Science
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Title: Predicting global killer whale population collapse from PCB pollution

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One Sentence Summary:

Legacy chemicals threaten killer whales

Abstract:

Killer whales (*Orcinus orca*) are among the most highly polychlorinated biphenyl (PCB)-

5 contaminated mammals in the world, raising concern about the health consequences of current

exposures. Using an Individual Based Model framework and globally available data on tissue

PCB concentrations in killer whales, we show that PCB effects on reproduction and immune

function threaten the long-term viability of >50% of the world's killer whale populations. PCB-

mediated effects over the coming 100 years predicted that killer whale populations near

10 industrialized regions, and those feeding at high trophic levels regardless of location, are at high

risk of population collapse. Despite their near global ban over 30 years ago, PCBs continue to

devastate marine ecosystems.

Main Text:

The widespread industrial and household use of polychlorinated biphenyls (PCBs) during

15 the 20th century led to ubiquitous contamination of the biosphere, with significant harm among

different wildlife populations (*1*). PCBs are toxic anthropogenic compounds shown to impair

reproduction, disrupt the endocrine and immune systems, and increase the risk of cancer (*2*, *3*).

While environmental declines were evident after local and international efforts to phase-out PCBs

(*4*), improvements were short-lived and PCB levels have remain stable in many species since the

20 1990s (*5*). Tissue PCB concentrations remain exceedingly high in high trophic-level killer whales

(*Orcinus orca*) and other dolphin species (*5*, *6*). It has been suggested that high PCB concentrations

in killer whales may be contributing to observations of low recruitment and population decline,

potentially leading to local extinctions (*5*, *7*). To date, only one study, focusing on resident killer

whales in western Canada, has investigated population risk from PCB exposure (*8*). Exposure modelling predicted protracted health risks in these resident populations over the next century, underscoring the vulnerability of this long-lived species to PCBs (*9*). With many killer whale populations facing significant conservation pressures there is an urgent need to assess the impact of PCBs on global killer whale populations.

We compiled blubber PCB concentrations (sum-PCBs, mg/kg lipid weight) in killer whale populations around the world, and compared these to established concentration-response relationships for reproductive impairment and immunotoxicity-related disease mortality using an Individual-Based Model framework (*8, 10*). This model incorporates published killer whale fecundity and survival data to construct a stable age-structured baseline population. The model then simulates the accumulation and loss of PCBs in blubber through placental and lactation transfer to the fetus and calf as well as prey ingestion after weaning. Simulated PCB concentrations are then evaluated against concentration-response relationships for calf survival and immune suppression. Immunity is linked to survival probability using relationships between immune suppression and disease mortality (*11*). We then forecast the predicted effects of PCB exposure on killer whale population growth around the world over the next 100 years.

PCB concentrations in killer whales around the world reflect proximity to PCB production and usage, as well as diet and trophic level (Fig. 1, Table S1). Global PCB production (1930 to 1993) was estimated between 1 and 1.5 million tonnes, mostly occurring in the USA (~50%), Russia (~13%), Germany (~12%), France (~10%) and the UK (5%) (*12, 13*). The global manufacture of PCBs corresponded well with the observed pattern of PCB levels in killer whale populations, which ranged widely from lowest values in Antarctica, <10 mg/kg lw (*14*), to values above 500 mg/kg lw in individuals near the highly industrialized areas of the Strait of Gibraltar,

the UK, and the Pacific Northeast (*5*, *15*, *16*). Diet contributes importantly to PCB accumulation in killer whales via biomagnification across trophic levels, resulting in sharp differences between populations feeding on marine mammals, tuna (*Scombridae*) and sharks (*Selachimorpha*) to those feeding on lower trophic level fish (Fig. 1; Table S1). This is exemplified in the Pacific Northeast where marine mammal-eating transient killer whales carry 10-20 fold higher PCB burdens compared to fish-eating northern residents, despite sharing the same coastline (*15*, *17*). Overall, females exhibit lower blubber PCB levels than males due to maternal sequestration to young during foetal development and lactation (*18*, *19*). Exceptions have been reported in the most highly PCB-contaminated populations, including the UK, Strait of Gibraltar (*5*), and transient individuals in the Northeast Pacific (*17*), suggesting that PCBs may be limiting successful reproduction with the consequence of reducing the maternal loss of PCBs.

Model forecasting over the next 100 years shows the significant potential impact of PCBs on population size and long-term viability of long-lived killer whales around the world (Fig. 2). Killer whale populations with similar PCB levels were grouped together and assigned to exposure groups (*10*, Fig 2C,D, Table S1). The modelled reference (unexposed) population grew by 141% (interquartile range (25/75th) = 96.3-176.5%) over the 100-year simulation period. The least contaminated populations (group 1) included Alaskan residents, Antarctica type C, Canadian Northern residents, Crozet Archipelago, Eastern Tropical Pacific, and Norwegian populations. These are estimated to accumulate 1 mg/kg lw of PCBs per year, resulting in median blubber concentrations of 7.9 (4.7-14.0) mg/kg lw and effects causing a population decrease of 8.8% (-4.1-25.3%) or 15.4% (3.5-25.2) relative to the reference population for reproductive effects alone or combined reproductive and immune effects, respectively. However, while relative population-level effects were observed for these low exposed populations, the model still predicts a net

doubling in their population size over 100 years (Fig. 2C, Fig. S2-S3). Annual PCB accumulation rates of 3, 6, 9, 15, 18, and 27 mg/kg are represented by exposure groups two through seven, which have incrementally greater blubber PCB levels (Fig. 2C, Table S1). Alaskan offshore, Faroe Islands, and Iceland whales (group 2) have similar PCB burdens (13.9-41.5 mg/kg lw) and are predicted to have modest population growth over the 100-year simulation period, albeit at reduced growth relative to the reference population; modelled PCB effects on reproduction alone or in combination with immune suppression resulted in a population reduction of 22.6% (14.0-38.3%) or 40.5% (32.6-48.7%). Alaskan transient and Canadian Southern resident populations have similar PCB profiles (group 3: 28-83 mg/kg lw), and PCB effects are predicted to inhibit population growth or cause a gradually decline of ~15% (-33.9-4.3%) for reproductive or combined effects, respectively. These represent median reductions of 54.7 and 64.7% relative to unexposed populations. Greenland, Canary Islands, Hawaii, Japan, Brazil, Northeast Pacific transient, Strait of Gibraltar, and UK populations all possess PCB levels above 40 mg/kg lw (Fig. 2C), and this level of exposure is predicted to cause population declines at various rates depending on the exposure group. Populations of Japan, Brazil, Northeast Pacific transient, Strait of Gibraltar, and UK are all tending towards complete collapse in our modelled scenarios.

To quantify and compare the global risk of PCB exposure in killer whales, population trajectories from the model were used to calculate potential annual population growth rates (λ). The achievable growth rates, incorporating combined PCB effects on both reproduction and immune function, were at or below the growth threshold ($\lambda=1$) for 10 of the 19 populations for which information on PCB exposure is currently available (Fig. 2D and Table 1). These results suggest that chronic exposure to persistent PCBs has the potential to impact long-term population viability in over half of all studied killer whale populations. Of these, Alaskan transient and Canada

Southern resident populations are at moderate risk of population-level effects (λ=1), while Brazilian, Northeast Pacific transient, Canary Islands, Greenlandic, Hawaiian, Japanese, Strait of Gibraltar, and the UK populations are at high risk of collapse over the next 100 years. The model predicted low PCB risk and stable population growth (λ>1) for the remaining nine populations (Fig. 2d and Table 1).

Our global assessment here of PCB-related effects on the long-term viability of killer whale populations represents a fundamental advancement in our understanding of population impacts from chronic exposure to these legacy chemicals in a long-lived marine apex predator. More than 35 years after the onset of the ban of PCBs, killer whales still have PCB concentrations as high as 1300 mg/kg lw (*24*). Killer whales once thrived from pole to pole but, today, only those in the less contaminated waters of the Arctic and Antarctic appear to be able to sustain growth (Table 1) (*7, 25*). We had no PCB data for killer whales in the Gulf of Mexico, but even before the Deep Water Horizon oil spill in 2010, estimates for killer whales in the region are consistent with a progressive population collapse from 277 individuals in 1991-1994, 133 in 1996-2001, 49 in 2003-2004, and only 28 in 2009 (*26*). Prey switching from low to high PCB-contaminated prey sources (e.g. fish to seals) has significantly increased PCB exposures in some killer whale populations like Northeast Scotland (UK) and Greenland that are now predicted to collapse (*27*). This new feeding behaviour may be partly linked to the recovery of seal populations after decades of hunting. Taken together, our results lend credence to the threat facing killer whales from PCBs and highlights how legacy contaminants have potentially devastating consequences for long-lived wildlife populations, even decades after discontinued production.

The status-quo efforts to protect killer whales from conservation threats are likely to fail because PCBs have remained at levels associated with health risks over the past decades (*5, 7, 9*).

Concerted efforts beyond those listed under the Stockholm Convention on POPs are urgently needed to reduce PCB exposure in vulnerable wildlife populations. It is estimated that more than 80% of global PCB stocks are yet to be destroyed, and at present rates of PCB elimination, many countries will not achieve the 2025 and 2028 targets as agreed upon under the Stockholm Convention on POPs (*28*). Although killer whale populations face other anthropogenic stressors such as prey limitations, ship strikes, and underwater noise pollution (*25*), our assessment here clearly demonstrates the high risk of collapse for many killer whale populations as a consequence of their PCB exposures alone.

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Supplementary Materials:

Materials and Methods

Figures S1-S3

Tables S1-S2

References (30-*56*)

Fig. 1. Global PCB concentrations in killer whales. A. Conceptual model of PCB

bioaccumulation and magnification leading to elevated PCB concentrations in killer whale

populations. **B**. Global overview of PCB concentrations in killer whale blubber. Light and dark

green circles represent males and females, respectively. Also shown is population density-

normalized cumulative global usage of PCBs per country from 1930 to 2000 (*12*). Number labels

indicate populations with measured PCB concentrations (Table S1).

Fig. 2. Simulated killer whale population size in response to reproductive and immune

effects of PCB exposure. A. Calf survival as a function of maternal adipose PCB lipid weight

concentration. **B.** Immune suppression as a function of blubber PCB lipid weight concentration.

C. Simulated effect of PCB exposure on population size (% initial size, N_0) of killer whales over

the next 100 years. Simulations include the unexposed reference population (**black**), effects on

reproduction (**red**), and combined effects on reproduction and immunity (**blue**). Bold lines and

shading represent the median and interquartile range. Each plot represents a different PCB

exposure group noted by the interquartile range of PCB concentrations in each panel (*10*). **D.**

Annual population growth rates (λ) for modelled populations according to exposure group.

Table 1. Global assessment of population-level risk from PCB exposure.

PCB risk	Population	Location	Population size	Protection status
Low (λ>1)	Alaska offshore	North Pacific	>200[†]	none[†]
	Alaska resident	North Pacific	2347[†]	none[†]
	Antarctica type C	Southern Ocean	unknown	unknown
	Canada North resident	North-East Pacific	290[‡]	threatened[‡]
	Crozet Archipelago	South Indian Ocean	37-98[§]	unknown
	Eastern Tropical Pacific	Tropical Pacific	8500[†]	unknown
	Faroe Islands	North-East Atlantic	unknown	unknown
	Iceland	North Atlantic	376[¶]	NA[¶]
	Norway	North-East Atlantic	500-1100[£]	unknown
Moderate (λ=1)	Alaska transient	North Pacific	587[†]	none/depleted[†]
	Canada South resident	North-East Pacific	78[‡]	endangered[‡]
High (λ<1)	Brazil	South-West Atlantic	unknown	unknown
	Northeast Pacific transient	North-East Pacific	521[†]	none[†]/threatened[‡]
	Canary Islands	Atlantic Ocean	unknown	unknown
	Greenland	North Atlantic	unknown	none
	Hawaii	Tropical Pacific	101[†]	none[†]
	Japan	North-West Pacific	unknown	unknown
	Strait of Gibraltar	Mediterranean	36[¥]	vulnerable[¥]
	United Kingdom	North-East Atlantic	≤9[Ψ]	none

Risk categories were set based on predicted growth rates (λ) and significant difference using a one-sample t-test against a reference of no growth (λ=1): low risk (λ>1, little to no effect on population growth), moderate risk (λ=1, stagnant population growth), high risk (λ<1, population decline).

[†] National Oceanographic and Atmospheric Administration (NOAA) stock assessment reports (http://www.nmfs.noaa.gov/pr/sars/species.htm#smallwhales); AT1 transients in Alaska are a subgroup considered depleted under the US Marine Mammal Protection Act

[‡] Government of Canada, Species at Risk Public Registry (http://www.sararegistry.gc.ca/default.asp?lang=en&n=24F7211B-1)

[§] (20) [¶] (21) [£] (22) [¥] (23) [Ψ] (5)