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Severe ecological impacts caused by one of the worst orphan oil spills worldwide

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ABSTRACT

Orphan oil spills pose a severe risk to ocean sustainability; however, they are understudied. We provide the first synthetic assessment of short-term ecological impacts of the most extensive oil spill in tropical oceans, which affected 2900 km of Brazil's coastline in 2019. Oil ingestion, changes in sex ratio and size of animals, morphological abnormalities of larvae and eggs, mutagenic, behavioral, and morphological alterations, contamination by polycyclic aromatic hydrocarbons, and mortality were detected. A decrease in species richness and abundance of oil-sensitive animals, an increase in opportunistic and oil-tolerant organisms, and simplification of communities was observed. The impacts were observed in sponges, corals, mollusks, crustaceans, polychaetes, echinoderms, turtles, birds, fish, and mammals. The majority of studies were conducted on bioindicator substrate-associated organisms, with 68.4% of the studies examining the benthos, 21.2% the nekton, and 10.4% the plankton. Moreover, most of the current short-term impacts assessment studies were focused on the species level (66.7%), with fewer studies on the community level (19%), and even fewer on oil-affected ecosystems (14.3%). Oil-related impacts were detected in five sensitive habitats, including blue-carbon ecosystems (e.g., mangroves and seagrass beds) and coastal reefs. These results call for the development of new ocean-basin observation systems for orphan spills. Finally, we discuss how these mysterious oil spills from unknown sources pose a risk to sustainable development goals and ocean-based actions to tackle global climate change.

1. Introduction

The effects of oil spills on marine and coastal biodiversity can be acute or chronic, and require both short- and long-term studies to support science-based actions for recovery and damage mitigation (Castège et al., 2014; Beyer et al., 2016; Egres et al., 2019). In 2019–2020, the southwestern Atlantic coast (Brazil) was disturbed by a large oil spill (5–12 million liters) (Zacharias et al., 2021), which affected approximately 2890 km of Brazil's tropical coastline (Magris and Giarrizzo, 2020; Soares et al. 2020a, 2020b). This was the most extensive oil spill ever recorded in tropical oceans worldwide and, according to the first reports, the worst environmental disaster in South America (Soares et al. 2020a, 2020b; Magalhães et al., 2021). This event was an orphan oil spill (Carvalho et al., 2021) of unknown origin, likely the result of illegal dumping from a ship or a historical shipwreck leakage (Zacharias et al., 2021; Soares et al. 2020a, 2020b). This "mysterious Brazil oil spill" is thus different from other large-scale oil spills worldwide (e.g., Prestige oil spill or Deepwater Horizon oil spill), where the culprits were known and bore the financial responsibility for the recovery and long-term monitoring of socioeconomic and environmental impacts (Caballero-Miguez and Fernández-González, 2015; Sutton et al., 2022).

The chemical composition of this orphan spill along the southwestern Atlantic coast indicated that the spill originated from a single source (Lourenço et al., 2020). The oil was recently characterized as a fuel oil made from at least two petroleum products with aromatic-rich, non-distilled material from a Venezuelan sedimentary oil basin (Reddy et al., 2022). In this regard, 5379 tons of this fuel oil residue was collected from the tropical coastline between 2019 and 2020 (IBAMA, 2019; Soares et al., 2022). This spill has affected at least 57 coastal and marine protected areas (MPAs) on the Brazilian coast (Soares et al. 2020a, 2020b). A recent review on contamination by polycyclic aromatic hydrocarbons (PAHs) in Latin America found 53 affected MPAs

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over the last decade (Nunes et al., 2021). Thus, the high number of MPAs affected by this single spill, which has outnumbered past contamination, indicates that environmental impacts are likely severe (Soares et al., 2022) and need further studies, especially on scarcely known tropical coastal ecosystems.

Orphan oil spill impacts, such as this, can affect coastal and marine biodiversity in terms of their structure, functioning, and ecosystem services such as carbon sequestration (Rohal et al., 2020a; 2020b). Despite the advances made in previous studies (Soares et al. 2020a, 2020b, Magalhães et al., 2021; Mendes et al., 2021), a systematic review of the impacts of the spill on biodiversity is lacking. Previous reviews and perspectives have focused on the slowness, lack of coordination, and mismanagement of the Brazilian federal government in remediating the oil spill. A multidimensional analysis is required to understand the oil-related impacts on lifestyle (e.g., benthos, plankton, and nekton), ecosystems (e.g., beaches and rocky environments), and species (from lower to higher trophic levels, such as fish, mammals, and turtles).

The present analysis provides insights into the vulnerability, restoration, and resilience of tropical biodiversity with respect to this orphan spill. In this regard, we conducted a review of short-term (four years after the accident) ecological impacts based on published data. A systematic review of the literature was conducted to obtain updated findings derived from articles and official technical reports concerning the impacts of this extensive oil spill. In this context, our synthetic article analyzed published data and information to provide the first assessment of the ecological impacts of this harmful orphan spill that appeared in Brazil in 2019. The synthesis proposed in this article is important for environmental managers, non-governmental organizations, and local traditional communities. Our study can be utilized for further research on the long-term effects to provide scientific data and ocean-based solutions for programs such as Sustainable Development Goals 13 (Climate Action) and 14 (Life Below Water) under the United Nations Ocean Decade (Schuckmann et al., 2020; United Nations, 2022).

2. Methods

A systematic review of available literature was conducted to extract quantitative summaries from scientific articles and technical reports concerning the impacts of the extensive oil spill that reached Brazil in 2019/2020. First, the objectives and questions were defined. Next, a prescreening of terminologies was performed to ensure that the search terms and strings used in the database query were aligned with the most prevalent scientific terminology used since the orphan oil spill in 2019. After the literature search, the manuscript selection workflow followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).

The objective of this research was to assess the current knowledge of ecological impacts for the 2019 Brazil oil spill and to obtain updated information regarding its effects on coastal and marine biodiversity. The following research questions guided our systematic literature review: 1. What are the characteristics of the published research? 2. What are the main characteristics of studies (level of biological organization such as species, population, ecosystem)? 3. What are the methods and approaches used (laboratory or field monitoring studies)? 4. What are the oil-affected tropical habitats? 5. What are the displacement capabilities (plankton, benthos, or nekton) of the evaluated oil-affected species?

A qualitative and quantitative analysis of the published literature with laboratory and field studies was performed in two stages according to systematic reviews (PRISMA methodology). First, the terms "oil spill," "mysterious oil spill" AND/OR "Brazil," "2019/2020," "2019," "South Atlantic," "Southwestern Atlantic," "Crude oil," "Environmental disaster," "oil spilled," "Brazilian oil spill," "biodiversity," and "ecosystems" were searched in online search engines (Google Scholar, Science Direct, Web of Science, and Scopus). The search was limited to titles, keywords, and abstracts of the evaluated papers. Second, the results of the literature search were restricted to the ecological impacts (ecosystems and species). The impact of the oil spill on water and sediments was not considered. No time-scale boundaries were imposed.

Studies published in scientific peer-reviewed journals, official technical reports (environmental agencies), or books were included. Grey literature, extended abstracts, congress presentations, and non-English (or non-Portuguese) papers were excluded. Articles providing biological information were selected, and relevant information from the selected articles was identified. Extracted data were exported to a spreadsheet according to a pre-determined list of attributes, and the synthesis of the results was conducted.

To identify articles overlooked during the first selection step, we also consulted the references cited in each relevant official report (IBAMA, 2019), article, and review (Magris and Giarrizzo, 2020; Soares et al. 2020a, 2020b, 2022; Lourenço et al., 2020; Mendes et al., 2021; Campelo et al., 2021; Cerqueira, 2021). All papers with a Portuguese/English title and abstract were manually screened for content, and the selected papers were downloaded and examined individually (54 articles). A total of 21 published peer-reviewed articles (2019–2022) and official reports of the Brazilian Institute of Environment and Renewable Resources (IBAMA) met our established criteria addressing the impacts of this orphan oil spill on coastal and marine biodiversity.

Data from the selected published literature was extracted for four attributes to conduct a multidimensional assessment of coastal and marine biodiversity affected by the oil spill in the south Atlantic (Brazil, 2019–2020). The first attribute was the level of biological organization where oil-related impacts were studied and detected at the a) species/population, b) community, or c) ecosystem levels. In the case of species-level studies, the taxonomic group was verified (e.g., sponges, corals, mollusks, crustaceans, echinoderms, turtles, mammals, and birds). The second attribute was the lifestyle (benthos, plankton, and/or nekton). The third attribute was the state of Brazil in which the study was conducted. Finally, the fourth attribute was the habitat, such as reefs, estuaries, seagrass beds, beaches, and/or rhodoliths. When the study covered several taxonomic groups or ecosystems, each taxonomic group (or ecosystem) were counted. Therefore, for attributes 1 and 4, the sum could be greater than 100%. Graphs, tables, and images were generated for multidimensional descriptive analysis of these four attributes.

We used VOSviewer 1.6.19 to visualize and analyse trends in the form of bibliometric maps about the ecological impacts of this orphan oil spill (Brazil 2019). We used this software to do data mining, mapping, and grouping topics that were taken from the Web of Science database (2020–2023) (van Eck and Waltman, 2010). The minimum number of relationships with terms in the use of VOSviewer was set to 2 terms.

3. Results and discussion

3.1. Effect of orphan oil spill on biodiversity in South Atlantic

Oiled animals, oil ingestion, changes in sex ratio and size, morphological abnormalities of early life stages (larvae and eggs), mutagenic, behavioral, and morphological alterations, contamination by toxic metals and/or PAHs, increased mortality, and changes in survival rates were detected as the result of the orphan spill (Table 1). A decrease in the overall species richness and abundance of oil-sensitive taxa, an increase in opportunistic and oil-tolerant organisms, and simplification of tropical benthic communities were reported in oil-affected areas in shallow waters (<10 m deep) in the southwestern Atlantic (Table 1). Negative effects unrelated to the oil spill have also been reported (Table 1).

Most of the current short-term impacts assessment studies were focused on the species level (66.7%), with fewer studies on the community level (19%), and even fewer on oil-affected ecosystems (14.3%) (Fig. 1). Oil-related species-level impacts from this orphan spill have been detected in several taxonomic groups (Table 1; Figs. 1 and 2) such as seagrasses (Magalhães et al., 2021), sponges (Lira et al., 2021; Miranda et al., 2022), corals (Campelo et al., 2021; Miranda et al.,

Table 1
The currently known effects of the orphan oil spill that occurred in the tropical southwestern Atlantic and reached Brazil in 2019–2020 on marine and coastal biodiversity.

Biodiversity component	Orphan fuel oil spill effects/References
Algae	Oil stains observed in direct contact with crustose coralline algae and macroalgae species (Miranda et al., 2022)
Sponges	Oil stains on surface and channels of marine sponge *Cinachyrella* sp. (Lira et al., 2021)
	Oil stains observed in direct contact with sponges (Miranda et al., 2022)
Cnidarian	Threat to the recruitment and health of endemic reef-building corals (*Mussismilia harttii*) (reproductive event close to oil spill) (Campelo et al., 2021)
	Oil stains observed in direct contact with colonies of the reef-building coral *Siderastrea stellata* (Miranda et al., 2022)
	Oil on tentacles of the Portuguese man o' war (*Physalia physalis*) (Soares et al., 2020b)
	Laboratory analysis indicated interference of symbiont–host relationship of tropical corals. Carcinogenic/mutagenic polycyclic aromatic hydrocarbons (PAHs) identified as responsible for reduced population growth of the coral endosymbiont *Symbiodinium glynnii* (Müller et al., 2021)
Mollusks	Oil contamination of mollusks with PAHs, mainly naphthalene (134 ng g^{-1}) (Magalhães et al., 2022)
	Contamination of oyster *Crassostrea gigas* and mussel *Perna perna* in the affected oil spill area with PAHs mainly benzo[*a*]anthracene, benzo[*a*]pyrene, and benzo[*b*]fluoranthene (Melo et al., 2022)
	Contamination of *Anomalocardia brasiliana* with PAHs, mainly fluoranthene, naphthalene, phenanthrene, fluorene, and acenaphthylene (29.8–114 ng g^{-1}) (Soares et al., 2021)
	No evidence of short-term or acute impacts on benthic mollusks *Donax gemmula* on sandy beaches (Rosa 2022)
Polychaeta	Simplification of reef benthic communities (reduced species richness and abundance) after oil arrival. Increase in opportunistic taxa (*Branchiomma luctuosum)* (Craveiro et al., 2021)
	Oil stains on surface and pharynxes, increased mortality and reduced population size (Lira et al., 2021)
	No evidence of short-term or acute impacts on benthic polychaeta *Scolelepis* sp. on sandy beaches (Rosa 2022)
Crustaceans	Paracalanidae and Cyclopoida copepods and zoea larvae affected by ingestion of oil and oil contact (oil droplets on locomotory and feeding appendages of copepods and oil on mouthpiece of crab larvae) (Campelo et al., 2021)
	Oiled copepods (Campelo et al., 2021), *Acanthonyx* sp., and amphipods and increase in opportunistic taxa (*Janaira gracilis*) (Craveiro et al., 2021)
	Mortality of barnacles (*Chthamalus bisinuatus*) (Gusmao et al., 2021)
	Oil contamination (PAHs, mainly naphthalene; 73.9 ng g^{-1}) (Magalhães et al., 2022)
	Contamination of shrimp *Penaeus* spp. with PAHs, mainly benzo[*a*]anthracene, benzo[*a*]pyrene, and benzo[*b*]fluoranthene, in the affected oil spill area (Melo et al., 2022)
	Oil impacted the sex ratio (decrease in females) of the crab *Pachygrapsus transversus* due to closure of burrows used for protection. Negative synergistic oil impacts (together with tourism) on the size and maturation of Grapsidae crabs (Santana et al., 2022)
	No evidence of short-term or acute impacts on benthic crustaceans *Chlamydopleon dissimile* and *Excirolana armata* on sandy beaches (Rosa, 2022)
Echinoderms	Oil in the intestinal content of sea cucumber *Holothuria* (*Halodeima*) *grisea* and mortality increased (mortality rate not calculated) (Cerqueira, 2021)
Fishes	Oil contamination of fishes with PAHs, mainly naphthalene (45.3 ng g^{-1}) (Magalhães et al., 2022)
	Contamination of *Thunnus* spp. with PAHs, mainly benzo[*a*]anthracene, benzo[*a*]pyrene, and benzo[*b*]fluoranthene, in the affected oil spill area (Melo et al., 2022)
	Oil contamination of fishes with PAHs, mainly fluoranthene, naphthalene, phenanthrene, fluorene, and acenaphthylene (14.28–32.06 ng g^{-1}) (Soares et al., 2021)
	Lowered abundances and taxonomic richness of larvae, and decreased larval size (34 fish larvae taxa from 29 families and fish eggs) after the oil spill. Increase in morphological abnormalities in fish larvae and eggs (Souza et al., 2022)
Turtles	Threatened marine species *Lepidochelys olivacea*, *Chelonia mydas*, *Caretta caretta* (IBAMA, 2019; Soares et al., 2020b; Oliveira et al., 2021)
	105 oiled animals and dead animals (>95 individuals) (IBAMA, 2019)
Birds	39 oiled birds and dead animals (IBAMA, 2019)
Mammals	Exposure in laboratory resulted in mutagenic damage to bone marrow blood cells and behavioral and morphological alterations in wild rodent *Calomys laucha* (e.g., lethargy, bristly hair, locomotion difficulty, muscular mass alterations, and changes in weight of the kidneys, liver, and spleen) (Almeida et al., 2021)
	Oiled and dead manatee *Trichechus manatus* (IBAMA, 2019)
Seagrasses	Potential area (+325 km^2) and richness of seagrasses affected by oil (5 eco-engineer species of *Halodule* spp. and 1 species of *Ruppia maritima*) (Magalhães et al., 2021)
Rhodolith beds	Potential risks to extensive rhodolith beds along the Brazilian coast (Sissini et al., 2020)
Threatened species and coastal ecosystems	27 threatened species (IUCN redlist) occur within the fuel oil-affected Brazilian area. Ecosystems affected: estuarine water bodies (4929.74 km^2 of area affected), followed by mangrove forests (489.83 km^2), seagrass meadows (324.77 km^2), beaches (185.3 km^2), tidal flats (63.64 km^2), intertidal hard bottoms such as sandstone reefs (45.95 km^2), and shallow-water coral reefs (9.69 km^2) (Magris and Giarrizzo, 2020)

2022), polychaetes (Craveiro et al., 2021; Lira et al., 2021), echinoderms (Cerqueira, 2021), turtles, birds (IBAMA, 2019; Oliveira et al., 2021), fishes (Magalhães et al., 2022; Melo et al., 2022; Soares et al., 2021; Souza et al., 2022), and marine mammals (IBAMA, 2019). In addition, the most studied groups were crustaceans (47.4%) and mollusks (31.6%) (Soares et al., 2022; Campelo et al., 2021; Craveiro et al., 2021; Gusmao et al., 2021; Soares et al., 2021; Magalhães et al., 2022; Rosa, 2022; Santana et al., 2022) (Fig. 1; Table 1).

The majority of studies were conducted on bioindicator substrate-associated organisms (e.g., sponges, corals, mollusks, echinoderms, polychaetes, and seagrasses) (Table 1), with 68.4% of the studies examining the benthos, 21.2% the nekton (e.g., fishes, turtles, and mammals), and 10.4% the plankton. The predominant use of benthic organisms (e.g., macrofauna) as useful ecological indicators of oil-impacted areas is important and has been used in previous oil spill disasters such as the Deepwater Horizon (Washburn et al., 2016) and Prestige oil spills (Castège et al., 2014; Junoy et al., 2013).

The association of benthic organisms with the affected substrate in oil-disturbed habitats led to taxonomic and functional changes (Egres et al., 2019) such as the short-term reduction in richness detected after this orphan spill (Table 1). In contrast to benthos, only two studies have analyzed plankton, particularly zooplankton and ichthyoplankton (Table 1). No acute impacts on phytoplankton or microbial communities have been reported to date after this extensive spill. In this regard, ingestion of oil residues by zooplankton organisms (Brachyura zoea, Calanoida, Paracalanidae, and Oithonidae copepods) was detected after the Brazilian disaster (Campelo et al., 2021). The larval phases of crabs and scleractinian corals were vulnerable to this orphan oil spill, suggesting that this event likely affected the benthic–pelagic coupling (Campelo et al., 2021). Regarding ichthyoplankton, a high rate of abnormalities in embryonic development of fish eggs was observed in oil-affected areas in Salvador (Bahia, Brazil), and fish larvae presented

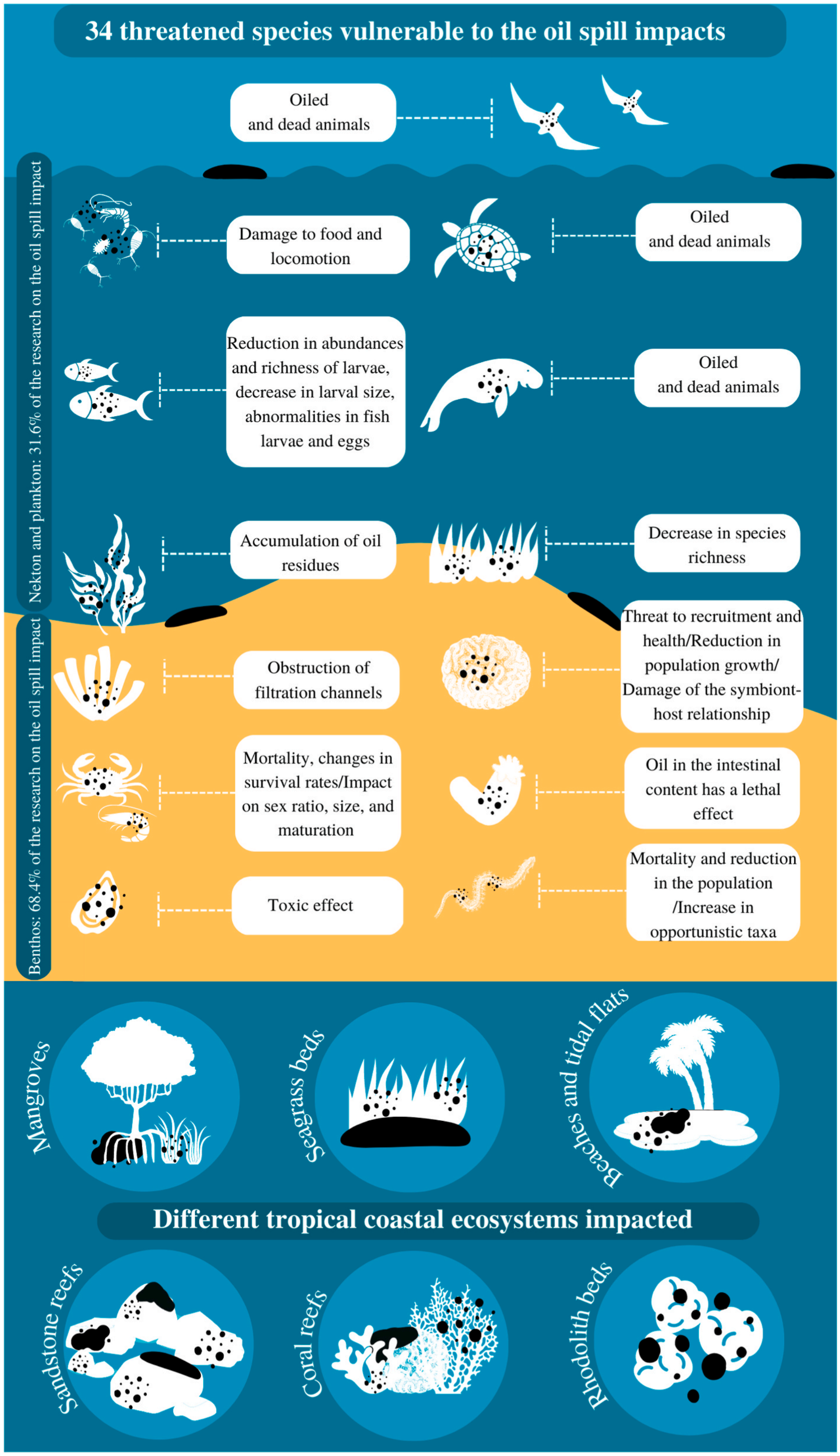

Fig. 1. Taxonomic groups and environments affected by the orphan and most extensive oil spill in tropical southwestern Atlantic (Brazil, 2019–2020).

deformity of the spine and yolk sac edema (Souza et al., 2022), which indicates oil-related impacts in early life stages. These results highlight the need for new research in the orphan spill areas to assess biomagnification processes at different trophic levels in the marine food webs.

The bibliometric analysis indicated there were 5 clusters (green, yellow, blue, red, purple) which showed the relationships between the oil research topics regarding the Brazil 2019 event. The size of letters and circles was determined by the frequency of occurrences (network visualization) with larger circles for more cited topics in the Abstracts. It can be seen that the keywords density, reduction, abundance, ingestion, and individual are in the same cluster (green area). This suggests that

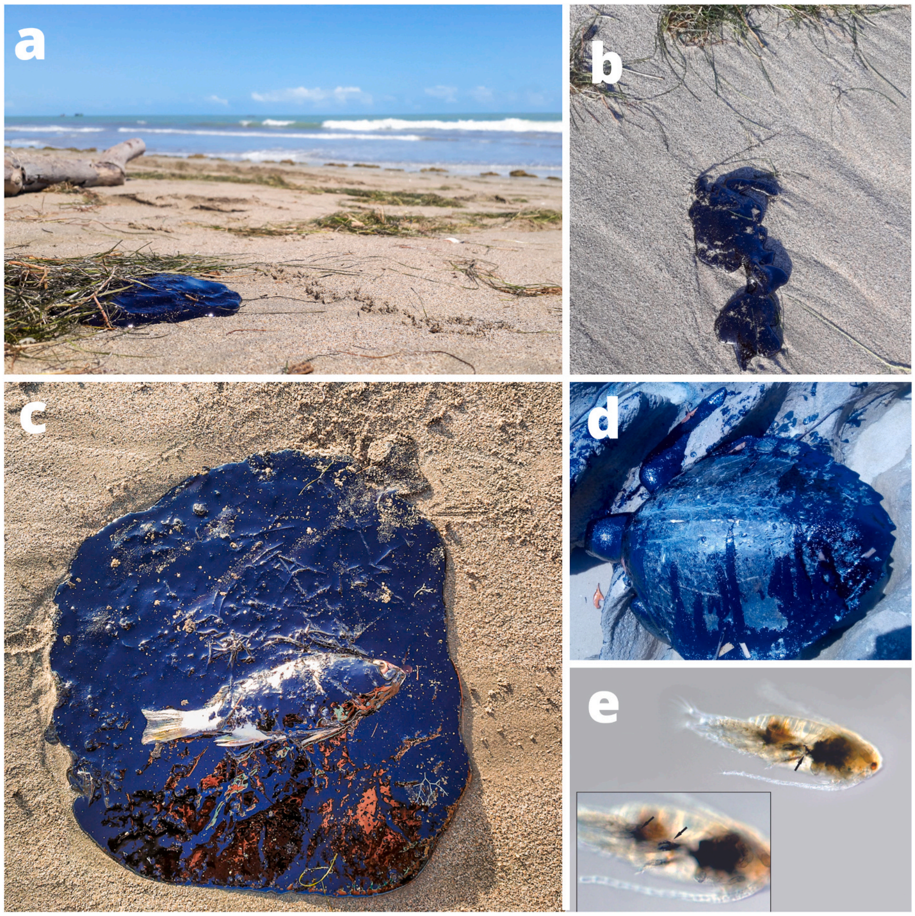

Fig. 2. Photos of oiled animals and environments affected by the orphan spill in tropical southwestern Atlantic (Brazil 2019. A) and B) Icapuí beach with oil in seagrasses (Ceará coast); C) oiled fish (Soares et al., 2022); D) oiled turtle (source: Instituto Verdeluz); E) oiled copepod (Source: Renata Campelo).

there is close relationship between them. Similar relationships can be seen for the other clusters (e.g., PAHs on red cluster – left side) (Fig. 3).

This orphan spill affected 11 Brazilian states (Soares et al. 2020a, 2020b, 2022) and at least 10 different tropical coastal ecosystems, mainly estuarine water bodies (4929.74 km^2 of area affected), mangrove forests (489.83 km^2), seagrass meadows (324.77 km^2), beaches (185.3 km^2), tidal flats (63.64 km^2), intertidal hard bottoms such as sandstone reefs (45.95 km^2) (Fig. 1), and shallow-water coral reefs (9.69 km^2) (Magris and Giarrizzo, 2020) (Table 1). This orphan spill potentially affected at least about 5827.98 km^2 of blue carbon ecosystems (seagrass

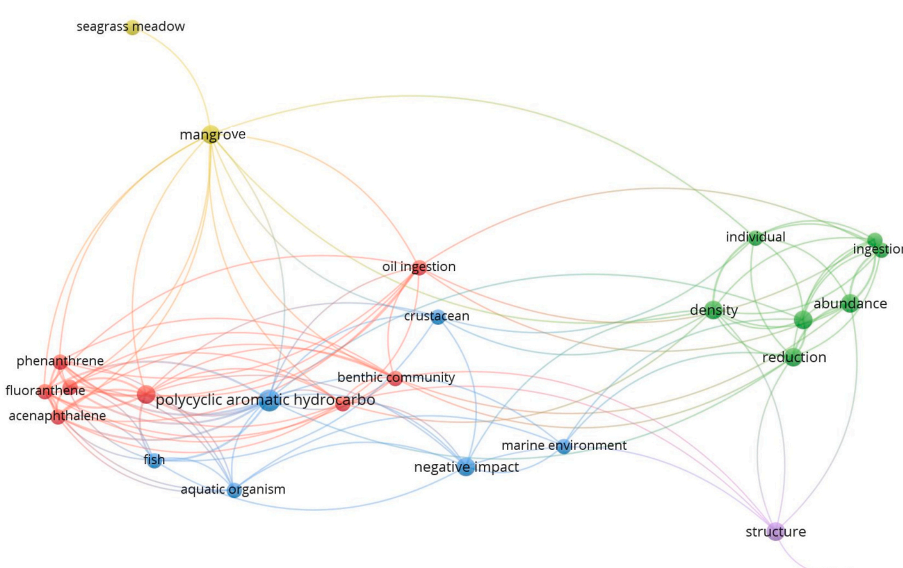

Fig. 3. Visualization topic area (ecological impacts of Brazil 2019 oil spill) using VOSviewer (network visualization).

beds, estuarine water bodies, mangrove forests, and tidal flats). Carbon dioxide (organic and inorganic forms) that is captured from the atmosphere and sequestered in coastal and marine ecosystems is collectively known as blue carbon (Soares et al., 2022b).

The oil-affected areas shelter at least 35 threatened species (according to IUCN) that are vulnerable to spill impacts, including 11 elasmobranchs, 10 fishes, 5 invertebrates, 4 migratory birds, 3 marine turtles, and 2 marine mammals (IBAMA, 2019; Magris and Giarrizzo, 2020; Soares et al., 2020a,b, 2022) (Table 1).

Although the 2019/2020 oil spill event affected 10 ecosystems (Magris and Giarrizzo, 2020; Soares et al., 2022), oil-related impacts have been detected in only five tropical ecosystems to date: rhodolith beds (7.14% of the studies), sandy beaches (14.3%), seagrass (14.3%), estuaries with mangroves (21.4%), and mainly shallow-water and intertidal reefs (78.6%), with the last ones standing out as the most studied ecosystem (Fig. 2). An estimated area of 6048.92 km^2 of Brazilian tropical ecosystems (including estuaries, mangroves, beaches, seagrasses, beaches, tidal flats, and reefs) was impacted by this orphan oil spill (Magris and Giarrizzo 2020). Of this total, the oil-affected reef area was the smallest (55,64 km^2 or 0.9% of the total area) (Magris and Giarrizzo 2020). In other words, the most studied ecosystem had less oil-affected areas than other ecosystems, according to this mapping.

This result of the most studied ecosystem may be explained by several factors. First, tropical reefs are among the richest marine ecosystems, and even a small amount of oil can impact this important habitat (Nordborg et al., 2020; Rajendran et al., 2022); for example, an interference in symbiont–host relationships of corals was detected owing to the presences of oil along the Brazilian coast (Müller et al., 2021). Second, oil stains that reach a reef may remain in the hard-bottom habitat for a long time, as seen in the Brazilian mystery oil spill, because the removal was only mechanical (Soares et al., 2022), thus generating a long-term source of oil contamination (e.g., PAHs) in Brazilian tropical reefs (Domínguez-Hernández et al., 2022). In contrast, other habitats such as oil-affected highly dynamic sandy beaches (Bejarano and Michel, 2016) appear to be more resilient owing to the dispersion by waves, currents, and tides in the study area (Soares et al., 2022; Rosa, 2022), resulting in no detected negative impacts (Rosa, 2022). Finally, the existence of intertidal reefs in the affected Brazilian tropical area, which are easily accessible to researchers and were impacted by the event (Magris and Giarrizzo, 2020), could increase the number of studies detected here.

Most oil-related impact studies (88.2%) were conducted on the stretch of the tropical coastline that received the most oil (97.9%). The amount of the fuel oil collected in four northeastern states (Pernambuco, Bahia, Alagoas, and Sergipe states) was 5269.68 tons, which corresponds to 97.9% (the total oil collected along the Brazilian coast was 5379.76 tons) (IBAMA, 2019; Soares et al., 2022)· Interestingly, this area occupies approximately 52% (1511 km) of the estimated 2890 km of the coastline (Soares et al., 2022) affected by the orphan spill. This suggests a concentrated biodiversity impact in the region that likely received the most oil. However, other areas (48% of the coast) that received less oil (2.1% of all collected residues), such as the shores of the states of Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, Espírito Santo, and Rio de Janeiro, should also be monitored and analyzed. A recent review of the Brazilian tropical region revealed that hydrocarbons from human sources can induce adverse effects on marine organisms even at low to moderate levels (Fernandes et al., 2022). Thus, even small spill volumes have immediate adverse effects (Brussaard et al., 2016), which underscores the importance of further ecotoxicological studies.

The effects of the orphan oil spill in the tropical southwest Atlantic did not occur in isolation, but instead had a cumulative and synergistic impact on the region's marine and coastal biodiversity, which was already impacted by numerous human activities. (Soares et al., 2022; Sissini et al., 2020). The likely impacts of this orphan spill in conjunction with marine heatwaves and tourism have been detected (Müller et al., 2021; Santana et al., 2022). In the first case, mass coral bleaching and unprecedented mortality was observed in the first half of 2020 (one half year after the oil spill). Although heatwaves, the most intense one of this century, was the primary driver, a possible cumulative impact on bleaching was hypothesized (Pereira et al., 2022), as experiments have shown that this orphaned oil affects the relationship between microalgae and corals and causes a decrease in photosynthetic endosymbionts (Müller et al., 2021). In the second case, the impact of oil along with intense tourism (trampling) may have led to changes in the size and maturation of Grapsidae crabs (Santana et al., 2022) (Table 1).

3.2. Problem-based research and global policy actions

To elucidate the magnitude of ecological oil-related impacts and to contribute to adequate restoration and monitoring programs, we emphasize the urgent need for problem-based research focusing on the following issues: (1) the effects of long-term contamination at all trophic levels and provision of ecosystem services (Rohal et al., 2020a; 2020b) such as blue carbon sequestration; (2) toxicity (e.g., PAHs) and ecotoxicological effects from fuel oil and its residue in less studied organisms (e.g., phytoplankton, microbial communities, and marine mammals) (Zengel et al., 2022; Neethu et al., 2019; Somee et al., 2021) and ecosystems (e.g., rhodolith beds and tidal flats); (3) mesocosm experiments with oil-affected biota; and (4) surveillance of the acute and chronic impacts on human communities and tropical ecosystems. The studies should mainly focus on the acute impacts of the 2019/2020 oil spill, and long-term monitoring is required to identify chronic effects at all levels of biological organization (especially at community- and ecosystem-level analysis), as it was done for the Deepwater Horizon oil spill (Kujawinski et al., 2020).

The data available here show acute and short-term impacts four years after the onset of the orphan Brazilian oil spill. Similar short-term impacts have been noted in the Deepwater Horizon oil spill in the Gulf of Mexico (Beyer et al., 2016; Washburn et al., 2016) and the Prestige oil spill in the north Atlantic (Junoy et al., 2013; Pérez-del-Olmo et al., 2022). The short-term impacts observed here are important as a baseline for future studies in comparison to long-term decadal studies. This could be done on biodiversity impacts and recovery rates in the oil-affected areas, as has been done in other spills worldwide (Beyer et al., 2016; Pérez-del-Olmo et al., 2022). Recovery rates of biological communities affected by oil spills vary from months (Craveiro et al., 2021; Rosa, 2022) to decades (Deis et al., 2020), with deep-sea benthic ecosystems taking longer (estimated 97 years for 1979 Ixtoc-I and 50 years for 2010 Deepwater Horizon) (Rohal et al., 2020a; 2020b). We obtained quantitative information on oil-related impacts only in Brazilian coastal ecosystems (Table 1 and review here), but the real impacts may be underestimated owing to the lack of in-depth research of deeper environments (e.g., mesophotic habitats) (Sissini et al., 2020). Thus, monitoring over several decades and benthic analysis of the sublittoral zone (>10 m deep) are necessary for this orphan oil spill.

In addition to studies on ecological effects, monitoring the adverse effects on human health is extremely important, especially in low-income regions that depend on marine resources for food security. Food safety must be prioritized, and the investigation of the harmful effects of both ingestion of contaminated animals and manipulation of oiled fishing resources are of paramount importance. Although negative effects have already been reported (Araújo et al., 2020; Magalhães et al., 2022), medium- and long-term studies on human population in Brazil are lacking. In addition, studies on the socioeconomic impacts of the 2019–2020 oil spill and the potential threats to the future of subsistence fishing along the Brazilian coast are also important. Moreover, rapid government mobilization can minimize the harmful effects of orphan spills on ecosystems and humans. To prepare for the possibility of future oil spills, urgent action is needed to develop local contingency plans tailored to the unique needs of each region and tropical coastal ecosystem. These plans should prioritize rapid and efficient responses to minimize the damage caused by any new spills.

In conclusion, our study provides novel and synthetic information on the ecological impacts of one of the worst orphan spills worldwide. Our results indicate that orphan spills (where the source is unknown) pose a major risk to ocean sustainability. The severe impacts demonstrated here draw attention to the need for decarbonization of the global economy and the development of ocean basin observation systems for orphan spills. Economic decarbonization can significantly reduce the risk of new and severe oil spills (Little et al., 2021). Currently, in the traditional fossil-fuel economy, many developing countries have ineffective systems of marine environmental protection and oil spill response, low enforcement and surveillance on the sea, and low scientific and technological capacity to detect orphan spills (Little et al., 2021). This leads to inability to identify culprits of environmental crimes, while governments and/or the low-income human population and tropical biodiversity end up bearing the burden of the socioeconomic, ecological, and public health costs (Soares et al. 2020a, 2020b).

International cooperation in marine science and technology may be an alternative approach for the development of orphan spill observation systems in the current United Nations Decade of the Ocean (2021–2030) (United Nations, 2022), which has not yet been incorporated into any transnational plan. Moreover, these spills pose a risk to sustainable development goals (SDGs) and ocean-based actions tackling global climate change. Our results also draw attention to the impacts of oil spills on blue carbon ecosystems (such as mangroves and seagrass beds), which are important ocean-based systems for carbon sequestration and climate change mitigation (Soares et al., 2022b). Biodiversity and climate regulation losses considering blue carbon ecosystems should drive policy actions regarding the global consequences related to new oil exploitation fields, new oil spill events, orphan spills, and their climate change impacts (Soares et al., 2022; Horta et al., 2023). In addition, the impacts on tropical marine biodiversity determined here show that orphan oil spills pose a real risk to SDGs (in particular, SDG 14, Life Below Water) and need to be considered in global and national plans to tackle marine pollution and climate change worldwide.

CRediT author statement

Marcelo de Oliveira Soares: Conceptualization, Writing - Original Draft, Writing - Review & Editing, Formal analysis, Methodology, Supervision. **Emanuelle Fontenele Rabelo:** Conceptualization, Writing - Original Draft, Writing - Review & Editing, Methodology, Formal analysis.

Availability of data and materials

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

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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