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ECOSYSTEMS

Oil Spill Disaster in Southwest Atlantic Coast: an Evaluation of Short-Term Effects on Coral Reef Benthic Assemblages

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Abstract: Oil pollution has significantly contributed to coral reef decline in the last five decades and a major oil spill reached Brazilian tropical coast in August 2019. Here, we report the first evidence of direct crude oil contact from that spill on reef coral species, and evaluate the effects of this disaster on coral vitality and benthic assemblage structure on the largest coastal marine protected area (MPA Costa dos Corais) in Brazil. We compared benthic cover in reefs with and without oil and monitored *Siderastrea stellata* colonies 90 days after oil contact. Oil stains between 0.5 and 150 cm were found in two of the 17 reef sites investigated. Multivariate analyses did not detect significant differences between oiled and non-oiled reefs and there was no evidence of *S. stellata* health deterioration. These results indicate minimal acute effects on coral vitality and intertidal reef benthic assemblage structure. Future studies should investigate oil effects on specific aspects of coral biology as growth, reproduction, bleaching susceptibility and metagenomics which can deteriorate over longer time frames, and we recommend long-term coral reef monitoring to support a robust assessment and mitigation of chronic oil impacts.

Key words: *Siderastrea stellata*, Acute effects, Costa dos Corais, impact, pollution.

INTRODUCTION

Oil pollution has been a major environmental threat on the oceans in the last decades, with acute and chronic effects that persist over long periods and which contribute to ecosystem deterioration (Peterson et al. 2003). Oil pollution has several sources, some of worst being massive oil blowouts, pipeline ruptures, and explosions at storage facilities (Burgherr 2007). Although the number of spills and the quantity of spilled oil globally decreased between 1970 and 2000, more recent disasters have impacted sensitive reef areas with uncertain long-term consequences (Seveso et al. 2021). For example, while some studies have evaluated oil effects in the lab (Peterson et al. 2003), little is known about oil effects on key species and ecosystem processes.

Oil spills are among the drivers that contribute to rapid decline of coral reefs worldwide (Loya & Rinkevich 1980, Hughes et al. 2017). Oil impacts on reef species depend on quantity and density of the oil, as well as the exposure time and biological characteristics (Santos et al. 2015). Due to coral's importance for reef structure and trophic interactions, acute effects of oil on corals could cause an ecosystem collapse (Loya & Rinkevich 1980), such as the extensive mortality of shallow subtidal reef corals and a rapid decrease in species diversity (Jackson et al. 1989, Guzmán et al. 1991).

In late August 2019 crude oil of unknown origins began to wash up on the Brazilian coastline (Escobar 2020, Magris & Giarrizzo 2020). Five months after the first report at least 5,000 tons had been found along > 3,000 km of coast in 11 states, including more than 980 localities. This made the oil spill the worst environmental disaster - in terms of oil quantity and geographic range - ever recorded at the South Atlantic Ocean. The crude oil from the spill reached at least 57 Marine Protected Areas (MPA), including iconic beaches, mangroves, seagrass, rhodolith beds and coral reefs (Sissini et al. 2020, Soares et al. 2020a). The Brazilian reefs are unique representatives of the largest biodiversity hot spot in the southern Atlantic Ocean, harbouring relic coral species with highest levels of endemism (Leão et al. 2003). However, no studies have assessed short-term effects of the oil spill on corals of Brazil and the magnitude of the impact on coral reefs remains largely unknown (Miranda et al. 2020a).

In the present study, we report on direct interactions between crude oil and reef coral species in the largest coastal marine protected area (MPA) in Brazil (the Environmental Protected Area of Costa dos Corais - APACC). We evaluate whether crude oil negatively affected the benthic assemblage structure and coral species vitality in the short-term after oil contact. To achieve this, we tested whether: (1) reef sites where crude oil was found have different structure of benthic assemblages compared with non-oiled sites, and (2) direct contact with oil causes a decrease in vitality of coral species, such as bleaching, tecidual necrosis, diseases, corallites number decrease or algae overgrowth.

MATERIALS AND METHODS

Study area

The study was conducted at the marine protected area of Costa dos Corais (hereafter indicated as APACC - Portuguese acronym) the largest multiple use coastal MPA in Brazil. APACC is located along the coast of Pernambuco and Alagoas states, in the northeast of the country in the Southwestern Atlantic (9°01’S, 35°11’W) (Fig. 1). This MPA extends 413,563 hectares and includes 12 municipalities, diverse coral reefs and other important ecological systems (Pereira et al. 2018, Miranda et al. 2020b). The fringing reefs are extensive along the APACC on the inner shelf forming up to three lines parallel to coast (Maida & Ferreira 1997, Leão et al. 2003, Ferreira & Maida 2006). These reefs harbor endemic, vulnerable and endangered species, and are one of the “target areas” of National Action Plans for Conservation, a government strategy to improve species conservation, mitigate impacts and encourage sustainable use of natural resources (BRASIL 2016). The APACC management plan restricts human activities on these reefs, establishing spatial zoning such as no-take and tourism zones, where only scientific research and controlled tourism visitation are allowed (BRASIL 2013).

APACC was one of the Brazilian MPAs most affected by oil spill; an estimated 1,671.83 tons of oiled residues (crude oil plus beach sand and others) were cleaned up by volunteers on the beach, especially in Japaratinga and Maragogi (Fig. 1) municipalities, where 734.32 and 583.43 tons removed respectively, as well as 327.24 tons in Tamandaré/Barreiros, 13.58 in São José da Coroa Grande, 12.34 in Barra de Santo Antônio, 0.75 in Maceió (Ipióca), 0.15 in Passo do Camaragibe and 0.02 in Porto de Pedras (ALAGOAS 2020, IBAMA 2020).

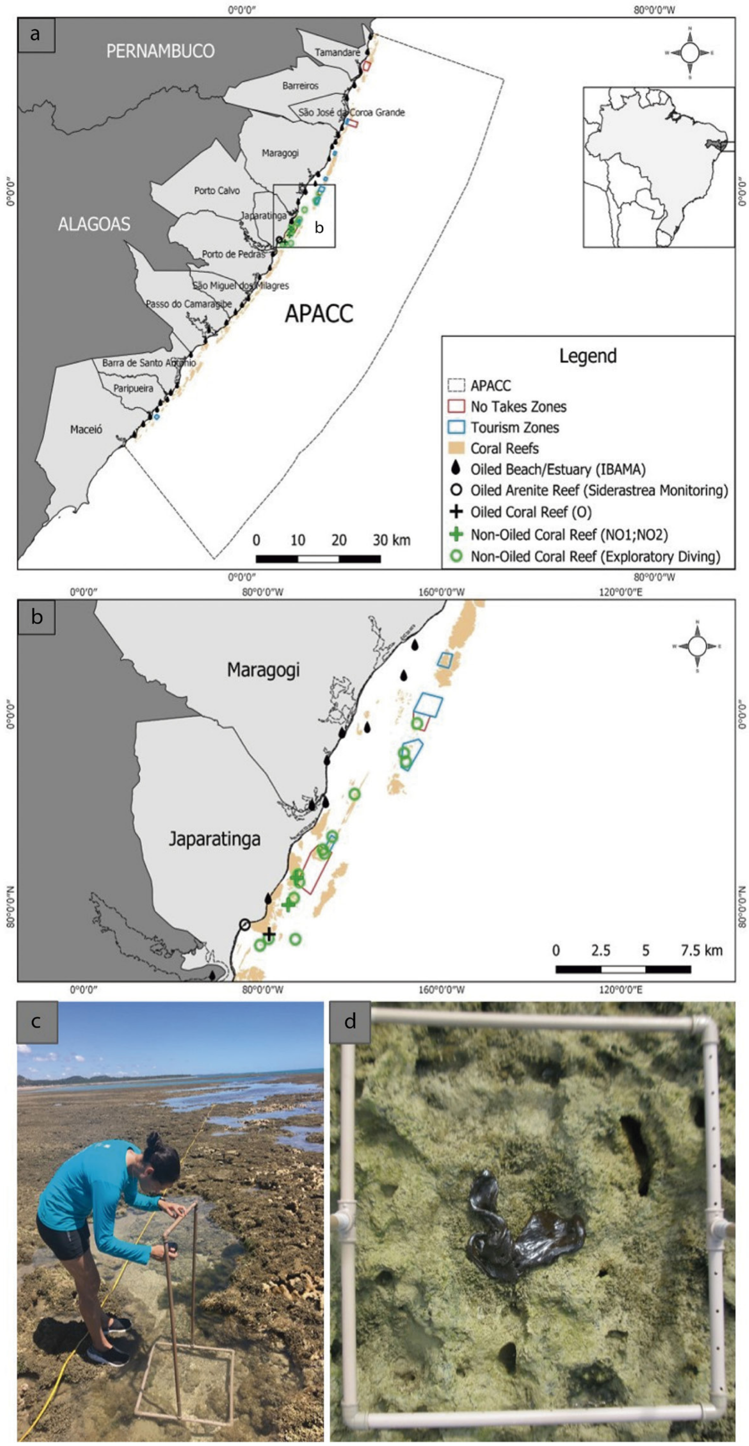

Figure 1. a-b) Map of study area, oil occurrence (beach, estuary and reef sites) and c-d) sampling approach (photo quadrats) in marine protected area Costa dos Corais (APACC), Brazil. O, NO1 and NO2 represent sites of the mensurative experiment to evaluate oil spill effects on benthic assemblages. Oil occurrence data on beaches and estuaries sites from IBAMA (2020). Photos: Ricardo J. Miranda.

Identification of oil stains in the subtidal reefs

To investigate the presence of the oil stains on subtidal reefs (2 to 15m depth), we used snorkel and SCUBA diving surveys in 13 sites determined by the visual observation of three 100 m transects in each site. The surveys were conducted between October and December 2019 in reefs located inside no-take or tourism zones or near to beaches where oil had been reported by local people (Fig. 1).

Evaluation of the oil spill effects on benthic assemblages and coral vitality in the intertidal reefs

We investigated oil presence on the intertidal reefs (4 sites) during low tides by walking. When oil stains were found on the reef, we estimated the range extension and identified direct contacts on coral colonies to monitoring individual short-term effects. To evaluate whether the occurrence of oil stains affected the coral reef benthic assemblage structure, we sampled the benthic cover in an oiled coral reef area (hereafter indicated as *O*, represented by black cross in Fig. 1) and compared with that in two non-oiled reef areas (NO1 and NO2, hereafter denoted *NOs*; represented by green cross in Fig. 1). We selected the non-oiled areas based on their similarity in size (900 m^2), reef structure composition (biogenic coral reef) and environmental conditions (i.e., intertidal, wave exposure and distance of the coast) to the oiled area. The non-oiled areas, where oil stains were not found, were 1.5 km apart. We used an asymmetrical design to compare the benthic cover between *O* and *NOs*. This design, with two non-oiled ("control") locations (*NOs*), produces better estimates of natural variability than the use of a single "control" area, which was appropriate for this situation in which there was only a single impacted location (*O*) that could not be replicated (see Underwood 1992, Glasby 1997, Terlizzi et al. 2005a, b, Miranda et al. 2016). Therefore, our design had two factors: Treatment (*O* and *NOs*, fixed and orthogonal) and Area (O, NO1 and NO2 random, nested in Treatment).

Between December 2019 January 2020, we characterized the benthic assemblages on intertidal reefs by walking using photo-quadrats (0.5 x 0.5 m) along 20 m transects. We haphazardly took 120 photographs per area (O, NO1 and NO2), 40 in each transect (n=3). We estimated the percentage of benthic cover per species through 30 randomly distributed points per photo-quadrat (3,600 points per area, 1,200 per transect) using the Coral Point Count with Excel Extensions Software (CPCe) (http://www.nova.edu/ocean/cpce/) (Kohler & Gill 2006). The benthic categories included scleractinian corals, zoanthids such as *Palythoa caribaeorum* and *Zoanthus sociatus*, sea urchins, hydroids, macroalgae, turf algae, crustose coralline algae, calcareous articulated algae, *Halimeda* spp. and non-biotic categories as reef substrate and oil stains.

To evaluate potential oil effects on coral species vitality we monitored *Siderastrea stellata* colonies (n=2) in the intertidal arenite reef (Fig. 1) 30, 60 and 90 days after oil contact (November and December 2019 and January 2020). We used photo-quadrats (0.25 x 0.25 m) and visual observations to analyse signals of vitality decrease as bleaching, tecidual necrosis, diseases, decreases in corallite numbers or algae overgrowth.

Data analysis

We analysed the data using multivariate procedures to evaluate the variations in the structure of benthic assemblages. We used a permutational multivariate analysis of variance (PERMANOVA, Anderson 2001) to test for differences between assemblages in *O* and *NOs*, based on Bray–Curtis dissimilarities using 9999 random permutations. To check homogeneity of dispersions we used a permutational analysis of dispersions (PERMDISP) with untransformed data. The analyses were conducted in PRIMER 6+Permanova with a significance level (α) of 0.05.

RESULTS

Oil occurrence on the reefs

Our survey showed that the oil stains were found in two reef sites located in area locally called as

Boqueirão beach, in Japaratinga, Alagoas (Figs. 1 and 2). Oil stains varied between 0.5 and 150 cm and were found in the holes, crest, crevices, and tide pools in the two intertidal reef sites, one with 4,200 m^2 (arenite reef, Fig. 2a-b d-e and g-h) and one more with 900 m^2 (coral reef, Fig. 1 c-d; Fig. 2c and f). No oil stains were found in subtidal reefs inside or around no-take and tourism areas in the APACC.

Evaluation of oil effects on benthic assemblage structure and coral vitality

The top five most abundant benthic categories (mean cover ≥1 %) in the intertidal coral reef were reef substrate (49.4 ± 9.9, mean ± SE %), hydroids (21.5 ± 6.6), calcareous articulated algae (CAA, 11.1 ± 5.5), macroalgae (6.9 ± 4.3) and zoanthids (2.8 ± 1.5). The scleractinian coral cover was low (0.3 ± 0.1) represented by species *S. stellata* and *Favia gravida*. The PERMANOVA did no detected significant differences in the

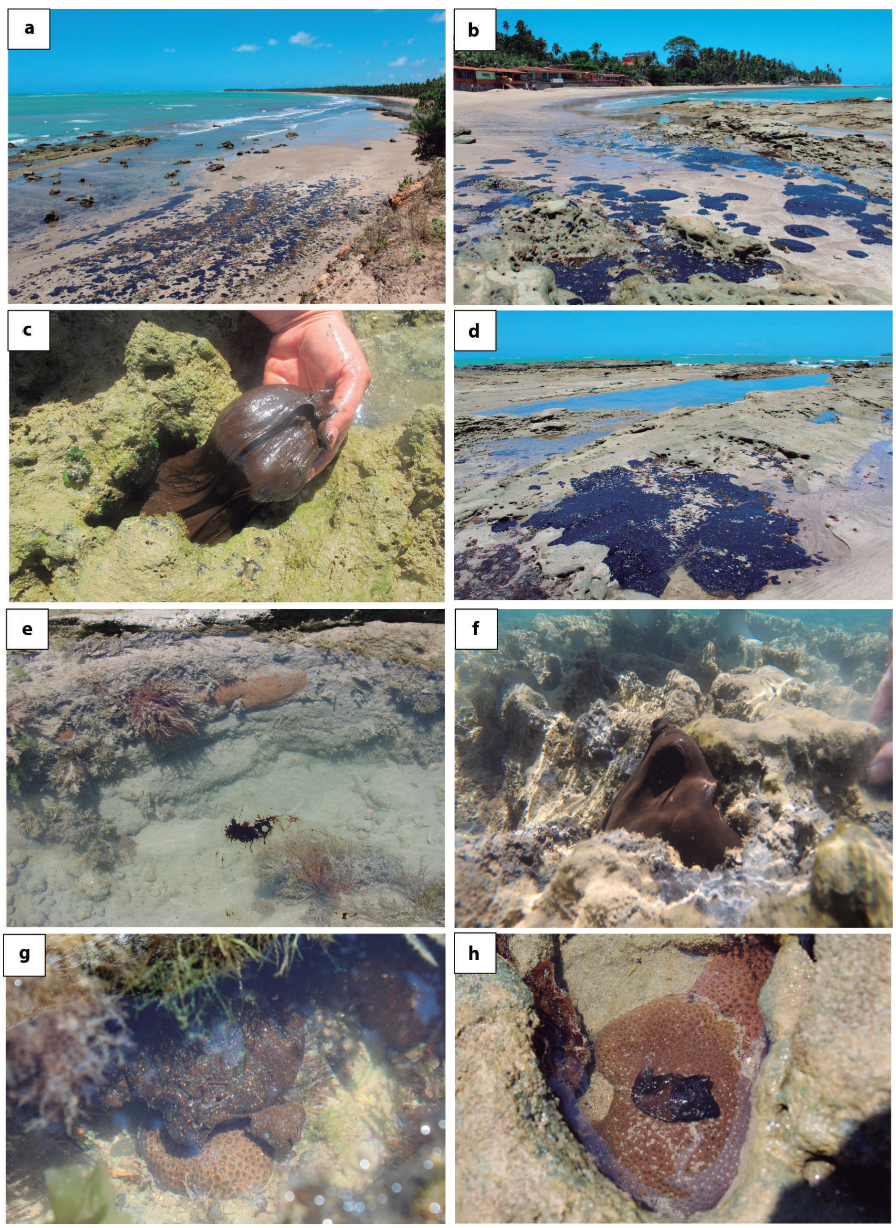

Figure 2. **a-b) Massive oil occurrence on the Japaratinga reefs, marine protected area Costa dos Corais, Alagoas, Brazil in 17 October 2019 including habitats as c) hole, d) crest, e) tide pools, and contacting reef species as f) crustose coralline algae, g-h) scleractinian coral *Siderastrea stellata*. Photos: a-e, g-h) Ricardo J. Miranda; f) Pedro Pereira.**

cover patterns of benthic assemblages between *O* and *NOs* (Table I, Fig. 3), but differences were found between *NOs* (Table I). In the oiled reef area, the oil stains covered 0.8 ± 0.3 and the most abundant benthic groups were hydroids (33.3 ± 8.2), reef substrate (29.9 ± 4.3), CAA (27.6 ± 10.0) and zoanthids (5.6 ± 3.6) (Fig. 4). In the non-oiled areas, reef substrate cover predominated (49.5 ± 18.1 in NO1 and 68.7 ± 13.6 in NO2), but hydroids (26.9 ± 11.2), *Halimeda* spp. (12.3 ± 5.5), CAA (3.3 ± 0.5) and turf algae (3.1 ± 1.2) cover pattern in NO1 differed from macroalgae (19.0 ± 9.8), hydroids (4.5 ± 2.1), *Halimeda* spp. (2.6 ± 0.4) and CAA (2.4 ± 1.7) in NO2 (Fig. 4).

Oil stains were observed directly contacting two colonies of the coral *S. stellata*, as well as sponges, crustose coralline algae and macroalgae species (Fig. 2). During three months following the oil spill, *S. stellata* colonies were apparently healthy and did not show signs of bleaching, tecidual necrosis, diseases, decrease in corallites or algal overgrowth.

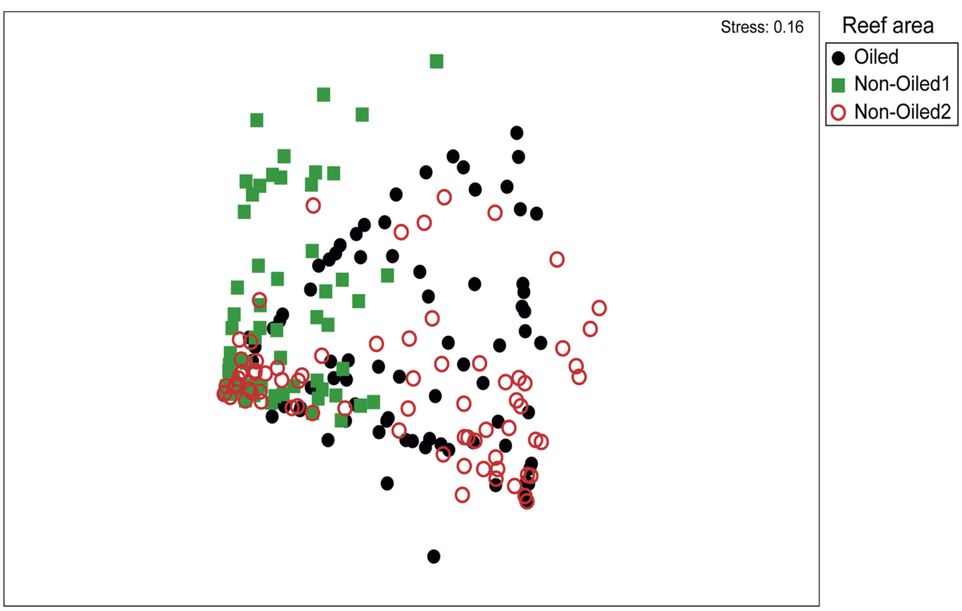

Figure 3. Multidimensional scaling (MDS) of benthic groups (i.e. relative cover of different organisms and abiotic categories) in oiled and non-oiled reef areas based on Bray–Curtis similarities of centroids of each replicate (photo-quadrats).

Table I. **Asymmetrical PERMANOVA based on the Bray–Curtis dissimilarities (untransformed data) of the benthic assemblages.**

Source	DF	MS	Pseudo-F	Unique perms	*p* (MC)
Treatment	1	73814	1.7476	3	0.3024
Area (Treatment)	1	42236	21.116	9953	0.0001
Res	267	2000.2			
Total	269				

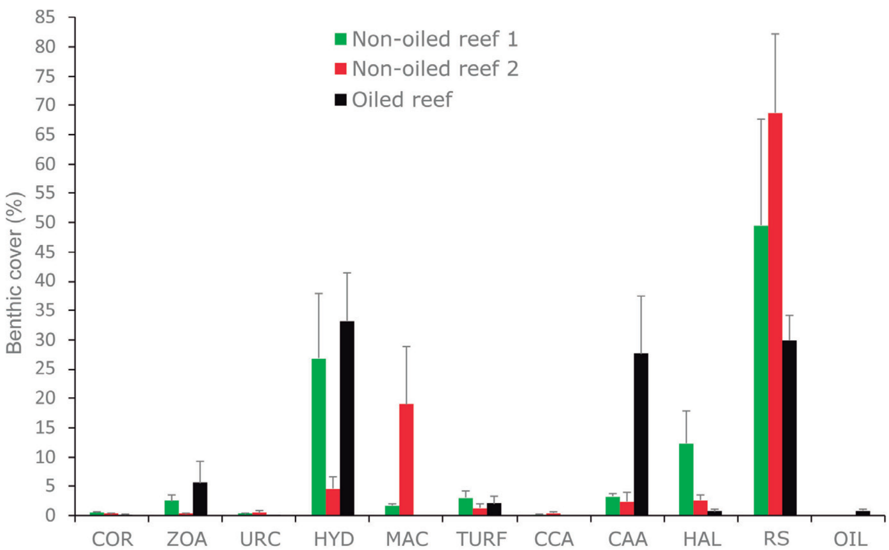

Figure 4. Mean cover (±SE) of benthic groups in oiled (O) and non-oiled (NO1 and NO2) reefs in Japaratinga, marine protected area Costa dos Corais, Alagoas, Brazil. COR=scleractinian corals, ZOA=zoanthids, URC=urchin, HYD=hydroid, MAC=macroalgae, TURF=filamentose turf algae, CCA=crustose coralline algae, CAA=calcareous articulated algae, HAL=Halimeda spp., RS=reef substrate, OIL=oil stain.

Figure 5. Oil remotion activities performed for volunteers between October 2019 and January 2020 during a massive spill episode in Japaratinga, marine protected area Costa dos Corais, Alagoas, Brazil. Photos: Ricardo J. Miranda.

DISCUSSION

We provide evidence that the crude oil from the largest spill disaster in Brazil reached APACC coral reefs and came into direct contact with coral, sponge, crustose coralline algae and macroalgae species. Crude oil accumulated on two reef areas (coral and arenite reefs) within holes, crevices, and tidal pools. However, oil cover found on the reef was low and we did not find differences in patterns of benthic cover structure between oiled and non-oiled reefs. Additionally, the scleractinian coral colonies as *S. stellata* that had direct contact with the oil did not show a loss of vitality (bleaching, tecidual necrosis, disease presence or algal overgrowth) during the three-month monitoring period.

Previous studies show that oil state, quantity and exposure duration can strongly influence the impacts of oil exposure on species and communities (Peterson et al. 2003, Shafir et al. 2007). In fact, the crude state of the oil and the quick action of the volunteers, who quickly removed the oil from the study area (Fig. 5) almost certainly minimized negative short effects on the studied reefs. The crude oil spilled from an unknown source probably passed over numerous submerged reefs and accumulated on the intertidal reefs and mostly on sand beaches and estuaries. Environmental factors such as tide and wave action may also have influenced the accumulation of oil on intertidal reefs.

The coral species monitored (*S. stellata*) is known to be tolerant of a wide amplitude of variation of physical/chemical conditions and water quality, which may have conferred heightened resistance to crude and dissolved oil, at least in the short-term. Others common or endemic corals of Southwest Atlantic may be particularly tolerant to stress conditions; for example, *Mussismilia harttii* showed the capacity to quickly remove heavy crude oil from its surface by producing mucus, gas bubbles and mesenterial filaments (Santos et al. 2020) which effectively reduced exposure to the toxic water-soluble fraction (Santos et al. 2015). However, the relative resistance of these coral species to acute negative effects of crude oil must not be interpreted as a lack of impacts on species and coral reef health. Chronic oil impacts are known to disturb coral growth and metabolism (Loya & Rinkevich 1980), and reduce the number of reproductively viable coral colonies, gametes, life expectancy, as well as modifying planulae behaviour (Guzmán & Holst 1993). As chronic impacts that reduce coral health can appear over longer time frames (Bak 1987), the investigation of specific aspects of coral biology (e.g., growth, reproduction, bleaching susceptibility and metagenomics) are needed to comprehensively assess the long-time consequences of this oil spill on the APACC coral communities.

Although declines in the number of accidents and quantity of oil spilled into the world's oceans have been reported over the last decades (Burgherr 2007), the massive oil spill described in present study and another recent episode off Mauritius in 2020 (Seveso et al. 2021) demonstrates that coral reefs are still vulnerable to oil pollution. Even though volunteers quickly removed a significant quantity of crude oil, this was not enough to avoid ongoing environmental and social-economic consequences. For example, traces of ingestion of oil were observed in microzooplankton, key organisms to coral heterotrophy that represent the base of marine food webs (Campelo et al. 2021). Government inaction, weak coordination and delayed actions in response to the spill (Brum et al. 2019) amplified this social tragedy for traditional coastal communities, affecting human health and key economic activities such as fishing and tourism (Soares et al. 2020b, Magris & Giarrizzo 2020, Estevo et al. 2021, Zacharias et al. 2021).

The socio-ecological consequences of the oil spill associated with a growing interest in oil exploration in the region (ANP 2020), highlights the importance for long-term monitoring to provide a broader view of the threat of oil pollution in the region. Thus, we recommend the continuation of long-time monitoring of socio-ecological aspects in APACC reefs, including oil effects on coral biology, trophic interactions and fishing and tourism activities. These strategies will contribute to a robust assessment of the chronic oil impacts, supporting mitigation and restoration actions that will be needed in the future.

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Author contributions

R.J.M. designed the study. R.J.M., J.W.S., and P.H.C.P. performed the research. R.V.R.L. developed the map. R.J.M. and T.K.P. analysed the data. R.J.M., T.K.P., R.V.R.L., J.W.S., C.L.S.S., R.G.S., P.H.C.P., A.T.C.C., A.C.M.M. and R.J.L. contributed to the writing of the manuscript.