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Baseline

Non-native coral species dominate the fouling community on a semi-submersible platform in the southern Caribbean

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ABSTRACT

A coral community was examined on a semi-submersible platform that was moored at the leeward side of Curaçao, in the southern Caribbean, from August 2016 until August 2017. This community included several non-native or cryptogenic species. Among them were two scleractinian corals (*Tubastraea coccinea* and *T. tagusensis*) and two octocorals (*Chromonephthea* sp. and an unidentified Nephtheidae sp.). This is the first reported presence of *T. tagusensis* in the southern Caribbean, and the genus *Chromonephthea* in the Caribbean region. An ascidian, *Perophora* cf. *regina*, is also reported from the southern Caribbean for the first time, as well as a coral-associated vermetid gastropod, *Petaloconchus* sp., first recorded in the Caribbean in 2014. Lack of biofouling management could potentially harm indigenous marine fauna through the introduction of non-native species. Therefore monitoring communities associated with semi-submersible platforms is essential to track the presence and dispersal of non-native, potentially invasive species.

Ship-hull biofouling is a common vector for the transport of marine benthic organisms and responsible for species introductions in coastal areas around the world (Hewitt et al., 2009; Farrapeira et al., 2011). Moving oil platforms also facilitate the long-distance dispersal of benthic organisms (Ferreira et al., 2006; Page et al., 2006; Wanless et al., 2010; Friedlander et al., 2014), including tropical corals (Costa et al., 2014; Miranda et al., 2016; López et al., 2019). Many coral species attach easily to sunken or floating metal surfaces, such as ship hulls, shipwrecks, docks, buoys, gas tanks, and oil/gas platforms (Gass and Roberts, 2006; Yeo et al., 2010; Hoeksema et al., 2012, 2023; Kolian et al., 2017; Samimi-Namin et al., 2022; Serrano et al., 2023), where they can form artificial reefs when metal structures remain stationary for substantial periods of time (months to years), such as for example in the case of shipwrecks or oil/gas platforms operating or undergoing maintenance (Bieler et al., 2017; Bull and Love, 2019; Ilieva et al., 2019; van Elden et al., 2019; Monchanin et al., 2021; Torquato et al., 2021).

As ships and platforms also traverse the globe, the benthic communities they acquired start moving as well, often moving species outside their native ranges where they can potentially establish themselves within local, native communities (Sammarco et al., 2004; Wanless et al., 2010; Pajuelo et al., 2016; López et al., 2019; Derouen et al., 2020; Braga et al., 2021; Soares et al., 2020; Coelho et al., 2022).

Scleractinians of the genus *Tubastraea* Lesson, 1820 (Dendrophylliidae) are the best documented examples of coral species that were introduced from the Indo-Pacific to the West Atlantic. They now inhabit coastlines from Georgia (USA) and the northern Gulf of Mexico down to southern Brazil (Creed et al., 2017). The first *Tubastraea* species that established itself in the Caribbean was the orange cup coral,

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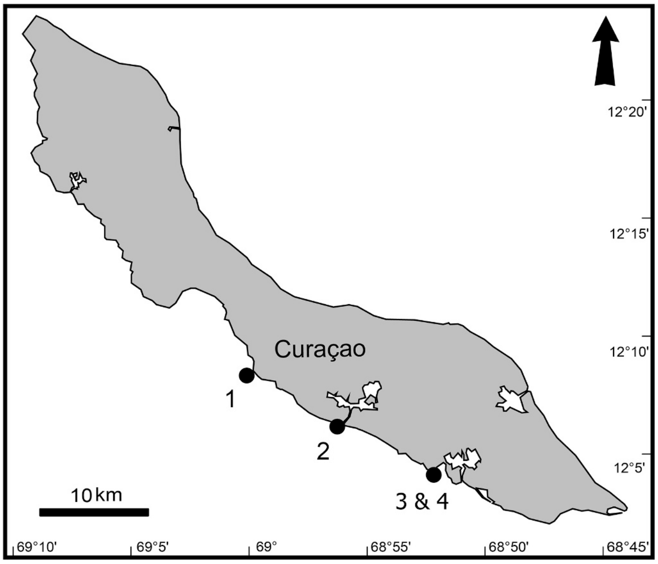

Fig. 1. Localities at the leeward side of Curaçao where semi-submersible platforms are berthed: (1) mooring buoy at Boca Sami, St. Michiel's Bay (12.14719°N, 69.00058°W); (2) two large piers (Megapier 1 and 2) (12.10438°N, 68.94180°W; 12.10556°N, 68.94541°W); (3,4) two piers at the eastern side of Caracas Bay (12.07260°N, 68.86322°W; 12.06938°N, 68.86227°W).

T. coccinea Lesson, 1829, which was first noted in Curaçao and Puerto Rico in the 1930s (Boschma, 1953; Cairns, 2000), implying that at that time the species was already widely distributed in its non-native range. It continued to spread rapidly afterwards and within two decades it had become very common on natural and artificial substrates in shallow water in Curaçao and its neighboring islands Aruba and Bonaire (Boschma, 1953). This was due to its ability to settle on a wide variety of substrates such as concrete, plastics, glass, rubber, metal, and wood (Vermeij, 2006; Ho et al., 2017; Hoeksema and Hermanto, 2018; Faria and Kitahara, 2020; Mantelatto et al., 2020). In Curaçao, *T. coccinea* – initially identified as *T. aurea* (Quoy & Gaimard, 1833) and *T. tenuilamellosa* (Milne Edwards & Haime, 1848) – now occurs, locally abundantly, on limestone rock, shipwrecks, and other artificial substrates along the leeward coast of the island (Boschma, 1953; Roos, 1964; Hoeksema et al., 2019). No other *Tubastraea* species have been reported from Curaçao since the arrival of *T. coccinea*. Other *Tubastraea* species have, however, been introduced elsewhere in the Western Atlantic region, such as *T. tagusensis* Wells, 1982. This species has been found in Brazil since 2000 (de Paula and Creed, 2004; Capel et al., 2019) and in the northern Gulf of Mexico since 2015 (Figueroa et al., 2019). A third introduced *Tubastraea* species, *T. micranthus* (Ehrenberg, 1834), has been reported from oil rigs in the northern Gulf of Mexico since 2006 (Sammarco et al., 2014; Creed et al., 2017). It was believed that there was a fourth introduced *Tubastraea* species in Brazil, with wider and shorter polyps than *T. coccinea* (Figueroa et al., 2019; Alidoost Salimi et al., 2021), but molecular analyses later identified this species as a morphological variety of *T. coccinea* (Bastos et al., 2022). In addition to the three non-native *Tubastraea* species, there is a fourth scleractinian that could have been introduced in the West Atlantic by ship-hull biofouling, which is the cryptogenic coral *Oculina patagonica* de Angelis, 1908, recorded near a harbor in the southern Gulf of Mexico in 2017 and originally discovered in the Mediterranean Sea (Colín García et al., 2018).

In addition to calcifying coral species, three octocoral species are considered introduced or cryptogenic in the West Atlantic. The first, *Carijoa riisei* (Duchassing & Michelotti, 1860), has already been reported in the Caribbean since 1860 (Bayer, 1961). Based on molecular studies it is considered cryptogenic; implying that it may have been introduced in the Caribbean by vessel fouling already before its initial description in the 19th Century. It is now also known to occur in the Central Pacific since 1972, the East Pacific since 2009, and the East Atlantic since 2011 (Concepción et al., 2010; Sánchez and Ballesteros, 2014; Quintanilla

Fig. 2. Coral reef areas where the *Safe Regency* was recorded: Cantarell Field (1997–2016), Aruba (the 2nd quarter of 2016), and Curaçao (August 2016–August 2017 Q3).

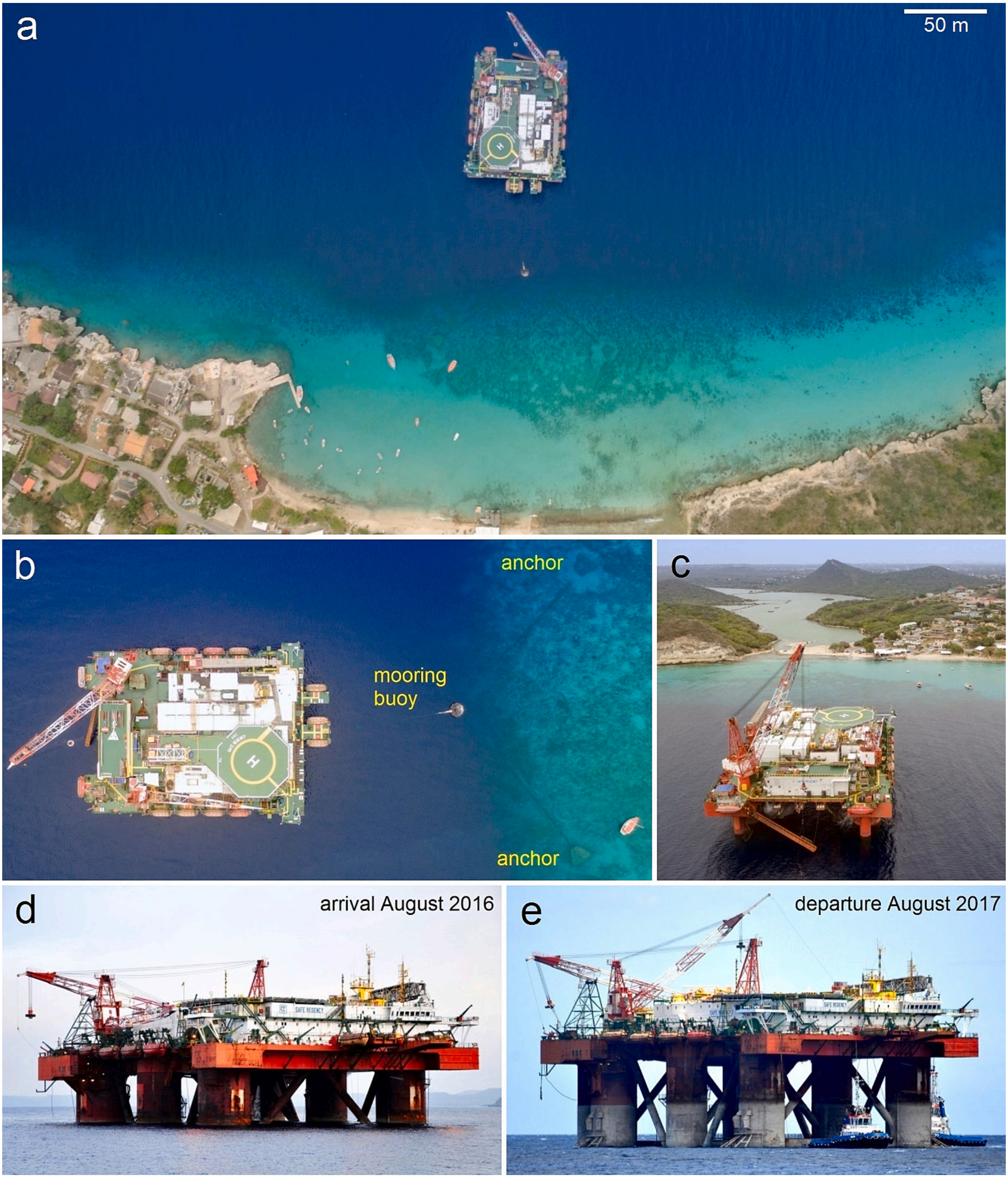

Fig. 3. The platform *Safe Regency* at the mooring buoy of Boca Sami, Curaçao. (a–c) Aerial views by drone (April 2017), showing proximity to the reef. (d) View from the shoreline (12.14704°N 68.99903°W; August 2016) showing the platform's lowered position in the water column immediately after arrival. (e) Similar view just before its departure in August 2017, showing the platform's raised position after de-ballasting, indicated by the grey sections above the water line.
Photo credits: (a–c) F. Ermert (Dronepicr; CC-BY-2.0); (d, e) C. Bustraan (ShipSpotting.com).

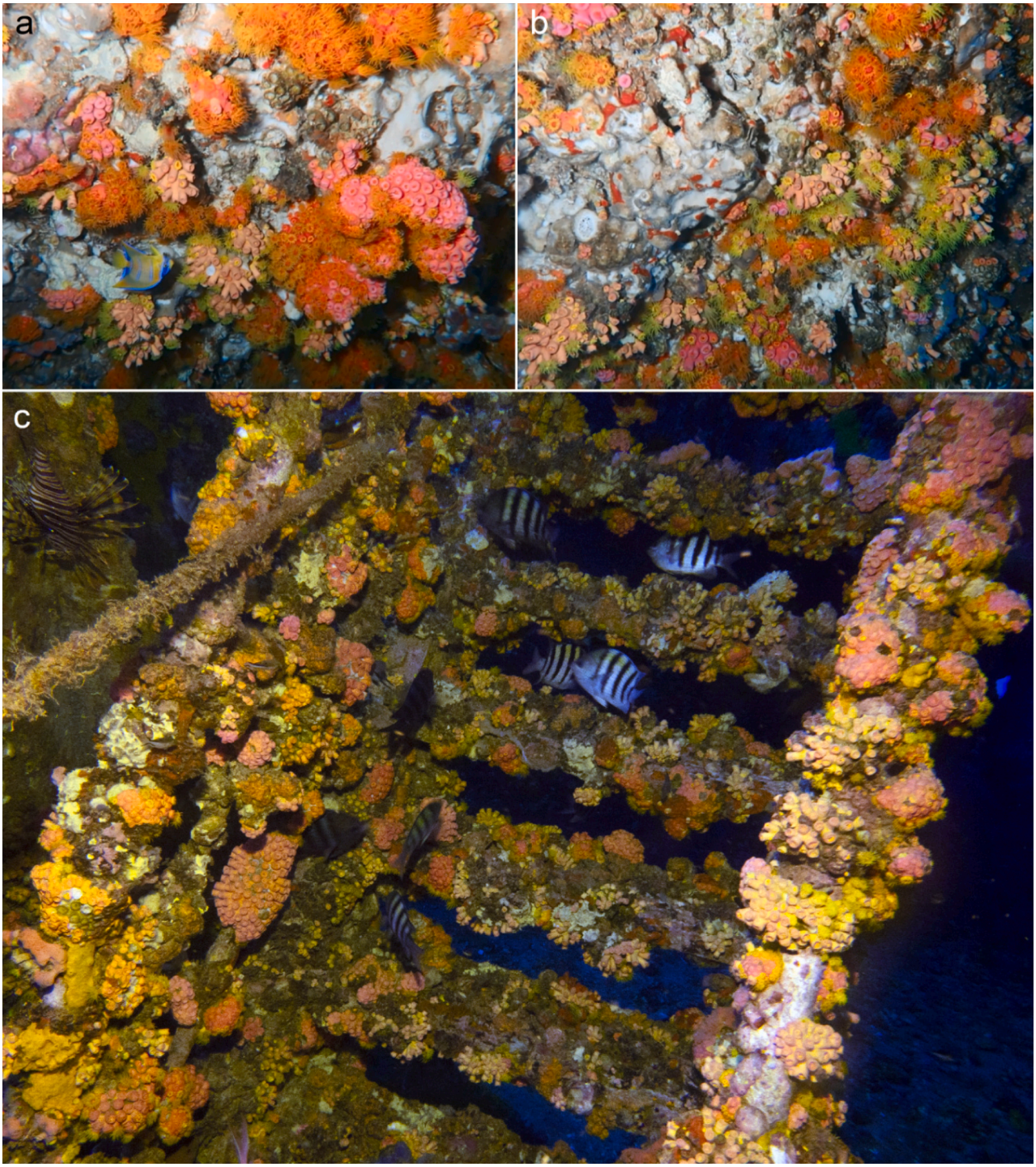

Fig. 4. Impressions of the well-developed fouling coral community dominated by *Tubastraea* spp. on the submerged sections of the platform *Safe Regency* in Curaçao (April–May 2017).
Photo credit: J. Bruijninckx.

et al., 2017; Lopes et al., 2021). *Carijoa riisei* is common on man-made structures, such as pier pilings, shipwrecks, and oil/gas platforms (Coles and Eldredge, 2002; Gracia et al., 2021; de Pádua et al., 2022), where it can overgrow native coral and oyster communities (Kahng and Grigg, 2005; Normah et al., 2021). The second non-native octocoral in the West Atlantic belongs to the genus *Chromonephthea*, which is native to the Indo-Pacific. The cryptogenic species *C. braziliensis* van Ofwegen, 2005, originally misidentified as *Stereonephthya* aff. *curvata* (Kükenthal, 1911), was discovered on sand and rubble in shallow bays near Rio de Janeiro, Brazil, where it was assumed to be introduced by visiting oil platforms (Ferreira, 2003; van Ofwegen, 2005). The third cryptogenic non-native octocoral species found in the West Atlantic is *Stragulum bicolor* van Ofwegen & Haddad, 2011, a species frequently found on ship hulls and other artificial substrates (Bumbeer and da Rocha, 2016; Altvater et al., 2019; Samimi-Namin et al., 2022; Hoeksema et al., 2023). The introductions of these three octocoral species in the West Atlantic

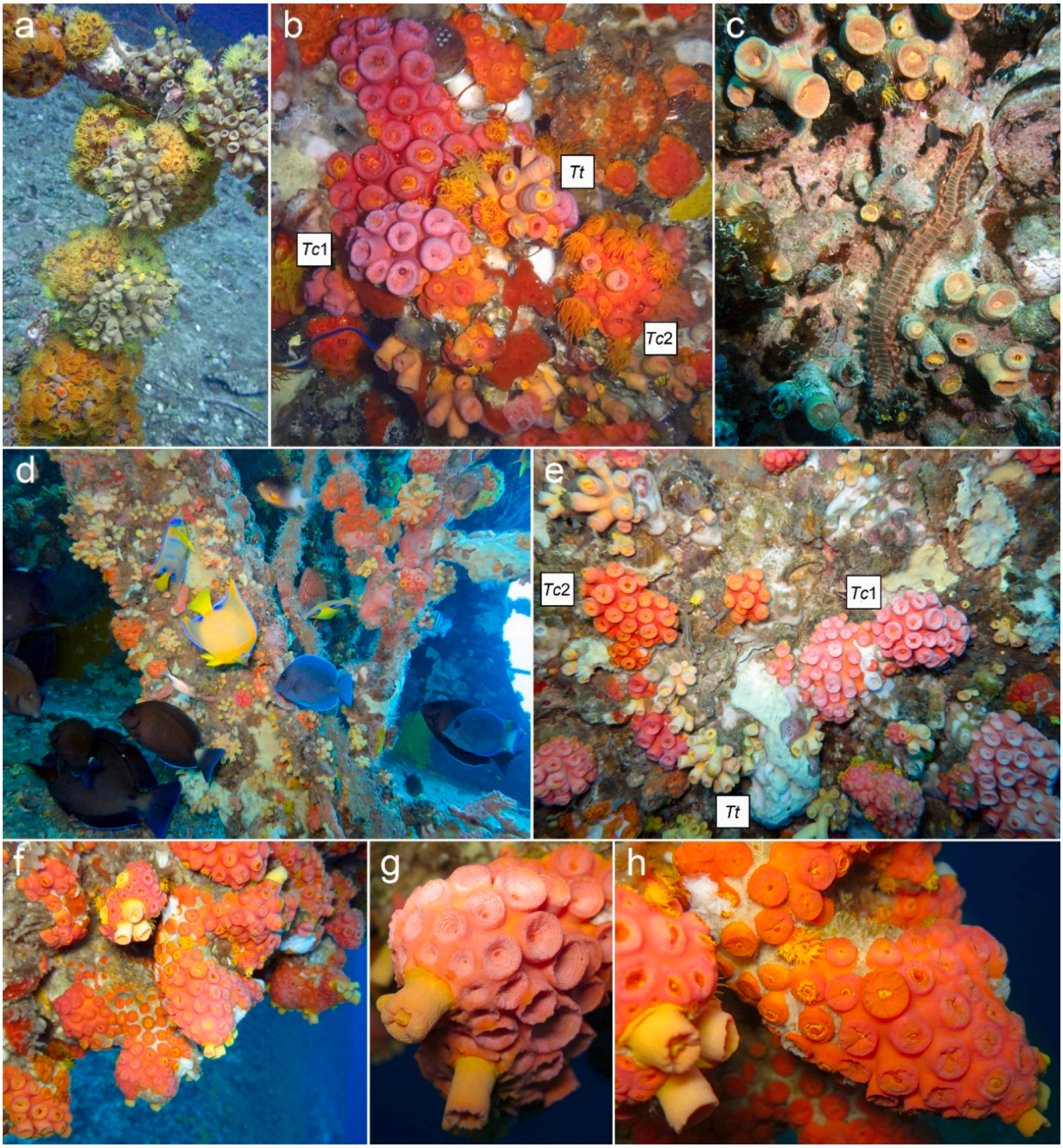

Fig. 5. Morphotypes of *Tubastraea* on the platform's submerged sections, March 2017. (a) *T. tagusensis* [Tt]; (b, d, e) *T. coccinea* morphotypes 1 [Tc1] and 2 [Tc2], and *T. tagusensis*; (c) a corallivorous worm, *Hermodice carunculata*, crawling over *T. tagusensis* corals; (f–h) fusion of *T. coccinea* morphotype 2 with polyps of *T. tagusensis*.
Photo credits: (a–c) T. Weber; (d–h) M.J.A. Vermeij.

have all been linked to hull biofouling. In addition, there are also some octocorals that have been introduced here through the international aquarium industry, such as species of the Indo-Pacific genera *Latissimia*, *Sarcothelia*, and *Unomia* (Mantelatto et al., 2018; Ruiz-Allais et al., 2021; Menezes et al., 2022; de Carvalho-Junior et al., 2023; Lolis et al., 2023).

Semi-submersible platforms are thus often identified and proposed as vectors for the introduction of non-indigenous marine species in the Caribbean and elsewhere in the world (Apolinario and Coutinho, 2009). These platforms can travel long distances, either self-propelled or towed by tugboats (Wanless et al., 2010; Speight, 2015; Orimolade et al., 2018), although most of the time they are stationary, when they are on active duty in an oil field, anchored offshore, or berthed near shore for e.g., maintenance and repairs. Many of such platforms visit Curaçao (12°N, 69°W) for e.g., assemblage, maintenance, bunkering, crew changes, or to prepare for its final voyage to a ship scrapping yard (Table S1). Curaçao has four berthing sites for visiting platforms, which are located in deep water due to the island's steep reef slopes: a large mooring buoy 175 m from the shore in St. Michiel Bay, two large piers (Megapier 1 and 2) near the island's capital Willemstad and primarily used to dock cruise ships, and two piers in Caracas Bay (Fig. 1; Appendix S1). Megapier 1 and 2 are used for short-term berths of platforms when there are no cruise ships. The other three localities are used for long-term mooring of platforms for up to 1 year (Table S1).

This study concerns the semi-submersible platform *Safe Regency*

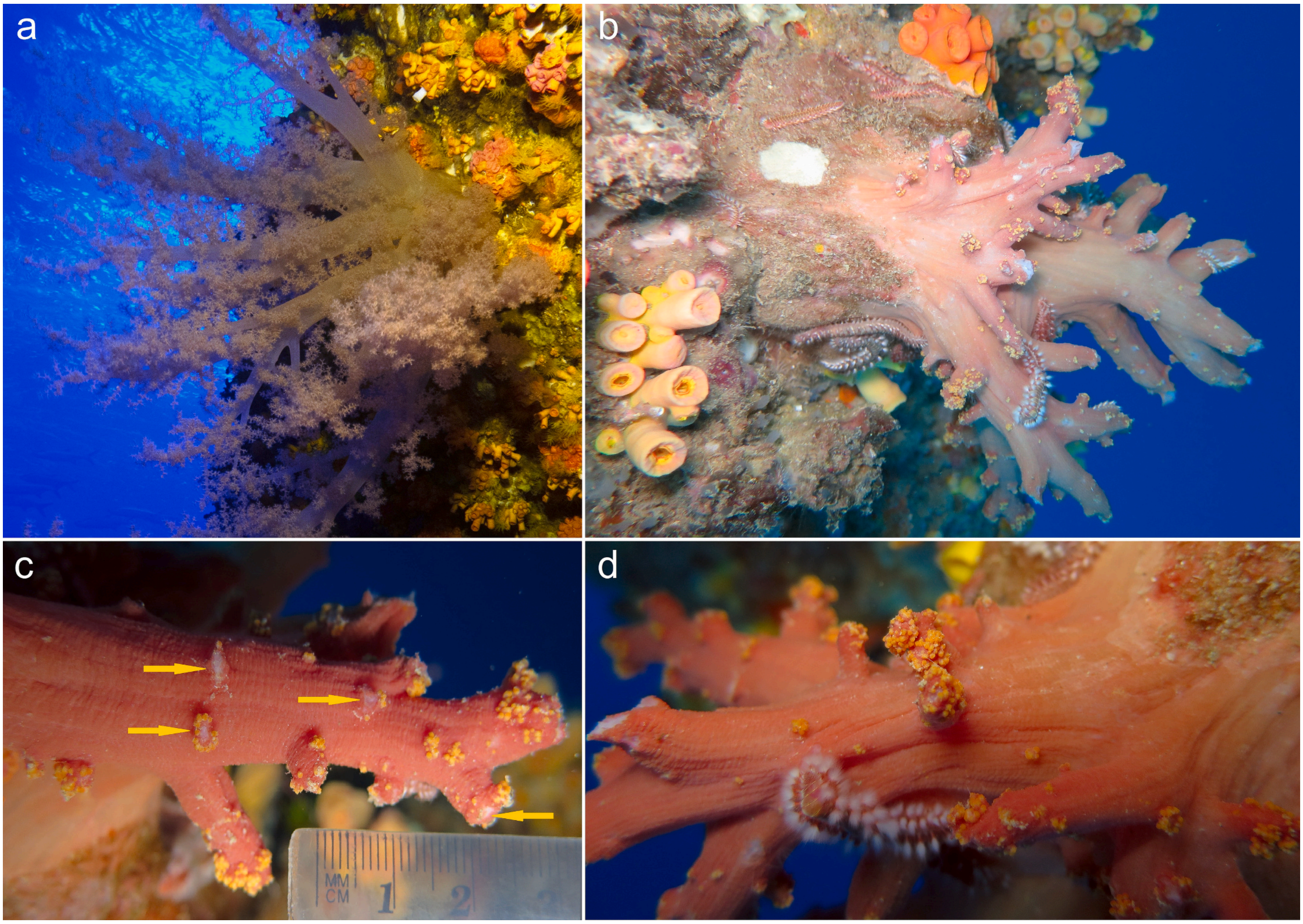

Fig. 6. *Chromonephthea* sp. on the platform *Safe Regency* in Curaçao, March 2017. (a) Coral and polyps extended. (b, d) Overview and close-ups of a single colony, stalk and polyps retracted, covered by several individuals of the native corallivorous worm *Hermodice carunculata*, causing predation injuries (c: arrows). Photo credits: (a) J. Bruijninckx; (b–d) M.J.A. Vermeij.

(IMO 8758835), which served as an accommodation vessel ('flotel' or 'floatel') in offshore oil fields and visited Curaçao for a year-long lay in 2016 and 2017. It was built in 1982 as the *Safe Felicia*, after which its name was changed two times (Appendix S2). It served in the northern North Sea in 1988–1994 as *Safe Felicia* and as *Port Regency*. In 1997 it was renamed *Safe Regency* and moved to the Cantarell Field in the southern Gulf of Mexico, where it operated two decades (Fig. 2). In the 2nd quarter of 2016 it was temporarily anchored off the leeward coast of Aruba, ca. 100 km to the west of Curaçao, after which it was moved to Curaçao (Fig. 2) and stayed there from August 2016 to August 2017 (Table S1; Fig. 3) before it was sold as scrap for demolishing in Turkey (Appendix S2).

In Curaçao, the *Safe Regency* was moored in close proximity (ca. 60 m) to a dive site in the bay of Boca Sami (Fig. 3). In contrast to other platforms that are moored in non-accessible locations (such as secure harbors and offshore oil fields), the fouling fauna on the *Safe Regency* could relatively easily be explored due its location near an existing dive site. Multiple dives were made in 2017 on March 2nd, March 27th, and May 31st, to photographically document and to sample the coral community on the platform down to its maximum depth of 19 m. Video footage (taken April 26th and May 7th) showed that parts of the platform were fully covered by a fouling community that had formed a 2-dm thick crust on most of the underwater surfaces of the *Safe Regency* (Fig. 4; Videos 1, 2). Before departure, the platform was raised for safe transport through de-ballasting (Fig. 3d, e).

Tubastraea tagusensis and two different morphotypes of *T. coccinea* (*sensu* Bastos et al., 2022) occurred abundantly on the platform and were sampled for morphological analysis (Fig. 5; Appendix S3: Fig. S5). The dark pink *T. coccinea* morphotype-1 (Fig. S5a–c) had placoid, wide polyps with much space between them, whereas the orange *T. coccinea* morphotype-2 (Fig. S5d–f) was also placoid but had narrow polyps with little space between them. *Tubastraea tagusensis* (Fig. S5g–i) was primarily identified based on its yellow coloration and phaseloid (long) polyps (Fig. S5i). Some *T. coccinea* morphotype-2 colonies were encountered with *T. tagusensis* polyps integrated within them (Fig. 5f–h). The present record of *T. tagusensis* is the first one for the Caribbean Sea as West Atlantic records till now had only been obtained from Brazil (Creed et al., 2017) and the northern Gulf of Mexico (Figueroa et al., 2019).

Based on morphological and molecular examination (Appendix S3: Figs. S6–9) one octocoral species could be identified as *Chromonephthea* sp. at the genus level (Fig. 6). A more precise morphological identification of the specimens was not possible due to extensive damage by corallivorous worms at the time of collection. Moreover, another nephtheid species was present, but its exact identity remains uncertain because it was not sampled (Fig. S10). Molecular and SEM analyses indicated that this *Chromonephthea* sp. differs from *C. braziliensis*, which so far has only been reported from natural substrates along the coastline of Brazil and as biofouling species on oil rigs and vessels (Oliveira and Medeiros, 2008). It also differs from the West Atlantic soft coral *Neospongodes atlantica* Kükenthal, 1903 (Fig. S7), which belongs to the same family as *Chromonephthea* sp. and is native to Brazil, where it has been observed at depths over 10 m in proximity to sandy bottoms (Cordeiro

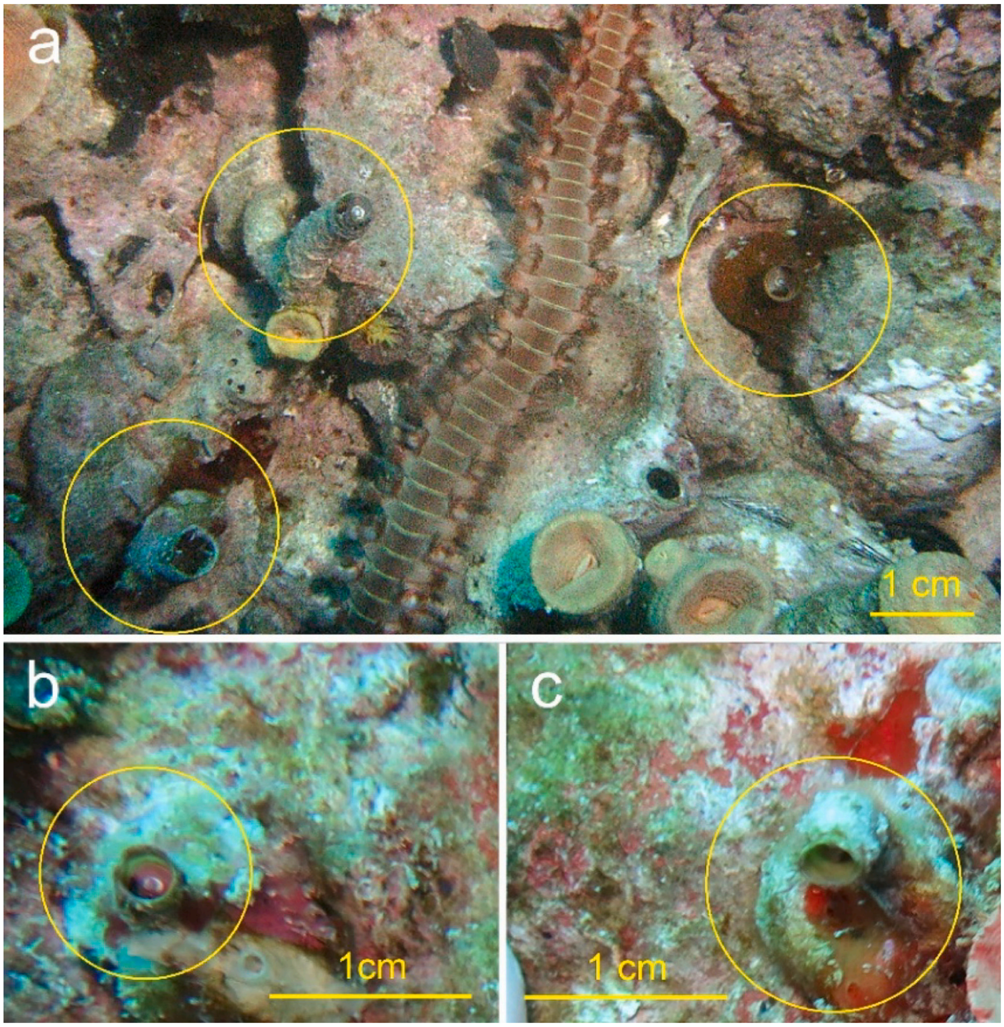

Fig. 7. The cryptogenic coral-associated worm snail *Petaloconchus* sp. in association with *Tubastraea tagusensis* on the *Safe Regency* in Curaçao, March 2017. Photo credits: (a) T. Weber; (b, c) M.J.A. Vermeij.

et al., 2022).

A perophorid ascidian encountered on the platform (Fig. S11) resembles *Perophora regina* Goodbody & Cole, 1987. This species was originally described from Belize in the western Caribbean where it grows on mangrove roots (Goodbody and Cole, 1987; Goodbody, 1994). Since then, it has been reported from southern Brazil (Rocha and Faria, 2005; Rocha et al., 2005) and North Carolina, USA (34.49967°N, 76.89817°W; obis.org). The presence of *P. regina* on the *Safe Regency* would be the species' first record in the southern Caribbean. The fact that the species arrived in the southern Caribbean is furthermore corroborated by the fact that it was never encountered during earlier surveys in the region (Millar and Goodbody, 1974; Goodbody, 1984a, 1984b; Rocha et al., 2010).

The dense, non-native coral assemblage on the platform hosted a variety of native reef organisms, such as the arrow crab *Stenorhynchus seticornis* (Herbst, 1788) (Fig. S10b), the coral-dwelling Christmas tree worm *Spirobranchus giganteus* (Pallas, 1766) (Appendix S3: Fig. S12), and the bearded fire worm *Hermodice carunculata* (Pallas, 1766), which was observed feeding on colonies of *T. tagusensis* (Fig. 5c) and *Chromonephthea* sp. (Fig. 6). In addition, the cryptogenic worm snail *Petaloconchus* sp. was found in association with *T. tagusensis* (Fig. 7).

By visually surveying the semi-submersible platform *Safe Regency* in Curaçao, we found that such vessels are able to not only transport individuals of single species, but entire communities of non-native coral to locations where species comprising such communities do not occur naturally. The *Safe Regency* most likely obtained its fouling community in the southern Gulf of Mexico, where it stayed for two decades prior to arriving in the southern Caribbean.

Besides *T. coccinea*, *O. patagonica*, and *C. riisei* no records of other non-indigenous or cryptogenic corals are known from the southern Gulf of Mexico (Fenner, 2001; Zarco-Perelló et al., 2013), so it could well be that the non-native coral fauna of oil rigs in the southern Gulf of Mexico remains understudied at present and that the species encountered here are more common and widespread on rigs and platforms in the Gulf of Mexico than currently thought. Secondly, it is also remarkable that *Safe Regency*'s well-developed fouling community persisted while the platform was traversing open water in the Caribbean, resisting physical and physiological stressors (Coutts et al., 2010; Clarke Murray et al., 2012). The typical speed at which these platforms can move is slow, like 3.5–5.5 km/h when towed (van Hoorn and Devoy, 1990), and appears not to be sufficiently strong to dislodge coral colonies of a variety of species.

The corals *T. tagusensis* and *Chromonephthea* sp., as well as the ascidian *Perophora* cf. *regina*, represent new occurrence records for the southern Caribbean and are also expected to occur in the southern Gulf of Mexico, where the *Safe Regency* remained for two decades prior to arriving at Curaçao. *Tubastraea coccinea* has been a common coral species on Curaçao since the 1950s (Boschma, 1953; Hoeksema and ten Hove, 2017; Hoeksema et al., 2019) and the vermetid gastropod *Petaloconchus* sp. has just been recorded from the southern Caribbean since

2014, where it occurs in association with 21 native coral species and appears to be harmful to its hosts (Hoeksema et al., 2022). *Tubastraea tagusensis* on the *Safe Regency* represents a new host record for this vermetid snail. Known West Atlantic vermetids do not associate with corals and usually occur as dense aggregations on rocky substrates in shallow subtidal water (Weinberger et al., 2010; Breves et al., 2017, 2022; Spotorno-Oliveira et al., 2018). Bieler et al. (2017: Fig. 2A) show a vermetid, *Thylacodes vandyensis* Bieler, Rawlings & Colins, 2017, about 5 cm away from a colony of *Tubastraea coccinea* on a shipwreck off the Florida Keys, but this co-occurrence appears to be coincidental. It seems therefore likely that *Petaloconchus* sp. became recently introduced to the southern Caribbean as a fouling organism, a hypothesis supported by our observations on the *Safe Regency*. The corallivorous polychaete *Hermodice carunculata*, which is known for its generalist diet (Wolf et al., 2014; Schulze et al., 2017), is here recorded with two prey species, *Tubastraea tagusensis* and *Chromonephthea* sp.

Lack of biofouling management resulting in the introduction of non-native species can have harmful effects on indigenous marine faunas (Davidson et al., 2016; de Castro et al., 2017; Wells et al., 2019; Alidoost Salimi et al., 2021). Biofouling communities may also hamper the operation capacity of the semi-submersibles themselves (Apolinario and Coutinho, 2009). Therefore, worldwide monitoring of semi-submersible platforms for the presence of non-native biota is an urgent environmental and economic management requirement. The present findings highlight the importance of defouling of submersible platforms, either dry-docked (Yeo et al., 2010) or in-water (Hopkins and Forrest, 2010), to prevent the colonization of reefs by non-native species once platforms become berthed nearshore for long periods of time. In-water hull cleaning can be counter-productive when it happens nearshore, because *Tubastraea* colonies can survive as free-living corals after they drop to the seafloor (Capel et al., 2020). Another method to prevent long-distance dispersal of biofouling corals could be the use of semi-submersible heavy-lift vessels, which transport platforms out of the water by so-called 'dry-towing', rather than wet-towing them, but there are weight and size limits to the load capacity of such vessels (van Hoorn, 2008; Sharma et al., 2010; Zhang et al., 2012).

The present report shows that accurate track records of semi-submersible platforms may not only tell which species can survive long-distance transport that potentially may lead to range extensions, but also which non-native species were present during departure, possibly revealing new distribution records for the departure area.

CRediT authorship contribution statement

Bert W. Hoeksema: Conceptualization, Supervision, Investigation, Writing – original draft, Writing – review & editing. **Kaveh Samimi-Namin:** Investigation, Photography, Writing – review & editing. **Catherine S. McFadden:** Investigation, Molecular analysis, Writing – review & editing. **Leen P. van Ofwegen:** Investigation. **Rosanna M. Rocha:** Investigation, Writing – review & editing. **Auke-Florian Hiemstra:** Investigation. **Mark J.A. Vermeij:** Investigation, Photography, Writing – review & editing.

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

All data is available as ESM and will be published along with the article if accepted.

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115354.

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