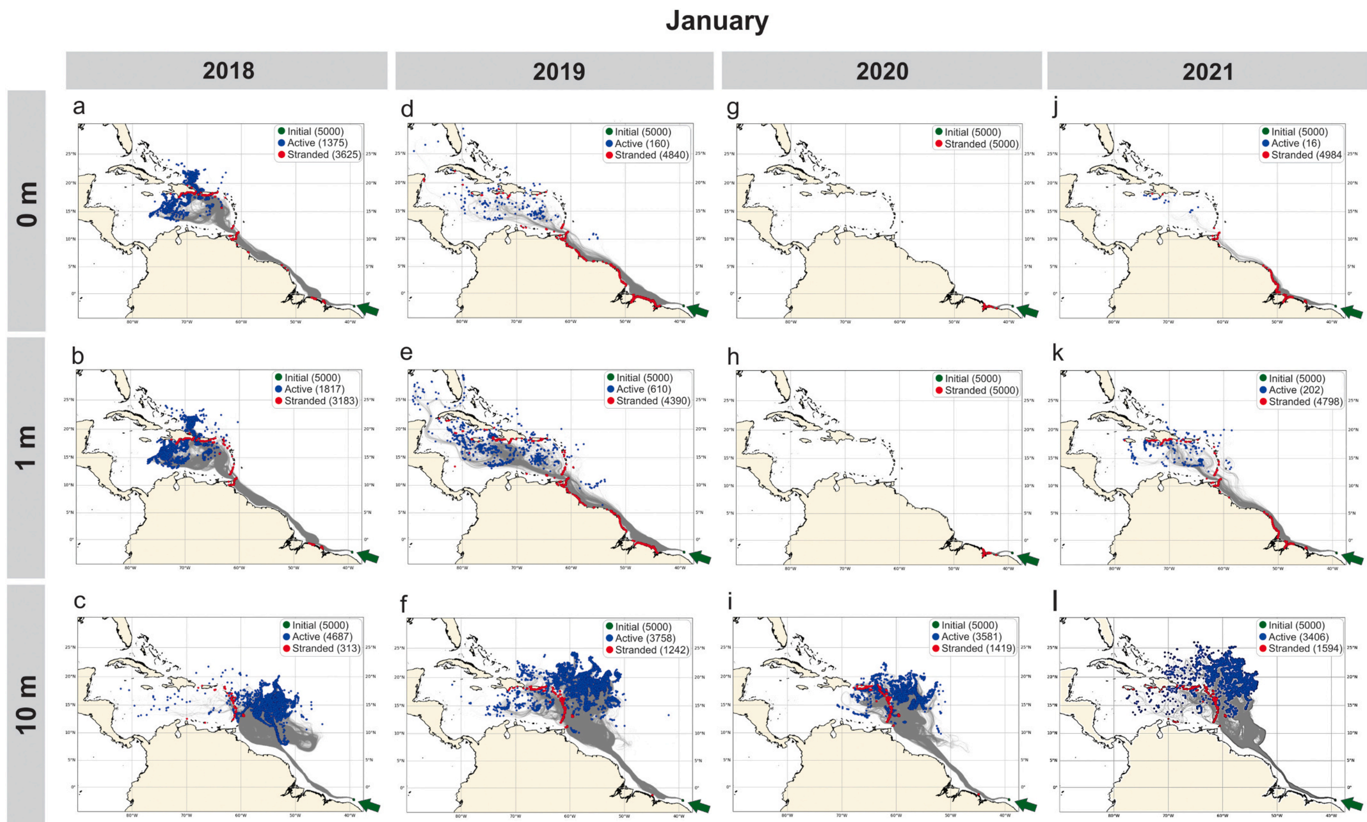

Fig. 3. Intra-annual and depth variation of virtual particles trajectory (i.e., litter-rafting *Tubastraea* spp.) released on the 1st of January 2018, 2019, 2020 and 2021. These particles are released at 0, 1 and 10 m depth and allowed to drift for 180 days. Green arrows indicate the particle release sites (Brazilian semiarid coast, Ceará Brazil - northernmost record of *Tubastraea* spp. in Southwestern Atlantic). Blue dots show the particles still active after 180 days of simulation. Red dots show particles stranded on the coast.

is not present and the particles are transported northwestward by the NBC, GC and CC.

The 48 simulated scenarios showed that particles arrived in the Caribbean in 85.4 % of the scenarios, while particles reached the Amazon in 70.8 % of the scenarios, and 8.3 % remained active, without stranding (Table 2). Furthermore, in most of the simulated scenarios (64.6 %) the virtual particles arrived in both the Caribbean and the Amazon. The number of scenarios where particles reached a single region such as the Caribbean (20.8 %) or the Amazon coast was smaller (6.3 %) (Table 2).

Inter-annual variability is indicated by the different trajectories considering both depths and months (Figs. 3 to 6). For example, in January 2018 and 2019 the particles released at the surface were transported further westward into the WCR (Fig. 3a, d). A few scenarios resulted in the transport to the Amazon coast, such as particles released at depths 0 and 1 m in January (2020) (Fig. 3g, h). Particles released on 1st of August in most years (2018, 2019, 2020) (Fig. 5) were not transported to the Amazon coast and were transported to the open ocean.

The particles released at a depth of 10 m in August (Fig. 5c, f, i) were transported back eastward by the NBC retroflection and washed out into the open ocean. Particles released at this depth were thus less likely to be transported to the Caribbean Sea or Amazon Coast. This is supported by the particle emission approach (Fig. 7) where a lower density of particles was transported to the Caribbean Sea when released at 10 m.

Our continuous particle release approach showed that debris density is highest along the Amazon coast and lower in the Caribbean region (Fig. 7). Particles released at the surface when offshore (out of the continental shelf) were dispersed over the longest distances and were transported mostly to the Caribbean Sea. Particles released at 10 m when offshore were concentrated at the region dominated by the NBC flow, its meso-scale activity (e.g., regions reached by eddies released by the NBC), and its retroflection area.

Considering the continuous release simulations, 62 %, 57 % and 11 % of all particles released within surface waters (i.e. 1–10 m) from January 1st 2018 to December 31, 2021 (n = 146, 100) ended up stranded in the northward receptor regions (Amazon and Caribbean coasts). The 2.5 %, 25 %, 50 %, 75 % and 97.5 % displacement percentiles for the stranded particles are 568 km, 1,107 km, 2,904 km, 3,586.46 km and 5,481.40, respectively. The same percentiles for the particles stranding age (time from the release to stranding) are 16, 40, 75, 110 and 172 days (Fig. 7).

Shade plot analysis demonstrates a separation of the months and years according to the stranding locations (i.e., Wider Caribbean and Amazon coast) (Fig. 8). We found a formation of significant groups according to SIMPROF analysis ($p < 0{,}05$) (Fig. 8). On the Amazon coast the percentage of stranded particles was higher than the Caribbean Sea, suggesting a higher propagule pressure in this region (Fig. 8). In December 2020 and 2021 there is a higher (compared to other months) percentage (%) of stranded particles suggesting a higher risk of invasion in both the Caribbean and Amazon coast (Fig. 8).

Our study estimated a previously unknown dispersal pathway for *Tubastraea tagusensis* and *T. coccinea* corals via rafting of anthropogenic marine debris. In <180 days, particles can cover distances between 264 and 7170 km moving from the equatorial Brazilian semiarid coast (donor region) to the Amazon coast and eight regions in the Wider Caribbean (receptor regions) (Figs. 3 to 7). Our results predict a high risk of bioinvasion of the Caribbean Sea and Amazon coast with the increase in floating marine debris. Currently, the Amazon coast is not affected by *Tubastraea* spp. invasion and the Caribbean Sea is not invaded by

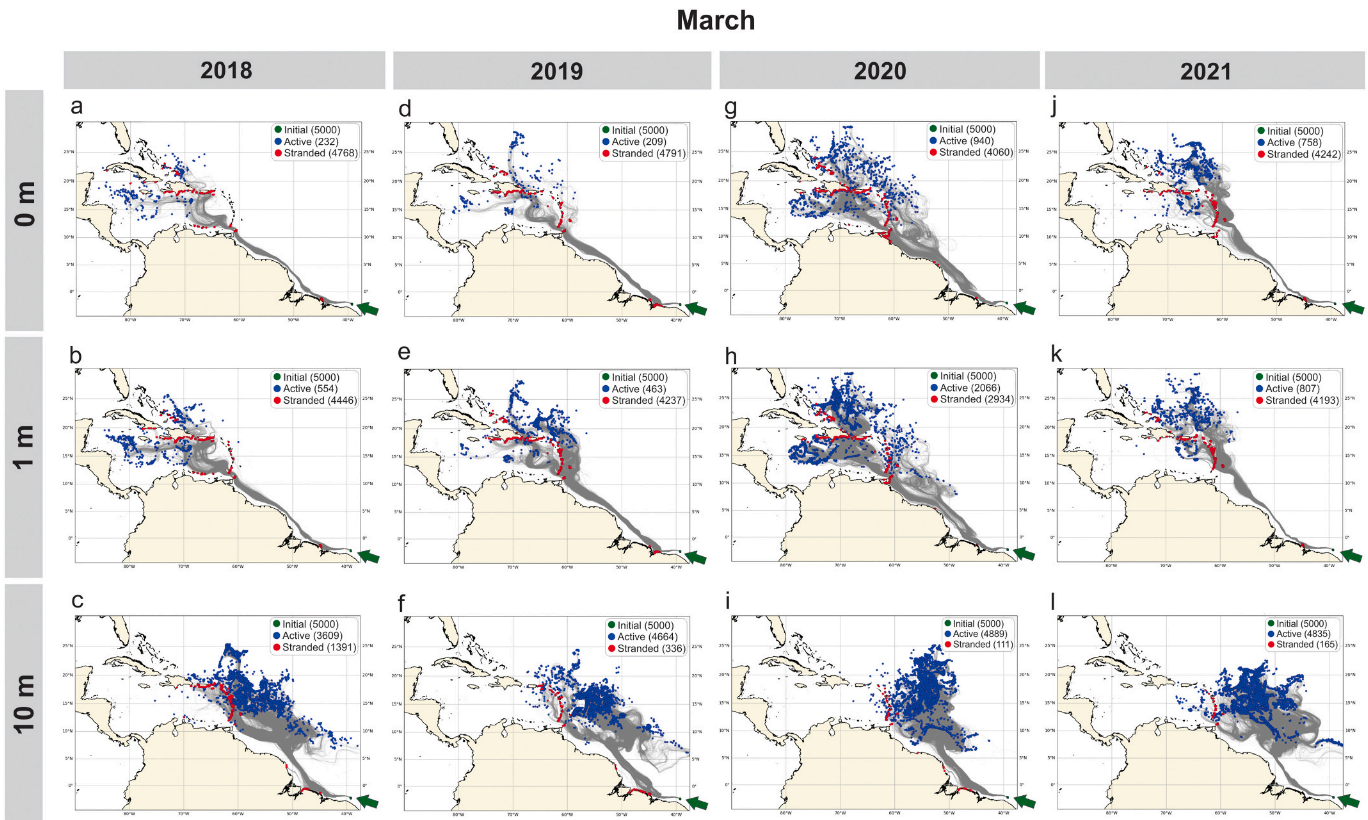

Fig. 4. Intra-annual and depth variation of virtual particles trajectory (i.e., litter-rafting *Tubastraea* spp.) released on the 1st of March 2018, 2019, 2020 and 2021. These particles are released at 0, 1 and 10 m depth and allowed to drift for 180 days. Green arrows indicate the particle release sites (Brazilian semiarid coast, Ceará Brazil - northernmost record of *Tubastraea* spp. in Southwestern Atlantic). Blue dots show the particles still active after 180 days of simulation. Red dots show particles stranded on the coast.

T. tagusensis. Although most (~86 %) of our scenarios or simulations (Figs. 3 to 6) showed dispersion towards the WCR, the amount of particles (density) reaching the Amazon is greater (Fig. 7) under the ~71 % of the scenarios. Therefore, the Amazon coast would be under greater propagule pressure (than the Caribbean Sea) by these rafting invasive species. This highlights the imperative need for an ocean governance shift in prevention, control, and eradication, not only focused on local actions to prevent the spread of invasive species but also a broad international action to decrease and mitigate marine debris pollution globally.

3.2. Anthropogenic marine debris as a new and long-distance pathway for invasive corals dispersion

Tubastraea spp. larvae from the Brazilian semiarid coast are unlikely to disperse naturally to the Caribbean Sea due to their short life span (14 to 100 days; according to Paula et al., 2014). However, the long-distance dispersion of larvae needs further study considering larval lifespan time frame (Coelho et al., 2022). Another way of *Tubastraea* dispersal between these two regions is through biofouling of ships, considering the intense maritime traffic in the Western Atlantic. This is unlikely because the invasive corals are sensitive to rapid water movements associated with modern ships and boats and are generally absent when compared to other fouling organisms (Creed et al., 2017; Capel et al., 2019). *Tubastraea* spp. have been observed to survive well on slow moving drill ships and objects (oil platforms and monobuoys) (Creed et al., 2017). In this sense, Creed et al. (2017) argued that the *Tubastraea* spp. were introduced in Rio de Janeiro in the mid-1980s through biofouling on oil platforms and/or drill ships, probably redeployed from Africa, the Gulf of Mexico or Indo-Pacific via the Straits of Magellan or the Cape of Good Hope.

In this context, our simulations (between 0 and 10 m depth) show a long-distance dispersion risk for floating materials with attached *Tubastraea* colonies (Figs. 3 to 7). Our numerical modeling approach shows that litter-rafting invasive adult colonies could travel large distances overcoming limitations of short lifespan of larvae and their vulnerability to high-velocity ships (Paula et al., 2014; Mantellato et al., 2020). Thus, the hypothesis of long-distance transport of rafting corals on marine debris to the Wider Caribbean and Amazon coast is supported. In addition, a recent analysis showed that marine debris (i.e., rubber bales) are carried by the NBC from the Ceará shelf (the same donor region) to the Caribbean region (Teixeira et al., 2021), and the Equatorial Atlantic continental coast could act as a donor area for rafting corals, starting a secondary invasion event in the Amazon coast and intensifying the invasion process to the WCR. In fact, around 17 % of the marine debris that enters the North Atlantic Ocean originates in the South Atlantic and it is mainly advected by the NBC-GC-CC system (Onink et al., 2019), thus increasing the likelihood of litter-rafting *Tubastraea*. Supporting this hypothesis and our numerical models, *Tubastraea* corals observed on rope debris entangled on an artificial reef in the Florida Keys suggest a real litter-rafting dispersal mechanism (Parsons et al., 2023). When invasive corals in marine litter arrive at a site, reproductive processes and larval production can occur that can lead to establishment in a new region (Mantellato et al., 2020).

The impacts of *Tubastraea* on marine biodiversity are well known in the literature and our research highlights a concern of possible invasion to unaffected tropical marine ecosystems. Studies showed that *Tubastraea* spp. dispersion success, range expansion, and invasiveness in the Atlantic Ocean were linked to biological characteristics such as asexual reproduction, competition strategies, early reproduction, high recruit

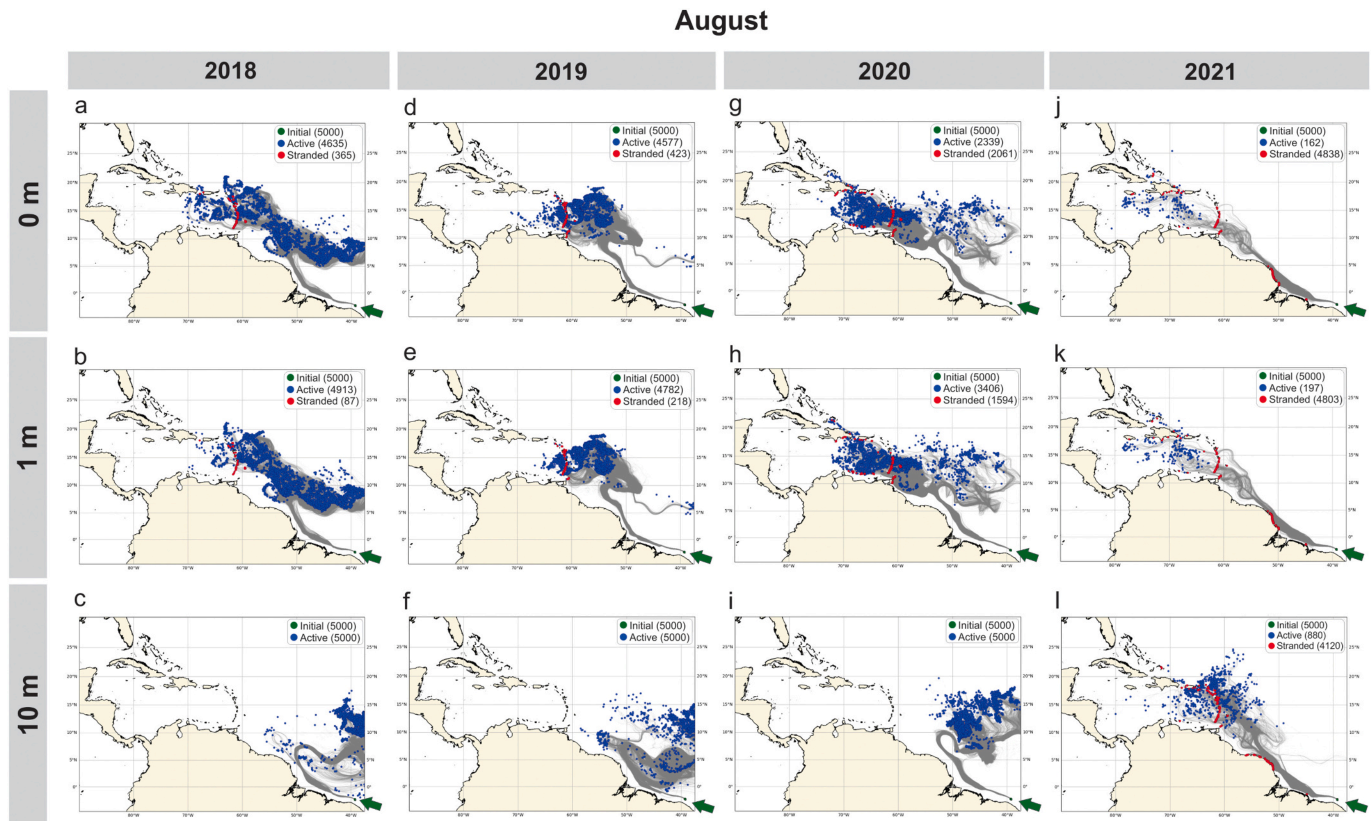

Fig. 5. Intra-annual and depth variation of virtual particles trajectory (i.e., litter-rafting *Tubastraea* spp.) released on the 1st of August 2018, 2019, 2020 and 2021. These particles are released at 0, 1 and 10 m depth and allowed to drift for 180 days. Green arrows indicate the particle release sites (Brazilian semiarid coast, Ceará Brazil - northernmost record of *Tubastraea* spp. in Southwestern Atlantic). Blue dots show the particles still active after 180 days of simulation. Red dots show particles stranded on the coast.

numbers, heterotrophic feeding, environmental plasticity, and high degree of competition against native species such as reef-building corals and sponges (Paula et al., 2014; Capel et al., 2017; Creed et al., 2017; Saá et al., 2020; Tanasovici et al., 2022). Further, *Tubastraea* has high suspension feeding rates, reproduces asexually, is resistant to variable environmental conditions (e.g., temperature), survives air exposure for short periods of time during low tides, early reproductive capacity, generalist substrate use including debris (Capel et al., 2017; Mantellato et al., 2020) and plasticity in modular growth despite hydrodynamic conditions (Tanasovici et al., 2022). Together they favor debris rafting as an additional and long-distance mechanism of dispersion to new receptor and sink regions investigated here.

3.3. The receptor regions of litter-rafting invasive species: Amazon and Caribbean as major sinks

The results shown here (Figs. 3 to 8) reinforce that marine debris may be a new, faster (<180 days), frequent (>65 % of simulations), and a rising factor in the dispersal of invasive species. This is of global concern considering the increase in marine debris in the oceans each year (including in the Latin America) (Ostle et al., 2019; Videla and Araujo, 2021; Stubbins et al., 2021) and also the introduction risk of *Tubastraea* spp. (Mantellato et al., 2020) into two of the most relevant shallow-water and mesophotic ecosystems on the planet: 1) the uninvaded Amazon reefs off the Northern coast of Brazil and French Guyana; and 2) the Wider Caribbean marine ecosystems; which already has both invaded and unaffected habitats.

The Amazon Reef System is an extensive mesophotic ecosystem (>56,000 m^2) that has already received non-indigenous species like the brittle star *Ophiothela mirabilis* (Moura et al., 2016) and recently the invasive lionfish *Pterois* spp. (Luiz et al., 2021). The shallowest region of the Amazon reefs (<100 m depth) is susceptible to invasion of *Tubastraea* spp. because this is a suitable depth to these azooxanthellate corals (Creed et al., 2017; Soares et al., 2018, 2020; Coelho et al., 2022). The Amazon coast presents habitat suitability (Moura et al., 2016; Francini-Filho et al., 2018) and has the highest risk (99.93 of 100) of invasion by *Tubastraea* due to favorable environmental conditions (Barreto, 2022). Although our models showed that dispersion is more frequent towards the WCR (Figs. 3 to 6), the amount of particles (density) reaching the Amazon is greater (Fig. 7). Therefore, the Amazon coast would be under greater propagule pressure.

Propagule pressure is a key element to understand why some introduced populations fail to establish whereas others succeed (Lockwood et al., 2005). Once established somewhere on the Amazon coast *Tubastraea* can disperse locally, including by larval stages (Coelho et al., 2022). In this context, the recent findings of ceriantharian larvae (*Isarachnanthus nocturnus*) on the Pará state coast (Lopes et al., 2023) suggest that anthozoan larvae may be transported to inner, coastal areas of the Amazon coast, from shelf waters as donors, since adult ceriantharians are unknown to occur for the region. This subject needs further investigation, since the larval lifespan of ceriantharians are longer than *Tubastraea* (Stampar et al., 2015).

The other susceptible systems are the shallow-water and mesophotic Caribbean habitats (especially on Eastern Caribbean, Southern Caribbean, and Greater Antilles), where the invasion process is already happening in some sites, mainly by *Tubastraea coccinea* and *T. micranthus* (Creed et al., 2017) and could be intensified by these litter-rafting corals such as *T. tagusensis* (one of the main species in donor areas in Brazil and not yet recorded in the Caribbean) (Creed et al., 2017). In fact, *Tubastraea coccinea* has a long history of invasion in shipwrecks (Hoeksema

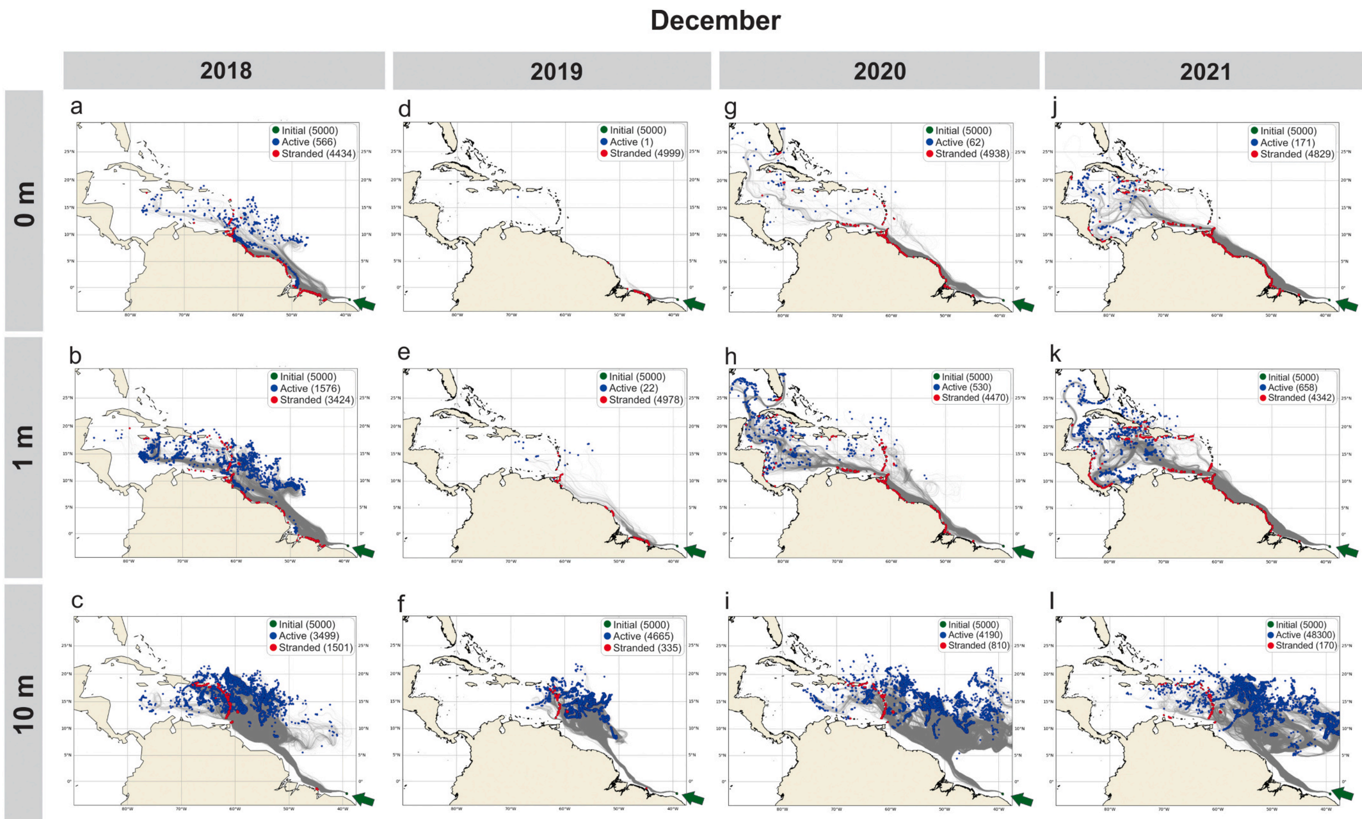

Fig. 6. Intra-annual and depth variation of virtual particles trajectory (i.e., litter-rafting *Tubastraea* spp.) released on the 1st of December 2018, 2019, 2020 and 2021. These particles are released at 0, 1 and 10 m depth and allowed to drift for 180 days. Green arrows indicate the particle release sites (Brazilian semiarid coast, Ceará Brazil - northernmost record of *Tubastraea* spp. in Southwestern Atlantic). Blue dots show the particles still active after 180 days of simulation. Red dots show particles stranded on the coast.

Table 1
Analysis of the 48 simulated scenarios (4 years × 4 months × 3 depths) and particles stranded in the Amazon (North Brazil/French Guiana) continental shelf (A), Wider Caribbean (C), or Wider Caribbean and Amazon (C-A). "W" represents the scenarios when the particles remain only active (e.g., floating debris) and without stranding. 48 simulations in Figs. 3 to 6. Jan = January, Mar = March, Aug = August, Dec = December.

	2018				2019				2020				2021			
Depth (m)	Jan	Mar	Aug	Dec	Jan	Mar	Aug	Dec	Jan	Mar	Aug	Dec	Jan	Mar	Aug	Dec
0	C - A	C - A	C	C - A	C - A	C - A	C	A	A	C - A	C	C - A	C - A	C - A	C - A	C - A
1	C - A	C - A	C	C - A	C - A	C - A	C	C - A	A	C - A	C	C - A	C - A	C - A	C - A	C - A
10	C	C - A	W	C - A	C - A	C - A	W	C - A	W	C - A	W	C	C - A	C	C - A	C

C - A Caribbean / Amazon; A Amazon; C Caribbean; W Without stranded

et al., 2023) and natural areas such as in shallow-water habitats below the tide line and in mesophotic environments (Hoeksema et al., 2019). Recently, *Tubastraea* corals observed on rope debris entangled on Florida artificial reefs indicate a litter-rafting dispersal mechanism in the Wider Caribbean Region (Parsons et al., 2023).

The Caribbean tropical marine ecosystem is already under human pressure from global warming, marine heatwaves, nutrient pollution, overfishing and extreme weather events (Karr et al., 2014; Hughes et al., 2018). In addition, invasive species such as *Pterois* spp. have been modifying the Caribbean reef communities (Arias-González et al., 2011; Goodbody-Gringley et al., 2019). The risk of invasive *Tubastraea tagusensis* and *T. coccinea* into uninvaded Caribbean habitats and reefs is another stressor that may have cumulative and synergistic impacts with existing ones described above. Furthermore, even after sinking, subsurface and seafloor material can often be transported to other areas after storms, strong wind or wave action in shallow waters (Mantellato et al., 2020) that can: 1) roll, skip or hop the material along the bottom; and/or 2) break, fragment and resuspend material to the sea surface (Mantellato et al., 2020).

To reach the WCR, litter-rafting *Tubastraea* corals must first pass through the Amazon coast, where the inner continental portion is affected by the Amazon River estuarine plume (Mahiques et al., 2019).

Table 2
Number of simulations/scenarios where the virtual particles were stranded in the Wider Caribbean, in the Amazon, Caribbean and Amazon, or being only active (not stranded) in each year (2018, 2019, 2020, and 2021). Based on the 48 simulations/scenarios presented in Figs. 3 to 6.

	Caribbean	Amazon	Caribbean/Amazon	Not stranded
2018	3	0	8	1
2019	2	1	8	1
2020	3	2	5	2
2021	2	0	10	0
Total	10	3	31	4
%	20.8	6.3	64.6	8.3

This low-latitude region is a porous and selective biogeographic barrier for marine biodiversity (Rocha, 2003; Tosetto et al., 2022), having structured speciation processes for some species and currently functioning as an important reef corridor (30-220 m deep) between South Atlantic and Caribbean fauna (Cordeiro et al., 2015; Moura et al., 2016; Francini-Filho et al., 2018).

Our results have distinct temporal scenarios. Overall, most of the transport of debris to the Caribbean can take place outside the continental shelf or on the shelf break in the second half of the year. Therefore, outside the influence of the estuarine plume for most of the time and, consequently, a reduced biogeographic barrier for litter-rafting invasive corals. For the few cases where the transport takes place on the inner shelf, we have two distinct situations: (1) the estuarine plume is intense mostly in the rainy season (first half of the year) and not during the dry period (second half of the year) (Prestes et al., 2018; Mahiques et al., 2019). Therefore, the "barrier" effect in the simulated scenarios for September to December (dry season) is diluted due to lower influence of freshwater flow and wider dispersion towards the Central Equatorial Atlantic (Molleri et al., 2010). Moreover, the widest plume dispersion in the shelf occurs from July to August (Molleri et al., 2010); and (2) for the few scenarios where transport takes place on the inner shelf in the months of January through April (Molleri et al., 2010), the reduction in salinity may act as a barrier to the litter-rafting invasive corals. The Brazilian equatorial region studied (semi-arid and Amazon coast) (Fig. 1) is affected by higher precipitation in the first five months of the year. However, Barreto (2022) using ecological modeling analysis indicated environmental suitability for *Tubastraea* in the Amazon shelf and the highest risk for invasion in the Brazilian coast even with salinities between 15.1 and 37.5 in the inner continental shelf (during the rainy season). Additional research on the biology and adaptation of *Tubastraea* spp. exposed to the environmental variability in areas under the influence of the estuarine plume are further needed to elucidate these scenarios.

Our results (Figs. 3 to 8) provide a numerical and validated modeling approach for evaluating not only *Tubastraea* corals but also other litter-rafting invasive species dispersion. The donor region in our study is a hotspot of bioinvasion with 26 introduced and 26 cryptogenic marine species (Soares et al., 2021). Among these litter-rafting invertebrates, some species are recognized as drivers of impacts such as the bivalves *Isognomon bicolor* and *Perna viridis*, and the bryozoan *Membraniporopsis tubigera* (Soares et al., 2021). The main marine rafting organisms identified to date worldwide were mollusks (23 %) and bryozoans (22 %) (Póvoa et al., 2021). In this regard, Pinochet et al. (2020) detected a strong preference of invertebrate larvae for plastics due higher and faster settlement in this substratum than on wood or concrete. This phenomenon also drives higher fitness and can potentially extend the distribution range of many invasive marine species as they are able to

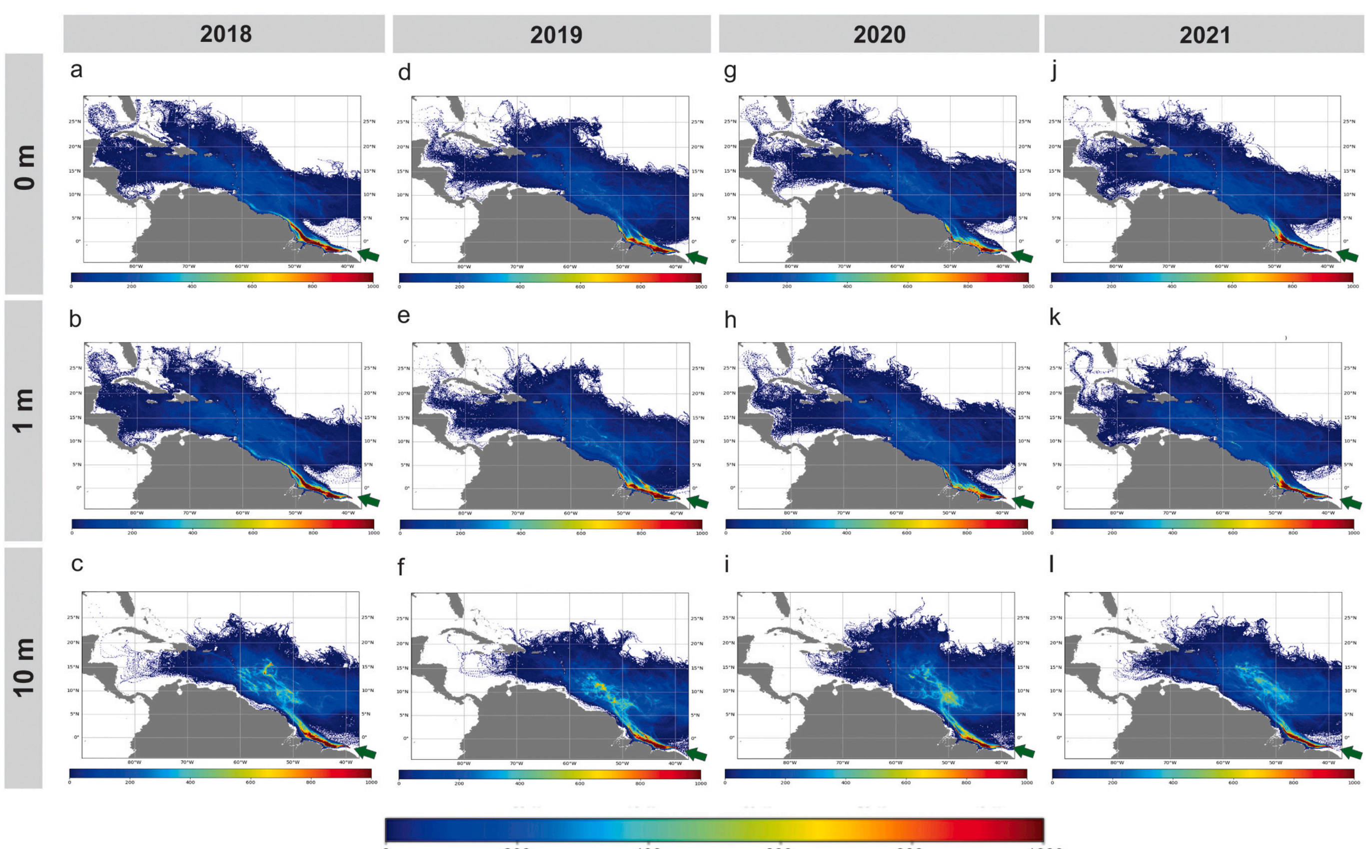

Fig. 7. Density maps showing the number of particles released during 2018, 2019, 2020 and 2021 crossing a 10 × 10 km grid cell. 100 particles were evenly released and trajectories followed daily for 180 days, between January 1, 2018, and June 30, 2021. Green arrows point to the release of the particles on the Brazilian semiarid coast (northernmost record of *Tubastraea* spp. in South Atlantic). Highest densities in yellow, orange, and red. Lowest densities in Blue and Green.

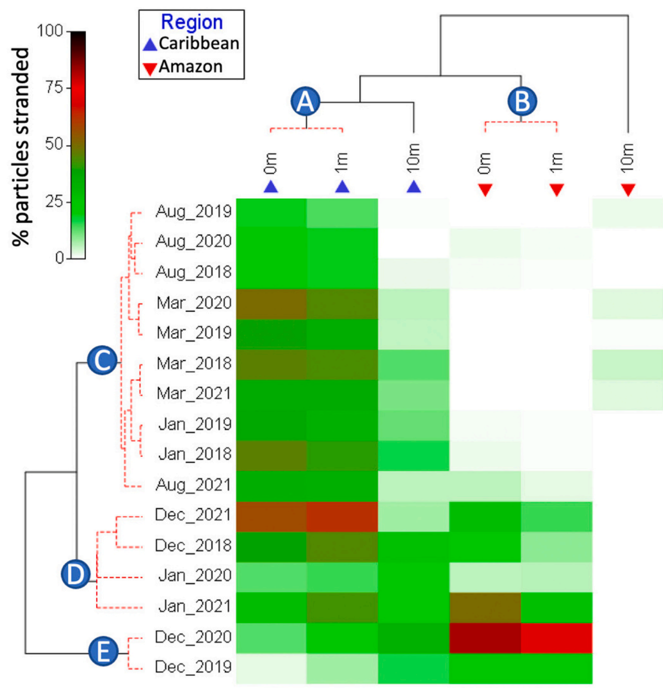

Fig. 8. Shade plot of the distribution of the number of the virtual particles (percentages) stranded in the Amazon coast and the Wider Caribbean Region across three depth strata (top dendrogram), and in 16 time scenarios (4 years × 4 months) (left cluster). The color gradient from green to black indicates the relative contribution (0–100 %) of the number of the virtual particles stranded. Significant groups (SIMPROF test) of scenarios are depicted with capital lettering on dendrograms and indicated with red dotted lines.

travel long distances attached to floating debris (Pinochet et al., 2020).

3.4. Models limitations and further research

Detailed studies of individual species and validated models contribute to our understanding of debris as a transport vector for litter-rafting invasive species and aid efforts to evaluate potential risks associated with marine debris (Maximenko et al., 2018; Miller et al., 2018). Despite the unprecedented advances of our study, future research is needed to improve the understanding of the association between marine debris and invasive species like *Tubastraea*. Since only daily average outputs of the Mercator model are available, semi-diurnal tidal currents are not represented, however the residual tidal currents are small in most of the shelf and almost zero in the deeper ocean. Wave driven Stokes drift is also not included in the simulations. Since coastal processes such as tides and wave driven stokes drift are an important component in the dispersion of marine debris in coastal zones (van Sebille et al., 2020), we emphasize that the results of this study close to the shore must be interpreted with the absence of these two processes in our simulations.

Plastic debris is heterogeneous in the ocean, varying in composition, shape and size. This, associated with other physical and biological processes (e.g., biofouling), can influence the transport and fate of plastics in the marine environment (Klink et al., 2022). Our numerical models represent litter-rafting invasive species traveling at different depths. Current numerical models allow the choice for density and size of marine debris (Lobelle et al., 2021) and are useful to simulate it for one or few cases. However, this type of scientific choice disregards numerous debris densities and sizes. For example, the styrofoam density (one of the materials where *Tubastraea* can travel according Mantellato et al., 2020) range is about 28–34 kg/m^3 and tends to stay close to the surface, while polyethylene terephthalate (PET) has a density (~1,350 kg/m^3) higher than sea water.

Large particles (diameter > 1 mm), made of buoyant plastic polymers (density range 800–1000 kg/m^3), remained between the surface and 10 m, while smaller particles were more easily entrained into deeper layers (Klink et al., 2022). Therefore, we opt to simulate buoyant materials that have densities that allow positive or neutral buoyancy and are transported in shallow ocean layers. In this regard, we keep particles advected at 0, 1, and 10 m (floating debris with positive or neutral buoyancy debris at 1 and 10 m).

We suggest that future studies analyze the risk of *Tubastraea* invasion using debris with different densities (e.g., fishing buoy, styrofoam, rope, electric cable, sandal, tree fragments and bottles according Mantellato et al., 2020). For example, the recent TrackMPD is specifically for plastics-debris paths at the sea (Baudena et al., 2022). Further studies also could focus on numerical models that evaluate the effect of the floating material densities on its vertical displacement and biofouling (Lebreton et al., 2012; Critchell et al., 2015). Finally, future biological studies can evaluate the effect of low salinity and macrotides (Prestes et al., 2018) in the Amazon River plume and the survival of adult *Tubastraea* colonies because this barrier is known to be porous, dynamic, and transient (Rocha, 2003; Tosetto et al., 2022).

4. Conclusions

Our novel results using numerical modeling indicate that marine debris provide a fast and seasonal route by spreading litter-rafting invasive species into one of the most scarcely known marine ecosystems of the world (Amazon coast) and intensifying the ongoing process into Caribbean coastal habitats. Accordingly, marine debris increase the invasion risk and provide long-distance pathways for the tropical coasts not only for the invasive corals analyzed here, but also other non-indigenous species, which underscores the importance of species-specific studies and management policies actions in the world's oceans.

The urgent policies suggested by Rech et al. (2016) should reduce litter production worldwide, control donor areas (such as those analyzed in this article) and protect potential sinks and receptor regions. Plastic debris and other floating marine litter endanger severely unknown and vulnerable ecosystems such as the tropical reefs discussed here. This highlights the imperative need for a paradigm shift in prevention, control, and eradication not only focused on local and national actions against invasive species but also a broad international and coordinated action to decrease and mitigate the presence of marine debris on world's oceans in the United Nations Decade of Ocean Science for Sustainable Development (2021–2030).

CRediT authorship contribution statement

Marcelo O. Soares: Conceptualization, Writing – original draft, Writing – review & editing, Formal analysis, Methodology, Supervision. **Tatiane M. Garcia:** Writing – original draft, Writing – review & editing, Formal analysis. **Tommaso Giarrizzo:** Writing – original draft, Writing – review & editing, Formal analysis. **José Eduardo Martinelli Filho:** Writing – original draft, Writing – review & editing, Formal analysis. **Tallita C.L. Tavares:** Writing – original draft, Writing – review & editing, Formal analysis. **Patrizia Ziveri:** Writing – original draft, Writing – review & editing, Formal analysis. **Tyler B. Smith:** Writing – original draft, Writing – review & editing, Formal analysis. **Sonia Bejarano:** Writing – original draft, Writing – review & editing, Formal analysis. **Carlos Eduardo Peres Teixeira:** Conceptualization, Writing – original draft, Writing – review & editing, Formal analysis, Methodology, Supervision.

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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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.

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