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Health Review

Overview of oil spills worldwide and impacts on marine megafauna

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Abstract: Oil spills have a significant impact on the environment, posing threats to various marine species. This review aims to gather information on various oil spills that have occurred worldwide and discuss their impact on marine megafauna (marine mammals, sea turtles, and seabirds), to provide useful insights that can be applied in decision-making during rescue and rehabilitation efforts. Oil spills can cause lethal damage to marine biodiversity, affecting individuals of different ages and species, including human health. Although the acute effects of oil contamination on wildlife are evident, it is challenging to treat and recover from. Hydrocarbons can persist in the environment for a long time, leading to prolonged exposure of animals to the contaminants. In conclusion, this research demonstrates that the effects of oil spills on marine megafauna may not be observed in the short term, such as contamination through the bioaccumulation of compounds in the food chain. It is necessary to conduct systematic studies on local fauna at all developmental stages of oil activities, including seismic research, exploration, and oil distribution to address the impact of oil spills on marine megafauna.

Keywords: Bioaccumulation; Marine environment; Oil exposure; Pollution.

1. Introduction

Offshore oil exploration activities have existed for many years ant the platforms were installed in 1897 in California (USA) [1]. Currently, oil exploration occurs in several continents and can affect all oceans, since oil spills occur in all phases, from exploration to distribution [2–5]. Identification of oil spill risks is also diverse, since oil has different characteristics, depending on the location of extraction and the exploration phase; besides, it may have different toxicities and dispersion capacity [5]. Oil is more toxic in hot waters, and toxicity depends on its chemical composition and how its original characteristics are changed in the environment through a process called "weathering" [6, 7]. There are also oil contamination sources unrelated to spills, such as tar balls, which are by-products of ship operations (e.g., bilge tank flushing), illegally discarded from tank washes and other operations on board, which are even more persistent in the environment [7].

Usually, oil spill affects several taxa, including aquatic mammals [8, 9], sea turtles [10–15], and seabirds [16, 17]. Many of these species are endangered, posing a major problem for marine life conservation [18]. Oil spills affect animals directly through contact with oil or indirectly by reaching all levels food chain thus enduring in the environment on a large scale and for many years [1, 11, 19–23]. This occurs because the effects of an oil spill on animals are not always clearly observed and nor immediately after the accident [24].

Since the first oil spills, in the 20th century, clinical and pathological effects of oil on aquatic animals have been described [25]. In the 1990s, studies on exposure to crude oil were carried out on loggerhead turtles, showing effects on their mucous membranes and skin (e.g. irritation and inflammation), oil adhered to the mucous membranes of nostrils, eyes, upper esophagus, and in the feces of individuals kept in laboratory [26]. Each source of natural oil has a unique molecular composition. In other words, every extracted material possesses its own distinct characteristics, which provide information about its origin. This applies whether it is collected from the environment or harvested during the cleaning of affected animals [27, 28].

Records of oil spills are crucial for species conservation, as they allow identifying the parts responsible and thus charging responses and adoption of mitigation measures. Underreporting oil spills and their impacts on wildlife has hampered research on their effects as well as the decision-making process for conservation. Given the relevance of these impacts to the environment, we conducted a review of various reported oil spills worldwide and discussed their impact on marine mammals, sea turtles, and seabirds, in order to enhance knowledge that can be useful for oil spill response and assessment efforts.

2. Survey of oil spills worldwide

To the authors' knowledge, the first major oil spill was recorded in 1903 in Port Phillip Bay, Victoria, Australia, with an estimated 1,300 tons of oil spilled into the sea [29]. Since then, oil spills have been described in countless regions in the continents (Figure 1); nevertheless, they have been underestimated in scientific literature, requiring research in the media, such as newspapers at the time of the accident. Between 1967 and 2017 a total of 2316 oil spill incidents were recorded worldwide with an average of 33,255 barrels spilled per incident (amounting 56 234 000 barrels), including the 1691 incidents in which volume of oil spill was reported [30]. It is important to emphasize the oil spills occurred in the Persian Gulf in 1983 as a result of the Iran-Iraq war [31].

Little information on accidents at the beginning of the 20th century is available, and little is known about how spills affected the marine fauna. Since the 1960s, the number of accidents recorded has increased significantly. However, these records may not correspond to the actual number of accidents, since many spills may not have been registered, especially the oldest ones (Figure 2). Since 1967, with the supertanker SS Torrey Canyon accident in England that affected 75,000 birds, reports of the impact on the marine fauna have become more common. Among the first major spills, the SS Torrey Canyon stands out as one of the largest in the history of the country, with the spill reaching as far as part of France [32]. In December in 1968, the SS Witwater tanker burst in the Caribbean waters spilling more than 588,000 gallons of diesel and Bunker C oil [33]. The oil reached beaches, rocky shores, and mangroves on Galeta Island causing death to mangroves, algae, and invertebrates [34]. In 1969, another very serious spill of crude oil from the coast on Union Oil's Platform A occurred in the Santa Barbara Channel, Southern California, United

States of America (called "Santa Barbara spill"), reaching several taxonomic groups, such as birds and pinnipeds [35].

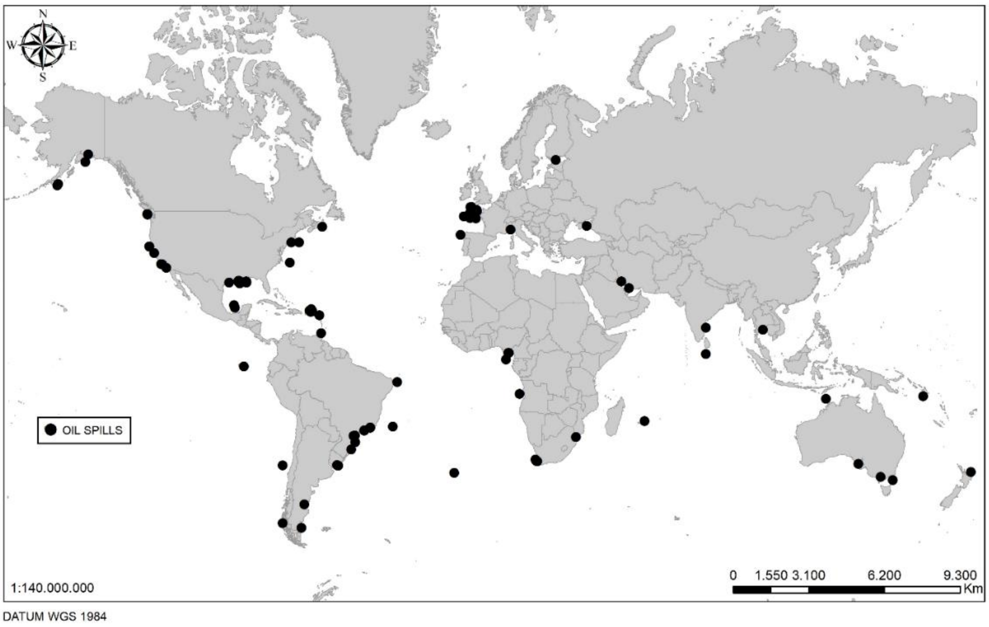

Figure 1: Locations of oil spills registered from 1903 to 2019. Map drafted by the authors.

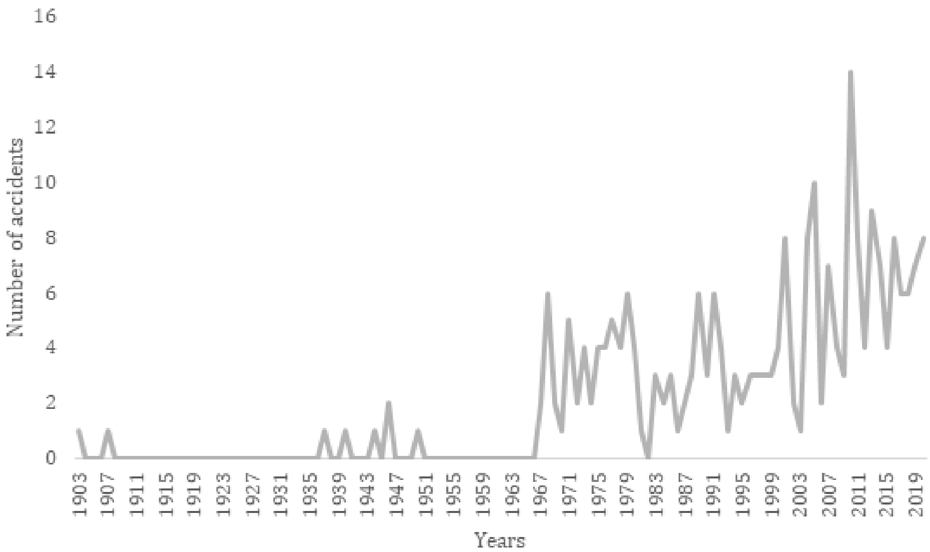

Figure 2: Amount of oil spill (fuel and crude) recorded per year according to literature. Graphic produced by the authors.

In the 1970s and 1980s, major accidents of this type triggered discussions about legislations to standardize responses, both for the fauna and the environment [6, 36, 37]. In Central America, in June 1979, an explosion on the Ixtoc I offshore platform in Campeche Bay, Mexico, and in July 1979 in Tabago, the Caribbean, marked the region for this type of occurrence. In Brazil, in the Guanabara Bay, Rio de Janeiro, in March 1975 and in Bertioga, São Paulo, in October 1988, also marked this period [5, 38]. One of the best-known spills that occurred at this time was the Exxon Valdez oil tanker in March 1989 in Alaska, carrying approximately 37,000 oil tons (or 11 million gallons), reaching about 4,000 marine animals of different species, and birds were the most affected taxonomic group [36, 37].

However, before the Exxon Valdez spill, a number of others occurred in the Persian Gulf between January and October in 1983, resulting in nearly 42 million oil gallons spilled as a result of the Iran-Iraq war. Later, another war – Gulf War in 1991 – resulted in 252-335 million oil gallons spilled [31].

Still in the 1990s, spills caused serious environmental damage: (1) In August 1993, a collision resulted in the spilling of 336,000 gallons of fuel oil in Tampa Bay, Florida, even reaching spawning areas for sea turtles; (2) In January 1994, tank barge Morris J. Berman ran aground in San Juan, Puerto Rico, drifting and pouring fuel oil for many days resulting in the contamination of extensive natural resource areas; (3) In June 1994, the ore carrier Apollo Sea sank near Cape Town in South Africa resulting in a serious oil spill [2, 3, 31, 39]. These oil spills are characterized as major environmental catastrophes and are associated to the growing concerns with the environment in the 1990s. In Brazil, Ordinance No. 170 of the Oil National Agency prescribed that companies communicate and implement measures to remedy or reduce the impacts oil spills on the environment. Thus, from the 1990s onward, greater rigor in measures were implemented worldwide to prevent and contain these environmental disasters.

Nevertheless, the beginning of the 21st century was marked by major oils spills. In January 2000, a leakage of Petrobras pipelines reached the Guanabara Bay, Rio de Janeiro State, Brazil, and about 4 million liters of oil were spilled [4]. In June 2000, there was a shipwreck between the Dassen and Robben Islands in South Africa: Ore carrier Treasure carried approximately 1,344 tons of fuel oil, 56 diesel tons, and 64 tons of lubricating oil, which were spilled reaching many adjacent areas and seabirds [3]. In August 2000, an oil spill of unknown origin occurred along the east coast of Florida, reaching many beaches in the middle of the sea turtle spawning season [31].

In November 2002, the tanker Prestige split in half and sunk at in the southwestern flank of the Galicia Bank, about 260 km west of Vigo, spilling oil and contaminating a vast coastal area from northern Portugal to France [20]. Ten years after the Treasure disaster in South Africa, the Deepwater Horizon (DWH) disaster in 2010 resulted in more than 800 million liters of crude oil spilled for nearly three months in the Gulf of Mexico [40]. This was one of the most serious spills for the marine fauna in history, leaving roughly 474 oiled turtles (456 alive and 18 dead), 4348 visibly oiled birds (2085 alive and 2263 dead), and 140 dead cetaceans, besides the increased number of stranded dolphins in subsequent years [13, 41]. Due to its complexity, this spill was a milestone for the elaboration of decontamination protocols for oiled fauna [42].

In July 2019, a Liberian ship spilled approximately 400 oil liters near the islands in Algoa Bay, the second oil spill to reach that area in three years [17]. In August 2019, occurred the largest oil spill recorded in Brazil and tropical coastal regions, and one of the worst in the world [28, 43–45]. According to Brum et al. [43], more than 5,000 tons of oiled residues were removed from Brazilian beaches, mangroves, and coral reefs between August 2019 and January 2020. The spill reached all states in the Brazilian northeast, causing damage on mangroves, estuaries, and grasslands of needle grass [9, 24], and it is estimated that the oil reached more than 3,000 km off the Brazilian coast, including marine conservation units and priority areas for the conservation of endangered species, including the manatee (*Trichechus manatus*). According to report from Brazilian Institute of the Environment and Renewable Natural Resources (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis-IBAMA) and published data, 159 animals (105 sea turtles, 39 seabirds, 2 marine mammals, and 13 non-identified and classified as 'others') were directly affected and assisted voluntarily mainly by non-governmental organizations (NGOs) and Brazilian public universities [24, 28, 45]. To date, there is no evidence of the oil origin and the exact location where the accident occurred [28], and the affected marine ecosystems are still under oil effects.

During the oil spill event in Brazil, in 2019, the Projeto Cetáceos da Costa Branca-Universidade do Estado do Rio Grande do Norte (PCCB-UERN) and the Centro de Estudos e Monitoramento Ambiental (CEMAM), with a partnership of regional government and NGOs, monitored the affected areas in the coast of Rio Grande do Norte state, and rescued stranded and oiled animals. The monitoring revealed seven affected municipalities and 15 oiled animals, including 14 sea turtles and one sea bird [45].

3. Contamination

The animals are affected by oil spills through contact with the oil or by reaching all levels of the food chain [11]. In consequence, the effects of oil can be direct or indirect: (1) Direct, when animals die from asphyxiation or cover of the body by the spilled material or from clinical impairment by poisoning due to contact or ingestion of the material; (2) Indirect, when animals experience reduced fertility rates, loss of food resources due to trophic groups, bioaccumulation of contaminants, or gradual ecological death [46]. The direct effects of oil spill on marine megafauna can vary in severity depending on the material viscosity and the species affected [7, 47, 48]. Studies show that marine mammals affected by oil spills displayed irritation of their sensitive tissues (e.g., membranes around the eyes, nose, mouth) while materials with higher density tend to cause death of animals affected (Figure 3) [5, 48]. However, long-term impacts on communities of marine mammals are still poorly understood, requiring greater attention to these taxa in the years following the oil spill [49].

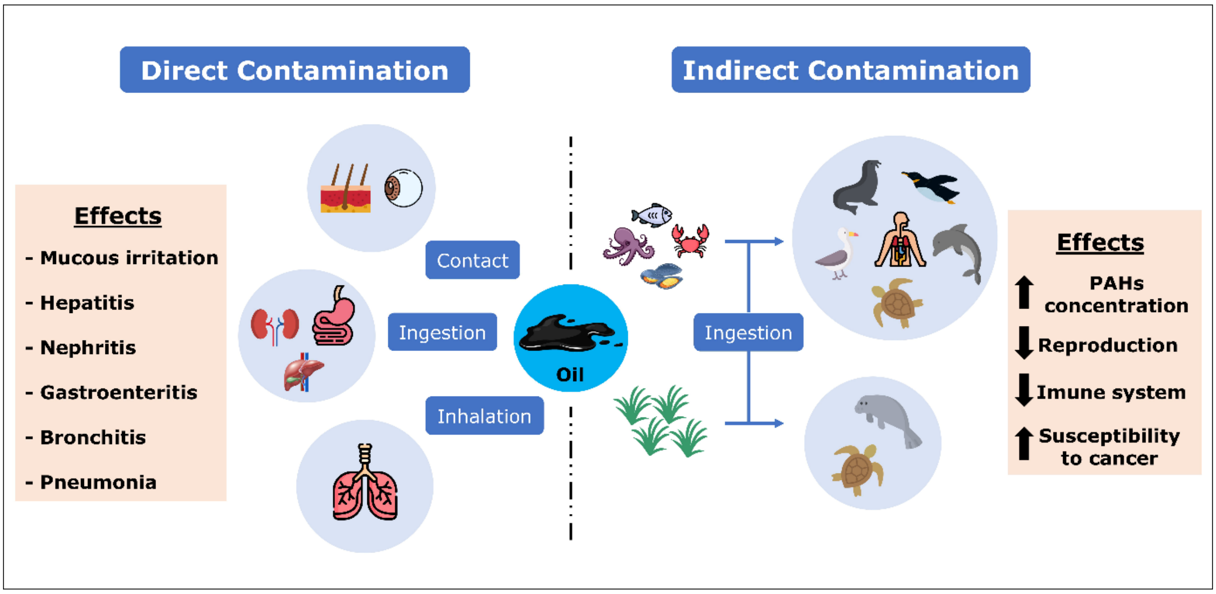

Figure 3: Diagram showing the main effects of direct and indirect oil contamination on organisms. Illustration designed by the authors. Animal silhouettes used are available under a Public Domain (https://www.flaticon.com/br/).

The National and Oceanic Atmospheric Administration (NOAA) in the United States of America has been mapping oil spills worldwide since the 1980s and has found an average of 96 (15-193) spills per year [27]. Marine fauna has been mostly affected in small and large oil spills worldwide. However, direct effects of this type of occurrence are usually underreported, mainly for mammals and sea turtles, as many reports cite "countless", "some" or "several" animals affected, without providing exact numbers on these records.

4. Impacts by taxon

4.1 Cetaceans

The group of cetaceans comprises whales, dolphins, and porpoises distributed worldwide inhabiting oceanic or coastal waters, as well as rivers or inlets. Cetaceans are at the top of the food chain, have a long lifespan, and are considered environmental sentinels, warning about threats that may eventually become irreversible [50, 51]. Whales and dolphins have three main forms of exposure to oil contamination: respiratory, dermal, and oral [52, 53].

Cetaceans, unlike fish, have pulmonary respiration and need to rise to the surface, which makes them more susceptible to inhaling volatile oil compounds [54]. Light compounds can linger for weeks in the environment, depending on water and air temperature [55]. Concentrations of toxic oil vapor are also deleterious to the health of organisms [56], causing inflammatory processes in mucous membranes, besides pneumonia, and neural and hepatic changes [56, 57]. Researchers have investigated the behavior of cetaceans in places where oil spills occurred. Studies suggest that these animals avoid these regions or even change their behavior, staying submerged longer without breathing [47, 58]. The mechanisms they use to recognize these threats and therefore change behaviors, if in fact this occurs, have not been clarified; however, it is believed that it may be by echolocation or taste [47].

Although cetaceans have a thick skin, lesions by anthropic activities or natural marks can favor oil absorption and cause inflammatory processes in the tissues [47]. Oil contact can cause skin irritation, often progressing to an infectious process, leading to death of the animal not by direct contamination, but in a secondary way [18]. Geraci [56] reported that whales rescued after the Exxon Valdez spill in 1989 presented irritations in the eyes and skin, but without associating this to the death of these animals. Moreover, cetaceans have a thick layer of fat that accumulates lipophilic contaminants, including polycyclic aromatic hydrocarbons (PAHs) found in the crude oil and its derivatives.

Ingestion of contaminated prey or foraging attempts in affected areas is one of the main ways of direct contact with oil components [48, 55]. Cetaceans feed by suction, filtration or capturing prey. At these times, the oil in the water can join the food and make it more available for ingestion by cetaceans [59]. Effects, such as loosening of mucosa in the gastrointestinal tract and ulcerations, are observed due to contact with oil components [48]. Cetaceans classified as mysticetes, when filtering water during feeding, either clog filtration plates of fins or become contaminated after oil ingestion [18].

In 1994, the barge Morris J. Berman spilled in Puerto Rico and affected many vertebrates. A bottlenose dolphin (*Tursiops truncatus*) with oil on its back was sighted off one of the piers of Bahía de San Juan, but later no dolphins were reported stranded during the emergency period [39]. A year after the oil spill, on 14 February 1995, a 262-cm male bottlenose dolphin was recovered dead within the Bahía de San Juan at Isla de Cabras, and upon internal examination, its stomach was found with streaks of oil imbedded in the lumen [60]. A humpback whale was also reported offshore near oil patches close to the scuttling site [39].

After the spills of Santa Barbara in 1969, Exxon Valdez in 1989 and Deepwater Horizon in 2010, there was an increase in the number of strandings of cetaceans in the regions of the events; nevertheless, without confirmation about their direct relationship to deaths of the animals [13, 41, 56]. Comprehensive analyses require systematic studies in risk areas, before a spill or even when spills do not occur. In the Deepwater Horizon spill, bottlenose dolphins that lived in the region developed secondary diseases, such as bacterial pneumonia, hypoadrenocorticism, consistent with adrenal toxicity and lymphoid depletion [8, 61–64]. Disease conditions of these cetaceans, with exposure to oil hydrocarbon, were significantly higher in terms of prevalence and severity, when compared to dolphins from other regions not affected by the spill, indicating the long-lasting oil spill effects, raising significant concerns with long-term consequences for these dolphin populations [63, 64].

Lane et al. [62] used 10 pregnant dolphins out of 32 captured in 2011 assess the effect of oil spills on reproductive success and cetacean survival. After capturing the animals, all received identification marks on the dorsal fin and a tag connected by satellite, and then were released and monitored for 47 months. Only 20% of pregnant animals produced viable offspring, compared to a previously reported pregnancy success rate of 83% in a reference population. In addition, 57% of females that did not successfully produce their offspring had been previously diagnosed with moderate to severe lung disease. Thus, the authors confirmed significant reductions in reproductive success and high mortality rates when compared to populations not affected by the spill. The risks of threats to cetaceans can be as variable as the diversity among species and theirs habits, and species that occur in restrict areas during at least part of their lives are more oil-prone than those that migrate or use different areas in the sea [65]. So, events such as oil spills can be more harmful to endemic species and can affect their density, abundance, movement, and areal extent of their habitat.

4.2 Pinnipeds

Pinnipeds are aquatic mammals, classified into Order Carnivora, and although they live mostly in water, they spend part of their life on land, mainly during the reproduction season. Representatives of this group of animals are seals, elephant seals, fur seals, walruses, and sea lions [48]. The clinical effects of oil on pinnipeds primarily cause direct contamination, impairing the capacity of animals to swim, or causing hypothermia, or eventually death. In some cases, oil has caused thermoregulatory imbalance, disruption of the central nervous system, interstitial pulmonary emphysema, aspiration pneumonia, anemia, conjunctivitis, corneal edema, and gastrointestinal irritation. In histological aspects, oil causes hepatic lipidosis, renal tubular lipidosis, and adrenal gland dysfunction [47, 66–68].

Contact of oils with the skin, especially the viscous type, can lead to a prolonged coating of the body surface and hamper the ability to swim; and can cause burns as reported by previous study [47, 65]. In addition, inflammatory changes under oil spill can increase blood flow in the dermis and favor heat loss, leading to hypothermia [69]. Pinnipeds depend mainly on their fats for thermal insulation and vulnerability to an oil spill is possibly determined by the degree and time of exposure [48]. After the Exonn Valdez spill, about 37 pinnipeds were found with hypothermia, one of the main effects on the animals [70]. However, in the months following the spill, no unusual stranding was observed [71].

Inhalation of the volatile hydrocarbon fraction from an acute oil spill affects the respiratory system of seals and leads to the absorption of toxic compounds with additional effects on their physiology or behavior [66, 72]. Meek or lethargic behavior can be explained by brain damage caused by the toxic systemic effects of inhaled hydrocarbons [66]. It has been well known that when crude oil is exposed to the environment, it undergoes a process called “weathering”. As some species of pinnipeds, such as seals, breathe air just above the sea surface, where concentrations of these toxic compounds are higher, the first days and weeks after a crude oil spill are more critical [73]. When seals are exposed to oil at sea, they ingest it and the oil is absorbed quickly from the intestine into the blood, transferring to the muscles, liver, and fat [74, 75]. Contaminants in these organs are less detected in exams, as the days of oil exposure pass [47], highlighting the need for immediate actions to assess the impact on animals after an oil spill. Study carried out by Geraci and St Aubin [65] collected reports of pinnipeds associated with oil, and brings records of damage in eyes (e.g. burns and hyperemia of the ocular mucosa) and presence of oil in gastrointestinal tract of the affected individuals, besides large-scale mortality after the events.

4.3 Sirenians

Sirenians are currently divided into four species, three known as manatees (*T. manatus*, *Trichechus inunguis*, and *Trichechus senegalensis*) and one dugong (*Dugong dugon*). These animals are herbivores and have few records of direct contamination by oil spills possibly because they usually inhabit coastal or estuarine sheltered waters [42].

St Aubin and Lounsbury [76] reported that during the winter of 1981 and 1982, three dead manatees were recovered near Jacksonville, Florida, and one along the Little Manatee River, Florida, and examination of their carcasses revealed oil in the gastrointestinal tract. While of the 53 carcasses of dugongs (*D. dugon*) found during five months in the Persian Gulf, after the oil spill in 1983, the presence of oil was not verified. During the spill event in 1994 caused by the barge Morris J. Berman in Puerto Rico, manatees were observed on more than two occasions from the air near oil slicks [39]. After the Deepwater Horizon spill in 2010, there were no direct occurrences of siren deaths due to oil contamination, even though it is an area of significant occurrence of Antillean manatees [77]. In Brazil, in the 2019 oil spill, the death of one manatee was recorded during the spill; however, the effects of oil on this individual have not been described [9].

Manatees feed mainly on marine phanerogams, such as *Halodule wrightii* and *Ruppia maritima* in addition to seaweed [78], which are susceptible to both oil contamination and decrease in size of prairies that force animals to leave the area of origin, due to food loss [48, 77, 79, 80]. In 2019, during the worst oil spill in Brazil, at least 324.77 km² of needle grass meadows were affected by the spilled material [24], with many animals affected indirectly by food contamination [80].

Little is known on direct effects of oil spills on manatees and dugongs. According to Geraci and Aubin [65], skin may not accumulate large amount of oil due to the presence of scarce fur but lungs and eyes tend to be more affected. Sirenians can be seriously affected by oil spill events once spend their life-time in restrict and coastal areas, and they may be even more susceptible in their reproductive stage when they seek calm waters

4.4 Sea turtles

Sea turtles have a long lifespan, slowed growth, and wide distribution in the seas, occupying multiple habitats throughout their development [81]. During their life cycle, sea turtles undergo ontogenetic changes that have a major impact on exposure to human-caused dangers [82]. Oil spills affect the different life stages of these animals: embryonic phase eggs on the beach, post-after hatchings and, when young and juveniles in the open ocean gyres, and in the sub-adults and adult phases in nearshore waters, habitats close to the coast and adults during migration [7, 26]. During adult life, sea turtles are also contaminated; however, according to Milton et al. [7], the contamination risk of adults is lower, compared to the young, as adults spend less time on the sea surface. However, a literature review has shown that the effects of oil spills on sea turtles are rarely reported, despite the prevalence of this type of accident in areas where these animals inhabit [30].

Sea turtles do not exhibit escape behavior when they encounter oil stains in water, thus, exposing their skin to the oil [7]. In addition, when they rise to the sea surface to breathe, they inhale or ingest oil, causing contamination by both the respiratory and the gastrointestinal tracts [5, 7]. The oil ingested by a sea turtle can be retained for several days in the digestive tract, increasing internal contact and possibility of absorption of toxic compounds, causing significant changes in the hematological profile and in the biochemical parameters of the blood [7, 45]. An experiment on the physiological and clinical-pathological effects revealed that the entire body system could be affected by short exposure to oil [26]. Prolonged exposure to oil could result in poor body condition of these animals by impairing their general condition (searching for food, for example), making them less resistant to other stressors, increasing susceptibility to diseases [10].

A laboratory study on the effects of fresh oil on eggs during incubation revealed a decrease in hatching survival, and hatched chicks showed developmental deformities, such as significant deviations in the number of shields [83]. In addition, the study showed that oil contamination at nesting sites could be more harmful if fresh oil is spilled during the nesting season. Experimental studies revealed that the presence of oil on egg surface reduced considerably the survival of embryos of flatback (*Natator depressus*) and green sea turtles (*Chelonia mydas*) due to the impediment of gas exchange [84].

When they reach the water, juveniles become as exposed to the effects of oil as adults; however, exposure could be even greater considering that they spend more time at the air-water interface than adults do [7]. Despite being less toxic than fresh oil, tar balls also pose a significant threat. Studies in Florida have reported the presence of these by-products in the jaw, tongue, esophagus, and stomach of hatchling loggerhead turtles [7, 85]. Juveniles can starve, even die due to blockage of their mouths and esophagus by tar balls [86], and thus become less active due to lack of nutrients and more vulnerable to predators.

Lutcavage et al. [26] carried out a study with loggerhead turtles (*Caretta caretta*) aged 15-18 months exposed to oil. The results showed changes in some hematological parameters, such as: (1) a tendency to increase hemoglobin levels; (2) a reduction of about 50% in the erythrocyte count, whose values did not return to reference values after the recovery period; (3) polychromasia in erythrocytes; and (4) an increase in leukocyte count, which persisted for more than a week after recovery. Changes in glucose and urea values were also found in the control group, indicating a possible consequence of starvation during the confinement period. However, in the group exposed to oil, these values continued to decrease for 10 days. Further study on turtles under rehabilitation after rescue during the Deepwater Horizon oil spill in 2010, revealed (1) anemia in 6.58% (21/ 319) of the individuals; (2) increased anisocytosis, polychromasia, basophilic stippling, mitotic figures, and/or immature red blood cells precursors; (3) heterophilia in 90 of the 319 turtles; (4) hyperglycemia in 49.53% (159/319), and hypoglycemia in 17.55% (56/319). Heterophils normalized by Days 11 to 20 (80 turtles) and by Days 21 to 30 (the remaining 10 turtles), and glucose concentrations stabilized within 5 days after admission in rehabilitation [41]. One oiled olive Ridley (*Lepidochelys olivacea*) found during the largest oil spill recorded in Brazil in 2019 was kept under rehabilitation, and the first laboratory analysis revealed (1) little higher hemoglobin value (102 g/L) and higher mean corpuscular volume (945 fL) than reference values (73.7–97.6 g/L and 255.5–341.5 fL, respectively; [87], and (2) lower lymphocytes and thrombocytes count (770 and 3,500 cells/μL, respectively) in contrast to reference counts (920–2,540 and 6,750–19,750, respectively; [88]; after 7 days of treatment a second blood count showed these parameters in normal range [45].

Damage on the skin of loggerhead turtles studied by Lutcavage et al. [26] was also descripted, and it came off in layers and this condition lasted for 1-2 weeks after removing the oil but return to normal texture only after about a month. Biopsies revealed the presence of a diffuse infiltrate composed of heterophils, moderate to extensive multifocal epithelial necrosis, and edema in the dermis with the presence of heterophils. During the biggest oil spill disaster in Brazil in 2019, one juvenile male green turtle (*C. mydas*) with all its body surface coved by crude oil was necropsied by PCCB-UERN and CEMAM team. The gross and histopathological examinations revealed crude oil in the oral cavity and esophagus; congestive areas, edema, and infiltrate of mononuclear cells and heterophils in the lamina propria of the esophagus; modified epithelium, apparent oil-induced damage to the goblet cells, and hemorrhage in the trachea [89].

Study carried out by Stacy et al. [41], revealed that the majority of oiled sea turtles rescued during the Deepwater Horizon oil spill in 2010 were Kemp's ridley (*Lepidochelys kempii*) (60%; 192/319), followed by green (*C. mydas*) (35%; 113/319), loggerhead (*C. caretta*) (3%; 9/319), and hawksbill turtles (*Eretmochelys imbricata*) (2%; 5/319). The mean rehabilitation interval was 98 days (between 30 and 360 days), and the admitted turtles gained an average of 39% in body weight. Only four individuals died after admission: three Kemp's ridley turtles from severe hyponatremia, and one green turtle that was euthanized due to severe bacterial colitis. All other turtles were successfully rehabilitated and eventually released.

In 2019 during the biggest oil spill disaster in Brazil, among the 14 sea turtles recorded across the Rio Grande do Norte state one alive olive ridley (*L. olivacea*) was found with all its body surface covered by crude oil. The field team of PCCB-UERN rescued the individual and carried out to stabilization, decontamination and rehabilitation, and after 67 days the turtle was released [45]

4.5 Seabirds

Seabirds are considered bioindicators, as they have both costal and pelagic habits [20]. In the event of an oil spill, seabirds are usually the most affected taxonomic group and may die from contamination, asphyxiation, or drowning. When they dive to capture food or fly over for rest, seabirds come into direct contact with oil, which compromises their impermeability and heat exchange, resulting in hypothermia and reduced ability to fly [27, 90]. As a result, they become dehydrated, as they mobilize their energy reserves and lose body mass. Oil intake could make seabirds anemic and immunosuppressed, leading to death if immediate responses do not occur [27, 91, 92]. However, species respond differently to oil pollution, due to foraging strategies, geographic distribution, and reproduction, and the greatest impact occurs on species that spend much time in contact with the sea surface and dive to capture their prey [93]. Underhill et al. [2] revealed that even quite small amounts of oil on plumage of penguins induce them to make a landfall on a breeding island or on the nearest mainland as a behavioral characteristic of these birds.

Generally, birds perform great migration movements and can move between different continents, mainly in the reproductive period [94]. Thus, spills that affect these animals in a certain region could cause ecological problems in other continents. This is because effects of oil exposure could also reflect on the conservation of populations of species that migrated. Secondarily, spills could also trigger a reproductive problem, because adults that do not find enough food for their young could abandon them in the nests, causing death to the young due to the absence of parental care, or even because oil contamination prevents eggs from hatching [18]. According to Underhill et al. [2], six situations can occur between oiling and restoration to the breeding population, which result in death or reduced breeding productivity: (1) Oiled penguins do not come ashore, but die at sea; (2) Oiled penguins ashore die before being captured; (3) Oiled penguins die during transport to and initial stabilization at the rescue center; (4) Penguins die during treatment; (5) Penguins die shortly after release or 'discharge' and thus fail to be rehabilitated, as defined in this paper; and (6) Rehabilitated penguins do not breed successfully, or have reduced breeding productivity, and thus fail to be restored.

On 24 March 1989 the Exxon Valdez grounded and spilled more than 260,000 barrels of crude oil in the northeastern corner of Prince William Sound, northern Gulf of Alaska, that hosts some of the largest populations of marine birds in North America such as fulmars, petrels, cormorants, kittiwakes, murres, and puffins [95]. Between 25 March and 1 August 1989, a total of 29,175 dead birds (26,869 identified) were retrieved concluding that 10% of the existing Gulf of Alaska population of Common Murres, >50% of the population at the Barren Islands were probably killed and estimating a mortality of about 250,000 birds [95, 96].

In South Africa, two serious shipwrecks resulted in tons of oil spilled, affecting thousands of birds: (1) In 1994, Apollo Sea sank and left approximately 10,000 African penguins (*Spheniscus demersus*) oiled, and the Southern African National Foundation for the Conservation of Coastal Birds (SANCCOB) successfully cleaned and released 5,213 of the birds [2]; and (2) In 2000, the bulk Treasure spill reached penguin foraging areas and left many of these animals severely oiled, also affecting other species, such as bank cormorant (*Phalacrocorax neglectus*), cape cormorant (*Phalacrocorax capensis*), crowned cormorant (*Phalacrocorax coronatus*), great (white-breasted) cormorant (*Phalacrocorax carbo*), kelp gull (*Larus dominicanus*), hartlaub's gull (*Larus hartlaubii*) and swift tern (*Sterna bergii*) [3]. Study on rehabilitation of oiled little penguins (*Eudyptula minor*) was also carried out after the worst oil spill in New Zealand when the C/V Rena grounded on the Astrolabe Reef on October 2011, and appeared to successfully reverse the negative effects of oiling on the post-release survival of treated penguins [97]. A total of 39 incidents were reported to have impacted 83,224 seabirds. Among these, African penguins (*Spheniscus demersus*) were the most severely affected, accounting for 91.0% of the affected population, followed by cape gannets (*Morus capensis*) at 8.5%. The causes of these seabird-impacting spills varied, with unknown sources accounting for 46% of incidents, bulk/cargo carriers at 43%, tankers at 38%, and ship-to-ship transfers at 14% [17].

After the Prestige oil spill in 2002, a total of 12,023 seabirds, waterbirds and waders were recovered from beaches in Galicia by trained volunteers during a beached bird survey scheme (data provided by Dirección Xeral de Conservación da Natureza, Xunta de Galicia appud Munilla et al. [20]). Between 16 November 2002 and 5 March 2003, over 95% of the oiled birds were reported and the majority of them (81.7%; n=9826) were alcids (i.e., auks), including Common Murres, *Uria aalge* (37.4%; n=4492); Razorbills, *Alca torda* (23.8%; n=2861); and Atlantic Puffins, *Fratercula arctica* (20.6%; 2473); and the alive birds (20.6% of Murres, 25.4% of Razorbills and 6.8% of Puffins) were taken to rehab centers but only 2.46% of aquatic birds (n=301) and 1.81% of alcids (n=178) survived and were released [20].

5. Impact by food web

Many impacts on fauna occur indirectly or through the trophic web, since animals may also be contaminated when feeding on contaminated organisms [7, 18, 27, 63, 76, 77]. When these animals bioaccumulate contaminants through the trophic web, they become environmental sentinels, revealing environmental information related to impacts to the fauna [98, 99]. The greatest accumulation of hydrocarbons occurs in sediments (adsorption) and in animals at the food chain base (bioaccumulation), such as benthic organisms and some fish species [100, 101]. Species that feed on these organisms, such as those described in this study, may be susceptible to indirect contamination, often identified only after post-mortem examinations.

In 1989 the oil tanker Exxon Valdez spilled 260,000 barrels of crude oil in Prince William Sound, Alaska, resulting in abrupt changes in marine fish communities that reflected in the diet of many marine mammals [96]. Thus, species that feed on fish, bivalves, crustaceans, and zooplankton may be more vulnerable to oil effects through the food vector, due to the high capacity of these organisms to bioaccumulate hydrocarbons and other heavy metals [57, 98, 102, 103]. Except for Sirenians, all other groups of marine megafauna animals feed on these organisms and thus are exposed to contaminants through cumulative transfer. However, questions about the detoxification capacity of the physiological system of these animals are not fully understood, hindering explanations of differences in bioaccumulation between species [104].

Sirenians are herbivorous animals (second trophic position) and may be less vulnerable to bioaccumulation of certain contaminants [105]. However, this does not mean that sirenians are not contaminated by feeding on foods that had contact with oil, such as needle grass or contaminated water itself [99, 106, 107]. After the Deepwater Horizon spill, the number of manatees with accumulation of contaminants in the blood increased and some of these contaminants might be related to the spill or even to oil activities in the region [107, 108].

6. Human Health

The contamination of oceans due to oil spills has far-reaching consequences, not only for marine fauna but also for human populations [24, 109]. The intricate network of interactions within the trophic system leads to indirect impacts on humans through the bioaccumulation of contaminants in the food chain. Consequently, the effects of oceanic oil contamination can affect human populations through the consumption of contaminated shellfish, crustaceans, and fish [109]. The complex interplay within the trophic web underscores the importance of understanding these ecological dynamics for both environmental conservation and human health.

Sufficient evidence exists to establish a connection between the consumption of food containing PAHs contamination and an elevated risk of cancer [109]. Although the potential toxicity of PAHs is acknowledged, to assess whether there is a risk in consuming seafood in oil-contaminated areas, a level of concern must be established [110].

The PAH4 group, which includes benzo[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, and chrysene, as well as the PAH8 group, comprising benzo[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[ghi]perylene, chrysene, dibenzo[a,h]anthracene, and indeno[1,2,3-cd]pyrene, are recognized indicators of chemical contamination in food. Following oceanic oil disasters, the potential health risks for consumers of seafood become a matter of heightened concern. Entities like the European Union establish upper limits for benzo[a]pyrene (5 μg kg−1) and PAH4 group (30 μg kg−1) in bivalve mollusks [109]. The Food and Drug Administration (FDA) provides guidelines for the types and quantities of seafood that consumers can safely consume after the oil spill in the Gulf of Mexico [111].

PAHs with 2 to 6 rings are a concern for short- and medium-term food safety [112]. Profiles of high-molecular-weight and carcinogenic PAHs have been observed in bivalve mollusks, even though these food products represent only 29% of the total PAH consumption [113]. While low-molecular-weight PAHs are not classified as carcinogenic, their chronic intake can have negative impacts on human health [114].

7. Conclusions

An oil spill can lethally damage marine biodiversity, affecting individuals from all ontogenetic stages and from different taxonomic groups, including human health. Acute impacts of oil contamination on wildlife are evident, although difficult to treat and recover. However, persistence of hydrocarbons in the environment could result in continued exposure of animals for many years after an oil spill. Thus, systematic studies on local fauna at all developmental stages of oil activities are crucial, including seismic research, exploration, and distribution of oil. Continuous monitoring of risk areas as well as of the health of animals that dwell in these areas allows data comparison for a long period. Thus, in the event of an oil spill occurs, it is possible to analyze its real impact on marine fauna and consequently on the environment.

Immediate measures must be taken, such as increasing international inspections of activities at risk of oil spills. Stricter international agreements among countries should be adopted to ensure that only companies with security protocols transport and trade the oil. Systematic monitoring of fauna and environment must be mandatory during the entire process, from oil exploration to transportation. Efforts on rescue, stabilization and rehabilitation of oiled animals depend on many factors, such as organizational and operational framework team, trained personnel, resources and equipment, and decision making. Temporary and/or permanent screening facilities are necessary to admit and hold the oiled and injured wildlife. National and international standard protocols for the rehabilitation care should be encouraged in all countries, and must contain detailed clinical procedures, such as the use/dose of medicines and sampling collection, in addition to the standard procedures for emergency care. Responses to accidents and the monitoring of sites should be modernized accordingly, seeking to use means that speed up responses.

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