Ocean and Coastal Research

**Original Article**
Special Article Collection
Souza, R. B. and Lopes, R. M. (eds), Environmental variability and hazards on the coastal and continental shelf regions of South America and the Caribbean

http://doi.org/10.1590/2675-2824071.22153bzn
ISSN 2675-2824

# Marine Protected Areas Affected by the most extensive Oil Spill on the Southwestern Atlantic coast

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## Abstract

This study identified the marine protected areas (MPAs) affected by the most extensive oil spill recorded on the Southwestern Atlantic coast, Brazil (2019/2020). We found that 81 MPAs suffered the direct or indirect effects of spilled oil, producing chemical, biological and socioenvironmental impacts over approximately 3.0% of the 2,659 protected areas currently established in Brazil. Although estimates suggest a moderate volume of spilled oil, the incident reached wide coastal strips, probably producing more damage to MPAs than other cases worldwide. Further, the generated negative impacts affected the already fragile environmental protection system in Brazil, potentially leading to negative impacts on global networks of MPAs and worldwide biodiversity.

**Descriptors:** Pollution, Aromatic hydrocarbons, Environmental impacts, Socioeconomic impacts.

## INTRODUCTION

Seeking to protect natural resources and biodiversity, global authorities such as the International Union for Conservation of Nature – IUCN have implemented conservation tools (Edgar et al., 2014). Several strategies have been proposed, especially lists of threatened species and ecosystems at risk of collapse, world database on critical areas for biodiversity, and creation of protected areas (UNEP/WCMC, 2019). Protected areas (PAs) are legally established zones, covering different forms of management (e.g., no-take/restricted protection or direct/multiple use) of physical spaces and natural resources aiming to conserve global biodiversity. Due to the innumerous ecosystem services (in addition to the massive marine biodiversity) IUCN definitions (Nicoll and Day, 2017) also included marine and coastal protected areas (MPAs). Overall, MPAs are directly related to the marine heritage of the world by a global representative system managed according to a world conservation strategy. Despite global efforts, recent studies have shown that the conservation objectives of these MPAs may be under threat (Abessa et al., 2018). Biodiversity losses currently relate to five main drivers, these being climate change, habitat alterations, introduction of invasive

Submitted: 20-Nov-2022
Approved: 12-Apr-2023

Editor: Rubens M. Lopes

species, over-exploitation of natural resources, and pollution (Young et al., 2016). Unfortunately, the release of hazardous substances and waste has increased pollution rates, compromising biodiversity even within MPAs (Castro et al., 2021).

Accidents involving oil spills have occurred over the past years causing socioecological and economic damages on vulnerable coastal and oceanic regions (Wikelski et al., 2001; Oliveira, 2013). Such spillages have become one of the main threats to marine and coastal environments, with long-term impacts on the economy and human and environmental health (Xu et al., 2020). Furthermore, oil leakages also occur due to natural exudations or during routine processes linked to oil and gas production chains (Doshi et al., 2018; Xu et al., 2020). In both cases, the generated chronic and acute impacts were initially limited to a small spatial scale (Spaulding, 2017). However, meteorological, oceanographic, and physicochemical processes can disperse oil slick, reaching wider geographical areas and marine substrates (Ye et al., 2020).

From August 2019 to March 2020, weathered oil reached almost 3,000 km of the Brazilian tropical coast. Oil slicks were observed in 120 municipalities along the northern, northeastern, and southeastern coast of Brazil (Escobar, 2019). Although the precise origin of the spillage is yet to be elucidated, estimates suggest that the release occurred approximately 700 km off the Brazilian coast, spilling from 5,000 to 12,500 $m^3$ of oil (Zacharias et al., 2021) with geochemical characteristics compatible with Venezuelan sedimentary basins (Oliveira et al., 2020). Despite this moderate to low spilled volume, based on its extension, mismanagement of oil mitigation, and the hit locations, this accident was considered the most extensive to ever reach tropical oceans worldwide (Soares et al., 2020a). In fact, the event attracted wide international attention due to its geographic magnitude (>3,000 km of coastline affected). Affected areas included highly vulnerable tropical environments such as estuaries of important rivers, mangroves, rocky shores, tidal flats, algae banks, seagrasses, coral reefs, and rhodolith beds (Sissini et al., 2020; Soares et al., 2020a; 2020b). Although preliminary estimates have indicated impacts in several MPAs (Soares et al., 2020a), the extent of the damage caused by this accident remains unknown, especially considering the different IUCN management categories (WCPA, 2019) and potentially affected threatened fauna.

The proper management of MPAs depends on environmental information about the potential impacts on their surroundings (e.g., buffer zones). Despite this, few studies have evaluated the occurrence of petroleum-based hazardous residues within MPAs (Nunes et al., 2021). Using available georeferenced database of affected coastal areas overlapped with MPA polygons enables the assessment of critically impacted zones, identifying each MPA hit by the oil spilled on the South Atlantic. This strategic approach plays an essential role in the recognition of affected MPAs, enabling managers to establish mitigation plans to recover degraded areas in the shortest time possible. Therefore, this study aims to systematically assess the MPAs potentially affected by the most extensive oil spill ever recorded in South Atlantic coast (Brazil 2019/2020).

## MATERIAL AND METHODS

During the whole oil spill accident period (August 2019 to March 2020), the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA), Navy, Federal Police, National Petroleum and Biofuels Agency(PETROBRAS), and local environmental agencies monitored the occurrence of oil slick and provided georeferenced data in official reports (IBAMA, 2022). The latest update (issued in March 2020) of these data, including geographic coordinates of all oiled beaches assessed during the incident, was downloaded from https://www.ibama.gov.br/manchasdeoleo, converted into a .CSV file, and imported into QGis program. The polygons delimitating the geographic information system (GIS) data of global protected areas (freely available on the WDPA database, www.protectedplanet.com) was also downloaded and intersected with the layer containing oil slick locations. Using a vector analysis tool, the number of affected points identified within each MPA was counted. Seeking to assess oil contamination in the immediate surroundings of MPAs, a buffer zone of 0.01 degrees (~787 m) was added and the layers were overlapped again. The number of contamination records within and around each MPA was inserted in a third layer, allowing to graphically visualize the occurrence of oil slick. After this step, the affected MPAs were grouped according to IUCN management categories (Dudley, 2008) to qualitatively assess potential threats resulting from the oil spill. This approach, using data insertion into a GIS and overlapped with worldwide shapefiles, has been previously adopted to identify MPAs affected by hazardous substances worldwide (Castro et al., 2021; Nunes et al., 2021, 2023). Considering the lack of information on size and volume of each oil slick, presence of oil was used as a parameter to define affected areas, indicating environmental threats.

## RESULTS AND DISCUSSION

### Marine Protected Areas affected by the oil spill

IBAMA made 1,009 oil slick sighting records available up to March 2020, when monitoring activities were demobilized. Lessa et al. (2021) found the same number of affected areas. From these, 480 were located inside the boundaries of MPAs and another 346 were outside but within the buffer zones limits (0.01°/~787 m) established to assess impacts on MPAs surroundings (Figure 1 – see a detailed view of all affected MPAs in the Supplementary material, Figures S1 to S4). This buffer approach was adopted since, in the case of oil spills, dilution and dispersion of toxic molecules may suffer the influence of the tides, wind, and nearshore currents reaching adjacent areas (Ye et al., 2020). Oil slicks reported on the limits of MPAs (around 787 m/0.01°) may also chemically impact such areas (Nunes et al., 2021). In fact, management plans have proposed buffer zones up to 5 Km to safeguard MPAs from oil releases (Makatounis et al., 2017). Crude oil is a complex mixture of thousands of toxic compounds mainly composed of hydrocarbons, including mono- and polyaromatic molecules and trace elements (Zhang et al., 2019). After leaking into seawater, oil tends to spread out and subsequently suffer weathering processes, such as emulsification, adsorption, biodegradation, dispersion, dissolution, evaporation, and photo oxidation, resulting in semisolid masses with densities significantly higher than water (Lourenço et al., 2020). Therefore, the emulsified oil that reached Brazilian MPAs presumably affected sandy beaches, seagrass beds, intertidal and subtidal coral reefs, and mangrove ecosystems or was deposited on top of other essential benthic environments (Magalhães et al., 2021).

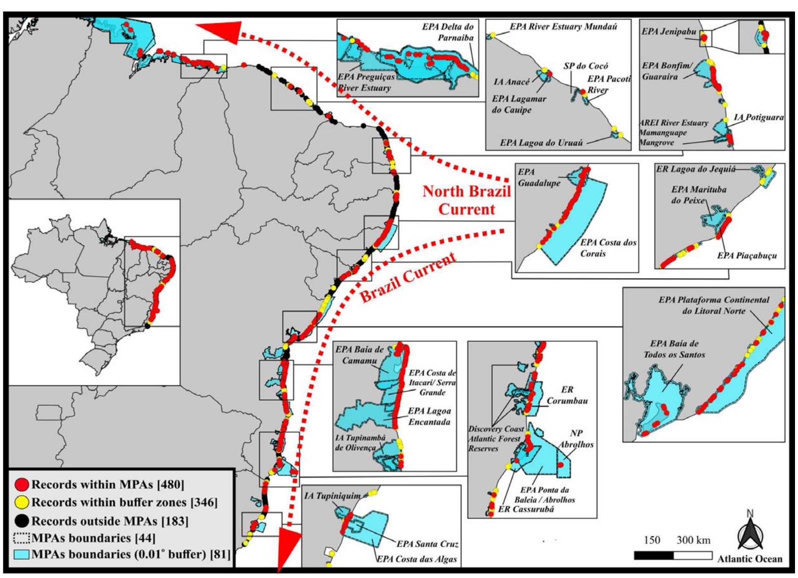


**Figure 1.** General overview of the marine protected areas (MPAs) affected by the most extensive oil spill in tropical oceans (Brazilian coast, 2019/2020). AREI = Area of Relevant Ecological Interest; EPA = Environmental Protection Area; ER = Extractive Reserve; IA = Indigenous Area; NP = National Park; SP = State Park.

The official reports this study searched showed that 44 MPAs had oil spill records within their boundaries, but considering the buffer zones, 81 MPAs would potentially suffer the effects of the spilled oil (Figure 2). According to the national panel of conservation units, Brazil currently has 2,659 protected areas in different biomes and categories (Ministério do Meio Ambiente, 2023). Therefore, approximately 3% of such areas suffered the direct or indirect effects of this oil spill. Considering only the marine biome, the oil spill reached approximately 41.5% of the 195 Brazilian MPAs. Unfortunately, MPAs worldwide often show contamination. A recent study reported 341 records of polycyclic aromatic hydrocarbons (PAH) during the last 10 years, spread over 36 MPAs in nine Latin American and the Caribbean countries (Nunes et al., 2021). Similarly, a review assessing the levels and biological effects of tributyltin (TBT) in Latin American costal zones from 2000 to 2018 (18 years) totaled 259 contamination records in 53 MPAs, including biosphere reserves, Ramsar sites, and national parks (Castro et al., 2021). Both studies suggest that the MPA protection system has been unable to protect species from chemical impacts. Pollution features among the top five causes of Anthropocene defaunation (Young et al., 2016). Therefore, considering the huge number of MPAs contaminated by this single oil spill in addition to the amount of oil that reached the ecosystem, the damage to affected conservation areas will presumably be higher than decades of PAH and TBT in MPAs. We should highlight that the pollution status of most MPAs worldwide remains unknown (Abessa et al., 2018). This situation is even more critical in Latin American countries since the financial costs to monitor large sample grids is an issue to be overcome (Castro, 2019).

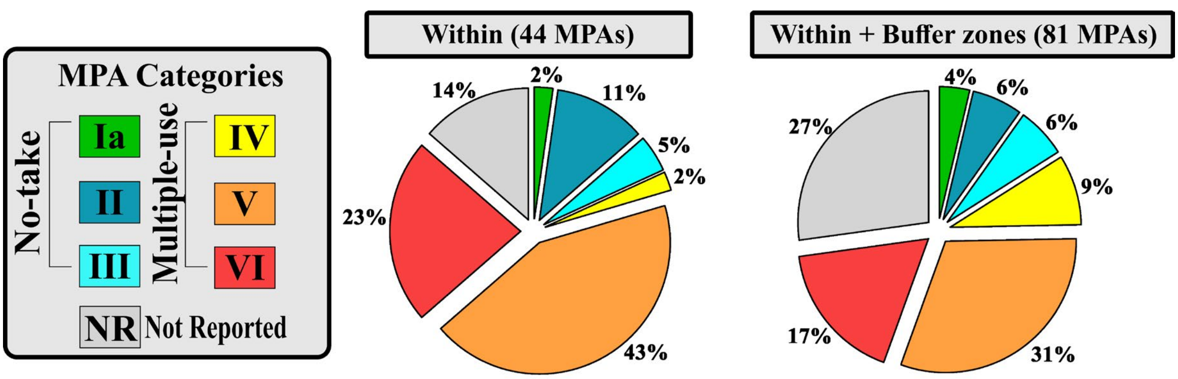


**Figure 2.** Distribution (%) of records of oil residues in different MPAs categories, including no-take and multiple-use ones: within the limits of MPAs (a), considering MPAs boundaries and buffer zones (b).

Protected areas have common goals aiming to conserve the composition, structure, function, and evolutionary potential of biodiversity (Mora and Sale, 2011). The IUCN classifies protected areas according to six categories and provides a global guide for its implementation and management. Overall, Nature Reserves (Ia), Wilderness Areas (Ib), National Parks (II), and Natural Monuments or features (III) configure no-take PAs (unmodified or slightly modified) with less human interference and integral protection. Categories II and III allow visits and recreational activities (Dudley, 2008). This study reports contamination in all MPAs categories, including no-take and multiple-use groups. It recorded oil slicks within or around 13 MPAs belonging to more restrictive classes, in contrast to the 68 multiple-use MPAs that received direct or indirect (buffer zones) impact (Figure 2). Considering only MPAs with oil residues, 18% were no-take and 68% were multiple-use areas (Figure 2a). It found a similar pattern that included buffer zones (16% no-take / 67% multiple-use areas), even though the number was almost twice as high. Unfortunately, this extensive disaster affected many restricted protected areas, many of which offer important ecosystem services to local communities (Table 1).

**Table 1.** Marine Protected Areas affected by the oil spill on the Brazilian coast between August 2019 and March 2020 by Management Categories (with and without buffer zones). AREI = Area of Relevant Ecological Interest; BR = Biological Reserve; EPA = Environmental Protection Area; ES = Ecological Station; ER = Extractive reserve; IL = Indigenous land; MNP = Municipal Natural Park; NM = Natural Monument; NP = National Park; NR = Category Not Reported; PNHR = Private Natural Heritage Reserve; SP = State Park; WR = Wildlife Refuge.

| MPA Name | IUCN Category | Records (0.01°buffer) | Records (MPAs) |
|---|---|---|---|
| BR Comboios | Ia | 3 | - |
| BR Santa Isabel | Ia | 22 | 14 |
| BR Una | Ia | 1 | - |
| NP Itaúnas | II | 7 | 2 |
| NP Jericoacoara | II | 1 | 1 |
| NP Monte Pascoal | II | 4 | 3 |
| NP Lençóis Maranhenses | II | 6 | 5 |
| NP Abrolhos | II | 3 | 3 |
| NM Falésias de Beberibe | III | 1 | - |
| WR Una | III | 5 | 3 |
| WR Frades River | III | 1 | - |
| WR Santa Cruz | III | 6 | 1 |
| WR Mata Lanço dos Cações | III | 1 | - |
| AREI River Estuary Mamanguape Mangrove | IV | 2 | 1 |
| AREI Corredor Ecológico Lagoa Encantada | IV | 7 | - |
| AREI Barra do Rio Camaratuba | IV | 1 | - |
| PNHR Canto do Senhor | IV | 2 | - |
| PNHR Caju | IV | 1 | - |
| PNHR Dunas de Santo Antônio | IV | 2 | - |
| PNHR Mata Estrela | IV | 1 | - |
| EPA Bonfim/Guaraíra | V | 32 | 20 |
| EPA Baía de Camamu | V | 40 | 35 |
| EPA Baía de Todos os Santos | V | 7 | 7 |
| EPA Barra do Rio Mamanguape | V | 5 | 5 |
| EPA Caraíva/ Trancoso | V | 9 | 9 |
| EPA Conceição da Barra | V | 14 | 2 |
| EPA Costa de Itacaré/ Serra Grande | V | 25 | 17 |
| EPA Costa dos Corais | V | 69 | 41 |
| EPA Preguiças River Estuary | V | 32 | 27 |
| EPA Lagoa do Uruaú | V | 1 | - |
| EPA ReentrânciasMaranhenses | V | 5 | 5 |
| EPA Piaçabuçu | V | 20 | 17 |
| EPA Delta do Parnaíba | V | 52 | 43 |
| EPA River Estuary Mundaú | V | 1 | - |
| EPA Lagamar do Cauipe | V | 1 | 1 |
| EPA Barra Grande Mangrove | V | 1 | 1 |

continues...

| MPA Name | IUCN Category | Records (0.01°buffer) | Records (MPAs) |
|---|---|---|---|
| EPA Pecém | V | 1 | - |
| EPA Pacoti River | V | 1 | - |
| EPA Lagoa Encantada | V | 26 | 25 |
| EPA Lagoas de Guarajuba | V | 8 | - |
| EPA Lagoas e Dunas do Abaeté | V | 3 | - |
| EPA Plataforma Continental do Litoral Norte | V | 63 | 24 |
| EPA Ponta da Baleia / Abrolhos | V | 14 | 10 |
| EPA Santo Antônio | V | 16 | 9 |
| EPA Jenipabu | V | 7 | 4 |
| Amazon Estuary and its Mangroves | VI | 61 | 49 |
| ER Acaú-Goiana | VI | 1 | - |
| ER Corumbau | VI | 27 | 11 |
| ER Canavieiras | VI | 36 | 20 |
| ER Cassurubá | VI | 7 | 2 |
| ER Cururupu | VI | 2 | 2 |
| ER Lagoa do Jequiá | VI | 8 | - |
| ER Delta do Parnaíba | VI | 12 | 1 |
| EPA Caminhos Ecológicos da Boa Esperança | VI | 8 | - |
| EPA Costa das Algas | VI | 15 | 13 |
| EPA Marituba do Peixe | VI | 2 | - |
| EPA Guadalupe | VI | 14 | 14 |
| EPA Santa Cruz | VI | 7 | 7 |
| EPA Setiba | VI | 1 | - |
| AREI Degredo | NR | 6 | 2 |
| IL Aldeia Velha | NR | 1 | - |
| IL Anacé | NR | 2 | - |
| IL Barra Velha | NR | 6 | - |
| IL Cahy/Pequi | NR | 1 | - |
| IL Caieiras Velha | NR | 1 | - |
| IL Coroa Vermelha | NR | 16 | 10 |
| ES Pécem | NR | 2 | - |
| IL Mata Medonha | NR | 2 | - |
| SP do Cocó | NR | 2 | 1 |
| SP Ponta da Tulha | NR | 6 | - |
| MNP Dunas da Sabiaguaba | NR | 3 | - |
| MNP Jacarenema | NR | 1 | - |
| MNP Forte de Tamandare | NR | 5 | 2 |
| MNP Von Schilgen | NR | 5 | - |
| IL Potiguara | NR | 1 | - |
| PNHR Fazenda Caruara | NR | 1 | - |

continues...

| MPA Name | IUCN Category | Records (0.01°buffer) | Records (MPAs) |
|---|---|---|---|
| PNHR Vale do Cantassurá | NR | 1 | - |
| IL Tupinambá de Olivença | NR | 14 | - |
| IL Tupiniquim | NR | 2 | - |
| Discovery Coast Atlantic Forest Reserves | World Heritage | 13 | 6 |
| Reentrâncias Maranhenses | Ramsar site | 5 | 5 |
| TOTAL | | 826 | 480 |

## No-take or restricted protected areas

The most serious case occurred in Santa Isabel Biological Reserve - SIBR (category Ia) with 14 records of oil contamination spread within the limits and another eight in the surrounding areas. The SIBR is an important protected area in the São Francisco River Mangroves (northeastern Brazil), hosting a relevant spawn and nursery area. Thousands of sea turtles use the area seasonally (Santos et al., 2020), including the hawksbill turtle (*Eretmochelys imbricata*) — listed as critically endangered —, and the olive Ridley sea turtle (*Lepidochelys olivacea*) considered vulnerable according to IUCN Red List of Threatened Species (IUCN, 2019). Still considering this category (Ia), oil residues were also reported within the buffer zones of the Comboios Biological Reserve, potentially affecting nesting zones of sea turtles such as loggerheads (*Caretta caretta*) and leatherbacks (*Dermochelys coriacea*), considered as vulnerable species (Valdivia et al., 2019). The Una Biological Reserve is a no-take protected area that conserves an important remnant of the Atlantic Forest, and is part of the Biosphere Reserve (Teodosio and Flores-Lopes, 2020). At least 15 threatened species of birds live inside this reserve (Vaske Júnior and Lessa, 2005). Just one record of oil residue was reported within this area. Strict natural reserves (category Ia) aim to conserve outstanding ecosystems and species, safeguarding natural environments for scientific studies, monitoring, and education, including baseline areas (Dudley, 2008). Although the size and volume of reported oil slicks remain unknown, based on the number of records, especially at Comboios and Santa Isabel Biological Reserves (n=22), such distinguishing features may have been lost, at least temporarily.

The five affected National Parks (category II) affected (Table 1), have unique ecosystems, such as Lençóis Maranhenses Park with ecotones among the Amazonia, Caatinga, and Brazilian savanna, represented by the transition from the Pre-Amazonian black woods to extensive dune fields and blue carbon ecosystems such as mangroves (Dos Santos et al., 2019). Although this national park (the largest dune field in South America) shelter endangered and vulnerable fish species, it showed six records of oil residues added to one in the buffer zone. In the same category, the Itaúnas National Park was the most affected MPA, with two oil slick records within its limits and five others in its vicinities (Table 1). This area plays an essential role in the conservation of relevant ecosystems, including mangroves, dunes, plateau forests, and coastal wetlands that shelter some endangered bird and lizard species (Oliveira et al., 2018). Similarly, Abrolhos National Park concentrates the largest and richest coral reef formations in the South Atlantic with high species richness and local endemism (Magris and Giarrizzo, 2020), in which three oil slicks were recorded (Table 1). Recently, the Abrolhos Bank was also reached by another recent environmental disaster in Brazil, in which an ore tailings dam collapsed releasing over 50 million $m^3$ of material into the Rio Doce Basin, in November 2015. The particulate material and associate toxic elements were probably mobilized towards the Abrolhos Bank reefs (Coimbra et al., 2020). Therefore, the oil spilled was another chemical stressor threatening the Abrolhos National Park.

The Monte Pascoal National Park (four records inside it and one record in its buffer zone) houses one of the last remnants of the Atlantic Forest, and several endangered species and present configures a high priority area for conservation. Moreover, Indigenous peoples have claimed part of this area, triggering sociocultural conflicts (Ferreira, 2018) suggesting that additional socio-environmental conflicts may take place in the region. The Jericoacoara National Park had one record verified within its boundaries. This MPA conserves coastal areas with different features, including dunes field, coastal lagoons, sandy beaches, beach rocks, and mangroves (Irion et al., 2012), and currently it constitutes an important tourist destination in Brazil. Overall, National Parks are designed to conserve the natural state of the local physiographic and biological heritage and maintain ecosystem integrity. Such PAs also manage visitor use by considering the needs of Indigenous and local communities, seeking to contribute to local economies by tourism (Dudley, 2008). Thus, as Câmara et al (2021) point out, this oil spill compromised conservation goals and simultaneously increased the socio-environmental vulnerability of economies highly dependent of coastal resources, such as traditional human communities in Brazil.

According to the analyzed reports, four Wildlife Refuges (Una, Frades River, Santa Cruz, and Mata Lanço dos Cações) and one Natural Monument (Falésias de Beberibe) were affected by the oil spill, considering management category III (Table 1). In total, the Una Wildlife Refuge (WR) had three records., The refuge was created to protect relevant natural environments for the reproduction of resident species and migratory fauna. This area belongs to a protected areas mosaic that includes the above-mentioned Una Biological Reserve and the Indigenous land Tupinamba de Olivença (14 records in buffer zones), both affected by the oil leakage spill (Teodosio and Flores-Lopes, 2020). The buffer zone of Frades River WR buffer zone had one record. This MPA covers an extensive coastal strip composed of plains bordering a cliff, and shows rub areas in sandbanks as predominantly vegetation (Ramos et al., 2021). The Santa Cruz WR was created to protect biodiversity and coastal environments, especially the macroalgae banks and the associated benthic fauna. Resident and migratory species use the mangroves, coastal vegetation, and the sedimentary formations for food, reproduction, and shelter. This refuge showed one record of oil slick (in addition to other five in its buffer zones). We should highlight that the Santa Cruz WR was also affected by suffered from plumes of a particulate material generated by due to the mining dam break occurred in 2015 (do Carmo et al., 2017), indicating the occurrence of additional chemical contamination at this MPA. The only affected Natural Monument was Falésias de Beberibe (one record in its buffer zone), which was created to preserve the local coastal landscape and manage tourist activities in the region. The MPAs included in IUCN management category III are frequently small areas with high visitor tourism value and are devoted to protecting specific natural features in association with local biodiversity and habitats (Dudley, 2008). Although few records of oil residues have been verified in these MPAs, their effective conservation purposes (Bonaldo et al., 2017) could succumb even when exposed to local and/or small contamination inputs (Castro, 2019).

## Multiple-use protected areas affected by oil spill

Multiple-use protected areas (IUCN categories IV–VI) had 422 records, distributed in 29 MPAs. Considering their buffer zones, this number rises to 670 records in a total of 46 MPAs. Among these areas, nine MPAs were hit simultaneously by 20 or more records during the monitored period (Table 1). The presence of 43 slicks of oil residues was registered at the Environmental Protected Area (EPA) of Parnaíba Delta River. This area provides nursery zones and hydrological connectivity, playing a vital role in migration and recruitment of estuarine-dependent organisms, including oceanic species and vulnerable coral reefs (Guimarães-Costa et al., 2019). The EPA Costa dos Corais showed 41 oil records, in addition to another nine occurred in its surroundings. This EPA borders 12 coastal cities, covering ~413,000 ha, and it is the largest nearshore MPA in Brazil. It was created to protect large coral reefs and local mangroves besides the reminiscent populations of the marine manatee (*Trichechus manatus*) in the Brazilian coast (Araújo and Bernard, 2016). Moreover, other 22 MPAs classified as Ramsar sites, World

Heritage, Indigenous land, or not categorized (NR) by IUCN showed together a total of 26 and 96 records of oil residues considering inner and buffer zones, respectively (Table 1). Although sustainable-use MPAs enable a certain level of human interaction and even exploitation of natural resources (e.g., fishing and tourism), they must act toward protecting species and coastal habitats, seeking to maintain their distinguishing environmental features (Dudley, 2008).

Based on potential impacts related to the oil arrival in these protected zones even in small amounts, both, human and environmental dimension covered by such MPAs may have been jeopardized. A study assessing effects of oil exposure on early life-stages of coral reef fishes, showed that environmentally relevant PAH levels ($\leq 5.7$ μgL$^{-1}$), induces high mortality and stunted growth (Johansen et al., 2017). This study also reported alterations in habitat settlement and anti-predator behaviors, amplifying predator-induced mortality during recruitment. As soon as the oil reached the coast of Pernambuco State, the local Environmental State Agency sampled seawater from the most 14 most impacted beaches. These samples showed low PAH concentrations, varying from undetected to 0.078 μg L$^{-1}$, except at one sample, which showed 65.8 μg L$^{-1}$ (CPRH, 2020). This highest result should be carefully considered because small oil fragments could be seen spread in water, making this result non-representative of the soluble fraction in seawater. On the other hand, fragments presence indicates the high possibility of chemical transfer to the water column. Moreover, oil fragments collected from the beaches at the time of accident were used to investigate the effects of the crude oil water-accommodated fraction on the competitive fitness of *Symbiodinium glynnii* (a zooxanthellae species) (Müller et al., 2021). This study showed that carcinogenic/mutagenic PAH were related to a linear reduction in population growth of *S. glynnii*, in addition to the deleterious effects on physiology and competitive fitness (in terms of growth rate), due to DNA alterations. Such results shows that corals affected by this oil could be under threat. PAH were also analyzed in sediments from the surrounding area of the EPA Costa dos Corais. The area was clearly contaminated by the spilled oil and PAH concentrations were 3 to 6 times higher than those observed back in 2014 (Zanardi-Lamardo, unpublished data). Some individual PAH concentrations, such as acenaphthene, fluorene, phenanthrene, and dibenz[a,h]anthracene were higher than the threshold effect levels (TEL) that Macdonald et al. (1996) proposed, suggesting that the benthic organisms might be under threat. Moreover, a study conducted along 20 sampled sites distributed in the Alagoas and Sergipe coastal strips showed seawater levels of ΣPAHs reaching up to 275.49 ng L$^{-1}$, with naphthalene as the main contributor (Soares et al., 2021b). Although the potential risks to marine fauna are evident based on such findings, few studies have been published so far, reporting environmental levels of PAH in affected areas after the accident.

## Impacts on Aquatic biota

Some of the immediate oil impacts included killing vertebrate animals such as turtles, fish, dolphins, and birds along the affected areas (Craveiro et al., 2021). An oil-covered dead specimen of *Chelonia mydas* and several *Eretmochelys imbricata* nests contaminated with oil fragments were found in the Pernambuco coast (database from the Ecoassociados Non-Governmental Organization). At the same place, oil drops found in turtle feces were analyzed, showing the same hydrocarbons distribution as a sandy-oiled sample collected nearby, thus denoting the same source (Zanardi-Lamardo, unpublished data). According to Soares et al. (2022) at least 34 threatened species listed as vulnerable were living within contaminated areas and were potentially under threat. Invertebrate benthic species are also expected to be affected since sediment layers tend to accumulate higher hydrocarbons concentrations (Castro, 2019). Records suggest that three VU echinoderms live in contaminated MPAs (*Astropecten marginatus*, *Coscinasteria stenuispina*, and *Lytechinus variegatus*). The endangered anemone (*Condylactis gigantea*) and the endemic vulnerable coral *Mussismilia* *braziliensis* were also found inside the limits of the contaminated MPAs (Soares et al., 2022). Such species, registered in the Abrolhos National Park and EPA Ponta da Baleia, play a vital role in the ecological dynamics of the coral reefs. *M. braziliensis* represents approximately 70% of the coral cover in the Abrolhos bank, which has experienced a remarkable decrease during the last decade (Ribeiro et al., 2018). Bayesian models have reported a high bleaching incidence for the Abrolhos bank due to global climate change (Bleuel et al., 2021). Moreover, impacts related to overfishing, pollution, predation, storms, and an infectious diseases named white plague, have already negatively affected this coral species (Garcia et al., 2013). Facing so much stress, the coral is expected to be already weakened, becoming even more susceptible to PAH contamination. During the mysterious oil spill on the Brazilian coast, both symbiotic polychaete *Branchiosyllis* spp. associated with and the sponge *Cinachyrella* sp. showed oil stains. Following the accident, the polychaeta abundance declined abruptly (Lira et al., 2021). A similar effect (reduction of species richness and abundance) was observed for the benthic communities associated with the algae *Jania capillacea and Penicillus capitatus*, at a coral reef in Pernambuco (Craveiro et al., 2021).

An assessment of potential impacts generated due to a large oil leakage occurred in the Gulf of Mexico after the Deepwater Horizon oil well blowout, have also pointed out environmental risks to threatened species (Campagna et al., 2011). A comprehensive review evaluating physiological impacts of the oil spilled in Gulf of Mexico, concluded that oil toxicity may induce multi-target effects dependent on fish life-stages. Overall, fish species showed biological alterations, especially cardiotoxic effects, at ΣPAH exposures ranging from $<1$ μg $L^{-1}$ to $<8.6$ μg $L^{-1}$ with early life stages being up to -an order of magnitude more sensitive (Pasparakis et al., 2019). During the oil contamination on the Brazilian coast, PAH and their metabolites were investigated in the bile of *Stegastes fuscus* from contaminated reef areas (Pernambuco State) in addition to the biochemical biomarkers (phase I biotransformation enzymes (ethoxyresorufin-O-deethylase, EROD) and phase II biotransformation enzymes (glutathione S-transferase, GST), antioxidant defense (catalase, CAT), lipoperoxidation (TBARS), and acetylcholinesterase (AChE). The increased concentration of chrysene and pyrene (and their metabolites) in the bile were associated to an increase in EROD and CAT activities. The GST, AChE, and lipid peroxidation (TBARS) showed no significant association with bile PAH. Similar effects are expected for some MPAs hit by the oil residues, which could lead to severe ecological disruptions, not only affecting the threatened fish species, but also other species of commercial importance such as crustaceans and mollusks. This hypothesis is corroborated considering that since most of affected coral reefs and mangroves serve as nurseries for these organisms (França et al., 2012) and oiled planktonic organisms have been recorded in some estuaries after these mysterious accident (Campelo et al., 2021). Thus, although the Gulf of Mexico disaster has been considered as the largest accidental oil spill so far (Eckle et al., 2012), the oil that hit over >3,000 km of the Brazilian coastline may have the potential to cause similar damages on the threatened fauna.

## Socioenvironmental Remarks

Several MPAs and associated organisms were already under influence of multiple human impacts (e.g., organic pollution, global warming, overfishing, invasive species, and habitat destruction) even before this disaster exposition (Magris et al., 2020; Soares et al., 2022b). Indeed, based on studies assessing contamination and pollution levels globally and in Latin America (Abessa et al., 2018; Castro et al., 2021; Nunes et al., 2021), the effective conservation provided by Brazilian MPAs have been limited due to many governance flaws and lack of inspection. Poor management, issues linked to regional MPAs networks, an overly bureaucratic management and administrative system, budget cuts creating structural problems has been historically pointed out (Gerhardinger et al., 2011). In recent years, an institutional crisis faced by the federal government has hindered the adoption of environmental protection measures by environmental agencies (Abessa et al., 2018).

Unfortunately, the lack of last decades government actions to avoid and mitigate the frequent large-scale disasters has become globally evident over the last few years (and Do Carmo et al., 2017; Coimbra et al., 2020).

In the case of this mysterious oil accident, several factors hindered the making of the best decision for local and national contingency plans. The oil residue suddenly reached the coast and hit an extensive area. Its appearance featured oil partially degraded and visibly emulsified oil. Once outside the water column, this oil settled up on beaches, coral reefs, and others sensitive ecosystems. However, the high local temperature liquefied the residue, potentially released toxic vapors, and decreased its viscosity, sticking to organisms and penetrating the beach sand. Local and federal governments dealt with this unique situation slowly, and improperly, resulting in more negative socioenvironmental consequences. (Brum et al., 2020; Soares et al., 2020b). All these factors together amplified the impact upon biota, although volunteers anxiously tried to recover the environment. Communities that highly depending on fishing and tourism, which often carried out their economic activities within multiple-use MPAs and surrounding areas, have suffered relevant health and income losses (Camara et al., 2021). This is particularly relevant considering the goals of the global network of MPAs, which is designed to simultaneously support fisheries productivity, conservation, and food resources in local and worldwide scenarios (Roberts et al., 2001).

## CONCLUSION

Approximately 3.0% of the 2,659 PAs established in Brazil were directly or indirectly affected. The environmental disaster caused by the mysterious oil reaching the Brazilian coast in 2019/2020 also impacted several species of the threatened fauna. This large-scale environmental disaster may jeopardize the already fragile coastal and marine protection system in Southwestern Atlantic (Brazil), leaving a global recorded balance of 81 affected MPAs, which were exposed to hazardous substances, in addition to environmental and socioeconomic damages that will be difficult to overcome. Considering the extensive impacts and intrinsic connections of the global network of MPAs, this oil spill may have produced relevant impacts on worldwide biodiversity.

## ACKNOWLEDGMENTS:

This research was supported by the São Paulo Research Foundation (FAPESP n. 2020/03828-3) and the Fundo Brasileiro para a Biodiversidade/Instituto Humanize (n. 003/2021). I.B. Castro (PQ 302713/2018-2), E. Zanardi-Lamardo (PQ 311771/2019-0) and M.O. Soares (PQ 310165/2020-2) were recipients of research productivity fellowships from the CNPq. B.Z. Nunes was supported by the Coordination for the Improvement of Higher Education Personnel (CAPES / Finance code: 001).

## AUTHOR CONTRIBUTIONS

B.Z.N.: Methodology; Software; Formal Analysis; Investigation Writing – original draft.

E.Z.; M.O.S.: Writing – review & editing.

I.B.C.: Conceptualization; Investigation; Writing – original draft; Writing – review & editing.

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