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INFLUENCIA DE LA CONTAMINACIÓN MARINA SOBRE LAS ENFERMEDADES INFECCIOSAS EN MAMÍFEROS MARINOS: REVISION Y ANÁLISIS DE DATOS

Influence of marine pollution on infectious diseases in marine mammals: review and data analysis

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Abstract

Marine pollutants endanger marine mammals and their environment, and its harmful effects are increasing due to the world's human population growth. The consequences of this increase can be detected through the large number of cases of marine mammals that strand worldwide and the high levels of pollutants and heavy metals that can be found in their bodies. This study aims to review the current situation of marine plastics and their effects on marine mammals, as well as to analyse large-scale data to understand the relationship between the abundance of marine plastics in our oceans and the emerging infectious diseases in marine mammals due to immunosuppression and the bioaccumulation of pollutants.

Keywords: marine mammals, marine pollutants, strandings, immunosuppression, infectious diseases.

1. Introduction

Human activities are changing the Earth, especially marine environments, with serious consequences (Hoegh-Guldberg & Bruno, 2010). Due to these changes, some scientists have coined the term "Anthropocene" to emphasise human impact on geological and ecological processes (Crutzen, 2006). Some global scale effects of these activities include biodiversity loss and global warming (Steffen et al., 2007). However, the understanding of the effects on marine environments is more difficult mainly due to the ocean's complexity (Hoegh-Guldberg & Bruno, 2010). Some of the threats that endanger the oceans include overexploitation, climate change and alien species. Nevertheless, a major threat to marine life is the pollution by plastic debris (Derraik, 2002). Because of that, this study aims to review the current situation of plastics debris and its effects on marine mammals, as well as to analyse large-scale data to understand the relationship between the abundance of plastics in our oceans and the emerging infectious diseases in marine mammals.

1.1. Marine plastic debris

Due to the world's human population growth, the use of plastic and the resulting abundance of plastic debris have increased. About 335 million tons of plastics were produced worldwide in 2016, of which Asia is the largest producer (50% of the global production, of which 29% corresponds to China). It is followed by Europe (19%), North America (18%), Middle East and Africa (7%), Latin America (4%) and independent states (2%) (PlasticsEurope, 2017). The global production has increased by 500% over the last 30 years, and the consumption per capita has exploded by over 50% in the last decade. By 2050, it is expected that the global production will reach 850 million tons of plastics per year (Lebreton et al., 2012).

Plastic debris enters the marine environment by several transport pathways such as rivers, drainage or sewerage systems and wind (Gall & Thompson, 2015), apart from anthropogenic activities like fishing, shipping and sports (Fauziah et al., 2018). They are distributed across all oceans due to their properties of buoyancy and durability and because they are ubiquitous (Gall & Thompson, 2015). Plastic debris distribution depends on environmental and anthropogenic factors. Environmental factors have a larger impact and include wave currents, tides, cyclones, wind directions and river hydrodynamics. The more intense these factors are, the higher the plastic concentration is. On the other hand, anthropogenic factors include human activities that cause the accumulation of plastics in the marine environment (Fauziah et al., 2018). They normally converge in subtropical gyres, but also in closed bays, gulfs and seas surrounded by densely populated coastlines and watersheds (Eriksen et al., 2014). More than 600 million people (around 10 per cent of the world's population) live in coastal areas that are less than 10 meters above sea level (The Ocean Conference, 2017).

Plastics fragment and disperse in the ocean through different ways of degradation, but they are never entirely eliminated and consequently they stay in marine ecosystems as microplastics (Gall & Thompson, 2015). These are plastic particles smaller than 5 mm in size (Brennecke et al., 2016). According to their morphology and size, microplastics can be classified into primary microplastics that are manufactured in small size (such as pellets), and into secondary microplastics, which are derived from larger plastics. According to the source, they can be land-based (such as litter and microbeads) and sea-based (such as fishing nets). Primary microplastics come from spillage during plastic production or from personal care products (such as facial scrubs). On the other hand, secondary microplastics derive from the fragmentation of larger plastics (such as such as synthetic fibres) (Rezania et al., 2018). Furthermore, there are also chemical pollutants such as polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCBs), which are capable of sorbing to the plastic surface and can be ingested by animals. Moreover, there are heavy metals such as aluminium, zinc, cupper, nickel and mercury that are absorbed to plastics suspended in the marine ecosystems (Brennecke et al., 2016).

1.2. Effects of plastic debris on marine environments

Plastic debris has physical effects on the marine environment, and biochemical effects on its species. Firstly, the most common biological effect is ingestion, which can happen by filter feeding, direct engulfment, absorption of suspension materials and predation of lower trophic species that have previously consumed plastics. Plastic ingestion is very common due to the difficulty of organisms to distinguish between prey and plastics, such as happens with marine turtles, which mistakenly eat plastic bags. Although some organisms are able to excrete the plastic fragments without suffering any threat, most species consume the plastics and they are transported to digestive systems. This ingestion leads to physical, chemical and biological changes in the organisms, which include blockages that prevent the passage of food into the intestine tracts and consequently the ability of the animal to uptake food (Shahul et al., 2018). Plastic fragments were first seen in the guts of seabirds in 1960, when the global plastic production was about 25 million tonnes per year (less than 10% of the current figures). The number of fragments consumed has been increasing, while the mass of fragments seen in each bird has recently decreased. The autopsy of planktivorous fish from the North Pacific central gyre showed plastic fragments in the guts of approximately 35% of them. In the Clyde Sea (Scotland), plastic pieces were found in 83% of the studied individuals of an omnivorous crustacean (*Nephrops* sp) (Cole, 2011).

In addition, the most visible effect of plastic pollution is entanglement. It can happen due to “ghost nets”, which are lost or abandoned fishing gears that trap and kill marine animals, or because of balloons, plastic bags and ropes (Kühn et al., 2015). It affects marine mammals, reptiles (such as turtles), seabirds and fish. It is estimated that between 57000 and 135000 pinnipeds and baleen whales are entangled worldwide every year (UNEP, 2016). Many animals cannot escape and die because of injuries, starvation and general debilitation. They also suffer from suppurating skin lesions, ulcerating wounds and failed predator avoidance (Gregory, 2009). Marine mammals use to become entangled around their neck, flippers and flukes in different types of fishing gear. Seals become trapped in loop-shaped fishing items that enclose their neck when they are young and cause problems during growth. Some times entanglement happens because of the playful behaviour juvenile animals have, as occurs with young Califonia sea lions (*Zalophus californianus*) (Kühn et al., 2015).

Among the chemical effects, the additives that are added to plastics can cause hormonal disturbance in organisms with impacts on mortality, reproductive abnormities and neurological development depending on the ingested concentration (Shahul et al., 2018). Additives such as polybrominated dyphenyl ethers, phthalates and bisphenol-A can compete with and disrupt the synthesis of endogenous hormones (Cole, 2011). They alter the endocrine system because they compete with endogenous steroid hormone binding to its receptors and transport proteins and by altering gene expression (Talsness et al., 2009). Phthalates are related with inhibited locomotion in aquatic invertebrates, intersex conditions in fish and genotoxic damage (such as apoptosis in mussel haemocytes) in both. Bisphenol-A is an oestrogen agonist and an androgen antagonist and can be toxic to crustaceans and insects (Cole, 2011). Other additives such as benzene and 1,3-butadiene are carcinogenic, allergenic and mutagenic, and can cause high chronic toxicity and very high acute toxicity (Lithner et al., 2009). Vitellogenin synthesis and testicular abnormalities in a male flatfish (*Platichthys flesus*), both induced by alhylphenols, is an example of endocrine disruption (Matthiessen, 2003). Other study reported the ability of tributyltin (TBT) to inhibit P450-aromatase activity in the mussel *Ruditapes decussatus* (Porte et al., 2006). Furthermore, it is known that di-(2-ethylhexyl) phthalate causes endocrine disruption in the African sharptooth catfish (*Clarias gariepinus*) (Adeogun, 2018).

Also, the presence of plastics on beaches can alter the physical properties of the sediment, such as heat conductivity and water permeability. Furthermore, they can transport species that may become invasive to other marine ecosystems (Barnes, 2002), such as the eggs of *Homalopoma micans* (a pelagic insect), which are transported in plastic pellets (Goldstein et al., 2012; Majer et al., 2012).

1.3. Microplastics as vectors for heavy metal pollution

Microplastics and heavy metals are normally classified as two different types of marine pollutants, but several studies show that plastics can act as vectors for heavy metals in marine ecosystems. As an example, antifouling paints can be a source of metals to be absorbed by microplastics. It is known that plastic surface properties and its porosity are crucial factors on metal absorption behaviour, which means that a greater surface area and a higher polarity lead to higher absorption rates. The absorption mechanisms are due to the absorption of cations into charged sites of the plastic surface. This is because organic polymers compose microplastics and heavy metals have a high affinity to them. Furthermore, metal concentrations in plastics are higher than the ones found floating alone in the ocean, thus can become toxic and they are highly available for marine animals (Brennecke et al., 2016).

1.4. Immune system of marine mammals and immunosuppression

The main function of the immune system is to protect the organism against infectious diseases caused by parasites, viruses, bacteria or other microorganisms. It is composed of different tissues, cells and molecules and can be separated into two different functional systems that are interconnected. The innate immunity acts to protect the organism within minutes and hours of exposure, while the adaptive immunity protects the body against extracellular pathogens and responses through interactions with antigen-presenting cells to destroy them (Abbas et al., 2015).

Marine mammals are vulnerable to bioaccumulative plastic pollutants due to their position as top-predators in marine food webs. These pollutants persist in the marine environment and as marine mammals are long-lived animals they accumulate and magnify them in their bodies (Sharma & Chatterjee, 2017). Most species of marine mammals are exposed to periods of nutritional stress due to their reproduction, migration or hibernation patterns, which can cause the mobilization of pollutants (Desforges et al., 2016). Chemical pollutants are known to cause immunotoxicity, which is characterized by thymus atrophy and reduced T-cell function (Ross, 2002). Additionally, immunosuppression may include disruption of circulating immune cells (such as an increase in haptoglobin levels), suppression of lymphocyte proliferation and of phagocytosis, reduction of NK cell activity and the suppression the production of antibodies (Desforges et al., 2016). As a consequence, these chemical pollutants can cause the emergence of infectious diseases by reducing host resistance, increasing pathogens production as well as facilitating the transmission within and among populations. Thus, marine mammals with large amount of pollutants in their bodies are more vulnerable to impacts and ease the emergence of new diseases. Consequently, they suffer from higher mortality rates and represent susceptible host reservoirs (Ross, 2002).

1.5. Infectious diseases in marine mammals

Emerging infectious diseases involve the transmission of a pathogen to a new host species due to anthropogenic intrusion on previously uninhabited places, the increasing proximity of domestic animals to wild areas, the destruction of habitats and climate change, all of which alter the interactions which exist between the pathogens and their hosts (Ross, 2002). Human intrusion has lead to the emergence of these diseases by increasing population density and by intrusion into wildlife habitat (Morse, 2001). The transmission can also happen by reservoir animal populations, which are often domesticated species (McCallum & Dobson, 1995). In addition, global climate change causes changes in the geographic range and incidence of some infectious diseases (Daszak et al., 2000).

Many pathogens have a natural function in the regulation of marine mammal populations. However, anthropogenic activities may alter pathogen-host interactions throughout disturbance, fishing, habitat destruction and pollution (Ross, 2002). These activities include commerce, human travel and the “spill-over” of pathogens from domestic animals into wildlife. Furthermore, the removal of habitat's portions of host populations, the alteration of host migration patterns and the increase of host density can affect the transmission and emergence of infectious diseases (Daszak et al., 2001).

Marine mammals are part of the fish-eating wildlife, which implies that they are more exposed to high levels of environmental pollutants. As a consequence, they can easily accumulate them and therefore they are vulnerable to infectious diseases (Ross, 2002). These diseases may cause massive mortalities, limitation of the growth of wild animal populations, increase in the risk of extinction of small populations and consequently loss of biodiversity (Van Bressem et al., 2009; Daszak et al., 2000).

In recent years a large number of emerging infectious diseases have been reported in several species of marine mammals causing large-scale strandings, affecting reproductive rates, skin diseases and mortalities. These reports include sick or dead marine mammals that are found on the beach. A stranding event implies animals that usually beach alive, involving more than two marine mammals. On the other hand, a mortality event involves large numbers of animals that die (Gulland & Hall, 2007). Several studies show that the infectious diseases that cause these strandings and mortalities are mainly caused by virus pathogens, brucellosis, toxoplasmosis and lobomycosis. Cetacean morbillivirus (CeMV) belongs to the genus *Morbillivirus* and includes seven strains: porpoise morbillivirus, dolphin morbillivirus, pilot whale morbillivirus, Longman's beaked whale morbillivirus, Guiana dolphin morbillivirus and Indo-Pacific bottlenose dolphins. It is lymphotropic and epitheliotrophic and causes pneumonia and immunosuppression (Van Bressem et al., 2014). Brucellosis is caused by a gram-negative, facultative intracellular bacterium of the genus *Brucella*, which includes two species in marine mammals: *Brucella ceti* and *Brucella pinnipedialis* (affecting cetaceans and seals, respectively). It causes placentitis, orchitis, abortion, mastitis, pneumonia, subcutaneous lesions, arthritis, non-suppurative meningo-encephalitis and encephalitis, hepatic and splenic coagulative necrosis and lymphadenitis. Furthermore, neurologic diseases induced by brucellosis can lead to massive strandings (Van Bressem et al., 2009). Toxoplasmosis is caused by *Toxoplasma gondii*, which is an obligate intracellular protozoan parasite that belongs to the phylum Apixomplexa. The infection occurs due to the ingestion of contaminated food or via placenta. It is characterized by lymphadenitis, necrotizing adrenal adenitis, myocarditis, acute interstitial pneumonia, non-suppurative encephalitis and systemic disease. It is commonly related to immunosuppression following a morbillivirus infection or to high amounts of chemical pollutants. Lobomycosis is caused by *Lacazia loboi*, which is an uncultivated fungus that belongs to the order Onygenales. In cetaceans it causes greyish to pink verrucous lesions that can ulcerate and form plaques (Van Bressem et al., 2009). For this study, the majority of stranding cases and of diseased marine mammals cases were caused by Cetacean morbillivirus (47%), followed by several pathogens (31%) that include coinfection of *Toxoplasma* and CMV, for example (figure 1).

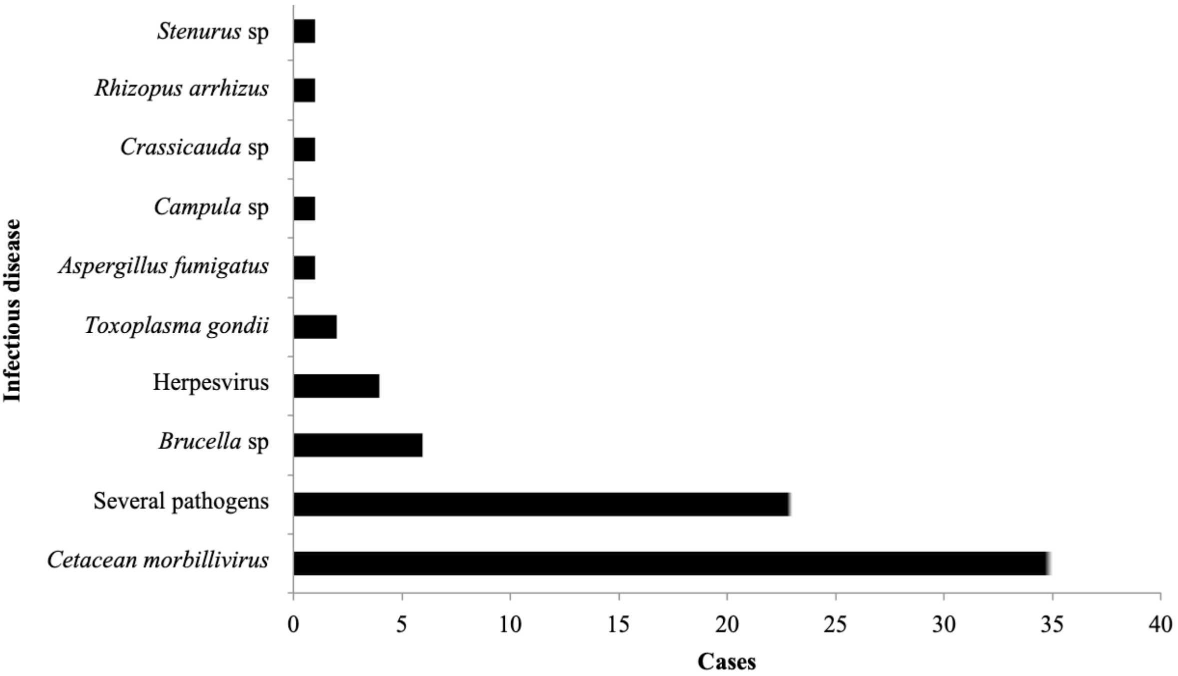

Figure 1. Pathogens and infectious diseases involved in each case used for the study. The cases refer to strandings or infectious diseases of the marine mammals reported by scientific papers. Source: table 1 (sup. material)

1.6. Mortality events

Unusual mortality events are defined under the Marine Mammal Protection Act as "stranding events that are unexpected, involve a significant die-off of any marine mammal population, and demand immediate response" (MMPA, 1972). Seven criteria are used to determine if an event is "unusual": (1) the number of stranded marine mammals is higher than expected in a given time and location; (2) there is a temporal change in mortality or strandings; (3) there is a spatial change in mortality or strandings; (4) the species, age or sex composition of the animals is different than that of the ones that are normally affected; (5) affected animals show similar pathologic findings or general physical conditions; (6) potentially significant mortality or stranding is observed in species or populations that are vulnerable and (7) mortality is related to an unexplained decline of a population or species (NMFS OPR, 2013).

Most of these unusual mortality events have occurred in the United States' coasts, especially in the ones of California and Florida. The most common marine mammals involved in them are bottlenose dolphins, California sea lions and manatees (NMFS OPR, 2013). The causes include biotoxins, viruses, bacteria, parasites, human interactions, oil spills and changes in oceanographic conditions. Meanwhile biological causes take place at irregular intervals, the mortality events related to climatic conditions usually occur at regular intervals, such as the ones associated with El Niño Southern Oscillation (Gulland & Hall, 2007).

The annual number of unusual mortality events reported in the United States doubled between 1980 and 1990. However, since 2000 it has remained at between seven and eight events per year (Gulland & Hall, 2007). Between 1992 and 1993, an unusual mortality event occurred involving about 1000 individuals of California sea lions that stranded along the coasts of California, mainly because of malnutrition (related to El Niño Southern Oscillation) and leptospirosis (Greig et al., 2005). In 2010, about 1141 cetaceans from different species stranded in the Gulf of Mexico due to an oil spill (Litz et al., 2014). Recently, between 2013 and 2015, about 1650 cetaceans (mainly bottlenose dolphins) stranded in the north-western Atlantic due to a cetacean morbillivirus infection (Kemper et al., 2016).

2. Materials and methods

For the review, I obtained information about the immune system of marine mammals, immunosuppression and infectious diseases, as well as data on the current situation of marine plastic pollution and its effect on marine ecosystems. All of this information was obtained from Web of Science system and Google Scholar using the keywords 'marine mammals', 'strandings', 'mortality', 'plastic debris', plastic pollution', 'heavy metals', 'effects of plastic debris'.

In order to quantify marine mammal mortality events, I did a systematic literature review to compile data on mortality events of marine mammals, as well as evidences of infectious diseases. Furthermore, I collected data on marine plastic's abundance in different countries and oceans. In order to compile this information, I used the Web of Science system using the keywords 'marine mammals' and 'Cetacean morbillivirus'. I obtained this information related to marine debris' abundance and to marine mammal mortality events independently to study if there was any correlation between both types of data. I extracted the location, date, species, number of dead and diseased animals and the infectious disease from each of the 75 papers obtained from Web of Science system and organized them in Table 1 (see supplementary material). Among the 75 cases, 7 were about animals that were caught for research, one was about an animal that died in a zoo and the rest belonged to stranded animals. The majority of the animals were Odontoceti (47 cases) and the rest belonged to Misticeti (6 cases) and to Pinnipedia (1 case). The 21 cases remaining belonged to numerous cetaceans of both cetacean orders (Odontoceti and Misticeti).

The papers of which the 75 cases were obtained were published between 1990 and 2018 in order to limit the search. The majority of the strandings took place during several years, some of them starting in the 90's and ending in the 00's. According to the number of publications, there is an increasing trend from 1997 to the current date. In the first years there are two peaks belonging to 2000 and to 2006. For the last four years (2014-2018) the number of papers published is generally higher, with a maximum in 2018 (11 papers published). In general, since 2010 there is a steady increase in the number of papers reporting mortality of marine mammals (figure 2).

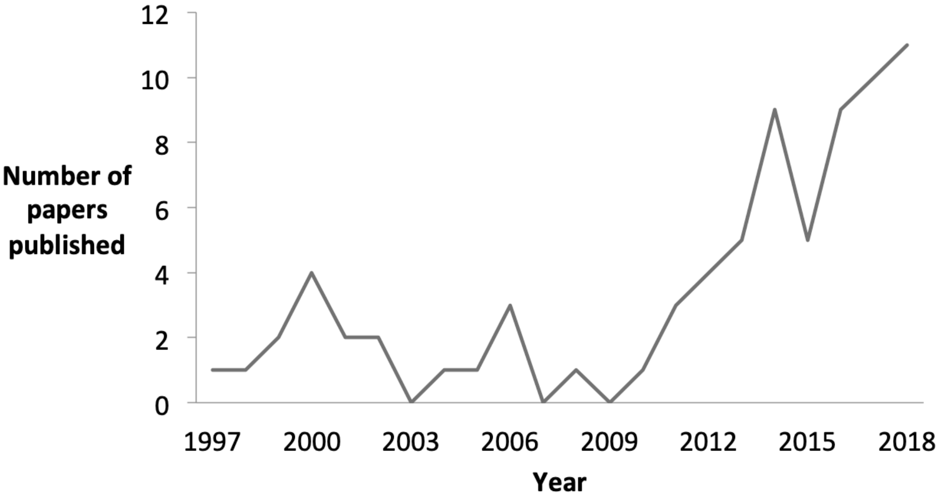

Figure 2. Number of papers reporting mortality of marine mammals published pear year from 1997 to date. There is an increase since 2010. Source: table 1 (sup. material)

3. Results

3.1. Distribution of diseased animals and microplastics particles per location

In order to represent the influence that the abundance and distribution of microplastics particles per location has on the abundance and distribution of diseased animals a graph (figure 3) was made, using as independent variable the number of microplastics particles per square kilometre and as dependent variable the number of cases of diseased animals. The microplastics' distribution was obtained from five categories of relative concentration (Kershaw, 2016), while the number of cases of diseased animals was previously obtained from the data collected from each article (table 2, see supplementary material). It takes into account not only the number of cases but also the number of individuals included in each stranding or infectious disease case. The Pearson correlation coefficient obtained was R^2=0,95, which means that about 95% of the independent variable is explained by the depended one (table 5, see supplementary material). The probability value obtained was p=0.005, which means that it is highly representative because it is lower than 0.05 ($p<0.05$).

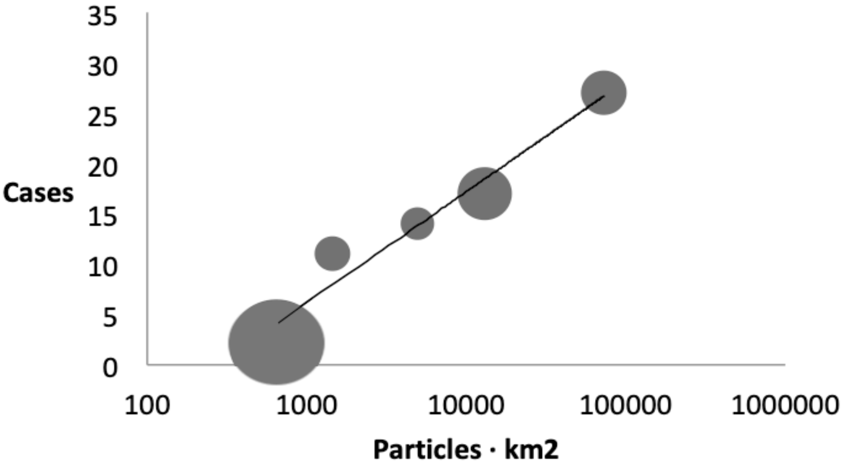

Figure 3. Number of individuals for each stranding or disease case per concentration of particles. Each bubble represents the number of cases of diseased animals, and the size of each of them shows the number of individuals involved. Source: table 2 (sup. material)

3.2. Distribution of diseased animals and particles per ocean

To show the influence of the abundance and distribution of plastic particles per ocean on the abundance and distribution of diseased animals a graph (figure 4) was made, using as independent variable the number of plastic particles per ocean and as dependent variable the number of animals suffering from infectious diseases per ocean. The plastic's distribution was obtained from existing literature (Eriksen et al., 2014), while the number of diseased animals was previously obtained from the data collected from each article (table 3, see supplementary material).

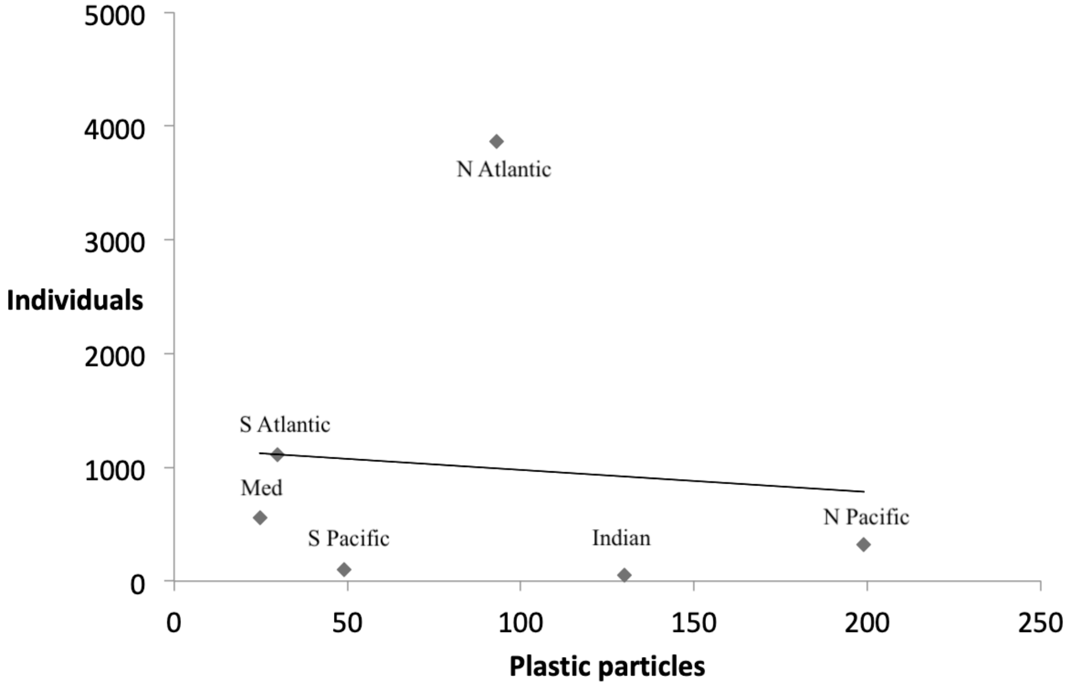

Figure 4. Number of individuals (stranded animals or animals suffering from an infectious disease) per plastic particles (x10^{10}) per ocean. Source: table 3 (sup. material).

3.3. Distribution of diseased animals and particles collected per country

With the aim of studying the influence that the number of plastic particles collected per country during 2017 had on the abundance and distribution of diseased animals a graph (figure 5) was made, using as independent axis the number of plastic particles collected per kilometre of beach and per people and as dependent axis the number of animals suffering from infectious diseases per country. The number of plastic particles collected per kilometre and people was obtained from the 2017 International Clean-up of *Ocean Conservancy* (Ocean Conservancy, 2017), while the number of diseased animals was previously obtained from the data collected from each article (table 4, see supplementary material).

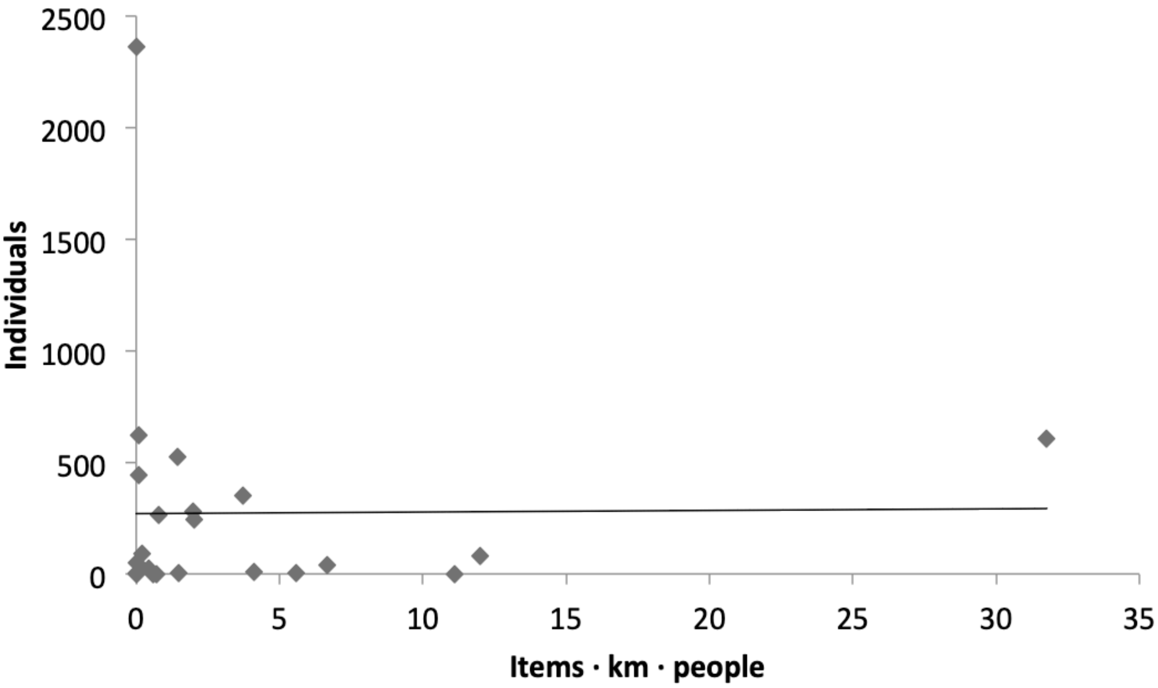

Figure 5. Number of individuals (stranded animals or animals suffering from an infectious disease) per items of plastic collected. The items represent the number of plastics collected by people and by kilometre of beach. Source: table 4 (supplementary material).

4. Discussion

For the analysis that studies the distribution of diseased animals and microplastics particles per location (figure 3) a directly proportional relationship was obtained, which means that where there were more particles per square kilometre, the number of diseased animals was higher. According to the number of individuals, the first bubble is larger because although it implies only two cases, the average number of stranded or diseased individuals (340) is higher. This could be because: (1) in Argentina and Russia (first category, 650) only large-scale epidemics or strandings are studied, so the number of cases is low but they involve a large number of individuals; (2) the number of papers published in Argentina and Russia is small, so there are only two cases reported but with a large number of individuals and (3) for the massive stranding in Argentina, only a few individuals suffered from infectious diseases but as a consequence of the social behaviour of cetaceans the entire pod followed them and stranded so a large number of individuals was wrongly reported.

For the test of the influence of the number of particles per ocean on the distribution of diseased animals (figure 4), an inversely proportional relationship was obtained, which means that the number of individuals that suffer from infectious diseases decreases as the number of particles per ocean increase. However, there is a lot of background noise and the result is not clear. There is a point that does not follow the distribution of the rest of the points, which is the one that corresponds to the North Atlantic Ocean. In the North Atlantic Ocean there are $93x10^{10}$ plastic particles, which places it in the third position according to plastic pollution. However, in this ocean there are 3866 individuals that suffer from infectious diseases, which places it in the first position according to infectious diseases. On the other hand, the North Pacific Ocean is the most polluted one ($199x10^{10}$ plastic particles) but according to the number of diseased animals (318 individuals) it is placed in the fourth position. Furthermore, the Mediterranean Sea is not very polluted ($24,7x10^{10}$ plastic particles) but it shows a large number of diseased marine mammals (557 individuals). This absence of correlation could be because: (1) the North Pacific is the most polluted ocean due to the large amount of plastic particles that are produced there (China is the largest producer worldwide, with 29%), but the number of researchers and of papers published are low; (2) the North Atlantic is less polluted but it has the largest number of diseased animals, which could be due to the large number of researches and of papers published in Europe and North America and (3) there are a large number of diseased animals in the Mediterranean sea but the number of plastic particles is low because it is smaller when comparing it with the largest oceans.

For the analysis of the distribution of diseased animals and particles collected per country (figure 5), a directly proportional relationship was obtained, which means that the number of individuals that suffer from infectious diseases decreases as the number of particles per ocean increase. However, again there is a lot of background noise and the result is not clear. There are two points that do not follow the distribution of the rest of the points, which are the ones that correspond to the United States and to Argentina. The United States is the country with the largest number of stranded or diseased animals (2363 individuals), but the number of plastic particles collected per kilometre and people is the lowest (0,001 items/km/people). Additionally, Argentina also has a large number of stranded or diseased animals (605 individuals) and the largest number of plastic particles collected (31,770 items/km/people). This could be because: (1) when taking into account the number of people and the kilometres of beach the number gets much more smaller for some countries such as the United States; (2) the number of items collected is not representative for the plastic pollution because plastic moves through ocean currents and wind so it is not a good indicator and (3) some species of marine mammals are migratory (Durban & Pitman, 2011; Stern, 2018), and therefore they can get contaminated in a place but strand in a different one (Williams, 2018) so there is no relationship between the polluted regions and the regions where the animals strand or where they are studied. As an example, some populations of killer whales are known migrate from California to Alaska every year. It could happen that one individual ingests a lot of microplastics near California and by the end of the year it moves to Alaska, where it is caught for studying the level of microplastics it has. It could be wrongly thought that the region highly polluted is Alaska, although the killer whale got contaminated near California.

Previous studies show a relationship between chemical pollution and mass morality in different marine mammal species (Handoh & Kawai, 2014), such as harbor seals (Van Loveren et al., 2000) and harbor porpoises (Jepson et al., 2005). The majority of the studies about this issue focus on certain chemical pollutants or on microplastics (Lusher et al., 2015). This review complies data on marine pollutants, including microplastics, plastic debris and chemical contaminants. Furthermore, this review compiles data on numerous cases of marine mammals strandings as well as of individuals that are caught for research. However, it is possible that a large number of cases of mass mortalities and strandings is missing due to the scarcity of research and of scientists in underdeveloped or developing countries (Gibbs, 1995). Additionally, there are more factors that can explain the absence of correlation in the data analysis of this study. Firstly, there are many species of marine mammals that have a migratory behaviour. Furthermore, the data about the abundance of plastic particles that comes from international clean-ups might not be representative for the amount of plastic of a certain country (Ryan et al., 2009). These clean-up programmes depend on the beach's length and on the amount of people that participate, as well as their effort. In addition, the distribution of plastic particles changes due to ocean currents and wind, so the sampling results may vary depending on the season of the year because of these currents. Finally, this lack of correlation could also be because some regions are so polluted that their inhabitants and resources are fully destroyed, so there are not marine mammals living in these regions. As a consequence, the probability of a stranding to happen there is lower.

5. Conclusion

The findings presented in this study should be considered as recommendations to take into account for further research and studies about the effect plastic and chemical pollutants have on marine mammals and on their mortality events. For creating a large and useful plastic pollution database worldwide, it would be a good idea to collect and analyse seawater from every place where a marine mammal strands, as well as where they are caught for research. This would be helpful for future studies about the relationship between plastic pollution and infectious diseases in these animals. It would also be useful for marine conservation because marine protected areas could be created in the most contaminated regions in order to reduce the impact plastic and chemical pollutants have and to protect marine mammals and the biodiversity of marine ecosystems.

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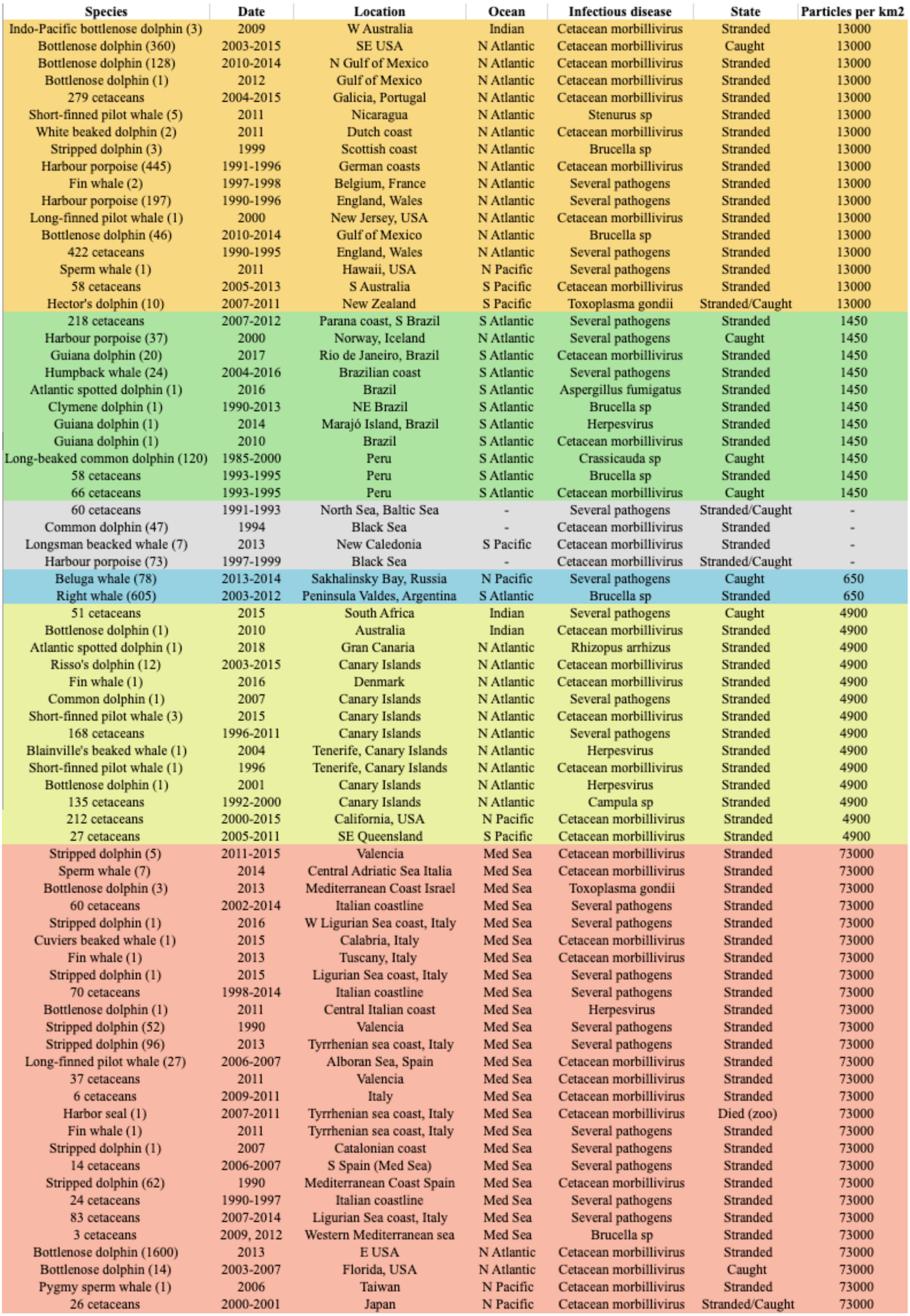
Supplementary material

Table 1. Data collected from each of the 75 papers. The number between brackets indicates the number of animals of each species that were caught or that stranded.



Species	Date	Location	Ocean	Infectious disease	State	Particles per km2
Indo-Pacific bottlenose dolphin (3)	2009	W Australia	Indian	Cetacean morbillivirus	Stranded	13000
Bottlenose dolphin (360)	2003-2015	SE USA	N Atlantic	Cetacean morbillivirus	Caught	13000
Bottlenose dolphin (128)	2010-2014	N Gulf of Mexico	N Atlantic	Cetacean morbillivirus	Stranded	13000
Bottlenose dolphin (1)	2012	Gulf of Mexico	N Atlantic	Cetacean morbillivirus	Stranded	13000
279 cetaceans	2004-2015	Galicia, Portugal	N Atlantic	Cetacean morbillivirus	Stranded	13000
Short-finned pilot whale (5)	2011	Nicaragua	N Atlantic	Stenurus sp	Stranded	13000
White beaked dolphin (2)	2011	Dutch coast	N Atlantic	Cetacean morbillivirus	Stranded	13000
Stripped dolphin (3)	1999	Scottish coast	N Atlantic	Brucella sp	Stranded	13000
Harbour porpoise (445)	1991-1996	German coasts	N Atlantic	Cetacean morbillivirus	Stranded	13000
Fin whale (2)	1997-1998	Belgium, France	N Atlantic	Several pathogens	Stranded	13000
Harbour porpoise (197)	1990-1996	England, Wales	N Atlantic	Several pathogens	Stranded	13000
Long-finned pilot whale (1)	2000	New Jersey, USA	N Atlantic	Cetacean morbillivirus	Stranded	13000
Bottlenose dolphin (46)	2010-2014	Gulf of Mexico	N Atlantic	Brucella sp	Stranded	13000
422 cetaceans	1990-1995	England, Wales	N Atlantic	Several pathogens	Stranded	13000
Sperm whale (1)	2011	Hawaii, USA	N Pacific	Several pathogens	Stranded	13000
58 cetaceans	2005-2013	S Australia	S Pacific	Cetacean morbillivirus	Stranded	13000
Hector's dolphin (10)	2007-2011	New Zealand	S Pacific	Toxoplasma gondii	Stranded/Caught	13000
218 cetaceans	2007-2012	Parana coast, S Brazil	S Atlantic	Several pathogens	Stranded	1450
Harbour porpoise (37)	2000	Norway, Iceland	N Atlantic	Several pathogens	Caught	1450
Guiana dolphin (20)	2017	Rio de Janeiro, Brazil	S Atlantic	Cetacean morbillivirus	Stranded	1450
Humpback whale (24)	2004-2016	Brazilian coast	S Atlantic	Several pathogens	Stranded	1450
Atlantic spotted dolphin (1)	2016	Brazil	S Atlantic	Aspergillus fumigatus	Stranded	1450
Clymene dolphin (1)	1990-2013	NE Brazil	S Atlantic	Brucella sp	Stranded	1450
Guiana dolphin (1)	2014	Marajó Island, Brazil	S Atlantic	Herpesvirus	Stranded	1450
Guiana dolphin (1)	2010	Brazil	S Atlantic	Cetacean morbillivirus	Stranded	1450
Long-beaked common dolphin (120)	1985-2000	Peru	S Atlantic	Crassicauda sp	Caught	1450
58 cetaceans	1993-1995	Peru	S Atlantic	Brucella sp	Stranded	1450
66 cetaceans	1993-1995	Peru	S Atlantic	Cetacean morbillivirus	Caught	1450
60 cetaceans	1991-1993	North Sea, Baltic Sea	-	Several pathogens	Stranded/Caught	-
Common dolphin (47)	1994	Black Sea	-	Cetacean morbillivirus	Stranded	-
Longsman beacked whale (7)	2013	New Caledonia	S Pacific	Cetacean morbillivirus	Stranded	-
Harbour porpoise (73)	1997-1999	Black Sea	-	Cetacean morbillivirus	Stranded/Caught	-
Beluga whale (78)	2013-2014	Sakhalinsky Bay, Russia	N Pacific	Several pathogens	Caught	650
Right whale (605)	2003-2012	Peninsula Valdes, Argentina	S Atlantic	Brucella sp	Stranded	650
51 cetaceans	2015	South Africa	Indian	Several pathogens	Caught	4900
Bottlenose dolphin (1)	2010	Australia	Indian	Cetacean morbillivirus	Stranded	4900
Atlantic spotted dolphin (1)	2018	Gran Canaria	N Atlantic	Rhizopus arrhizus	Stranded	4900
Risso's dolphin (12)	2003-2015	Canary Islands	N Atlantic	Cetacean morbillivirus	Stranded	4900
Fin whale (1)	2016	Denmark	N Atlantic	Cetacean morbillivirus	Stranded	4900
Common dolphin (1)	2007	Canary Islands	N Atlantic	Several pathogens	Stranded	4900
Short-finned pilot whale (3)	2015	Canary Islands	N Atlantic	Cetacean morbillivirus	Stranded	4900
168 cetaceans	1996-2011	Canary Islands	N Atlantic	Several pathogens	Stranded	4900
Blainville's beaked whale (1)	2004	Tenerife, Canary Islands	N Atlantic	Herpesvirus	Stranded	4900
Short-finned pilot whale (1)	1996	Tenerife, Canary Islands	N Atlantic	Cetacean morbillivirus	Stranded	4900
Bottlenose dolphin (1)	2001	Canary Islands	N Atlantic	Herpesvirus	Stranded	4900
135 cetaceans	1992-2000	Canary Islands	N Atlantic	Campula sp	Stranded	4900
212 cetaceans	2000-2015	California, USA	N Pacific	Cetacean morbillivirus	Stranded	4900
27 cetaceans	2005-2011	SE Queensland	S Pacific	Cetacean morbillivirus	Stranded	4900
Stripped dolphin (5)	2011-2015	Valencia	Med Sea	Cetacean morbillivirus	Stranded	73000
Sperm whale (7)	2014	Central Adriatic Sea Italia	Med Sea	Cetacean morbillivirus	Stranded	73000
Bottlenose dolphin (3)	2013	Mediterranean Coast Israel	Med Sea	Toxoplasma gondii	Stranded	73000
60 cetaceans	2002-2014	Italian coastline	Med Sea	Several pathogens	Stranded	73000
Stripped dolphin (1)	2016	W Ligurian Sea coast, Italy	Med Sea	Several pathogens	Stranded	73000
Cuviers beaked whale (1)	2015	Calabria, Italy	Med Sea	Cetacean morbillivirus	Stranded	73000
Fin whale (1)	2013	Tuscany, Italy	Med Sea	Cetacean morbillivirus	Stranded	73000
Stripped dolphin (1)	2015	Ligurian Sea coast, Italy	Med Sea	Several pathogens	Stranded	73000
70 cetaceans	1998-2014	Italian coastline	Med Sea	Several pathogens	Stranded	73000
Bottlenose dolphin (1)	2011	Central Italian coast	Med Sea	Herpesvirus	Stranded	73000
Stripped dolphin (52)	1990	Valencia	Med Sea	Several pathogens	Stranded	73000
Stripped dolphin (96)	2013	Tyrrhenian sea coast, Italy	Med Sea	Several pathogens	Stranded	73000
Long-finned pilot whale (27)	2006-2007	Alboran Sea, Spain	Med Sea	Cetacean morbillivirus	Stranded	73000
37 cetaceans	2011	Valencia	Med Sea	Cetacean morbillivirus	Stranded	73000
6 cetaceans	2009-2011	Italy	Med Sea	Cetacean morbillivirus	Stranded	73000
Harbor seal (1)	2007-2011	Tyrrhenian sea coast, Italy	Med Sea	Cetacean morbillivirus	Died (zoo)	73000
Fin whale (1)	2011	Tyrrhenian sea coast, Italy	Med Sea	Several pathogens	Stranded	73000
Stripped dolphin (1)	2007	Catalonian coast	Med Sea	Several pathogens	Stranded	73000
14 cetaceans	2006-2007	S Spain (Med Sea)	Med Sea	Several pathogens	Stranded	73000
Stripped dolphin (62)	1990	Mediterranean Coast Spain	Med Sea	Cetacean morbillivirus	Stranded	73000
24 cetaceans	1990-1997	Italian coastline	Med Sea	Several pathogens	Stranded	73000
83 cetaceans	2007-2014	Ligurian Sea coast, Italy	Med Sea	Several pathogens	Stranded	73000
3 cetaceans	2009, 2012	Western Mediterranean sea	Med Sea	Brucella sp	Stranded	73000
Bottlenose dolphin (1600)	2013	E USA	N Atlantic	Cetacean morbillivirus	Stranded	73000
Bottlenose dolphin (14)	2003-2007	Florida, USA	N Atlantic	Cetacean morbillivirus	Caught	73000
Pygmy sperm whale (1)	2006	Taiwan	N Pacific	Cetacean morbillivirus	Stranded	73000
26 cetaceans	2000-2001	Japan	N Pacific	Cetacean morbillivirus	Stranded/Caught	73000

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Table 2. Number of individuals (average) and cases for each category of relative concentration of microplastics' distribution.

Particles per km2	Cases	Individuals average
650	2	341,50
1450	11	49,73
4900	14	43,93
13000	17	115,47
73000	27	81,41

Table 3. Number of individuals and abundance of plastic particles per ocean.

Ocean	Plastic particles (n x 10^{10})	Individuals
North Pacific	199	318
Indian Ocean	130	55
North Atlantic	93	3866
South Pacific	49,1	102
South Atlantic	29,7	1115
Mediterranean Sea	24,7	557

Table 4. Number of individuals and items collected per country.

Country	Items/km/people	Individuals
Argentina	31,770	605
Russia	12,017	78
Belgium	11,111	1
Iceland	6,667	37
Israel	5,566	3
New Zealand	4,100	10
Italy	3,730	353
Peru	2,010	244
Portugal	1,988	279
Nicaragua	1,463	5
Spain	1,443	524
Brazil	0,767	266
France	0,707	1
Denmark	0,578	1
Japan	0,431	26
Australia	0,207	89
Germany	0,106	445
UK	0,094	622
Netherlands	0,019	2
China	0,019	1
South Africa	0,018	51
USA	0,001	2363

Table 5. Number of cases of diseased animals per concentration of plastic particles per km^2.