WHALE AND DOLPHIN CONSERVATION

TOXIC TIDES, TROUBLED WHALES:

How chemical pollution harms cetaceans

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Contents

Executive Summary

Chemical pollution is one of the main global environmental threats of our ocean, with synthetic contaminants now ubiquitous in the marine environment and the animals which live there.

Chemical pollution is one of the main global environmental threats of our ocean, with synthetic contaminants now ubiquitous in the marine environment and the animals which live there.
The chemicals typically considered of greatest concern are those which are highly resistant to degradation (i.e., persistent), bioaccumulative and toxic. Some of the best-known legacy and emerging Persistent Organic Pollutants (POPs) are polychlorinated biphenyls (PCBs), the insecticide dichlorodiphenyltrichloroethane (DDT) and per- and poly-fluoroalkyl substances (PFAS) amongst others. The toxicity of this class of compounds is high, with very low concentrations of POPs and heavy metals required to affect an organism compared to most other contaminants.

Whilst levels of legacy POPs appear to have generally been decreasing since 1992, the reported levels of PFAS have increased significantly in the last decade. Less well studied emerging pollutants often enter circulation intended as substitutions for toxic chemicals, however many are now classed as POPs themselves.

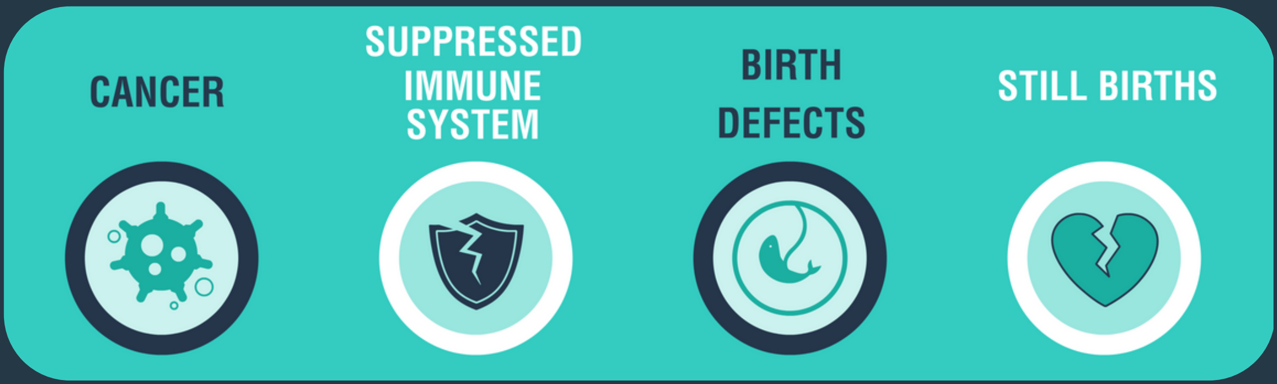
Exposure and bioaccumulation

Whilst the use of some POPs, such as PCBs and DDT, was banned some decades ago, they continue to enter the marine environment from various sources, including leaching from landfill sites and in industrial wastewaters. Organic contaminants, mostly released in warmer, low and mid-latitude areas readily evaporate and enter the atmosphere, where they are transported globally via atmospheric currents to cooler, higher latitudes where they condense and are deposited into the marine and terrestrial environment. As a result, high latitudes (polar and subpolar regions) are becoming the sink for POP accumulation.

Chemicals can be inhaled, consumed and absorbed through the skin of organisms. Some toxic chemicals are broken down into harmless substances before they can affect the organism. Many species have mechanisms to metabolise and excrete chemicals at low concentrations. However, in the case of POPs and some heavy metals, organisms cannot break down and expel the toxic substance and it instead accumulates within the animal. As long-lived animals, which are physiologically adapted to live a completely aquatic life, cetaceans have a thick layer of fat tissue or blubber, as insulation and as an energy store. Many POPs are lipophilic, meaning they are highly soluble in fatty tissues such as blubber. In cetaceans, blubber tends to be the body compartment containing the greatest quantities of lipophilic POPs. In the case of metals, concentrations occur in all tissues, however, zinc and lead have higher concentrations in the skin and bones and mercury accumulates to highest concentrations in the liver; PFAS preferentially bind to proteins. Cetaceans accumulate high body burdens of POPs over long periods of exposure. Once contaminants are stored in the body, negative effects are most likely to occur when they are remobilised and enter the blood during periods of stress such as starvation, pregnancy and lactation. Contaminants can be transferred to offspring during foetal development and lactation, which in the parent, can offset increasing pollutant concentrations otherwise associated with growth and ageing.

Impacts

There is clear and compelling evidence for severe impacts of chemical pollution upon specific species and populations of cetaceans. These impacts include



Legal framework

There are three key global environmental treaties relevant to chemical pollution all of which have the common objective of protecting human and environmental health from harmful chemicals and waste. Although these conventions provide a global framework to address chemicals such as PCBs, there appears to be a systemic shortfall by many signatories to allocate the necessary prioritisation and resources to this issue, given the severity of the impacts to wildlife and human health.

Conclusions

As a result of the insidious nature and effects of chemical pollution in cetacean populations, unfortunately, it's likely that the worst is yet to come; there is currently insufficient recognition of, or action to address, the dire consequences of man-made chemical pollution and the wide-ranging effects on the health and wellbeing of whales, dolphins and porpoises.

Urgent action is required to reduce the presence of these pollutants in the world's oceans to enable cetaceans to thrive into the future, including:

Recommendations

- Regularly re-evaluate the efficacy of current regulations and improve waste management to address chemical pollution.
- Increase elimination efforts and adopt a more precautionary approach to waste management to reduce the risk of chemicals entering the environment.
- Provide incentives, such as subsidy schemes and tax incentives, for the elimination of contaminants and participation in training and education to ensure safe disposal.
- Restrict the production and use of all emerging PFAS chemicals as a group under UK REACH by 2025.
- Establish an enforceable compliance mechanism for eliminating persistent organic pollutants (POPs).

- Provide additional capacity building and support to developing countries to achieve the 2025 and 2028 targets of the Stockholm Convention.
- Recognise and address the relationship between climate change and the risk of adverse health effects from POPs in future research and policy making.
- Improve education and awareness among the public regarding chemical management and disposal; many hazardous chemicals can be purchased and handled by the public and are present in everyday domestic goods and products.
- Put the burden of proof on industry that chemicals have no effects on the environment, to create greater producer responsibility.
- Require chemical companies to have mandatory public strategies to phase out PFAS.

- Implement mitigation measures such as limiting the dredging of PCB-contaminated rivers and estuaries, preventing PCB leakage from old landfills and regulating demolition of PCB-containing buildings and products.
- Include consideration of PCB tissue concentrations in the assessment of favourable conservation status of marine mammal species in European and UK policy.
- Support cross-disciplinary synergistic efforts to integrate chemical monitoring with ecological monitoring to break down silos between different environmental sciences, such as ecotoxicology, environmental chemistry and ecology.
- Make more funding available for analyses of extant and prospective samples from EU/global stranding networks.
- Coordinate and harmonise analyses of tissue samples with the goal to achieve regional/global datasets.

- Encourage or support the development of new non-invasive tests using easily sampled tissues to assess the impacts of POP exposure in cetaceans.
- Conduct toxicological studies to determine species-, age- and tissue-specific toxicity thresholds for a greater variety of POPs, including mixtures.
- Conduct further research and monitoring to assess global POP emissions, the extent of ongoing pollution and the effect of chemical mixtures on biodiversity.
- Increase monitoring of emerging pollutants and their concentrations and investigate their biological effects, particularly in urbanised coastal regions.
- Widely screen for non-targeted chemicals using high resolution mass spectrometry as an early warning system for overlooked contaminants.
- Increase long-term monitoring in the southern hemisphere, Arctic, and Antarctic regions due to their role as major sinks for persistent chemicals, particularly PCBs.
- Further assess the influence of climate change on the fate, transport, and distribution of POPs, and consider potential impacts on cetaceans and marine ecosystems.

Introduction

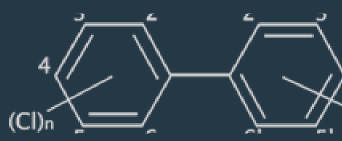
Chemical pollution is the contamination of the natural environment with chemicals which are not naturally present or are found in higher concentrations to their natural background values. It is one of the main global environmental threats faced today (Tornero & Hanke, 2017). Chemicals are everywhere in our daily lives and are subsequently ubiquitous in the environment (EC, 2020; Rowe, 2008). Synthetic contaminants have been used widely only in the past century (Rowe, 2008; Coulter, 2022). The chemicals typically considered of greatest concern are those which are persistent, bioaccumulative and toxic (PBT). PBT include both synthetic persistent organic pollutants (POPs) and heavy metals. POPs, have a specific set of characteristics, including 1) resistance to metabolism and degradation (i.e., persistence in the environment), 2) can be circulated globally via atmospheric transport and ocean currents over long distances from the source, 3) bioaccumulation potential through the food chain and 4) toxic effects (Baugh et al., 2023; Nadal et al., 2015). These effects can be direct or indirect, and can manifest at the molecular, individual and community level (OceanCare, 2021). Cetaceans experience the combined pressure of multiple human-made stressors including chemical pollutants within the marine environment. Whilst studies, risk assessment and regulation often focus on distinct pollutants and pressures, it must be recognised that cetaceans spend their lives in a “toxic soup” of pollution.

What is Chemical Pollution?

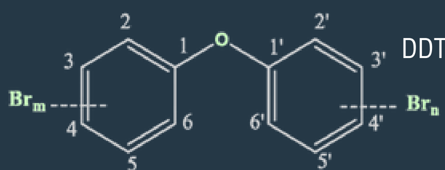
As of 2017, there were over 131 million registered chemical substances (Tornero and Hanke, 2017).

A subset of these have been identified under the Stockholm Convention (2001) as persistent, bioaccumulative and toxic. This list is dynamic and continues to grow. As of 2023, there are 38 chemical substances with severe harmful effects on the environment which have been identified for elimination, restriction or reduction (UNEP, 2019). These are a mixture of industrial chemicals, agricultural chemicals (such as pesticides) and unintentional releases, also known as byproducts.

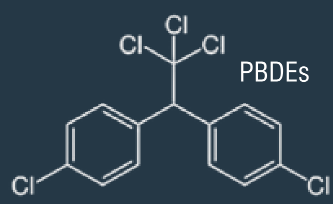
Some of the most well-known legacy POPs are the insecticide, dichlorodiphenyltrichloroethane (DDT), polychlorinated biphenyls (PCBs), polybrominated diphenyl esters (PBDEs), dioxins and a variety of organochlorine pesticides including aldrin, dieldrin, and endrin (Coulter, 2022). PCBs are a group of 209 persistent, bioaccumulative and toxic pollutants which were used extensively in a wide variety of uses, from heat exchange and insulting fluids in various electronic devices, over plasticisers in paints and cements to pesticide extenders as well as reactive flame retardants and sealants for caulking, adhesives and wood floor finishes (Madgett et al., 2022; Williams et al., 2020a). PBDEs are brominated flame retardants widely used in commercial and household products such as textiles, furniture and electronics (Rowe et al., 2008: Madgett et al., 2022). Other chemical pollutants of significant concern include polycyclic aromatic hydrocarbons (PAHs), generated primarily during the incomplete combustion of organic materials (e.g., coal, oil, petrol, and wood). Figure 1 sets out these key chemical groups known as POPs and the primary sources from which they originate. POPs can be divided into three key categories based on the original source: industrial, agricultural (pesticides) and unintentional byproducts. Unintentional POPs are those which are released as a byproduct of another process, for example PAHs are released during the burning of coal, oil and gas.



PCBs



DDT



PBDEs

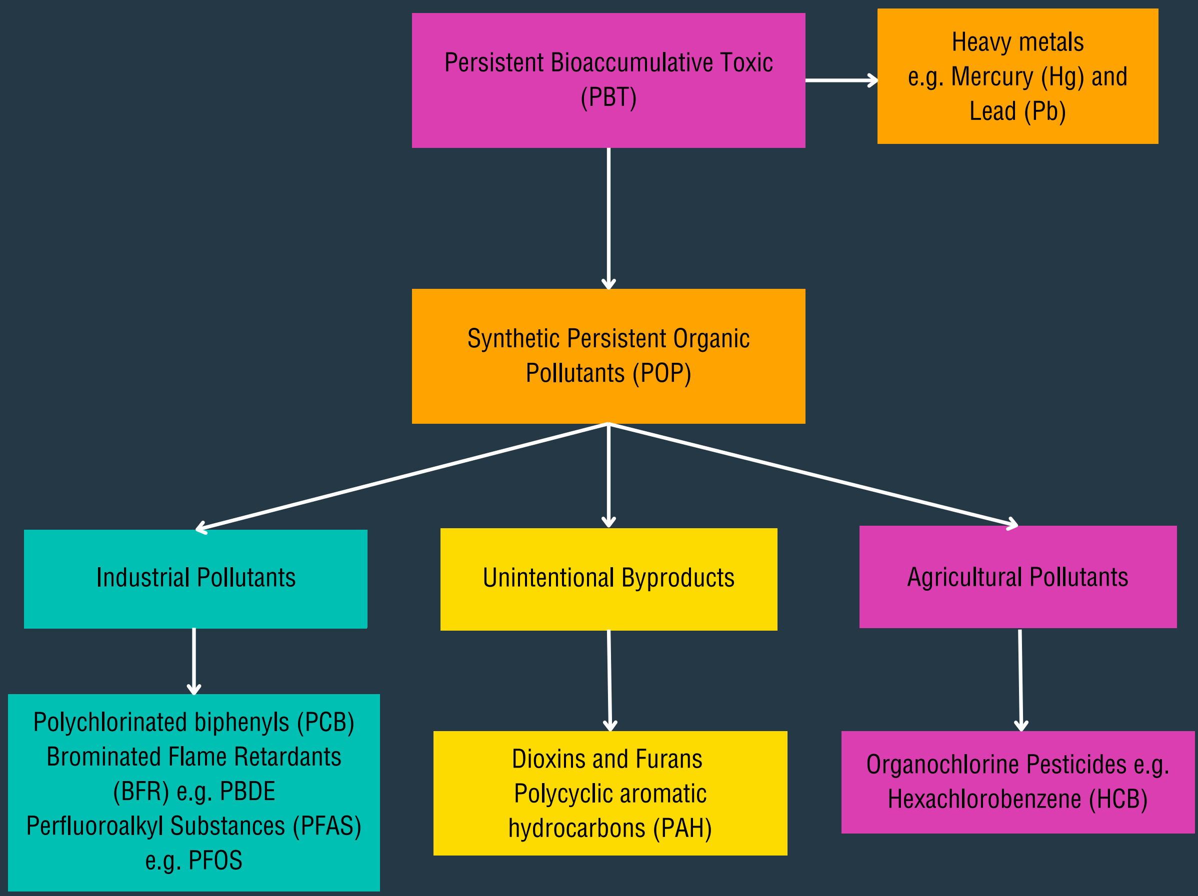


Figure 1. Key chemical groups known as persistent organic pollutants (POPs) and the primary sources from which they originate. Metals are classified as persistent, bioaccumulative and toxic (PBT) but not as POPs, as they also occur naturally in the environment.

Unlike POPs, which are man-made and therefore an "evolutionary novelty" to which wildlife have no adaptation, heavy metals are also naturally present in the environment (OceanCare, 2021). There are both 'essential' and 'non-essential' metals. Essential metals have a clearly defined function in the life of a species whereas non-essential metals have little or no known biological function. These non-essential metals, which include mercury, lead and cadmium, are often toxic even at low concentrations (Bowles, 1999; Delgado-Suarez et al., 2023). Inorganic mercury is converted to methylmercury by microbes in aquatic systems which readily binds to fats and proteins (Kershaw et al., 2019). Whilst many species, including cetaceans, do have detoxifying mechanisms to mitigate high concentrations of metals, once levels exceed this capacity, risk of adverse health effects increase (OceanCare, 2021).

Whilst many of the original, legacy POPs are now heavily restricted, they continue to enter the marine environment (e.g., by leaching from landfill sites and industrial wastewaters) (Madgett et al., 2022). In addition to municipal waste discharge, chemical compounds enter the environment through atmospheric transport, wet and dry deposition and river catchment runoff (Coulter, 2022; Madgett et al., 2022; Aznar-Alemany et al., 2017). The high vapour pressure of organic contaminants means they readily evaporate at warm, low latitudes. Once in the atmosphere these compounds are transported globally via atmospheric currents and remain there until reaching cooler, higher latitudes where they condense and deposit into the marine and terrestrial environment (Coulter, 2022). As a result, even though most POPs are released in low-mid latitude regions with higher temperatures, high latitudes become the sink for POP accumulation as a result of these atmospheric currents (Coulter, 2022; Tanabe et al., 1994). In the case of PCBs, it has been proposed that dispersal is driven by the gradient of contamination levels (Williams et al., 2020b). Animals can also act as vectors of pollutants. Irrespective of the mechanism, there is a continuously observed trend of high concentrations in lower latitude areas being transported to higher latitude areas. This capacity for long range transport means that many PBTs can disperse a considerable distance from the source (Coulter, 2022; Nadal et al., 2015; Andvik et al., 2023).

POPs are often referred to as organohalogens which is a group including organochlorines, organobromines and organofluorines. The name refers to the chemical structure of each group, for example organochlorine compounds have structures composed of hydrocarbons with more than one chlorine atom (Coulter, 2022). This is important to recognise as the mechanisms of toxicity and effects of different chemical constituents, known as congeners, vary according to these differences in structure (Williams et al., 2020a). For example, many POPs, such as PCBs and brominated flame retardants, are lipophilic, meaning they are highly soluble in fatty tissues such as blubber, whereas many emerging contaminants such as per- and poly-fluoroalkyl substances (PFAS) preferentially bind to proteins (Andvik et al., 2023). All 209 PCB congeners have the same basic structure: two connected phenolic rings with between one and ten chlorine molecules at different positions around the rings. Nevertheless, it has been shown that higher proportions of highly chlorinated congeners are found in adult female harbour porpoises and higher proportions of less chlorinated congeners are found in juveniles, suggesting that the structure of individual congeners also influences the risk and type of harmful effect. This observation is most likely due to lower degrees of chlorination resulting in lower lipid solubility (Williams et al., 2020a; Madgett, et al., 2022).

The structure, transport and ultimate fate of POPs means that they are prevalent in the oceans globally and they also accumulate in living organisms. Chemicals can be inhaled, consumed and absorbed across some organisms' skin. Some toxic chemicals are broken down into harmless substances before they can affect the organism. Many species have mechanisms to metabolise and excrete chemicals at low concentrations. However, in the case of POPs and some heavy metals, organisms cannot expel the toxic substance and it instead accumulates in the animal. Bioaccumulation is the process by which contaminants collect and build up in an organism. Due to the affinity of POPs for fatty tissues these chemicals readily biomagnify in ecosystems. Biomagnification (or bioconcentration) is the process by which contaminants are transferred from one trophic level, or step of the food chain, to the next (Figure 2). Contaminant concentrations accumulate and intensify as higher trophic level organisms feed on prey which is contaminated with POPs. Chemical compounds primarily enter the marine food web through uptake by phytoplankton. The phytoplankton are consumed by zooplankton and POPs then accumulate in the next level of the food chain. This process repeats at each predator-prey interaction (Coulter, 2022). This ultimately leads to exposure of chemical pollutants at often harmful or even lethal concentrations in species at the top of the food chain (apex predators) including cetaceans (Figure 2).

BIOMAGNIFICATION

Figure 2: Biomagnification of POPs from phytoplankton at the bottom of the food chain up to orcas, the apex predator, with a much greater load of the contaminant.

Legislation

There are three key global environmental treaties relevant to chemical pollution. They all have the common objective of protecting human and environmental health from harmful chemicals and waste (UNITAR, 2023; Tornero and Hanke, 2017).

The Basel Convention (adopted 1989) aims to protect human health and the environment against inappropriate management of hazardous wastes.

The Rotterdam Convention (adopted 1998) promotes global shared responsibility for chemicals, through cooperative efforts among signatories in the international trade of certain hazardous chemicals.

The Stockholm Convention (adopted 2001) sets out a list of POPs where emissions and/or production must be eliminated, or at least substantially reduced. There are specific aims for different groups of pollutants.

There are also many other global initiatives which have highlighted the harmful properties of other chemical pollutants. For example, the Executive Body of the United Nations Economic Commission for Europe (UNECE) developed a list of 16 priority substances under the 1998 Aarhus Protocol including 11 pesticides, two industrial chemicals and two by-products (Nadal et al., 2015). The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) developed a list of chemicals for priority action which includes PCBs and PBDEs and has developed a Hazardous Substances Strategy with the goal of achieving close to zero concentrations of man-made synthetic substances in the marine environment (Madgett et al., 2022; Tornero and Hanke, 2017). The International Convention for the prevention of Pollution from Ships, the MARPOL Convention, is the main international convention covering the prevention of pollution of the marine environment by oil from ships, as well as pollution by chemicals (Tornero and Hanke, 2017). Many of these Protocols ban the production of substances and schedule others for elimination at a later stage. Some agreements require signatories to reduce their emissions of certain chemical pollutants to a target level. For example, signatories of the Stockholm Convention must be working towards a target to eliminate use of PCB equipment by 2025 and to have environmentally sound waste management for PCB liquids and contaminated PCB equipment (above 0.005% PCB content) by 2028 (Stuart-Smith and Jepson, 2017). These long-term multinational agreements are necessary as many pollutants which are still present in the environment were banned decades ago. For example, PCB production was banned in the United States in 1979 (Toxic Substances Control Act 1976), in the United Kingdom in 1986 (The Control of Pollution (Supply and Use of Injurious Substances) Regulations 1986), most uses were banned or heavily restricted in the rest of the European Union by 1987 (EU Council Directive 76/769/EEC, later amended by Directive 85/467/EEC) and production and new uses were banned worldwide under the Stockholm Convention in 2004 (Madgett et al., 2022; Nadal et al., 2015). However, due to the highly persistent nature of these substances, and as a result of dilution and cross-contamination, they are widely present, despite some not having been produced for decades. For example, the mass of liquids and equipment containing or contaminated with PCB is much larger than the amounts of pure PCB produced: a single tonne of PCB can generate multiple tonnes of PCB wastes.

In the EU, key legislation includes the Classification, Labelling and Packaging (CLP) Regulation which requires that all chemicals on the market have to be classified as to whether or not they could damage the environment (Tornero & Hanke, 2017).

Registration, evaluation and authorisation of chemicals or REACH is the main EU law providing procedures to improve the protection of the environment from risks posed by chemicals (EC, 2023). The regulation places responsibility on the manufacturer to collect information on the properties and uses of the substances they manufacture and report risks to the European Chemicals Agency (ECHA). The UK Government has also committed to publishing an overarching Chemicals Strategy which will explore options to consolidate monitoring, develop an early warning system for identifying emerging chemical issues, ensure chemicals are safely used and managed and that the levels of harmful chemicals entering the environment are significantly reduced (Defra, 2018). As identified in the Government's A Green Future: Our 25 Year Plan to Improve the Environment (25 YEP), the UK will use these multilateral environmental agreements, such as the Stockholm and Basel Conventions, to ban and restrict chemicals with adverse impacts and develop guidelines to support safe movement of hazardous wastes internationally. The headline aims of the 25 YEP include: to eliminate the use of PCBs by 2025 as required under the Stockholm Convention, to reduce land-based emissions of mercury to air and water by 50% by 2030, to substantially increase the amount of POPs material being destroyed by 2030, to allow negligible chemical emissions to the environment and to fulfil all commitments under the Stockholm Convention (Defra, 2018).

The identification of priority chemicals is a universal challenge for regulators and researchers (Tornero & Hanke, 2017). Toxicity thresholds are concentration-effect thresholds derived as a unique function of chemical type, individual exposure and duration of exposure and are a key tool used for risk assessment (Rowe, 2008). This is the point at which our current understanding of adverse health effects suggests harm will occur. The commonly accepted toxicity thresholds for cetaceans are summarised in table 1 below:

Table 1: Toxicity thresholds for different marine mammals species, from Williams et al., (in revision).

Pollutant	Threshold	Species	Endpoint	Reference
PCBs	9mg/kg lipid	Marine mammals	Hepatic vitamin A, thyroid hormone concentration, natural killer cell activity, lymphocyte response	Jepson et al., 2016, Kannan et al., 2000
	5.42 mg/kg lipid	Cetaceans	Decreased lymphocyte proliferation (Effective concentrations giving a 1% response (EC1))	Desforges et al., 2016
	0.14 mg/kg lipid	Bottlenose dolphins	Decreased lymphocyte proliferation (Effective concentrations giving a 1% response (EC1))	Desforges et al., 2016
	7.1 – 15.1 mg/l ww	Harbour seals	Pooled blood samples from controlled groups for increased lymphocytes, granulocytes, basophils and decreased monocytes	de Swart et al. 1994, Reijnders 1988
	1.3 mg/kg lipid	Harbour seals	Several biomarkers (e.g., plasma retinol and AhR expression) and immune function endpoints	Mos et al., 2010
	41 mg/kg lipid	Baltic ringed seals	Pathological changes in seal uteri	Helle et al., 1976
	1.6 mg/kg lipid	Beluga	Disruption of vitamin A and E profiles	Desforges et al., 2013
PBDEs	1.5 mg/kg lipid	Grey seal pups		Hall et al., 2003
pp'-DDE	1.43 mg/kg lipid	Bottlenose dolphins	Minimum concentration associated with decreased lymphocyte proliferation	Lahvis et al., 1995

Exposure, bioaccumulation and biomagnification

Bioaccumulation refers to the build-up of substances, such as pollutants or toxins, in the tissues of living organisms over time. Biomagnification is the process by which the concentration of a contaminant increases as it moves up the food chain. In the case of cetaceans, blubber tends to be the body compartment containing the greatest quantities of POPs (Aguilar & Borrell, 1994a) as many POPs are lipid-soluble. In the case of metals, concentrations occur in all tissues, however, zinc and lead have higher concentrations in the skin and bones and mercury accumulates to highest concentrations in the liver (Bowles, 1999). Bioaccumulation potential is largely regulated by the duration of exposure, therefore long-lived species at the top of the food chain are at greatest risk of adverse health effects and population level impacts (Rowe, 2008). The strategies evolved by cetaceans, such as slow maturation, breeding multiple times and a high parental investment, are optimised for environmental conditions that are relatively stable over a long reproductive lifespan (Rowe, 2008). Cetaceans establish high body burdens of persistent, bioaccumulative and toxic contaminants over long periods of exposure which puts them at risk in this heavily altered environment (Rowe, 2008).

The trophic level at which different cetacean species feed is key when considering the exposure route and degree of risk. Toothed cetaceans (odontocetes) experience the greatest chemical exposure, even when occupying the same habitats as baleen whales (mysticetes), as they feed at a higher trophic level (Baugh et al., 2023; Bowles, 1999).Toothed cetaceans rely upon fish, cephalopods and mammals as prey meaning they are apex predators at the top of a long food chain. Some species of toothed cetaceans, more so than baleen whales, also tend to frequent coastal areas closer to anthropogenic sources of chemical pollution (Bowles, 1999). Mysticetes feed at a lower trophic level on copepods, crustaceans and small schooling fish and therefore, are part of a short food chain giving less opportunity for chemicals to bioaccumulate (Hall et al., 2017). It has been reported that the minimum concentration of mercury measured in the liver of toothed cetaceans is higher than the maximum concentration recorded in baleen whales (Bowles, 1999). Similarly for PCBs, the highest concentrations identified have been in the blubber of long-lived odontocetes such as orcas (Williams et al., 2020a). However, it should be noted that there are exceptions to this general principle, for example cadmium levels are usually higher in krill than in fish hence higher cadmium levels have been recorded in krill-eating minke whales from the Antarctic compared to fish-eating minke whales from the Pacific Ocean (Bowles, 1999). This is solely due to regional variations in diet and not the result of human-driven exposure to toxins. Exposure to lower concentrations in very long lived mysticetes with large lipid stores can also still lead to cumulative effects which should not be overlooked (Baugh et al., 2023). Species specific traits also need to be considered, for example exposure to chemicals by lactational transfer in fin whales is lower than that of other cetaceans because fin whales have a shorter lactation period (Aguilar & Borrell, 1994a). Relative contribution to total load also varies according to different species, for example fin whale muscle and bone are also significant lipid reserve sites (Aguilar & Borrell, 1994a). Once contaminants are stored in the body, negative effects are most likely to occur when they are remobilised and enter the blood. This can occur during times of stress, such as starvation and during pregnancy and lactation in reproducing females (Simond et al., 2019) but can also be driven by seasonal variation in blubber thickness. Nutritional stress results in remobilisation of lipid stores which has been shown to lead to higher offloading of chemicals in milk during lactation, which ultimately causes greater potential for toxicity in juveniles (Heuvel-Greve et al., 2021). Therefore, remobilisation of stored contaminants causes a “reexposure” to harmful pollutants following the original exposure and uptake into target tissues (Bartalini et al., 2022).

Cetaceans can be exposed to chemicals via both direct and indirect, habitat-mediated effects. They may suffer the direct effects from bioaccumulation through the marine food chain and/or may be affected indirectly by a reduction in prey availability which can also be a result of chemical toxicity (Bowles, 1999).

There are a wide array of variables influencing exposure to the chemical mixture any one individual may experience, adding further complexity to our understanding of the impact of chemicals to cetaceans. Chemical uptake and effect vary by sex, age, spatial factors, temporal factors and the life history parameters of specific species.

Whilst males and females of the same species as well as temporal and geographical range may experience the same exposure to chemicals, females typically have lower concentrations of contaminants stored in their body tissues. This is due to the transfer of contaminants to offspring during lactation, which offsets the increasing pollutant concentrations otherwise associated with growth and ageing. The amount of POPs transferred during a reproductive cycle also declines with age in females (Aguilar & Borrell, 1994b). However, there are again exceptions to this general principle, for example female bottlenose dolphins studied in Brazil had higher PCB concentrations in their blubber than males, suggesting that the specific congeners these dolphins are exposed to may not be offloaded through gestation or lactation as is the case for other POPs (Balmer et al., 2011). Exposure of POPs to juveniles during and after gestation is also complex. As the female's body burden decreases with subsequent reproductive cycles, the first calf born is most likely to be most affected by chemical pollutants (Aguilar & Borrell, 1994b). Whilst lipophilic POPs are efficiently transferred via milk in marine mammals, protein-associated mercury and PFAS are more efficiently transferred through the placenta. Hence, the type of pollutant and the dominant sequestration sites in different cetacean species will further influence exposure (Andvik et al., 2023). It has been found that whilst adult female harbour porpoise had the highest proportions of octa-chlorinated congeners, juveniles had the highest proportions of tri- and tetra-chlorinated congeners (Williams et al., 2020a). This is significant as studies have shown that levels of exposure that cause no effects in adults can cause harmful effects in more vulnerable, developing young.

The geographical range of an individual is also highly influential in exposure and potential for chemical bioaccumulation. Minke whale populations in the Arctic and Antarctic have different diets; Arctic minke whales feed principally on sand eels whereas those in the Antarctic feed primarily on krill. Higher concentrations of the heavy metal cadmium and lower concentrations of the heavy metal mercury are found in krill compared to fish, hence chemical exposure in these two populations of the same species, feeding in different high latitude habitats, are different (Bowles, 1999).

Two populations of fish-eating resident orcas inhabiting the same coastal waters of British Columbia (Canada) and Washington (USA) were found to have very different concentrations of total PCBs in their body tissues. Even though chinook salmon is the primary prey item for both populations, the PCB concentrations in the southern residents (146 mg/kg lw) were almost four times higher than the northern residents (37 mg/kg lw). The more contaminated orcas spent more time in near-urban waters whilst the northern residents remained in remote waters (Cullon et al., 2009). It was identified that southern chinook salmon had lower lipid contents and therefore the southern resident orcas may be compensating for the reduced nutritional value by increasing prey consumption. This spatial variability in chemical exposure due to ranging patterns has also been observed in bottlenose dolphins (Balmer et al., 2011). POP concentrations were measured in bottlenose dolphins living near a PCB point source. Individuals with the highest concentrations were identified as those ranging closest to the point source whilst individuals sighted furthest away had lower concentrations (Balmer et al., 2011).

Climate change has been found to result in changes in migration habits of some cetaceans (Bartalini et al., 2022) and as a result, certain species now spend more time in more contaminated lower latitude regions and in some cases act as vectors of contamination to initially less polluted areas. For example, the Cook Inlet (Alaska) beluga whale population has increased its residence time in the more industrialised and urbanised upper Cook Inlet during warmer years, thus increasing their exposure to chemical pollutants (Bartalini et al., 2022). In addition to spatial and geographical variations, temporal changes will impact exposure. In a recent modelling study, the year of stranding was a significant predictor of adverse effects suggesting that animals are exposed to different chemicals at different points in time (Williams et al., 2020a). An individual will also be exposed to a mixture of chemical pollutants which can have synergistic interactions with other POPs in the environment or already present in the cetaceans' body tissues (Baugh et al., 2023). Synthetic pollutants are only one of many pressures facing cetaceans. For example, prey limitation, noise pollution and disturbance from vessels have all been identified as factors in the at-risk status of many cetacean species (Hall et al., 2017). The combination of multiple stressors and the effect of cumulative impacts must be recognised to fully understand the real-world pressures facing cetaceans.

Case Study: Orcas

The orca is one of the species which are particularly vulnerable to biomagnification and bioaccumulation of pollutants due to its position as an apex predator, long life span, and thick blubber layer in which lipophilic POPs can accumulate. Recent risk assessment of an orca population in Norway had assumed fish were the primary prey source, and subsequently assessed the population as below the adverse effect threshold for PCBs (Andvik et al., 2020). However, it was later observed that some individuals also feed on seals. A recent study by Andvik et al., (2020) found much higher levels of PCBs in seal-eating compared to fish-eating orcas, which resulted in all seal-eating individuals being above the thresholds for adverse health effects. Levels of other organohalogen contaminants, including DDT and PBDEs as well as mercury in the skin, were also all higher in the seal-eating orcas than the fish-eaters. The results indicated that by feeding on seals, this orca population is at a higher risk of negative health effects from chemical pollution than had been previously recognised. This relationship is also observed in the NE Pacific where marine mammal-eating Bigg's orca carry a 10–20 times higher PCB burden than fish-eating northern resident orcas, despite sharing the same coastline (Desforges et al., 2018). All seal-eating orcas in the Norwegian study (compared to 54% of fish-eaters) exceeded the lower PCB threshold of 9 mg/kg (lw) (Andvik et al., 2020). These levels of PCBs in the seal-eating orcas suggest adverse health effects can be anticipated in this population. Concerningly, the median PCB levels in female seal-eaters (67 mg/kg lw) were comparable to that of female, tuna-eating orcas from the Strait of Gibraltar (51 mg/kg lw), which is a population with one of the lowest reproductive rates for orcas globally (Andvik et al., 2020). It has been hypothesised that some orcas in Norway diversified to eating seals as a response to the collapse of the herring fisheries in the 1970s which occurred as a result of overfishing and changing environmental conditions (Andvik et al., 2020). Prey switching from low to high PCB contaminated prey sources has significantly increased PCB exposures in other orca populations such as in Northeast Scotland (UK) and Greenland which have been predicted as near to collapse (Desforges et al., 2018). Future changes in prey availability could mean that more orcas switch to eating seals or incorporate a higher proportion of seals in their diet, with subsequent health and population effects.

Decades after the onset of the PCB ban, orcas still have very high concentrations of pollutants in their body tissues. In 2016, an orca was found dead on the coast of the Isle of Tiree (west coast of Scotland) after becoming entangled in rope from a crab pot. A post-mortem found that the tissues contained 957 mg/kg of PCB, 100 times the lower toxicity threshold of 9mg/kg (Brownlow et al., 2016). On examination of the individual's ovaries, it was concluded that the female had never been reproductively active, which was considered unusual for her age, estimated at 20 years old (Brownlow et al., 2016). Orcas once thrived in all oceans, but now only those in the less contaminated regions of the Arctic and Antarctic are sustaining population growth (Desforges et al., 2018; Andvik et al., 2020). Desforges et al., (2018) developed a model using global data which showed that PCB-mediated effects on reproduction and immune function threaten the long-term viability of over 50% of the world's orca populations. Although orca populations face other anthropogenic stressors, the study suggested that there is a high risk of collapse for many orca populations as a consequence of PCB exposure alone. This raises further concerns about the potential for other chemicals and stressors to generate additional harm (Desforges et al., 2018).

Current Concentrations

In a European meta-analysis of stranded and biopsied cetaceans, three out of the four species studied (striped dolphins, bottlenose dolphins and orcas) had mean PCB levels that greatly exceeded the PCB toxicity thresholds (Figure 3; Jepson et al., 2016). Table 2 further demonstrates the high but varied concentration of POPs around the world by summarising the mean, maximum and minimum PCB concentrations measured in bottlenose dolphin blubber (adapted from Marsili et al., 2018). Concentrations range from a mean of 368 mg/kg (lw) in the Mediterranean to 0 - 5 mg/kg (lw) in the Southwest Indian Ocean. Figure 4 further identifies the key hotspots for chemical pollution and impacts to marine mammals. Whilst thresholds are useful indicators of potential harm, PCB concentrations in the blubber of UK harbour porpoises have fallen below the established threshold for toxic effects (9 mg/kg lw) yet concentrations are still associated with increased rates of infectious disease related mortality due to immune suppression (Williams et al., 2020b) and is having a direct impact on fertility and potentially affecting the future breeding success of the species (see later section on reproductive impacts). Analysis of over a decade of epidemiological data suggests that for every 1 m/kg increase in PCB concentrations there is a 5% increase in risk of adverse health effects (Williams et al., 2020b).

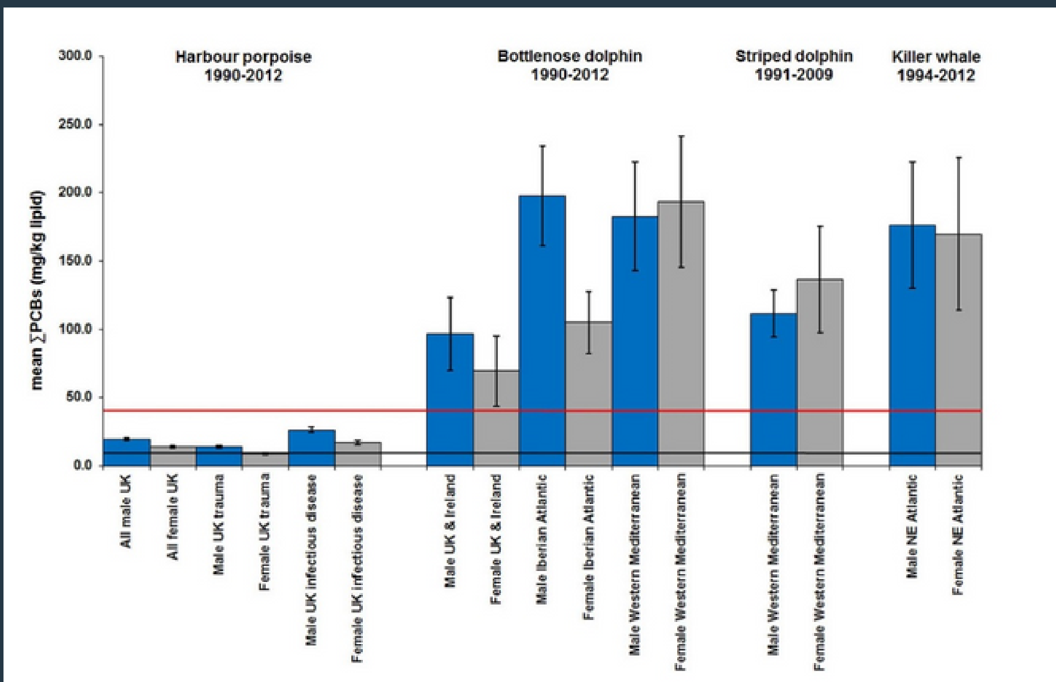


Figure 3: From Jepson et al., (2016): Mean PCB concentrations in male and female cetaceans of all ages. The lower line indicates the 9 mg/kg (lw) threshold for the onset of physiological effects in marine mammals and the higher line indicates the highest PCB toxicity threshold for marine mammals based on reproductive impairment in seals.

Table 2: Blubber PCB levels in bottlenose dolphins around the world, adapted from Marsili et al., (2018). For further details on sample size and numbers of males and females, please refer to the original data table in Marsili et al., (2018).

Ocean/Sea	**Year of Collection**	**PCBs (mg/kg lw)**		
		Mean	**Maximum**	**Minimum**
Mediterranean	2000-2002	150	272	29
	2000-2005	97	494	2
	2007-2009	368	-	-
	2011	110	293	29
NE Atlantic	2000-2002	24	60	8
	2001-2005	37	137	2
	2004-2007	94	447	4
	2004-2011	86	382	5
	2004-2012	71	125	9
NW Atlantic	2000-2007	160	658	16
	2000-2007	69	109	24
	2000-2007	39	86	17
	2010-2012	48	-	-
Mid Pacific	2009-2011	12	10	14
W Pacific	2000-2001	5	10	2
	2005	5	-	-
SW Atlantic	2000-2005	12	10	14
SW Indian	2000-2002	0	0	0
	2010-2011	5	68	0.1
SE Indian	2008-2009	9	25	2
	2009	22	54	10
SW Pacific	2004-2008	6	12	0.4

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Figure 4: From García-Álvarez et al., (2014): World map indicating the most relevant POP-polluted areas for marine mammals as indicated in the literature.

Figures 5 and 6 show the mean concentrations of PBDE in cetacean blubber and liver from around the world compared to the 1.5 mg/kg (lw) threshold (Bartalini et al., 2022).

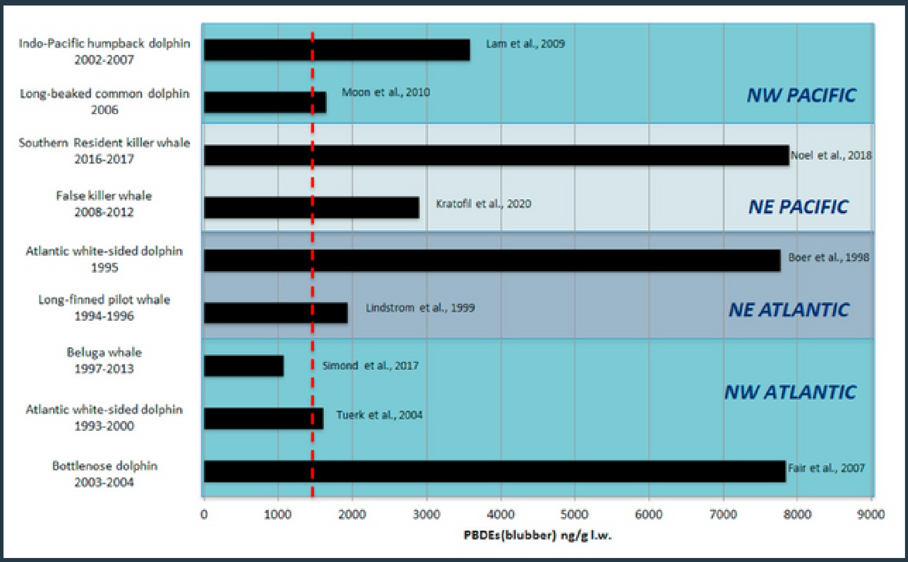

Figure 5: Bartalini et al., (2022): PBDE mean concentrations (ng/g* lw) in cetacean blubber from around the world. The red line indicates the thresholds for alteration to thyroid levels in seals (1500 ng/g lw). *1 ng/g = 1 mg/kg.

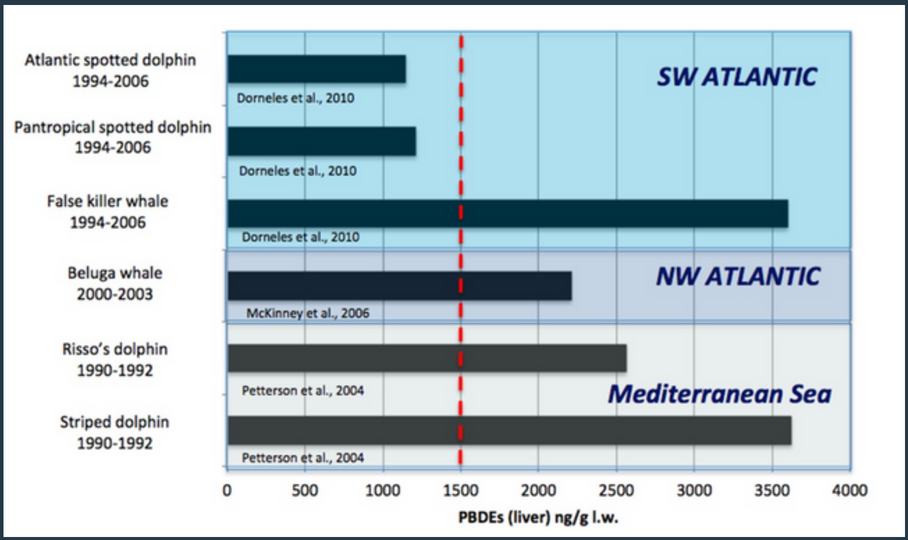

Figure 6: Bartalini et al., (2022): PBDE mean concentrations (ng/g* lw) in cetacean liver from around the world. The red line indicates the thresholds for alteration to thyroid levels in seals (1500 ng/g lw). *1 ng/g = 1 mg/kg.

Current Trends

During recent decades, concentrations of many POPs have decreased in the regions they were produced but have increased elsewhere as a consequence of atmospheric transport and redistribution by ocean currents (Aguilar et al., 2002). For example, PBDE concentrations above the toxicity threshold and non-decreasing trends have been related to continuous import of PBDE-containing products, even where PBDEs have never been produced (Bartalini et al., 2022). Non-decreasing levels of PBDEs documented in cetaceans from the Northwest Pacific Ocean have been linked to the increased e-waste import and ongoing production and use of deca-BDE that is still allowed in China (Bartalini et al., 2022). It is expected that the Arctic and Antarctic will become major sinks for chemical pollutants in the future (Aguilar et al., 2002; Sonne et al., 2021). Despite the EU ban on the use and manufacture of PCBs, blubber concentrations are still very high. It has been suggested that concentrations may have reached a "steady state" between environmental input and degradation (Jepson et al., 2016). In comparison to other POPs, the trend for PCBs has declined slowly despite legislation to control their production and disposal coming into force at a similar time to other POPs. The slower rate of decline may be a result of higher initial levels of contamination, greater persistence of PCBs and the continued release of PCBs into the marine environment via diffuse inputs. For example, despite findings that levels in UK harbour porpoise are declining, Williams et al., (2020b) observed a slower rate of decline in harbour porpoise when compared with trends in fish in the UK. There are also distinct geographical differences in the trends and overall levels, for example it was found that levels in West England and Wales are experiencing a slower decline than the rest of the UK (Williams et al., 2020b).

Emerging Pollutants

Many chemicals have not yet been identified, or even synthesised, and so are only just beginning to become present in the environment. These recently emerged and emerging chemicals are of significant concern due to their potentially catastrophic impacts. Reported emerging chemicals include PBDEs, PFAS, BFRs and polychlorinated naphthalenes (PCNs) (Andvik et al., 2023; Bartalini et al., 2022; Dam et al., 2011). These emerging contaminants often encompass large groups of related chemicals. For example, PFOS, PFOA and PFHxS are all classified as PFAS and have recently been included under the Stockholm Convention (Lee et al., 2022), however there are thousands of PFAS chemicals (Salvatore et al., 2022). As there are many different classes of PFAS, there are also wide-ranging applications from non-stick pans to commercial aircraft. Chemical properties include high durability, such as oil, temperature and fire resistance.

In many cases, emerging pollutants have been used as substitutions in response to bans of harmful legacy POPs, however there is often an absence of data regarding the behaviour of these replacement chemicals (Andvik et al., 2023; Lippold et al., 2022). Many replacement chemicals have since become classed as POPs themselves, for example emerging BFRs have been described as "regrettable substitutions" for PBDEs (Lippold et al., 2022). Whilst emerging chemicals have been detected in the marine environment, as well as in air, freshwater, soils, sediments, and in rain at levels that would be considered unsafe in drinking water in some countries, many are not well understood and consequently are not well regulated (Lee et al., 2022). Whilst these chemicals have received limited attention to date, it has been shown that they could be equally or more harmful than some more studied pollutants such as PCBs (Bartalini et al., 2022).

Emerging contaminants of concern have already been identified in the Arctic (Andvik et al., 2023). The presence of chemicals such as PFAS in Arctic wildlife is of concern due to this group's known toxicity following epidemiological studies. PFAS exposure, in particular PFOS and PFOA, cause disruption of the thyroid and sex hormones, liver toxicity, reduced postnatal growth and behavioural effects as well as being known carcinogens (Villanger et al., 2020; Sciancalepore et al., 2019).

Whilst levels of legacy POPs appear to have had a generally decreasing trend since 1992, the levels of PFAS compounds are reported as higher in comparison to 2011 levels (Andvik et al., 2023). The majority of research regarding new and emerging chemicals focuses upon their presence and concentrations in the environment. A ministerial level collaborative study by Dam et al., (2011), described as the Nordic project, reports the occurrence of emerging contaminants from Nordic Arctic waters and North-East Atlantic areas over a period of three decades. As an example, the highest concentrations of total PBDEs were found in toothed whales and BDE-47 was the most abundant congener accounting for 30–75% of the total burden across the different marine mammals studied (Dam et al., 2011). Another recent study identified four emerging BFRs, including hexabromobenzene (HBB) and pentabromotoluene (PBT) in the blubber, liver and muscle of adult common minke whales from the Barents Sea (Andvik et al., 2023). Nine PFAS compounds were also identified, and these were all at higher concentrations than those measured in a study of the same population in 2011. Recent research has also identified that PFAS are widespread in bottlenose dolphins along the North Adriatic Sea (Sciancalepore et al., 2019). PFAS were measured in liver tissue samples of stranded bottlenose dolphins (2008 and 2020). It was reported that the same five dominant PFAS were measured in all samples (PFOS > PFUnA > PFDA ≈ PFDoA ≈ PFTrDA) (Sciancalepore et al., 2019).

Impacts

Reproduction

Reproductive failure in marine mammals has been associated with exposure to POPs and heavy metals, such as mercury. Effects have been reported to occur at many stages of the reproductive cycle such as implantation failure, foetal death and increased first-born calf mortality (Murphy et al., 2015). Severe reproductive dysfunction through the development of cysts, cancer and hermaphroditism has been documented in Mediterranean striped dolphins and St Lawrence Estuary (SLE) beluga whales. These health effects have all been associated with high levels of exposure to POPs, specifically organochlorines such as PCBs and DDT (Murphy et al., 2015). Studies have focussed in particular on PCBs which have been associated with population declines in multiple species (Williams et al., 2021; Hall et al., 2017). High levels of CYP1A1 gene expression, an indicator of PCB exposure, in samples from live false killer whales found that 84% of individuals biopsied exceeded the suggested 14.8 mg/kg (lw) threshold for risk of maternal failure (Kratofil et al., 2020). In mammals, exposure to organochlorines just before birth has been reported to have a number of effects, including foetal malformations and mortality, low weight of newborns, diseases of the skin, skeleton, thyroid, and adrenals, behavioural alterations, immunity problems and decreased reproductive performance (Aguilar & Borrell, 1994b). It is well understood that POPs are transferred to offspring in cetaceans via placental transfer during gestation and lactation after birth. When nearing birth, the placental membranes decrease in thickness while the flow rate of the umbilical circulation increases (Aguilar & Borrell, 1994a). As a result, chemicals (particularly organochlorines) readily cross the placenta to the foetus. The composition of foetal tissues varies through gestation. For example, levels of lipids, for which organochlorines have a particular affinity, tend to increase near birth which enables the further retention of pollutants. Late prenatal and early postnatal exposure to chemicals is thought to represent the greatest hazard to physiological development, such as the endocrine and immune systems, compared to higher chemical exposures in later life (Williams et al., 2021; Aguilar & Borrell, 1994a).

UK-stranded female harbour porpoises (1990-2012) have been studied for both their reproductive status and health as well as PCB burden in the blubber. According to Murphy et al., (2015) almost 20% of sexually mature females showed direct evidence of reproductive failure (foetal death, abortion, difficult births or stillbirth). A further 16.5% had infections or tumours of the reproductive tract which could contribute to reproductive failure.

The highest mean values for PCBs (18.5 mg/kg) were reported in non-lactating or non-pregnant mature females followed by sexually immature (14.03 mg/kg), lactating (7.49 mg/kg) and pregnant (6 mg/kg) individuals. The total PCB burden (based on 25 congeners) was found to be a significant predictor of female reproductive status. Non-pregnant females were more likely to have a higher PCB burden. At least 48% of these mature females had not, at any point, offloaded their pollutant burden via gestation or lactation. In some cases, these females were previously pregnant, which suggests foetal or newborn mortality (Murphy et al., 2015). A recent study by Williams et al., (2021) investigated PCB exposure impacts on male fertility. Blubber tissue samples of UK-stranded harbour porpoises (1991-2017) indicated that PCB exposure is associated with reduced testes' weight in adult males with otherwise good body condition. Testes' weight is a strong indicator of fertility in breeding mammals as reduced testes weight can reduce the chance of successful reproduction, which would have impacts on the fitness of the entire population. These otherwise healthy individuals would typically be those that are most likely to reproduce in the population. Exposure to PCBs may cause individuals that could have successfully reproduced to be outcompeted which would reduce genetic diversity in the population (Williams et al., 2021).

A risk analysis for bottlenose dolphin populations off North Carolina, Florida and Texas (USA) indicated a high likelihood that reproductive success, primarily in females reproducing for the first time, is being severely impaired by chronic exposure to PCBs (Schwacke et al., 2002). Increased risk of reproductive failure (stillbirth or neonatal mortality) was estimated as 60% to 79% depending on the geographical area studied. Females which had previously off-loaded a majority of their PCB burden, exhibited a much lower risk. Schwacke et al. (2002) speculated that some females were experiencing a delay in their first successful reproductive event as a result of their high PCB body load, which will effectively increase the average age of the female at first birth. Raising the age of first birth will likely impact the future growth potential or even stability of the population.

Case Study: St Lawrence Beluga Whales

The effects of anthropogenic pollutants have been studied extensively over an extended period on a population of beluga whales resident in the St Lawrence River Estuary (SLE), Canada (see for example Bowles, 1999; Martineau et al., 1994). These whales have been exposed for many decades to industrial pollutants, including POPs, PAHs and heavy metals. Elevated concentrations of POPs and emerging halogenated flame retardants (HFRs) have been reported in individuals throughout the population (Simond et al., 2019). Compared to Arctic beluga whales, they have higher or much higher levels of mercury, lead, PCBs, DDTs, benzo(α)pyrene (B(α)P), equivalent levels of dioxins, furans and PAHs and lower levels of cadmium (Bowles, 1999; Beland et al., 1993). The population has a high incidence of lesions in the mammary glands (45% of adult females) and other glands (11%). No such lesions were observed in necropsies of Arctic belugas (Beland et al., 1993). Since the early 2000s, the population has been declining at a rate of approximately 1% per year (Simond et al., 2019) and the population's reproductive rate is half that found in other beluga populations (Bowles, 1999).

Concentrations of organochlorines and hexabromobenzene (HBB) were positively correlated with the transcription of thyroid and/or steroid related genes, while PCB concentrations were negatively associated with the transcription of glucocorticoid genes (Simond et al., 2019). This suggests that several biological functions including reproduction and energetic metabolism may represent potential targets for organohalogens in these whales. Female reproductive activity and success is low and there has been an increase of mortality related to dystocia (difficult labour) and postpartum complications have been reported over the last decade (Simond et al., 2019; Beland et al., 1993). Simond et al. (2019) suggests that female exposure early in life to elevated concentrations of endocrine disruptors (chemicals altering the activity or production of hormones) such as PBDEs, may lead to problems giving birth when mature. This hypothesis was based on studies showing that a number of the POPs reported in SLE beluga cause adverse developmental, neurological, reproductive and immune abnormalities in other mammals.

Although concentrations of PCBs and DDTs declined in SLE beluga blubber between 1987 and 2007, these chemicals are still at concerning levels. Increases in other emerging toxic chemicals such as HFRs and PBDEs have also been documented in their blubber (Simond et al., 2019). Exposure to toxic chemicals from the Great Lakes and St Lawrence basin have a significant impact on the life history parameters for individuals and the population as a whole (Bowles, 1999; Beland et al., 1993).

Immunosuppression

Our understanding of the adverse effects of POPs, particularly PCBs, on the immune system are well-established and are of particular concern for marine mammals (Hall et al., 2017). A number of disease epidemics have led to large-scale mortalities in marine mammal populations. It has been hypothesised that chemical pollution could be worsening the impact of natural infections by suppressing immune function and decreasing resistance in cetaceans (Hall et al., 2017). Studies on the immune system of cetaceans have focused on endpoints of both innate and adaptive immunity, such as cellular and antibody-mediated immunity, production of cytokines (proteins important in cell signalling), study of cetacean lymphoid cells, morphology of lymphoid organs and the immunotoxic effects of chemical contaminants (Marsili et al., 2019).

A correlation between PCB contamination and infectious disease mortality was identified in harbour porpoise around Germany, UK, Belgium, and France which exhibit a higher incidence of infectious diseases compared to animals from less contaminated Arctic water (Beineke et al., 2005). Thymic atrophy (shrinking of the thymus) and splenic depletion were significantly correlated to increased PCB and PBDE levels. Lymphoid depletion was also associated with starvation and impaired health status. This suggests contaminant-induced immunosuppression may be contributing to disease susceptibility in these harbour porpoises (Beineke et al., 2005). A contaminant-induced effect on the pulmonary or systemic immune system is also suspected to contribute to pneumonia in these porpoises (Beineke et al., 2005).

Symptoms such as shrinking of the thymus were predominantly found in juvenile animals (<3 years), suggesting that organochlorines may be of a greater immunotoxic threat to neonates and juveniles (Beineke et al., 2005). Another study of UK harbour porpoise investigated the relationship between PCB exposure and infectious disease mortality by comparing blubber concentrations between individuals that died of physical trauma (e.g., bycatch) and those which died of infectious disease (Jepson et al., 2005). Those that died from infectious disease had significantly higher PCB concentrations (mean 27.6 mg/kg lw) than those that died from physical trauma (mean 13.6 mg/kg lw). These findings were independent of age, sex, nutritional status, season, region or year. These findings support the evidence for an immunotoxic relationship between PCB exposure and infectious disease mortality (Jepson et al., 2005).

PCB concentrations in the blubber of bottlenose dolphins are among some of the highest concentrations reported in wildlife globally. For example, free-ranging dolphins along the southern coast of Georgia (USA) had concentrations up to 2900 mg/kg lipid in their blubber (Hall et al., 2017). Health evaluations among captured and released dolphins in this region found that thyroid hormone levels and T-lymphocyte (cells associated with the immune system) proliferation were negatively correlated with increased blubber PCB concentrations. Concentrations of 400 mg/kg lipid have been reported in blubber samples from orcas in Japanese waters, > 250 mg/kg lipid were also reported in the blubber of transient male orcas from British Columbia and transient females from British Columbia had mean levels exceeding 50 mg/kg lipid (Hall et al., 2017). All of these concentrations significantly exceed the higher proposed PCB toxicity threshold for effects upon immunity in cetaceans.

POPs are known to produce various types of liver lesions in mammals. For example, when dolphins chronically exposed to high levels of PCBs face a lack of food and mobilise fat, PCBs move into the bloodstream, reach the liver and can produce hepatic lesions (Aguilar & Borrell, 1994b). Damage to the liver would make it more challenging for an individual to overcome disease or infection. Since 1987, large-scale mortalities of dolphins have been reported along the Atlantic coast of North America, in the Gulf of Mexico, and in the Mediterranean Sea. Bottlenose dolphins which were studied from a large-scale mortality event along the Atlantic coast between 1987-1988 exhibited infections indicative of immune dysfunction (Lahvis et al., 1995). These individuals had high levels of organochlorines, such as PCBs and DDT. Data indicates that reduced immune response in these bottlenose dolphins was correlated with increasing concentrations of several chemical pollutants in the blood (Lahvis et al., 1995). PCB-induced suppression of the immune system is suspected to play a role in the morbillivirus epizootics in pinniped and cetacean species worldwide as it leaves cetaceans susceptible to opportunistic infection (Beineke et al., 2005; Lahvis et al., 1995).

PBDEs are an emerging contaminant which has also been associated with immunotoxicity in wildlife, however the effects of PBDEs and their mechanism of immunotoxicity in cetaceans is largely unknown. One recent study on Pantropical spotted dolphin fibroblast cells investigated the immune stimulation effects of PBDEs in vitro (Huang et al., 2020). This study found there was a continuous stimulation of anti-inflammatory cytokines following exposure to PBDEs. Pro-inflammatory cytokines are proteins only secreted following immune stress. Another recent study using fibroblast cells treated cultures with a mixture of organochlorines, flame retardants, PAHs and mercury found a similar response (Marsili et al., 2019). This study collected samples from free-ranging and stranded odontocetes and mysticetes. Most treatments resulted in an increase in the number and activity of proteins which are induced by stress and a modification of the immune system's response (Marsili et al., 2019). High levels of CYP1A1 expression, a biomarker of POP exposure, in samples from live false killer whales found that 71% of individuals exceeded the 17 mg/kg (lw) threshold for thyroid and immune system disruption in marine mammals (Kratofil et al., 2020). Associations have also been found between the concentration of emerging pollutant group PFAS in bottlenose dolphin blood plasma and decreased immune function (Fair et al., 2013).

Case Study: Mediterranean Striped Dolphins

As first described by Aguilar and Borrell (1994b), during 1990 and 1991 an epizootic occurred in the striped dolphin population of the Mediterranean Sea, a known chemical pollution hotspot (Marsili et al., 2018). This morbillivirus infection, a virus capable of producing major epizootics in marine mammal populations, produced fatal lesions in the lungs, nervous system and lymph nodes which were found to be the primary cause of death in the dolphins affected by the epizootic. In the striped dolphins examined during the 1990 outbreak, a number of unusual conditions were observed. For example, the load of external parasites in these dolphins was abnormally high when compared to individuals of the same species and region stranded in previous years. Many individuals also presented a lesion of uncertain origin in the liver which was not caused by the action of the morbillivirus (Aguilar & Borrell, 1994b). PCB levels were found to be significantly higher in the individuals that succumbed to the epizootic than in the healthy population sampled before and after the event.

Although a link appears to exist between epizootic mortality and elevated blubber PCB concentrations, it is not clear which of the two factors is the cause or effect of the other. Aguilar and Borrell (1994b) suggest three hypotheses to explain this link between high PCB levels and mortality caused by epizootics.

Suppression of the immune system caused by PCBs leads to an increase in individual susceptibility to the morbillivirus infection.

Mobilisation of fat reserves in response to stress leads to increased PCB levels in the blood which, in turn, produces liver lesion capable of increasing susceptibility to the morbillivirus infection.

Previous existence of a liver lesion impairs liver function which, in turn, leads to an increase in tissue PCB concentrations and to the morbillivirus infection.

Irrespective of its origin, impairment of the liver function would lead to reduced capacity to degrade and metabolise PCBs and consequently may result in an increased body load of these chemical pollutants.

Cancers, Hormones and other Abnormalities

Cancer rates are typically low in cetaceans (0.7 - 2.0 %), however the population of SLE beluga whales have been described as the "one notable exception" (Poirier et al., 2021). Pathological abnormalities such as bladder cancer, severe lesions and tumours have been reported in the population (Bowles, 1999). There is a high prevalence of tumours (40%) and high incidence of lesions in the digestive system (53%). No such lesions were observed in analysis of Arctic beluga tissue (Beland et al., 1993). Twenty-four neoplasms (abnormal growth of tissue associated with cancer) were found in 18 of the 45 individuals analysed (Bowles, 1999). The population has a high level of bacterial infections, pneumonia and tooth loss and 2% of individuals have spinal deformities (Bowles, 1999). The levels of B(α)P adducts in DNA in the beluga brain and liver are approaching levels which have also been associated with development of cancer in experiments on laboratory mammals (Beland et al., 1993). Correlations have been found in this population between long-term PAH exposure, PAH-DNA adducts (a measure of cancer risk) in cells of the small intestine and a high rate (7%) of gastrointestinal cancers (Poirier, 2021).

The northern Gulf of Mexico has a long history of PAH contamination as a result of anthropogenic activity, natural oil seepage and the 2010 Deepwater Horizon oil spill. The continental shelf edge of the same area is also a breeding ground for sperm whales. Poirier et al. (2021) identified significantly higher PAH-DNA adducts in the Gulf of Mexico sperm whales compared to sperm whales from the Pacific Ocean. The burden of PAH-DNA damage in Gulf of Mexico sperm whale skin suggests that these whales have an increased cancer risk.

Endocrine disruption has been increasingly associated with population decline and slow population recovery in cetaceans (Guo et al., 2023). Currently, bisphenol S (BPS), bisphenol F (BPF), bisphenol B (BPB), bisphenol P (BPP) and bisphenol AF (BPAF) are widely used to produce BPA-free products, which have driven a change in bisphenol profiles found in the environment. The hormone disruption of BPA and its alternatives was examined in Indo-Pacific finless porpoise by analysing five blubber hormones (Guo et al., 2023). Three of these hormones were significantly and positively correlated with BPA and its alternatives, suggesting that the risk of disruption to endocrine hormone homeostasis[1] may continue to occur despite shifts to BPA alternatives (Guo et al., 2023). BPA and its alternatives were detected in the liver of finless porpoise, sperm whales, short-finned pilot whale, minke whale, fin whale, dwarf sperm whale, Fraser's dolphin and striped dolphin from the South China Sea (Guo et al., 2023).

In Georgia (SE USA) health studies of bottlenose dolphins with ranges near a heavily contaminated coastline found that 26% of dolphins suffered from anaemia (Schwacke et al., 2012). The study also identified cases of reduced erythropoiesis (production of red blood cells) and microcytic anaemia (abnormally small red blood cells) with associated iron deficiency. Iron deficiency is often associated with hypothyroidism which can produce a variety of adverse health effects as thyroid hormones play a critical role in metabolism and growth. In general, iron levels decreased with higher blubber PCB concentrations (Schwacke et al., 2012). Interestingly, the dolphins studied off the coast of Georgia were smaller than expected based on measurements of dolphins from other areas (Schwacke et al., 2012). The effect of PBDE exposure has been examined at the cellular level in pantropical spotted dolphin skin cells (Rajput et al., 2021). A recent study demonstrated that certain PBDE congeners play a role in the dysregulation of oxidative stress and alteration of mitochondrial and cell membrane structure and activity in the cells (Rajput et al., 2021).

1 Any self-regulating process by which biological systems tend to maintain stability while adjusting to conditions that are optimal for survival.

Impairment of energy controlling organelles and cellular response could lead to cell death. Hence, an accumulation of PBDEs in dolphin tissue may cause adverse health effects due to local damage to the organs and tissues (Rajput et al., 2021).

Studies to ascertain the effects of metal concentrations in cetaceans are rare, although in certain non-cetacean species, mercury poisoning has resulted in serious disorders in the liver, kidney and brain, and methylmercury poisoning causes behavioural defects, loss of coordination and loss of vision (Bowles, 1999). In marine mammal species, high liver and renal mercury concentrations have caused failure in both organs. Bowles (1999) suggested that there may be a causal link between dolphin strandings and high mercury concentrations in the blubber. A recent review by Delgado-Suarez et al. (2023) collated data regarding metal concentrations in cetaceans worldwide. It was observed that very few studies consider the effects of the metallic concentrations reported, instead focussing upon concentrations in tissue. In addition to the effects commonly associated with PCBs such as immune system dysfunction, neoplasms, skin lesions and reproductive failure, specific metals were reported to have the following adverse effects; 1) High levels of copper can restrict regulation of potassium and osmotic balance in cells, 2) Mercury affects the nervous and endocrine system which leads to dysfunction in orientation, prey location and communication, 3) Lead leads to unusual behaviours which impair survival, growth and metabolism. Even at low concentrations, trace metals prevent the normal functioning of the central nervous system in marine mammals (Delgado-Suarez et al., 2023).

Recommendations

Although the Stockholm Convention provides a global framework to address chemical pollution there appears to be a systemic shortfall by many parties (member states which have committed to the targets) of the Convention to provide the necessary prioritisation and resources to this issue (Stuart-Smith & Jepson, 2017). For example, the lack of decreasing trends in PBDE concentrations along with reported changes in their congener profiles underpin the need to regularly re-evaluate the efficacy of current regulations and to improve waste management, both in developed and developing countries (Bartalini et al., 2022). The very high and stable concentrations of many PCBs in European wildlife today also indicates that current initiatives to eliminate contaminants are insufficient (Stuart-Smith & Jepson, 2017). Several countries have not yet ratified certain amendments of the Stockholm Convention and in many cases lack national regulations for production, use and disposal. For example, in the United States only 13 states have applied limitations on the use of PBDEs in certain goods (Bartalini et al., 2022). Many countries also use containment as an alternative to destruction of POP wastes (Stuart-Smith & Jepson, 2017). To reduce the risk of chemicals entering the environment it is important that elimination efforts are increased and a more precautionary approach to waste management is adopted. Efforts should also be made to improve education and awareness among the public. There could be incentives through subsidy schemes for elimination of contaminants and tax incentives for industries that participate in training and education on the identification, collection and disposal of contaminated equipment and materials, which are widespread in everyday domestic and industrial settings (Stuart-Smith & Jepson, 2017). For example, the use of PCBs was discontinued from the 1970s but unlike DDTs, which were readily substituted by a new generation of agricultural pesticides, PCBs had no immediate replacement. As a result, enforcement of the ban was poor and toxic compounds have remained in use in many applications (Aguilar et al., 2002).

Environmental groups have called on Defra to restrict the production and use of all emerging PFAS chemicals as a group under UK REACH by 2025. Environmental authorities from Denmark, Germany, the Netherlands, Norway and Sweden have already restricted their manufacture and use (Pickstone, 2023). In the UK, a report on PFAS regulation was due to be published in 2022 but has been delayed (Pickstone, 2023).

A recent report published by the International Chemical Secretariat (ChemSec) has identified that few companies have made significant improvements to their chemical management strategies as, for example, just four of the 54 chemical companies assessed have a public strategy to phase out PFAS (ChemSec, 2022).

At present rates, many countries including some European countries, will not achieve the 2025 and 2028 targets of the Stockholm Convention.

To encourage global efforts towards eliminating the threat from POPs, an enforceable compliance mechanism needs to be established, along with support for developing countries (Stuart-Smith & Jepson, 2017). At present rates, many countries including some European countries, will not achieve the 2025 and 2028 targets of the Stockholm Convention (Stuart-Smith & Jepson, 2017). Although there have been active efforts to reduce some applications of PCBs, such as transformers and capacitors, there is a growing risk from diffuse sources of PCBs, such as solvents and sealants, which is often overlooked in implementation efforts. For example, in Norway abrasive blasting of a painted concrete bridge released approximately 1600 kg of PCBs and increased contamination in the local environment (Jartun et al., 2009). PCB mitigation measures include the safe disposal or destruction of PCB-containing equipment, limiting the dredging of PCB-contaminated rivers and estuaries, reducing PCB leakage from old landfills and regulating demolition of PCB-containing buildings (Jepson & Law, 2016). There is also a significant risk posed by accumulating PCB contaminated equipment and materials in specific locations such as destruction facilities, therefore these must have sufficient capacity and capability to prevent collection depots from effectively becoming storage facilities. European member states have suggested that their lack of success in eliminating POPs are due to lack of resources such as destruction facilities and the European and global financial crises (Stuart-Smith & Jepson, 2017). Addressing PCB pollution remains a global concern for both developing and developed countries. Additional capacity building and support to developing countries has also been identified as essential in the achievement of the 2025 and 2028 targets (Weber et al., 2013).

The assessment of levels of chemical exposure is a significant factor in the long-term conservation of marine mammal populations (Aguilar et al., 2002). To date, much of the research has focused on exposure of marine mammals to POPs rather than the risk assessment approaches that are needed to determine the impacts of the exposure (Schwacke et al., 2002). Consequently, there is an urgent need for new non-invasive tests that use easily sampled tissues such as skin, which can be applied to all free-ranging cetacean species (Marsili et al., 2019). However, priority should also be given to the many thousands of samples from marine mammals/cetaceans collected by strandings schemes around Europe that remain unanalysed, largely due to budgetary constraints. These samples would likely have biological data/wider ancillary data that would provide more power to analyses than e.g., skin/biopsy samples from free ranging cetaceans.

A major limiting factor in the risk assessment of POPs on cetaceans is the lack of species-specific toxicity thresholds which can be used to assess potential health risks (Bartalini et al., 2022). Whilst it is essential that levels are below these toxicity thresholds, there are limitations to relying on this approach, particularly in the case of cetaceans (Williams et al., 2020b). are limitations to relying on this approach, particularly in the case of cetaceans (Williams et al., 2020b). Most studies use single chemical-based thresholds which do not represent real world exposure where a complex mixture of known and unknown natural and anthropogenic substances will occur. The risk from exposure to a mixture of chemicals typically exceeds that of each individual chemical on its own (European Commission, 2020). This means that exposure to a combination of chemicals can give rise to adverse health effects at levels otherwise considered ‘safe' for the individual chemical. For example, a recent study used the mixture of chemicals present in orca blubber and observed the response of cetacean immune cells to this mixture (Desforges et al., 2017). They found there was a lower effect level for complex mixtures. The current thresholds for toxic effects of pollutants such as PCBs are also derived from toxicological data on other species, such as mink, seals, and otters (Williams et al., 2020b; Jepson et al., 2005). Risk assessment of combined effects represents a particular challenge.

There is an urgent need for toxicological studies to focus on calculating species, age and tissue-specific thresholds for a greater variety of POPs, including mixtures (Bartalini et al., 2022). In the case of POPs with well-established toxicity thresholds, such as total PCBs, it has been suggested that they should be used to assess whether marine populations reach favourable conservation status under the Habitats Directives in European Policy (Jepson & Law, 2016).

There is a clear need for further research and monitoring to assess global POP emissions and the extent of on-going pollution (Stuart-Smith & Jepson, 2017).

Cetacean species living in urbanised coastal regions require particular attention due to the constant release of POPs in these areas and the subsequent high degree of contamination in their habitats (Bartalini et al., 2022). Future research should also recognise that even if the pollution levels from individual sources are low, the cumulative impact is high. This means that where individual substances are below their respective threshold for harm, combined exposure has been shown to lead to more harmful effects. This phenomenon, particularly in respect to pesticides, has been termed the "cocktail effect" (Soil Association & PAN UK, 2019). Therefore, there is an urgent need for future research to recognise the effect of chemical mixtures.

Data from the southern hemisphere and the Arctic and Antarctic Oceans is also extremely scarce. As these regions have been identified as future major sinks for the most persistent chemicals, particularly PCBs, long-term monitoring is urgently needed (Aguilar et al., 2002; Sonne et al., 2021). Studies on chemicals of emerging concern in Arctic wildlife have been identified as of significant importance in conservation and risk management (Lippold et al., 2022) hence, future research should also aim to identify and study emerging pollutants as well as those already established in the environment. The current state of knowledge calls for increased monitoring of concentrations of emerging chemicals and investigation of biological effects (Villanger et al., 2022). The relationship between climate change and the risk of adverse health effects from POPs must also be recognised in future research and policy making. Environmental variables such as temperature, wind speed, precipitation, and solar radiation influence environmental fate and transport of POPs (Nadal et al., 2015). As climate change will alter these factors to varying degrees, climate change will influence the fate, transport and distribution of semi-volatile organic chemicals. For example, increased temperatures can cause re-volatilisation of POPs stored in glaciers, vegetation and soils, leading to re-emissions of contaminants (Bartalini et al., 2022). Enhanced long-range transport, re-emissions from secondary sources and shifts in migration habits could lead to greater exposure and accumulation in cetaceans, especially species living in the Arctic (Bartalini et al., 2022). In addition, increased rainfall and extreme weather events associated with changing climates could carry a greater amount of contaminants to the marine environment. Changes in meteorological conditions have also been related to shifts in migration habits of some cetaceans (Bartalini et al., 2022).

Summary of Recommendations

Regulation

- Regularly re-evaluate the efficacy of current regulations and improve waste management to address chemical pollution.
- Increase elimination efforts and adopt a more precautionary approach to waste management to reduce the risk of chemicals entering the environment.
- Provide incentives, such as subsidy schemes and tax incentives, for the elimination of contaminants and participation in training and education to ensure safe disposal.
- Restrict the production and use of all emerging PFAS chemicals as a group under UK REACH by 2025.
- Establish an enforceable compliance mechanism for eliminating persistent organic pollutants (POPs).
- Provide additional capacity building and support to developing countries to achieve the 2025 and 2028 targets of the Stockholm Convention.
- Recognise and address the relationship between climate change and the risk of adverse health effects from POPs in future research and policy making.
- Improve education and awareness among the public regarding chemical management and disposal; many hazardous chemicals can be purchased and handled by the public and are present in everyday domestic goods and products.
- Put the burden of proof on industry that chemicals have no effects on the environment, to create greater producer responsibility.
- Require chemical companies to have mandatory public strategies to phase out PFAS.
- Implement mitigation measures such as limiting the dredging of PCB-contaminated rivers and estuaries, preventing PCB leakage from old landfills and regulating demolition of PCB-containing buildings and products.
- Include consideration of PCB tissue concentrations in the assessment of favourable conservation status of marine mammal species in European and UK policy.
- Support cross-disciplinary synergistic efforts to integrate chemical monitoring with ecological monitoring to break down silos between different environmental sciences, such as ecotoxicology, environmental chemistry and ecology.

Research and Education

- Make more funding available for analyses of extant and prospective samples from EU/global stranding networks.
- Coordinate and harmonise analyses of tissue samples with the goal to achieve regional/global datasets.
- Encourage or support the development of new non-invasive tests using easily sampled tissues to assess the impacts of POP exposure in cetaceans.
- Conduct toxicological studies to determine species-, age- and tissue-specific toxicity thresholds for a greater variety of POPs, including mixtures.
- Conduct further research and monitoring to assess global POP emissions, the extent of ongoing pollution and the effect of chemical mixtures on biodiversity.
- Increase monitoring of emerging pollutants and their concentrations and investigate their biological effects, particularly in urbanised coastal regions.
- Widely screen for non-targeted chemicals using high resolution mass spectrometry as an early warning system for overlooked contaminants.
- Increase long-term monitoring in the southern hemisphere, Arctic, and Antarctic regions due to their role as major sinks for persistent chemicals, particularly PCBs.
- Further assess the influence of climate change on the fate, transport, and distribution of POPs, and consider potential impacts on cetaceans and marine ecosystems.

Conclusions

Chemical pollution emerges and takes effect insidiously, so that populations deteriorate on a temporal scale that often delays recognition and application of protective measures before severe changes manifest (Rowe, 2008). It is imperative to recognise that impacts at the population levels may emerge very subtly within a human frame of reference. Furthermore, threats to the fitness and population status of long-lived species in much of the world may not have yet occurred (Rowe, 2008). Tanabe (1988) calculated that in the mid-1980s only about 30% of all PCBs produced had dispersed into the environment and by the end of the decade, it was estimated that only 1% of all PCBs produced had reached the oceans. Approximately 30% had accumulated in dump sites and sediment of lakes, coastal zones and estuaries meaning that future re-mobilisation and dispersal of chemicals into oceans reduces the likelihood of future declines in environmental concentrations (Aguilar et al., 2002).

As a result of their physiology, life strategies and global distribution, cetaceans are particularly susceptible to exposure to and bioaccumulation of persistent and toxic chemical pollutants. There is clear and compelling evidence for severe and detrimental impacts upon specific cetacean species and populations globally and in defined geographical areas. It is imperative that the complex, transboundary nature of chemical pollution is recognised as part of a holistic approach to mitigating and eliminating adverse health effects to cetaceans. These effects include depression of the immune system and the subsequent triggering of infectious diseases, reproductive impairment and failure, increased susceptibility to lesions and cancers, and alterations to developing young. Persistent, synthetic contaminants were developed and entered wide use only in the past century, yet this has already resulted in contamination of habitats on a global scale. Synthetic compounds such as organochlorine pesticides, PCBs and brominated flame retardants, such as PBDEs, and PFAS can persist in the environment for decades, providing continual exposure to organisms for all or substantial portions of their lifetimes (Rowe, 2008). The assessment of the levels of POP exposure, their effects and the specific life history parameters of geographically and physiologically different cetacean species are highly significant factors in the management and long-term conservation of marine mammal populations.

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References

Abdel-Shafy, H.I., Mansour, M.S.M., (2016). A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. Egyptian Journal of Petroleum 25, 107–123. https://doi.org/10.1016/j.ejpe.2015.03.011.

Aguilar, A., Borrell, A. (1994a). Reproductive transfer and variation of body load of organochlorine pollutants with age in fin whales (Balaenoptera physalus). Archives of Environmental Contamination and Toxicology. 27: 546–554. doi.org/10.1007/BF00214848.

Aguilar, A., Borrell, A. (1994b). Abnormally high polychlorinated biphenyl levels in striped dolphins (Stenella coeruleoalba) affected by the 1990–1992 Mediterranean epizootic. Science of the Total Environment. 154(2-3): 237- 247. doi: 10.1016/0048-9697(94)90091-4.

Aguilar A., Borrell A., Reijnders P.J. (2002). Geographical and temporal variation in levels of organochlorine contaminants in marine mammals. Marine Environmental Research. 53(5):425-52. doi: 10.1016/s0141-1136(01)00128-3.

Andvik, C., Jourdain, E., Ruus, Lyche, J., Karoliussen, R., Borga, K. (2020). Preying on seals pushes killer whales from Norway above pollution effects thresholds. Science Reports. 10:11888. doi.org/10.1038/s41598-020-68659-y.

Andvik, C., Haug, T., Lyche, J.L., Borgå, K. (2023). Emerging and legacy contaminants in common minke whale from the Barents Sea. Environmental Pollution. 319: 121001. https://doi.org/10.1016/j.envpol.2023.121001.

Aznar-Alemany, Ò., Giménez, J., de Stephanis, R., Eljarrat, E. and Barceló, D. (2017). Insecticide pyrethroids in liver of striped dolphin from the Mediterranean Sea. Environmental Pollution. 225: 346-353. doi: 10.1016/j. envpol.2017.02.060.

Balmer, B.C., Schwacke, L.H., Wells, R.S., George, R.C., Hoguet, J., Kucklick, J.R., Lane, S.M., Martinez, A., McLella,n W.A., Rosel, P.E., Rowles, T.K., Sparks, K., Speakman, T., Zolman, E.S., Pabst, D.A. (2011). Relationship between persistent organic pollutants (POPs) and ranging patterns in common bottlenose dolphins (Tursiops truncatus) from coastal Georgia, USA. Science of the Total Environment. 409(11):2094-101. doi: 10.1016/j.scitotenv.2011.01.052.

Bartalini, A., Muñoz-Arnanz, J., García-Álvarez, N., Fernández, A. (2022). Global PBDE contamination in cetaceans. A critical review. Environmental Pollution. 308(119670). doi.org/10.1016/j.envpol.2022.119670

Baugh, K., Robbins, J., Schultz, I., Ylitalo, G. (2023). Persistent organic pollutants in female humpback whales Megaptera novaeangliae from the Gulf of Maine. Environmental Pollution. 316(1), doi.org/10.1016/j.envpol.2022.120616.

Beineke, A., Siebert, U., McLachlan, M., Bruhn, R., Thron, K., Failing, K., Müller, G., Baumgärtner, W (2005). Investigations of the potential influence of environmental contaminants on the thymus and spleen of harbor porpoises (Phocoena phocoena). Environmental Science & Technology. 39(11): 3933-3938 DOI: 10.1021/es048709j

Beland, P., Michaud, R., DeGuise, S., Girard, C., Lagacé, A., Martineau, D., Muir, D., Norstorm, R., Pelletier, E., Ray, S. (1993). Toxic compounds and health and reproductive effects in St. Lawrence beluga whales. Journal of Great Lakes Research. 19: 766-775. 10.1016/S0380-1330(93)71264-2.

Bowles, D. (1999). An overview of the concentrations and effects of heavy metals in cetacean species. In: P.J.H. Reijnders, A. Aguilar and G.P. Donovan (eds.) Chemical Pollutants and Cetaceans. Journal of Cetacean Research and Management, Special Issue 1. International Whaling Commission. pp. 125-148.

Brownlow, A., Davison, N. and ten Doeschate, M. (2016). Annual Report, 1 January - 31 December 2016. Scottish Marine Animal Stranding Scheme. A report to Marine Scotland. http://uk601.directrouter.co.uk/~oxcuojji/wp-content/uploads/2021/05/SMASS_Annual_Report_2016.pdf

ChemSec. (2022). ChemScore 2022: Key Findings. International Chemical Secretariat. Available at: https://chemsec.org/publication/chemicals-business,chemscore,investors/chemscore-2022-key-findings/ [Accessed 12 April 2023].

Coulter, B. (2022). Polychlorinated organic contaminants in baleen from North Pacific Ocean whales. Master's thesis. Nova Southeastern University. Available here: https://nsuworks.nova.edu/hcas_etd_all/93.

Cullon, D.L., Yunker, M.B., Alleyne, C., Dangerfield, N.J., O'Neill, S., Whiticar, M.J., Ross, P.S., (2009). Persistent organic pollutants in chinook salmon (Oncorhynchus tshawytscha): implications for resident killer whales of British Columbia and adjacent waters. Environmental Toxicology and Chemistry. 28(1):148-61. doi: 10.1897/08-125.1.

Dam, M., Van Bavel, B., Rigét, F., Rotander, A., Polder, A., Auðunsson, G.A., Bloch, D., Víkingsson, G.A., Mikkelsen, B., Gabrielsen, G.W., Sagerup, K. (2011). “New” POPs in marine mammals in Nordic Arctic and NE Atlantic areas during three decades. Nordic Council of Ministers, Copenhagen. https://doi.org/10.6027/tn2011-564

DEFRA (2018). A Green Future: Our 25 Year Plan to Improve the Environment. GOV.UK. Available at: https://www.gov.uk/government/publications/25-year-environment-plan [Accessed 1 April 2023].

Delgado-Suarez, I., Lozano-Bilbao, E., Hardisson, A., Paz, S., Gutiérrez, Á., (2023). Metal and trace element concentrations in cetaceans worldwide: A review, Marine Pollution Bulletin, 192:115010. https://doi.org/10.1016/j.marpolbul.2023.115010.

Desforges, J.-P., Ross, P.S., Dangerfield, N., Palace, V.P., Whiticar, M., and Loseto, L.L. (2013). Vitamin A and E profiles as biomarkers of PCB exposure in beluga whales (Delphinapterus leucas) from the western Canadian Arctic. Aquatic Toxicology. 142: 317–328.

Desforges, J.-P.W., Sonne, C., Levin, M., Siebert, U., De Guise, S., Dietz, R., (2016). Immunotoxic effects of environmental pollutants in marine mammals. Environment International. 86: 126–139. https://doi.org/10.1016/j.envint.2015.10.007.

Desforges, J., Levin, M., Jasperse, L., De Guise, S., Eulaers, I., Letcher, R., Acquarone, M., Nordøy, E., Folkow, L., Jensen, H., Grøndahl, C., Bertelsen, M., Leger, J., Almunia, J., Sonne, C., and Dietz, R. (2017). Effects of polar bear and killer whale derived contaminant cocktails on marine mammal immunity. Environmental Science & Technology. 51(19): 11431-11439. doi: 10.1021/acs.est.7b03532

Desforges, J.-P., Hall, A., McConnell, B., Rosing-Asvid, A., Barber, J.L., Brownlow, A., De Guise, S., Eulaers, I., Jepson, P.D., Letcher, R.J., Levin, M., Ross, P.S., Samarra, F., Víkingson, G., Sonne, C., Dietz., R. (2018). Predicting global killer whale population collapse from PCB pollution. Science. 361(6409): 1373-1376. doi: 10.1126/science.aat1953.

de Swart, R., Ross, P., Vedder, L., Timmerman, H., Heisterkamp, S., van Loveren, H., Vos, J., Reijnders, P.J.H., Osterhaus, A. (1994). Impairment of immune function in harbor seals (Phoca vitulina) feeding on fish from polluted waters. Ambio. 23:155 – 159.

EC. (2020). Green Deal: Chemicals Strategy towards a toxic-free environment - Questions and Answers. European Commission. Available at: https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_1840 [Accessed 27 March 2023].

Fair, P.A., Romano, T., Schaefer, A.M., Reif, J.S., Bossart, G.D., Houde, M., Muir, D., Adams, J., Rice, C., Hulsey, T.C., Peden-Adams, M. (2013). Associations between perfluoroalkyl compounds and immune and clinical chemistry parameters in highly exposed bottlenose dolphins (Tursiops truncatus). Environmental Toxicology and Chemistry. 32: 736–746.

García-Álvarez, N., Boada, L.D., Fernández, A., Zumbado, M., Arbelo, M., Sierra, E., Xuriach, A., Almunia, J., Camacho, M. and Luzardo, O.P. (2014). Assessment of the levels of polycyclic aromatic hydrocarbons and organochlorine contaminants in bottlenose dolphins (Tursiops truncatus) from the Eastern Atlantic Ocean. Marine Environmental Research. 100: 48-56. doi: 10.1016/j.marenvres.2014.03.010.

Guo, Y., Shi, W., Liu, Z., Sun, X., Wu, J., Wu., Y (2023). Bisphenol A alternatives continuously contribute to the endocrine disruption in cetaceans. Environment International. 171, doi.org/10.1016/j.envint.2022.107679.

Hall, A.J., Kalantzi, O.I., Thomas, G.O., (2003). Polybrominated diphenyl ethers (PBDEs) in grey seals during their first year of life–are they thyroid hormone endocrine disrupters? Environmental Pollution. 126: 29–37. doi.org/10.1016/S0269-7491(03) 00149-0.

Hall, A.J., McConnell, B.J., Schwacke, L.H., Ylitalo, G.M., Williams, R. and Rowles, T. K. (2017) Predicting the effects of polychlorinated biphenyls on cetacean populations through impacts on immunity and calf survival. Environmental Pollution. 233: 407-418. doi: 10.1016/j.envpol.2017.10.

Helle, E., Olsson, M., Jensen, S. (1976). PCB levels correlated with pathological changes in seal uteri. Ambio. 5: 261–263.

Heuvel-Greve, M.J., van den Brink, A.M., Kotterman, M.J.J., Kwadijk, C.J.A.F., Geelhoed, S.C.V., Murphy, S., van den Broek, J., Heesterbeek, H., Gröne, A., IJsseldijk, L.L. (2021). Polluted porpoises: Generational transfer of organic contaminants in harbour porpoises from the southern North Sea. Science of the Total Environment. 20(796):148936. doi: 10.1016/j.scitotenv.2021.148936.

Huang, Y., Rajput, I., Sanganyado, E., Yajing, S., Yu, F., Liang, B. (2020). Immune stimulation effect of PBDEs via prostaglandin pathway in pantropical spotted dolphin: An in vitro study. Chemosphere. 254: 126717. doi.org/10.1016/j.chemosphere.

Jartun, M., Ottesen, R.T., Steinnes, E., Volden, T. (2009). 'Painted surfaces – Important sources of polychlorinated biphenyls (PCBs) contamination to the urban and marine environment'. Environmental Pollution. 157: 295–302.

Jepson, P.D., Bennett, P.M., Deaville, R., Allchin, C.R., Baker, J.R. and Law, R.J. (2005). Relationships between polychlorinated biphenyls and health status in harbour porpoises (Phocoena phocoena) stranded in the United Kingdom. Environmental Toxicology and Chemistry. 24(1): 238-248. doi: 10.1897/03-663.1.

Jepson, P.D., Law, R.J. (2016). Persistent pollutants, persistent threats. Science. 352(6292): 1388-1389. doi: 10.1126/science.aaf9075.

Jepson, P.D., Deaville, R., Barber, J.L., Aguilar, À., Borrell, A., Murphy, S., Barry, J., Brownlow, A., Barnett, J., Berrow, S., Cunningham, A.A., Davison, N.J., ten Doeschate, M., Esteban, R., Ferreira, M., Foote, A.D., Genov, T., Giménez, J., Loveridge, J., Llavona, Á., Martin, V., Maxwell, D.L., Papachlimitzou, A., Penrose, R., Perkins, M.W., Smith, B., de Stephanis, R., Tregenza, N., Verborgh, P., Fernandez, A. and Law, R.J. (2016). PCB pollution continues to impact populations of orcas and other dolphins in European waters. Scientific Reports. 6:18573. doi: 10.1038/srep18573.

Kannan, K., Blankenship, A., Jones, P., & Giesy, J. (2000). Toxicity reference values for the toxic effects of Polychlorinated Biphenyls to aquatic mammals. Human and Ecological Risk Assessment: An International Journal. 6(1), 181-201, DOI: 10.1080/10807030091124491.

Kershaw, J.L., Hall, A.J. (2019). Mercury in cetaceans: Exposure, bioaccumulation and toxicity. Science of theTotal Environment. 1(694): 133683. doi: 10.1016/j.scitotenv.2019.133683. Epub 2019 Jul 30. PMID: 31394330.

Kratofil, M.A., Ylitalo, G.M., Mahaffy, S.D., West, K.L., Baird, R.W. (2020). Life history and social structure as drivers of persistent organic pollutant levels and stable isotopes in Hawaiian false killer whales (Pseudorca crassidens). Science of the Total Environment. 733: 138880 https://doi.org/10.1016/J.SCITOTENV.2020.138880.

Lahvis, G.P., Wells, R.S., Kuehl, D.W., Stewart, J.L., Rhinehart, H.L., Via, C.S. (1995). Decreased lymphocyte responses in free-ranging bottlenose dolphins (Tursiops truncatus) are associated with increased concentrations of PCBs and DDT in peripheral blood. Environmental Health Perspectives. 103 (Suppl 4): 67-72. doi: 10.1289/ehp.95103s467.

Lee, K., José Alava, J., Cottrell, P., Cottrell, L., Grace, R., Zysk, I., Raverty, S. (2023).
Emerging contaminants and new POPs (PFAS and HBCDD) in endangered southern resident and Bigg's (Transient) killer whales (Orcinus orca): In utero maternal transfer and pollution management implications. Environmental Science & Technology. 57(1): 360-374, DOI: 10.1021/acs.est.2c04126.

Lippold, A., Harju, M., Aars, J., Blévin, P., Bytingsvik, J., Gabrielsen, G.W., Kovacs, K.M., Lyche, J.L., Lydersen, C., Rikardsen, A.H., Routti, H. (2022), Occurrence of emerging brominated flame retardants and organophosphate esters in marine wildlife from the Norwegian Arctic. Environmental Pollution. 15(315): 120395. doi: 10.1016/j.envpol.2022.120395.

Madgett, A., Yates, K., Webster, L., McKenzie, C., Brownlow, A. (2022). The concentration and biomagnification of PCBs and PBDEs across four trophic levels in a marine food web. Environmental Pollution. 309:119752. doi.org/10.1016/j.envpol.2022.119752.

Marsili, L., Jiménez, B. and Borrell, A. (2018). Persistent organic pollutants in cetaceans living in a hotspot area: the Mediterranean Sea. In: M.C. Fossi and C. Panti (eds.). Marine Mammal Ecotoxicology: Impacts of Multiple Stressors on Population Health. Academic Press. pp.185-212. doi: 10.1016/C2016-0-03201-1.

Marsili, L., Di Guardo, G., Mazzariol, S., Casini, S. (2019). Insights into cetacean immunology: Do ecological and biological factors make the difference? Frontiers in Immunology. 10: 1219. doi: 10.3389/fimmu.2019.01219

Martineau, D., De Guise, S., Fournier, M., Shugart, L., Girard, C., Lagace, A., Beland, P. (1994). Pathology and toxicology of beluga whales from the St Lawrence Estuary, Quebec, Canada – past, present and futures. Science of the Total Environment. 154(2-3): 201 – 215.

Mos, L., Cameron, M., Jeffries, S.J., Koop, B.F., and Ross, P.S. (2010). Risk-based analysis of polychlorinated biphenyl toxicity in harbor seals. Integrated Environmental Assessment and Management. 6: 631–640.

Murphy, S., Barber, J.L., Learmonth, J.A., Read, F.L., Deaville, R., Perkins, M.W., Brownlow, A., Davison, N., Penrose, R., Pierce, G.J., Law, R.J., Jepson, P.D. (2015). Reproductive failure in UK harbour porpoises Phocoena phocoena: Legacy of pollutant exposure? PLoS One. 10: e0131085. https://doi.org/10.1371/journal.pone.0131085.

Nadal, M., Marquès, M., Mari, M., Domingo, J. (2015). Climate change and environmental concentrations of POPs: A review. Environmental Research. 143(A): 177-185. doi.org/10.1016/j.envres.2015.10.012.

OceanCare (2021). Under Pressure: The need to protect whales and dolphins in European waters. An OceanCare report. 146pp. Available here: https://www.oceancare.org/en/stories_and_news/under-pressure-eu/.

Pickstone, S. (2023). 'Forever chemicals': Five member states seek EU-wide PFAS restrictions. ENDS Report. Last Updated: 13 January 2023. Available at: https://www.endsreport.com/article/1810145/forever-chemicals-five-member-states-seek-eu-wide-pfas-re [Accessed 27 March 2023].

Poirier, M. (2021). DNA damage in cetaceans: A mini review. Mutation Research/Genetic Toxicology and Environmental Mutagenesis. 870-871. doi.org/10.1016/j.mrgentox.2021.503392.

Rajput, I., Yaqoob, S., Yajing, S., Sanganyado, E., Wenhua, L. (2021). Polybrominated diphenyl ethers exert genotoxic effects in pantropic spotted dolphin fibroblast cell lines. Environmental Pollution. 271:116131. doi.org/10.1016/j.envpol.2020.116131.

Reijnders, P.J.H. (1988). Ecotoxicological perspectives in marine mammalogy: research principles and goals for a conservation policy. Marine Mammal Science. 4: 91 – 102.

Rowe, C. (2008). "The calamity of so long life": Life histories, contaminants, and potential emerging threats to long-lived vertebrates. BioScience. 58(7): 623–631. doi.org/10.1641/B580709.

Salvatore, D., Mok, K., Garrett, K.K., Poudrier, G., Brown, P., Birnbaum, L.S., Goldenman, G., Miller, M.F., Patton, S., Poehlein, M., Varshavsky, J., Cordner, A. (2022). Presumptive contamination: A new approach to PFAS contamination based on likely sources. Environmental Science and Technology Letters. 9: 983–990. https://doi.org/10.1021/acs.estlett.2c00502.

Sciancalepore, G., Pietroluongo, G., Centelleghe, C., Milan, M., Bonato, M., Corazzola, G., Mazzariol, S. (2021). Evaluation of per- and poly-fluorinated alkyl substances (PFAS) in livers of bottlenose dolphins (Tursiops truncatus) found stranded along the northern Adriatic Sea. Environmental Pollution. 291: 118186.

Schwacke, L.H., Voit, E.O., Hansen, L.J., Wells, R.S., Mitchum, G.B., Hohn, A.A. and Fair, P.A. (2002). Probabilistic risk assessment of reproductive effects of polychlorinated biphenyls on bottlenose dolphins (Tursiops truncatus) from the Southeast United States coast. Environmental Toxicology and Chemistry. 21(12): 2752-2764. 10.1002/ etc.5620211232.

Schwacke, L.H., Zolman, E.S., Balmer, B.C., De Guise, S., George, R.C., Hoguet, J., Hohn, A.A., Kucklick, J.R., Lamb, S., Levin, M., Litz, J.A., McFee, W.E., Place, N.J., Townsend, F.I., Wells, R.S., Rowles, T.K. (2012). Anaemia, hypothyroidism and immune suppression associated with polychlorinated biphenyl exposure in bottlenose dolphins (Tursiops truncatus). Proceedings of the Royal Society B: Biological Sciences. 279(1726): 48-57. doi: 10.1098/rspb.2011.0665.

Simond, E., Houde, M., Lesage, V., Michaud, R., Zbinden, D. (2019). Associations between organohalogen exposure and thyroid- and steroid-related gene responses in St. Lawrence Estuary belugas and minke whales. Marine Pollution Bulletin. 145: 174-184. doi.org/10.1016/j.marpolbul.2019.05.029.

Soil Association and PAN UK. (2019). The Cocktail Effect. Soil Association. Available at: https://www.soilassociation.org/causes-campaigns/reducing-pesticides/the-pesticide-cocktail-effect/ [Accessed 15 May 2023].

Sonne, C., Dietz, R., Jenssen, B., Lam, S., Letcher, R. (2021). Emerging contaminants and biological effects in Arctic wildlife. Trends in Ecology & Evolution. 36(5): 421-429, https://doi.org/10.1016/j.tree.2021.01.007.

Stuart-Smith, S., Jepson, P. (2017). Persistent threats need persistent counteraction: Responding to PCB pollution in marine mammals. Marine Policy. 84: 69-75, doi.org/10.1016/j.marpol.2017.06.033.
Tanabe, S. (1988). PCB problems in the future: foresight from current knowledge. Environmental Pollution. 50: 5–28.

Tanabe, S., Iwata, H., Tatsukawa, R. (1994). Global contamination by persistent organochlorines and their ecotoxicological impact on marine mammals. Science of the Total Environment. 154(2-3): 163-177. doi: 10.1016/0048- 9697(94)90086-8.

Tornero, V., Hanke, G. (2017). Potential chemical contaminants in the marine environment: An overview of main contaminant lists. ISBN 978-92-79-77045-6, EUR 28925, doi:10.2760/337288.
UNEP (United Nations Environment Programme). (2019). The POPs. Stockholm Convention. Available at: http://chm.pops.int/ [Accessed 5 April 2023].

UNITAR. Basel, Rotterdam, Stockholm Conventions. Available at: https://unitar.org/sustainable-development-goals/planet/our-portfolio/basel-rotterdam-stockholm-conv [Accessed 6 April 2023].

Unuofin, J. (2020). Garbage in garbage out: the contribution of our industrial advancement to wastewater degeneration. Environmental Science and Pollution Research. 27. 10.1007/s11356-020-08944-5.

Villanger, G., Kovacs, K., Lydersen, C., Haug, L., Sabaredzovic, A., Jenssen, B., Routti, H. (2020). Perfluoroalkyl substances (PFASs) in white whales (Delphinapterus leucas) from Svalbard – A comparison of concentrations in plasma sampled 15 years apart. Environmental Pollution. 263(A), https://doi.org/10.1016/j.envpol.2020.114497

Weber, R., Aliyeva, G., Vijen, J. (2013). 'The need for an integrated approach to the global challenge of POPs management'. Environmental Science and Pollution Research. 20: 1901-1906.

Williams, R. S., Curnick, D. J., Barber, J. L., Brownlow, A., Davidson, N. J., Deaville, R., Perkins, M., Jobling, S., Jepson, P. D. (2020a). "Juvenile harbour porpoises in the UK are exposed to a more neurotoxic mixture of polychlorinated biphenyls than adults." Science of The Total Environment. 708: 134835 1, doi.org/10.1016/j.scitotenv.2019.134835.

Williams, R. S., ten Doeschate, M., Curnick, D. J., Brownlow, A., Barber, J. L., Davison, NJ., Deaville, R., Perkins, M. W., Jepson, P. D., & Jobling, S. (2020b). Levels of Polychlorinated Biphenyls are still associated with toxic effects in harbour porpoises (Phocoena phocoena) despite having fallen below proposed toxicity thresholds. Environmental Science & Technology. 54(4): 2277-2286. doi.org/10.1021/acs.est.9b05453.

Williams, R.S., Curnick, D.J., Brownlow, A., Barber, J.L., Barnett, J., Davison, N.J., Deaville, R., Ten Doeschate, M., Perkins, M., Jepson, P.D., Jobling, S. (2021). Polychlorinated biphenyls are associated with reduced testes weights in harbour porpoises (Phocoena phocoena). Environment International. 150:106303. doi: 10.1016/j.envint.2020.106303.

Williams, R.S., Brownlow, A., Baillie, A., Barber, J.L., Barnett, J., Davison, N.J., Deaville, R., ten Doeschate, M., Murphy, S., Penrose, R., Perkins, M., Williams, R., Jepson, P.D., Curnick, D.J., Jobling, S. (in revision). Spatiotemporal trends spanning three decades show toxic levels of chemical contaminants in marine mammals that stranded around the coast of Great Britain.

Glossary

Term	Meaning
25 YEP	25-year plan to improve the environment, is a long-term strategic vision that sets out the UK government's goals and aspirations for environmental protection and sustainable development. The plan was launched in January 2018 by the UK government's Department for Environment, Food and Rural Affairs (Defra). The 25 YEP provides a framework for policy development and implementation across various sectors. It serves as a guiding document to ensure that the UK's actions align with its environmental goals and contribute to a greener, more sustainable future.
BDE-47	A specific congener of polybrominated diphenyl ethers, BDE-47 specifically refers to the compound where two bromine atoms are attached to the biphenyl structure. BDE-47 is one of the more commonly detected PBDE congeners in the environment and is of particular interest due to its persistence, bioaccumulation potential, and potential adverse health effects. It has been found in various environmental compartments, including air, water, soil, sediment, and biota. Exposure to BDE-47 can occur through ingestion, inhalation, or dermal contact. Like other PBDEs, BDE-47 has raised concerns regarding its potential impact on human and wildlife health. Research suggests that exposure to BDE-47 may be associated with developmental, neurological, endocrine-disrupting, and reproductive effects in both humans and wildlife. To mitigate potential risks, regulatory measures have been implemented in many countries to restrict the production, use, and presence of BDE-47 and other PBDE congeners in consumer products and the environment.

Term	Meaning
BFRs	Brominated Flame Retardants, a group of chemicals that are used to inhibit or delay the ignition and spread of fires. They are commonly added to various materials and products, including textiles, plastics, electronics, furniture, and building materials. BFRs work by releasing bromine atoms when exposed to high temperatures, which interferes with the combustion process and reduces the flammability of the material. Some BFRs, like PBDEs (see below), have been restricted due to concerns about their persistence and potential health effects. BFRs can accumulate in organisms and may have adverse impacts on health, such as developmental issues and endocrine disruption. Efforts are underway to find safer alternatives to BFRs.
Bioaccumulation	Refers to the accumulation of substances, such as pollutants or toxins, in the tissues of living organisms over time. When an organism is exposed to a substance, it may absorb or take up the substance from its environment. If the organism cannot metabolize or excrete the substance efficiently, it may build up in its body. This can occur in various organisms throughout the food chain.
Biomagnification	Refers to the process by which the concentration of a substance, such as a pollutant or toxin, increases as it moves up the food chain. In this process, organisms at higher trophic levels (such as predators) consume prey that have already accumulated a certain substance. Since these predators consume many prey organisms, the substances they contain become concentrated in their bodies. As a result, the concentration of the substance increases with each step up the food chain, leading to higher levels in top predators.
BPA	Bisphenol A, a synthetic compound that belongs to the group of chemicals known as bisphenols. It is primarily used in the production of plastics and resins and is commonly found in items such as food and beverage containers, plastic bottles, dental sealants, epoxy coatings, and thermal paper receipts.
BPAF	Bishpenol AF, a synthetic substance derived from BPA (see above) through a chemical reaction. Like other bisphenols, BPAF is used primarily in the production of certain types of plastics and resins. Like other bisphenols, there have been concerns about the potential health effects of BPAF. Some studies suggest that BPAF may have endocrine-disrupting properties, meaning it could interfere with hormone function in the body.
BPB	Bisphenol B, a chemical compound belonging to the group of bisphenols, similar in structure to other bisphenols, such as BPA (see above). BPB has been used in various industrial applications, including as a chemical intermediate and as a component in the production of certain polymers and resins. However, its usage is less common compared to other bisphenols like BPA.

Term	Meaning
BPF	Bisphenol F, a chemical compound that is structurally like BPA (see above). It is part of the bisphenol family and shares the characteristic phenol rings connected by a bridging carbon. Like BPA, BPF is used in the production of plastics and resins. While BPF has been considered as a potential BPA alternative, there are ongoing debates and studies regarding its safety and potential health effects. Some studies suggest that BPF may also have endocrine-disrupting properties like BPA, while other studies indicate that it may have a lower endocrine disruption potential.
BPP	Bisphenol P, a chemical compound that belongs to the group of bisphenols, like BPA (see above) and other bisphenol variants. BPP has been investigated as a potential alternative to other bisphenols in various industrial applications, particularly in the production of plastics and resins.
BPS	Bisphenol S, a chemical compound that belongs to the group of bisphenols, like BPA (see above) and other bisphenol variants. It is often considered as an alternative to BPA in various applications due to concerns about the potential health effects of BPA. Like other bisphenols, there have been concerns about the potential health effects of BPS. Some studies have suggested that it may have endocrine-disrupting properties, meaning it could interfere with hormone function in the body.
Cetaceans	Collective name for whales, dolphins and porpoises, various species of which occupy a wide variety of ecological niches. All cetaceans are entirely adapted to life in the water, with streamlined bodies, fin-like appendages, and blowholes for breathing.
CYP1A1 expression	A biomarker of exposure to persistent organic pollutants. CYP1A1 expression refers to the production or activity of the enzyme called cytochrome P450 1A1. CYP1A1 is a member of the cytochrome P450 enzyme family, which plays a significant role in metabolising various compounds, including drugs, toxins, and environmental pollutants. The expression of CYP1A1 is regulated by certain stimuli, such as exposure to certain chemicals. CYP1A1 is known for its ability to metabolise polycyclic aromatic hydrocarbons (see below).
Cytokines	A group of small proteins or peptides that play a crucial role in cell signaling and communication within the immune system. They are produced by various cells, including immune cells, and act as messengers to regulate immune responses and coordinate interactions between different cell types. Cytokines are involved in numerous biological processes, including inflammation, immune cell activation, cell proliferation and differentiation, cell migration, and the regulation of immune and inflammatory responses. They function by binding to specific receptors on target cells, triggering a cascade of cellular responses.

Term	Meaning
DDT	Dichlorodiphenyltrichloroethane, a synthetic pesticide that was widely used during the mid-20th century to control insect pests, particularly mosquitoes that transmit diseases such as malaria and typhus. DDT is an organochlorine compound, characterized by its chemical structure that includes chlorine atoms. It is a persistent organic pollutant (POP) that resists degradation in the environment, leading to its accumulation in soil, water, and living organisms. Although DDT was effective in combating insect-borne diseases, studies revealed its persistence in the environment, ability to bioaccumulate in the food chain, and potential toxicity to non-target organisms, including birds and fish which led to its ban or severe restrictions in many countries.
deca-BDE	Decabromodiphenyl ether, a flame retardant compound belonging to the polybrominated diphenyl ether (PBDE) group Deca-BDE is composed of ten bromine atoms attached to a central diphenyl ether structure. It has been widely used in various consumer products and materials, including electronics, textiles, and foam insulation, to enhance their fire resistance properties. However, due to concerns over its persistence, bioaccumulation, and potential adverse health effects, the production and use of Deca-BDE have been restricted or banned in many countries.
ECHA	European Chemicals Agency, established in 2007. ECHA plays a crucial role in implementing and enforcing the REACH regulation and other chemical-related legislation within the EU. Its activities contribute to the protection of human health and the environment while fostering the responsible and sustainable use of chemicals.
Endocrine hormone homeostasis	Endocrine hormone homeostasis involves maintaining the appropriate levels of hormones in the body to ensure optimal functioning. This is achieved through a complex system of feedback loops and regulatory mechanisms. For example, when hormone levels rise, feedback mechanisms may trigger a decrease in hormone production or release to prevent excessive levels. Conversely, when hormone levels are low, feedback mechanisms may stimulate the production and release of hormones to restore balance. Disruptions in endocrine hormone homeostasis can have significant effects on various bodily functions and lead to hormonal imbalances or disorders.
Erythropoiesis	The process by which red blood cells (erythrocytes) are produced in the body. It takes place primarily in the bone marrow. Erythropoiesis is crucial for maintaining adequate levels of red blood cells, which are responsible for carrying oxygen to tissues and removing carbon dioxide.

Term	Meaning
HBB	Hexabromobenzene, a chemical compound belonging to the group of brominated flame retardants (BFRs). It is a synthetic substance that contains bromine atoms and is used primarily as a flame retardant in various products and materials. Like other brominated flame retardants, hexabromobenzene has raised concerns due to its potential environmental and health impacts. It is persistent in the environment and has the potential to bioaccumulate in organisms. Studies have suggested that hexabromobenzene may have adverse effects on health, including possible carcinogenicity and developmental toxicity. Consequently, its use has been restricted or banned in some countries.
HCB	Hexachlorobenzene, a synthetic chemical compound belonging to the group of chlorinated organic compounds and is known for its persistence in the environment and potential for bioaccumulation. It has been found to have toxic effects on both humans and wildlife. Long-term exposure to hexachlorobenzene has been associated with adverse health effects, including damage to the liver, kidneys, and nervous system. Due to its hazardous properties, the production and use of hexachlorobenzene have been restricted or banned in many countries.
MARPOL	International Convention for the prevention of Pollution from Ships, MARPOL was adopted on November 2, 1973, and entered into force on October 2, 1983. It has been updated and amended several times. The primary objective of MARPOL is to minimise and prevent pollution of the marine environment from ships, including both accidental and operational pollution. The convention sets forth regulations and guidelines that cover various aspects of ship-generated pollution.
Microcytic anaemia	A type of anaemia characterised by smaller than normal red blood cells. The most common cause of microcytic anaemia is iron deficiency. Iron is essential for the production of haemoglobin, the protein responsible for carrying oxygen in the blood. In iron deficiency anaemia, there is insufficient iron available for proper haemoglobin synthesis, resulting in smaller and paler red blood cells.
Mysticetes	Baleen whales, filter feeding whales characterised by their baleen plates rather than teeth. They consume small prey by filtering water through their baleen while retaining the food. Baleen whales are known for their size, extensive migrations, and important ecological role in the oceans. There are 15 species of baleen whales including the blue whale, humpback whale, fin whale, and gray whale.
Odontocetes	Toothed whales, characterised by their teeth, which they use for capturing and eating prey. There are currently 77 known species of toothed whales which include species such as dolphins, porpoises, sperm whales, and beaked whales.

Term	Meaning
OSPAR	Oslo-Paris Convention for the Protection of the Marine Environment of the North-East Atlantic. OSPAR was established in 1992 as a regional seas convention that brings together 15 European countries, including Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom. These countries cooperate and work towards the protection and sustainable use of the marine environment in the North-East Atlantic.
PAHs	Polycyclic Aromatic Hydrocarbons, a group of organic compounds consisting of fused aromatic rings made up of carbon and hydrogen atoms. They are formed during the incomplete combustion of organic materials, such as fossil fuels, wood, and tobacco. PAHs can be released into the environment through natural processes like forest fires or human activities like industrial processes, vehicle emissions, and the burning of coal or biomass. PAHs are widespread environmental pollutants and can be found in various media, including air, soil, water, and sediments. They are persistent and can accumulate in the environment. Some PAHs are also considered to be toxic and potentially carcinogenic.
PBDEs	Polybrominated diphenyl ethers, are a group of chemical compounds that belong to the brominated flame retardant family. They are composed of multiple bromine atoms attached to a diphenyl ether structure. PBDEs have been used in a wide range of consumer products and materials to reduce their flammability and meet fire safety regulations. There are different forms of PBDEs, categorized based on the number of bromine atoms attached to the molecule. PBDEs are known to be persistent organic pollutants (POPs) and can bioaccumulate in the environment and living organisms. They have been detected in air, water, soil, and wildlife, including fish, birds, and marine mammals. Concerns have been raised about the potential adverse effects of PBDEs on human and animal health, such as developmental, neurological, and endocrine-disrupting effects. Due to their environmental persistence and potential health risks, many countries have taken regulatory actions to restrict or ban the production, use, and import of PBDEs.
PBT	Pentabromotoluene, a chemical compound belonging to the class of brominated aromatic hydrocarbon. Pentabromotoluene is primarily used as a flame retardant in various applications. It possesses properties that help reduce the flammability of materials, such as plastics, textiles, and electronics. Its bromine atoms contribute to the formation of a protective barrier that can inhibit or delay the spread of fire. Due to its bromine content, pentabromotoluene is classified as a POP (see below).
PBTs	Acronym for persistent, bioaccumulative and toxic substances. PBTs are a class of chemicals that exhibit specific characteristics and are of concern due to their potential impacts on health and the environment. Also referred to as POPs (see below).

Term	Meaning
PCBs	Polychlorinated biphenyls, group of 209 synthetic chemicals that were widely used as coolants and lubricants in electrical equipment, such as transformers and capacitors, due to their stable chemical properties, high heat resistance, and electrical insulating properties but are now recognized as persistent environmental pollutants with significant health and environmental risks. Their production and use have been banned or restricted due to their toxicity and harmful effects on health.
PCNs	Polychlorinated naphthalenes, a group of chemical compounds that are similar in structure toPCBs (see above). They are composed of chlorine atoms attached to naphthalene rings. PCNs were not intentionally manufactured but were formed as unintended contaminants in various industrial processes. Like PCBs, PCNs are persistent organic pollutants (POPs) that can persist in the environment for long periods. They are resistant to degradation and can bioaccumulate in organisms, including in the food chain. PCNs have been identified as potential environmental and health hazards. They are toxic and have been found to have adverse effects on human health, including impacts on the liver, immune system, and endocrine system. They are also suspected of being carcinogenic.
PFAS	Per- and poly-fluoroalkyl substances, a large group of man-made chemicals characterised by their strong carbon-fluorine bonds, which make them resistant to degradation in the environment. PFAS have been used in a wide range of products and applications, such as non-stick coatings (e.g., Teflon), water and stain-resistant treatments for fabrics, food packaging, firefighting foams, and many industrial processes. They are persistent in the environment and do not readily break down, leading to their accumulation over time. Some studies have shown that certain PFAS may have negative impacts on the immune system, liver, thyroid function, and reproductive health. They are also classified as potential carcinogens. Only a handful of PFAS are regulated under the Stockholm Convention (see below).
PFDA	Perfluorodecanoic acid, a type of PFAS (see above) compound that has been used in various industrial applications. It is a persistent organic pollutant (POP) that resists degradation, can bioaccumulate, and has potential adverse effects on health and the environment.
PFHxS	Perfluorohexane sulfonic acid, a type of PFAS (see above) compound used in various industrial applications. It is a persistent organic pollutant (POP) that resists degradation, can bioaccumulate, and has potential adverse effects on health and the environment. It has been added to the substances regulated under the Stockholm Convention (see below) in 2022.

Term	Meaning
PFNA	Perfluorononanoic acid, a type of PFAS (see above) compound that has been used in various industrial applications. It is a persistent organic pollutant (POP) that resists degradation, can bioaccumulate, and has potential adverse effects on health and the environment.
PFOA	Perfluorooctanoic acidm, a type of PFAS (see above) compound used in various industrial applications. It is a persistent organic pollutant (POP) that resists degradation, can bioaccumulate, and has potential adverse effects on health and the environment. It has been added to the substances regulated under the Stockholm Convention (see below) in 2019.
PFOS	Perfluorooctane sulfonic acid, a type of PFAS (see above) compound used in various industrial applications. It is a persistent organic pollutant (POP) that resists degradation, can bioaccumulate, and has potential adverse effects on health and the environment. It has been added to the substances regulated under the Stockholm Convention (see below) in 2009.
POPs	Persistent Organic Pollutants, toxic chemicals that persist in the environment for a long time without breaking down. They can cause serious health problems and harm ecosystems.
REACH	Registration, evaluation and authorisation of chemicals. It is a regulation implemented by the European Union (EU) that aims to protect human health and the environment from the potential risks posed by chemicals. The goal of REACH is to improve the knowledge and understanding of chemicals used in the EU, promote the safe use of chemicals, and ensure that risks associated with hazardous substances are effectively managed.
SLE	St Lawrence River Estuary in Quebec, Canada. Refers to the place where the fresh and salt waters mix between the St. Lawrence river and the Gulf of St Lawrence.
Stockholm Convention	An international environmental treaty that aims to protect human health and the environment from POPs (see above). It was adopted in 2001 and entered into force in 2004. The convention specifically targets POPs, which include substances like certain pesticides, industrial chemicals, and unintentional byproducts of industrial processes. The Stockholm Convention establishes measures to reduce and ultimately eliminate the production, use, and release of POPs. It requires participating countries to take various actions, such as developing national implementation plans, promoting the use of safer alternatives, regulating the handling and disposal of POPs, and supporting capacity-building and information exchange.

Term	Meaning
T-lymphocytes	Also known as T cells, a type of white blood cell that plays a central role in the immune response. They are a key component of the adaptive immune system, which is responsible for recognising and eliminating specific pathogens or abnormal cells. T cells have the ability to recognise specific antigens, which are molecules found on the surface of pathogens or other foreign substances. When a T cell encounters an antigen that it recognises, it initiates an immune response by either directly attacking and destroying the foreign invader or by activating other immune cells to mount a coordinated defence.
Thymic atrophy	Refers to the shrinkage or reduction in size and function of the thymus gland. The thymus is a specialised organ located in the chest behind the sternum and is a key component of the immune system. The thymus gland is responsible for the development and maturation of T cells (see above), which are crucial for the proper functioning of the immune system.
UNECE	United Nations Economic Commission for Europe, established in 1947, it is one of the regional commissions of the United Nations. Its purpose is to promote economic cooperation, sustainable development, and environmental protection among its member countries in Europe, North America, and Asia.

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