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On the Impact of Brazil's Largest Recent Oil Spill on Regional Oceans

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ABSTRACT

In 2019, an oil spill in Brazil, of unknown origin, severely impacted coastal environs with the worst environmental disaster ever recorded in any tropical coastal region globally severely damaging South Pirangi Reef area in the state of Rio Grande do Norte (RN). Here we discuss acute and chronic impacts including chemical contamination and economic consequences all over the world and show some evidence of the oil spill in this biodiverse area. Moreover, the lapse between the moment of the disaster, and the action to manage it, was hampered by a political agenda coinciding with local and global tragedies that redirected public attention. Meanwhile almost 2 years have passed still without the offending party identification or culpability; and poor communities may continue to absorb its deleterious impacts for decades without consideration or compensation. This disaster occurred during the Brazilian government's current issues involving extensive environmental mismanagement, resulting in a slow response from an inept system. It is with urgent necessity to spotlight this tragedy in this unique and sensitive reef habitat experiencing the ongoing damaging effects that include socio-economic losses not yet addressed.

1. Introduction

In late July 2019, Brazil passively witnessed its first major oil spill disaster, quickly reaching about 3000 km

of the country's northeast coast ^[1-5], which holds one of the main marine diversity areas in the South Atlantic ^[6]. Although the peak of the spill seems to have been in September ^[7], the oil arrived on beaches and in estuaries until

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at least the end of 2019 (Figure 1). Due to currents, local hydrodynamics and geography, the oil quickly spread into a north and a south branch^[8], traveling via the subsurface (between 50 cm and 1 m deep). It reached at least nine northeastern states^[9] affecting about 55 marine protected areas^[3]. To a lesser extent, the oil also arrived at two additional states in the southeast of Brazil. Such an impact, duration and extension explain why this spill is considered the worst environmental oil disaster ever recorded in tropical coastal regions^[3].



Figure 1. A) Locations affected by the oil spill along the Brazilian coast (updated in 03/19/2020). B) Sergipe state. C) Marau, Bahia state.

Source: <http://www.ibama.gov.br/manchasdeoleo-localidades-atingidas>. Examples from Brazilian northeastern sites affected by the oil spill:

Source: <http://www.ibama.gov.br/manchasdeoleo-galeria>.

The crude oil spilled was formed by a complex chemical mixture of thousands of hydrocarbon-type compounds and small amounts of chelated heavy metals^[10]. The origin of the spill itself remains a mystery even two years later! A significant amount of oil has been removed from the beaches, totaling about 5000 tons, in an effort coordinated by state institutions, the Navy and IBAMA (Brazilian Institute of the Environment), but especially pioneered by the civil society volunteers^[11]. Apart from the less visible environmental consequences, such as the accumulation of hydrocarbons in the food chain as of January 15, 2020, at least 159 oiled animals had been reported, of which 112 were found dead^[12]. In according to^[13] the spill probably occurred by buoyancy problems on the tanker losing its cargo. They hypothesis that the leak was caused by tanker buoyancy problems (hull rupture or engine failure) results in leak or dumping of a part of its cargo in the subsurface waters. The estimated volume (5000-12,500 m³) was similar to what was expected in a continuous leak from an internal compartment tanker with the size between PAN-AMAX and SUEZMAX.

In addition to immediate and visible consequences, such as habitat pollution and the death of oiled animals,

oil spill disasters have multiple short and long-term consequences on entire social and ecological systems that rely on the now contaminated environment. As such, oil spills should be approached in a broad, integrated and multidisciplinary way. Integrated scientific approaches should include disciplines and topics such as oceanography (chemistry, physics, and biology), ecology, spatial modeling, geology, toxicology, epidemiology, microbiology, fisheries, sociology, psychology and economics. If properly implemented, such an approach could provide more effective mitigation pathways and help develop strategies to avoid future disasters, and aid in decision and policymaking^[14].

Given the tools and technology available to prevent, deal with and mitigate spills, it is surprising that such a disaster did not merit a transparent cooperative approach in Brazil. The government first ignored the warnings, and then dismissed the criticism regarding its inaction and dismantling of environmental policies, including specific measures to deal with oil spills, and then finally it ideologized the debate. In the end, it acted only when confronted by the Federal Prosecution Service^[11], and after the media started registering the risks that marine-dependent people and volunteers were exposing themselves to while cleaning the beaches. Still, the federal measures were limited to cleaning the beaches and releasing insufficient funding for research, which was supplemented by more supportive technical and financial help from the affected states.

Brazil has opted for the easy way out hoping the problem either will disappear on its own or be forgotten as the more visible impacts fade away. This strategy may be facilitated, as the burden of contamination will be heavier on more vulnerable and powerless segments of the population, such as fishers and gleaners. These kinds of articles on the oil spill along the Brazilian coast in 2019 have shown that the response from Brazil's government to this disaster was slow, late, and with flawed remediation plans. Even though some of these important articles report the largest accident, they lack policies and research regarding severity of oil spills, environmental toxicity of the oil, and acute and chronic toxicity to communities (Figure 2). Besides that, the adverse impacts of the oil spill disaster upon Brazil's environment, economy and society were previously described mostly in Portuguese^[4,7,15-17] which unfortunately lacks international outreach and visibility. Fewer articles, with more impact^[2,4,13,18-22] have brought to attention information on the oil spill along Brazil's northeast and southeast seaboard, trying to find answers and fill data gaps on the geochemistry and identification of the source of the oily material. Discussion about environmental monitoring and response measures that must be implemented to minimize the ecological, economic, and social

effects of the spill; which is particularly relevant in areas with high tropical biodiversity while experiencing high social inequality, which is presently the case of this north-eastern accident in according to [3]. Even more recently, [23] argue that there is still a clear need for coordinated state interventions to mitigation the impacts, considering it's environmental, social, economic, human health and political dimensions even now, two years later. They have conducted focus meeting discussions with fishing communities in Alagoas (one of the most severely impacted states) to assess the local perceptions on the oil spill impacts and they estimate the impact of the oil spill on income generation and food security of coastal communities. The authors also analyzed the government action to handle such impacts and propose a set of recommendations to help alleviate the dramatic effects of this environmental disaster and to prepare for future ones.



Figure 2. Map showing area of affected area and the acute damages on the Plankton, Nekton, Benthos, water and sediment.

Almost 2 years later now, here we show that basic questions remain unanswered, including the scope of the ecological and social impacts of this spill. It is necessary to understand the dimension of these impacts, how long they are expected to last, anticipate collateral damages, and then propose mitigation options and mechanisms to reduce the magnitude of any future spill. As the oil becomes less and less visible to the naked eye, and the world is ravaged by new disasters (e.g. COVID-19 pandemic), and it is easy to let the largest oil spill in the South Atlantic fall into oblivion, leaving it to nature and for local hu-

man communities to bear its consequences for the decades to come.

Our paper deals with a specific site, the “Pirangi Reef area”, which was subjected to the oil spill In October 2019, and was previously studied in 2013 and 2014 with no spotting of oil patches in the sediment or in the water [24]. After the oil spill, we sampled new sites to compare and discuss questions on the human-induced changes on the reef system; therefore, water and surface sediments were recovered from areas of small reef patches near tourism boating sites.

2. Background on Oil Impacts over Marine Ecosystems

The release of hydrocarbons from oil spills into marine environments has immediate and acute effects on living organisms. In addition, chronic contamination has an effect over time as hydrogen sulphide, methane and ammonia are released in the environment acidifying the water-sediment interface. Dealing effectively with these impacts includes understanding how pollutants and contaminants in general are released and how they behave in the environment [25]. For example, hydrocarbon petroleum products are quite reactive in aerobic environments via microbial and photochemical reactions [26-29], and the production of hydrogen sulphide (H_2S) is a result of the microbial breakdown of organic materials of crude oil in the absence of oxygen. Hydrogen sulphide is a gas without color, and is flammable, poisonous and corrosive, noticeable by its rotten egg smell and with toxicity similar to carbon monoxide prevents cellular respiration. Monitoring and early detection of H_2S could mean the difference between life and death.

The contamination impact in the medium and long term is a silent one caused by oil being partially degraded and absorbed by the environment. Concentrations of PAHs sufficient to affect individual health following oil spills are common and can remain for long periods in some habitats [30,31]. The polycyclic aromatic hydrocarbons (PAHs) present in oil are immunotoxic to several wild aquatic species. The effects of immune toxicity include damage to the resistance of organisms, making them more subject to new diseases and increased parasitism, delaying population recovery [32], and teleost fish embryo is particularly sensitive to PAHs causing problems related to cardiac development [30].

A significant amount of oil (between 10 to 30%) has been found on the surface of marine substrates, increasing acute epifauna and infauna mortality by contamination and asphyxiation. The organisms that do not die may chronically incorporate the toxic substance in their tissues,

which then accumulates along the food chain ^[25]. Another serious consequence of crude oil in the sediment is the acidification and subsequent dissolution of calcium carbonate shells, ranging from microorganisms (foraminifera) to macro organisms (mollusks) as already evidenced by ^[24].

Studies on the catastrophic Deepwater Horizon (DWH) event in the Gulf of Mexico (GoM), in April 2010, which showed that the composition/accumulation of oil on the seabed was strongly influenced by sediment, texture, composition and sedimentary processes and accumulation rates ^[14].

It is known that certain types of oil will affect sedimentation in different ways. Heavier and thicker types of oil, which is the type identified in the Brazilian spill, are expected to settle on the substrate. Oil sedimentation may increase if the oil mixes with sand and sinks ^[25], which is again the case of Brazil's coast where the oil has extensively affected its sand beaches.

A variety of immediately known effects can be identified from organisms directly exposed to oil, such as oil-soaked birds and turtles. Ingestion, direct contact and oiling are part of the immediate threats compromising and affecting animal digestion, and causing eye and nostril irritation, in addition to inhalation of toxic vapors, asphyxiation and suffocation. Particles dispersed in water accumulate in the most sensitive epithelial tissue, such as gills and mucous membranes, obstructing and causing tissue degeneration. Filter feeder animals, such as bivalves, can ingest enough oil to the point of incapacitating their feeding. Other larger benthic animals such as octopuses, lobsters and morays that live in burrows and use them as shelter are most directly affected by the direct oil contact. Organisms with oiled gills are unable to obtain enough body oxygenation and soluble hydrocarbons enters the bloodstream through the respiratory tract. Another effect of oil dispersion into the open sea refers to the influence on plankton surface layers. Plankton is the first element in the food chain, supporting a considerable diversity of marine mammals, fish and invertebrates (Table 1) ^[12,25,33-36].

Hydrocarbon bioaccumulation is one of the major concerns when an oil spill occurs, but many of the components of oil and petroleum products are biodegradable at some level of the food chain ^[25] and evidences of the bioaccumulation phenomenon is scarce but can occur ^[37]. However, it is known that fish are especially sensitive to petrogenic compounds in their early stages of life (cardiotoxicity, phototoxicity), in addition to the carcinogenicity of PAHs and their impacts on the metabolic, immune and reproductive systems ^[38]. Considering the worldwide scenario of pollutants that are being discarded in the seas, contamination and chemical analysis is mandatory to con-

tinue investigations to guarantee the health of ecosystems.

The dimension of the environmental coastal impacts caused by oil spills also depends on the type of coast. The sensitivity of different substrates to oil varies considerably, from rocky shores to gravel beaches, sand, fine sand, mangroves, and coral reefs ^[25,37]. The oil that hit the Brazilian northeast coast, especially visible on sandy beaches, had an immediate and acute impact on the marine life of the intertidal zone. However, the extent of the coast affected included a great diversity of ecosystems beyond sand beaches, including estuaries, mangroves, reefs, coastal lagoons, riverbanks, etc. The prompt response of volunteers, and later of the government, removed much of the large and more visible patches of oil from the beaches. However, the days and months that followed the peak of the spill were marked by reports of people returning home with their feet stained with oil after walking on apparently clean beaches.

Smaller particles of oil on the sand can reach an extremely diverse benthic community, including mega, macro and half fauna formed by crustacean, Polychaeta, nematodes and mollusks ^[39,40]. These animals are the also low on the benthic trophic chain and make the link with other environments through feeding various animals in the water column; and the level of contamination in the trophic web needs further investigation.

In addition to the widely affected sandy beaches, the oil reached a range of habitats, from rocky outcrops to some highly vulnerable ones, such as mangroves, estuaries and reefs. These are not homogeneous habitats; they are subject to peculiar local coastal hydrodynamic regimes and present distinctions regarding shape, size and nature of their substrate. Rocky outcrops, for instance, can be severely affected, especially through the accumulation of thick layers of oil on their emerged portions where puddles rich in flora and fauna are formed ^[25]. Although yet to be fully quantified and assessed, preliminary evidence suggests that the abundant Brazilian northeastern rocky outcrops have undergone a similar oil accumulation process.

Mangroves, in turn, are sheltered ecosystems with low hydrodynamics, a scenario that favors the accumulation of fine sediments retaining contaminants for long periods. They are particularly sensitive to this type of pollution, first because the breathing of their aerial roots can be seriously impaired by a thin oil layer. Secondly, mangroves host numerous permanent and seasonal species. Many of these species, including some of commercial interest to fisheries, use the mangroves as nursery sites, spending sensitive periods of their life cycle there ^[25,41]. In addition, due to the important connectivity of species in the marine

Table 1. Possible effects of contamination on marine biota on the coast affected by the South Atlantic oil spill, considering duration of the effect (permanence) due to the gradual transformation and degradation of the oil and occurrence chance.

Effect	Reason	Reason based on local reality	Permanence (Short, medium or long term)	Occurrence chance	Reference supporting the listed effect
Damage or animal death by oiling	Oiling, covering and oil adhesion are very common in birds, turtles and marine mammals. These animals depend on regular contact with the water surface for feeding or surface breathing.	Approximately 130 oiled animals were registered in the first 4 months of the oil's arrival, about 90 sea turtles and 40 birds. There is no previous record of oiled mammals.	Short	***	(Cedre 2007; IBAMA, 2019b; Shigenaka & Milton 2003; Fry & Lowenstine 1985)
Damage or animal death by direct contact with oil particles	Oil particles can accumulate on epithelial tissue on gills, mucous membranes, clogging and damage them. Filter animals such as mollusks can suffer a toxic effect making them incapable of feeding. Organisms with oiled gills cannot accomplish oxygen exchange; soluble hydrocarbons can enter the bloodstream through the respiratory tract. The toxicity can be acute, for example with rapid death of organisms by ingestion. Other effects occur when the organism's survival capacity decreases due to decreased growth and reproduction rate.	The presence of oil was recorded in several filter mollusks such as oysters (<i>Crassostrea</i> spp.), in the gills and digestive tract of fishes, legs and mouth area of crabs.	Short, medium and long term	***	(Cedre 2007; IBAMA, 2019b; Viñas <i>et al.</i> , 2009; Law & Hellou, 1999; Uno <i>et al.</i> , 2017; Fleeger <i>et al.</i> , 2003)
Chemical contamination causing malfunction in marine organisms and ecosystem	Polycyclic aromatic hydrocarbons (PAHs) are the most toxic components of oil spills, mainly which are soluble and quickly available for marine organisms. This toxicity is the result of formation of metabolites by organisms which are associated with the DNA resulting in organism malfunctioning. Cardiotoxicity, phototoxicity and carcinogenicity in fish early stages of life	Not recorded. Insufficient research.	Medium and long term	*	Cedre 2007; Jeong <i>et al.</i> , 2015; Pérez-Cadahía <i>et al.</i> , 2004; Collier <i>et al.</i> 2013; Johnston & Roberts, 2009; Johnston <i>et al.</i> , 2015; Cesar <i>et al.</i> , 2014; Venturini & Tommasi, 2004; Venturini <i>et al.</i> , 2008; Camargo <i>et al.</i> , 2017.

The occurrence chance is based on the expert opinion of the authors associated with what is known in the literature (* little evidence in the literature; ** some evidence; *** strong evidence). By default, regional impacts are also local, while national impacts are local and regional.

environment, the oil pollution of mangroves can affect ecological productivity in the short, medium and long-term, compromising the biodiversity in general, and in fisheries in particular.

Reef coral ecosystems are protected by mucus secreted by their polyps and can withstand small isolated oil accidents, especially because a protective layer of water usually remains between the corals and the smooth oil surface. However, depending on the type of incident (intensity and repetition) and the polluting agent, these invertebrates can suffocate^[25].

Studies that modeled the distribution, destination and effects of oil, associated with toxicity tests of various species, suggested that more thorough conclusions about the damages caused by oil spills to natural resources is only elucidated after several years of monitoring and information^[42]. Poor cleaning, negligent monitoring and insufficient research, as Brazil has demonstrated, will not only delay conclusions, but also provide insufficient and inconclusive data. Some effects of contamination on marine biota are shown in Table 1.

3. Socioeconomic Impacts

Oil spills also have significant consequences on human livelihoods, by affecting social, cultural and economic activities (Table 2). Coastal tourism is immediately affected by tourists afraid of possible health effects caused by direct contact with oil^[43]. Coastal tourism is one of the main economic activities in the Brazilian tourism sector, given the country's permanent favorable weather, especially in the northeast. According to anecdotic information from the media, hotels and tourist activities were greatly impacted at the peak of the spill when the oil was clearly visible in the sea and on the beaches^[44]. As the oil reached the mangroves, aquaculture, especially exotic white shrimp (*Litopenaeus vannamei*), and salt production were affected as well. The northeast is the main exporter of Brazilian shrimp^[45] and produces 98% of Brazilian salt^[46]. Although it is yet to be quantified, the economic effects on tourist operators, farmers and salt businesses are expected to be less damaged than on artisanal fishermen and their families which are among the most economically vulnerable coastal groups^[47]. While larger businesses can possibly endure some level of economic hardship caused by such a disaster, this is often not the case for the local subsistence communities and commercial fisheries that depend on the sea. In the state of Bahia alone, an estimated 43,000 fishermen were affected by the disaster^[44].

Fisheries were inevitably affected in Brazil because the risks of contamination directly interfered with the sale of fish, with up to 50% drop in income being mentioned by artisanal fishers^[23]. Although part of this loss was due to

decreased catches, due to a lower consumer demand, fishermen also lost income due to lower prices enforced by middlemen even in areas not directly affected by the oil spill. Women working in fisheries, as gleaners for example, are especially vulnerable because the types of habitats they tend to use (mangroves and sandbanks) and the animals they tend to exploit (e.g., mollusks) are amongst the most sensitive to oil contamination because they are filters^[48]. Thus, a coastal oil disaster may accentuate gender vulnerability in fishing communities. Some eventual government support is likely to benefit only a small portion of fishers as per bureaucratic requirements, such as being registered by the fisheries secretariat, which gives them the right of a fishing license. In some of the northeastern states, about 10% of the artisanal fishers have a fishing license. Even if less bureaucratic means is adopted, such as having the villages and their local fishing associations identify the fishers to be compensated temporarily, this is still unlikely to fix their economic losses. This would be so because the fish from Brazilian artisanal fisheries are part of complex value chains, often with invisible links and no taxes attached^[49,50].

Additionally, fishers and their families are subject to different levels of health problems, from those caused by the direct contact with oil to psychological ones related to the socioeconomic uncertainty generated by the spill, such as the perspective of job loss and food insecurity^[51]. These effects can last for years and are not usually accounted for by governments in places where oil disasters have happened^[52,53].

4. Methodology

Photographs and videos released at the time of the event of the oil spill disaster confirmed by national media, locations where the oil was deposited on the marine substrate. We collected water and sediment samples in Pirangi reef area in Rio Grande do Norte state, once oil was spotted at this site in 2019.

This specific site of Pirangi was studied in 2013 and 2014 with no spotting of oil patches or other forms in the sediment and in the water in according to^[24]. After the oil spill, we sampled new sediment sites in October 2019 to compare with the same methodology described in by the abovementioned authors. We intend in this study to discuss questions on the human-induced changes on the reef system, therefore water and surface sediment were recovered by scuba divers from 55 stations at reefs at Pirangi in June 2013 and July 2014 (Figure 3). Samples were recovered from reef areas, sandy sediments, and macroalgae substratum using a small knife. In Pirangi in 2013, Stations 16 to 20, 27, and 28 and Stations 3 to 15 in 2014 were sampled from areas of small reef patches near

Table 2. Possible socioeconomic and health effects on the coastal human communities affected by the South Atlantic oil spill.

Effect	Reason based on local reality - effect	Scale	Impact	Reason - scale	Reference supporting the listed effect
Reduced fishing catches	Fish and seafood mortality may affect catches	Local	*	Fishers and gleaners are majorly from the small local communities affected. Industrial fisheries are less common in the region and tend to fish offshore areas, which are less likely to have been affected with the same magnitude	(Born et al. 2003)
Reduced fisheries income	Fish and seafood mortality and lower demand may force prices and revenues down. Some middlemen might abuse the vulnerability of coastal fishers	Local	***	The same as above	(Garza-Gil et al. 2006; McCrea-Strub et al. 2011)
Changes in fishing grounds and effort	If closer grounds are contaminated, fishers that have the means may switch grounds, with consequences on effort (e.g.: need to use different gear or spending more fuel to reach further grounds)	Local	**	Fishers in the region tend to fish closer to their homes, especially if they are small-scale	(Born et al. 2003)
Loss of food sovereignty	If fish and seafood are contaminated, coastal communities may need to purchase protein they would otherwise get for cheaper (just at the cost of their work and gear). However, there is a chance they would return to fishing even if still contaminated for not being able to afford purchasing protein	Local	*	Coastal communities are the only ones that rely directly on marine resources	(Jonasson et al. 2019)
Increased food insecurity	The dependency on external markets, conditioned to money payment, may force people to reduce their protein intake. Externally acquired protein may be of lower nutritional quality (e.g., canned meat and highly processed protein). Even if locals resume fishing, their food might not have the same quality due to contamination	Local	**	Same as above	(Osuagwu and Olaifa 2018)
Contamination from ingesting seafood	Heavy metals (cadmium, mercury and lead) from the spill can accumulate in the food chain, potentially causing neurological and reproductive damages, and even cancer. In the absence of affordable alternatives, locals may keep ingesting contaminated seafood	Regional	***	Especially important for the locals, but the fish sourced locally can be sold in the state markets	(Solomon and Janssen 2010)
Contamination from direct contact with oil	Removal of oil using makeshift gear (or no gear) expose people to defatting (resulting in dermatitis and skin infection), and temporary eye, nose, or throat irritation, nausea, or headaches. Those exposed for longer can have DNA damage	Regional	**	In addition to local volunteers, people from the region (and elsewhere) travelled to the contaminated sites to help with the clean up	(Solomon and Janssen 2010)
Increased rates of psychological problems	Increased rates of unemployment, reduced income and lack of clean (and free food) can increase the rates of depression, anxiety, post-traumatic stress disorder, and psychological stress	Local	**	Effect limited to those directly affected	(Solomon and Janssen 2010)

Effect	Reason based on local reality - effect	Scale	Impact	Reason - scale	Reference supporting the listed effect
Loss of cultural services, such as destruction of historically used grounds for work or leisure	Coastal communities rely on coastal habitats for their wellbeing and traditions.	Local	*	Coastal cultural ecosystem services associated to fisheries are locally dependent	(Outeiro et al. 2019)
Shrimp farming	This activity is developed in the mangrove, supposed to be one of the environments most affected by the spill	National		The region is the main national producer and international exporter of shrimp in Brazil	(Duke 2016)
Algae aquaculture	Practiced in banks very close to the shore, this activity is likely to have been widely affected by the spill			Agar-producing algae are exported to the remaining states	(Yang et al. 2020)
Community-based tourism		Local	*	Although more of an informal activity, it is relevant for some traditional communities as a source of income	(Bordelon et al. 2015)
Coastal tourism	Vacancy rate may increase soon after a disaster as tourists are afraid of contamination or fear that the site has lost its landscape attractions (e.g., clear water and white sand beaches)	Regional	*	Decreased taxes will particularly affect the states that have a strong reliance on tourism, but the impacts are expected to last while they are visually perceived	(Price-Howard and Holladay 2014)
Increased in gender inequality	Mangroves and sand banks, which are among the most affected areas, are especially harvested by female gleaners. Men often fish offshore, where some of them can target unaffected stocks	Local	**	Women in fishing communities are expected to be affected by the spill	(Defiesta and Badayos-Jover 2014)

The intensity of the effect is based on the authors' expert opinion associated to what is known in the literature (*little evidence in the literature; **some evidence; ***strong evidence). Impacts that are regional are by default also local, while those that are national, are also local and regional.

tourism boating sites. Each area was sampled twice, but exact station locations differed from 2013 to 2014.

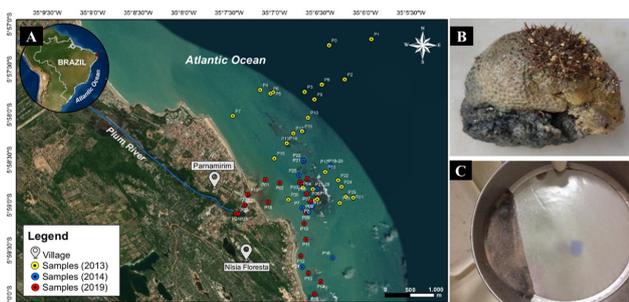


Figure 3. A) Random sampling points of the sediment collection carried out in June 2013, July 2014 (no oil spotting), and October/2019 (with 95% of samples containing oil). B) Portion of reef substrate with oil crude collected in Pirangi (RN). C) Sediment in a sieve showing oil pollution.

In October of 2019, after the oil spill, we focused on the Pium river area and sampled 15 more sediment, reefs and microalgae, and water samples to observe the presence of oil. Processing of marine sediments followed standard procedures from [24,54] where a fixed volume of 50

cm³ of sediment was washed over a 63 µm sieve to retire silt and clay and spot oil in analyzed sediment.

5. Results

Along the entire northeastern coast, considerable particles and portions of oil were buried in the sand and in organisms mainly due to the movements of coastal hydrodynamics. Sampling done in October 2019 in the same area previously sampled in 2013 and 2014 shows that more than 95% of the unconsolidated sediment samples, including some corals, had some evidence of oil (Figure 3). This is a striking contrast with samples done in the same region with the same methodology in two previous consecutive years (2013 and 2014), which showed no evidence of oil on the seabed and was evidenced by [4]. Figure 3 shows maps from 2013 and 2014 published data and no mention of oil in the sediment study; and samples collected in 2019 (Figure 4) with oil evidences on 95% of samples.

Oil mixed with sand has been found from a few centimeters to almost 10 cm deep into the sediment in beaches, and also buried in water depths between 3 and 12 m in some of the local reefs and estuaries. River Pium's estuary and the reefs of Pirangi do Sul, indicates that the scope of

the contamination is far beyond what was previously assumed. Thus, there is a considerable range of threats and impacts on the marine biota, many of which are yet to be assessed on the Brazilian coast, especially given that the area affected is on a continental scale (about 2500 km). To date, the magnitude of the event is given by the oil that has been removed in the form of stains or fragments on the surface of beaches.



Figure 4. The official map with damaged sites by IBAMA, which the site of Pirangi and Pium River are not included. They were however severely affected by the oil accident event in 2019.

6. Discussion

Almost twenty months after the first signs of the spill, governmental investigations are yet to clarify crucial points such as the origin, extent and cause of the spill, and specific characteristics of the oil, which seriously compromised immediate and posterior actions.

Still no estimate of the amount of oil that remains on marine sediments, estuaries or mangroves, or the amount that has infiltrated into the Brazilian sand beaches, and the magnitude of an oil accident cannot be measured by the amount of oil that has been removed and sighted on beaches and coastal areas.

As an example, Brazilian tropical reef ecosystems are not, in general, built by corals, but by a rich diversity of species that vary according to the region^[55]. This peculiar formation of Brazilian reefs prevents comparisons with previous oil spills in different reefs of the world when mucus secreted by the polyps of the corals could withstand isolated oil accidents^[25]. Thus, it is reasonable to assume that the living surface of these ecosystems may be impacted in the medium and long term, and thus chemical contamination on the reefs of the affected area must be investigated in detail considering their ecological and

socioeconomic importance. This indicates that the scope of the contamination continues its reach far beyond what was previously assumed since the Brazilian coastal area affected is very large on a continental scale.

6.1 Political Scenario

In the event of a major oil disaster, such as this one we are reporting, immediate containment and waste removal should happen, but not as isolated actions: they should be accompanied by the application of robust and effective strategies including waste containment, cleaning and removal protocols. The federal government took more than 40 days to adopt the Contingency Plan for Oil Pollution Incidents (PNC from Portuguese) previously in place since 2013, and they only implemented the Contingency Plan after being confronted by the Federal Prosecution Service twice^[11]. Part of this inaction was due to a systematic dismantlement and clearing of the Brazilian environmental programs, especially during 2019^[56]. In April 2019, less than four months before the oil spill, the federal government extinguished several councils, committees, commissions and collegiate bodies associated with the federal public administration (Decree 9,759 / 2019). This included two committees that were part of the PNC, explaining why it took so long for it to be implemented. A timely implementation of the PNC would have decreased the damage extension, instead, the official government response in the acute period of contamination was groundless propagandized ideological accusations (against Venezuela, for example) or, when these smoke screens did not work, the public got the silent treatment. Little information was disclosed other than the locations on a map affected by the oil spill along the Brazilian coast (updated in 03/19/2020) by federal agency IBAMA, the Brazilian Institute of Environmental and Renewable Natural Resources. After spotting oil in the water, a specific scientific mission was performed to evaluate the water and sediments situation in Pirangi do Sul. We have observed extensive areas where oil spillage has acutely damaged the ecosystem as a whole. This coral reef has been evaluated since 2013^[24,54,57,58] with no mention of oil in this specific site, until 2019 when we verified that it was impacted by this oil accident. We have then added a new information on the IBAMA original map as it follows in Figure 3 that includes the present site of Pirangi and Pium River as severely affected by the oil accident event in 2019 as we have shown in this article.

Under pressure by public opinion, in December 2019, the government published a timid research call of about \$320,000 US (maximum of US \$25,000.00 per project), being a negligible amount to properly investigate the ex-

tension of the damage caused by the oil spill accident. And in the same period, MCTI through “Ciências do Mar”, a program with actions forecasting 2019 to 2030 with the objective of managing knowledge for the conservation and sustainable use of the sea, launched an emergency action with the financing of approximately \$1.4 million US for research groups already established (INCTs and PELDs) to develop research for impact by oil spills.

Some state governments, on the other hand, although insufficient, have been more proactive and provided more amounts of funding. State initiatives have also counted on partnerships and collaborations with public and private research institutions, associations, universities and non-profit organizations.

While the origin of the oil remains a mystery, and any scientific effort to clarify that should have been welcome, the scientific community in Brazil has been subject to a smear campaign to discredit its findings and opinions. This is especially strong when academics denounce attacks on the environment and/or human rights, which make the topic of an oil spill especially delicate, as it touches on both issues^[59].

So far, and despite the length of time passed, none of the hypotheses on the origin of the spill has been confirmed due to lack of scientific consistency. Perhaps not surprisingly, many of these hypotheses have been aired first by the government, which has been effective in pointing fingers, but far less efficient in providing reliable and robust information. For example, the oil has been suggested to leak from: 1) oil tankers in waters beyond 200 nautical miles from Brazil, 2) cleaning of a vessel, 3) sinking of a foreign vessel with hull drilling and continued oil leakage, and 4) continued leakage from the national oil exploited in the pre-salt layer. However, we still have no concluding remarks.

6.2 Future Directions

Oil production, transportation and consumption continue to carry risks in the 21st century, which makes it necessary to think about the adoption of new policies that encourage cleaner and safer production associated with ambitious preventive and mitigation disaster plans. When disasters happen, they should teach us lessons on how to avoid them and how to make sure that the most vulnerable, in nature and in society, will not be the ones paying the highest price. It is a societal duty, including academia and government, to ensure these disasters are properly investigated and the consequences accounted for, even when media interest refocuses public attention. These types of efforts require working in partnership, where the scientific community is not to blame for societal problems, but rather

as a door to alternatives for this disaster and prevention of future environmental problems Brazil and the rest of the world may face.

A new disaster, even of a global magnitude, such as the ongoing pandemic (COVID-19), should not be a reason or distraction to forget about previous disasters, especially in places where poorer human communities suffer the highest losses. The unavailability of transparent results hinders actions focused on solving the problem.

This impact scenario, as witnessed, still has potential damages not yet measured or mitigated, leading us to a series of important considerations in order to have a less compromising future situation that is aggravated in countries of large territorial extension and high social inequality, such as Brazil.

It is essential and basic to have operating government protocols in place for immediate actions for oil removal, compensation for socioeconomic losses, assessments of the level of contamination in habitats, organisms and human beings. In addition to urgent measures, habitat recovery and monitoring of the level of contaminants must be used in order to guarantee the health of the environment. Integrating the various scientific areas of knowledge is essential for a holistic approach on this broad topic. For example, to understand the sum of stressors in reef environments, such as we are currently facing with warming waters and coral bleaching in tropical reefs off the Brazilian coast.

However, it is no longer possible to hide the urgent need for a change in actions in the face of the use of natural resources and oil exploration. The behavioral distortions in consonant with unrestrained consumption typical of societies that aim at high productivity, lead us to environmental catastrophes, scarcity, and contamination of our own resources. We have already opened our eyes and see the problems, now we need to make the necessary changes. In the absence of monitoring, this type of impact remains unrelated to past oil spill events, preventing further protective and mitigation measures for future disasters. A strategy for mapping impact on benthic habitats also needs to be addressed and discussed to increase better responses.

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