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Monitoring of persistent organic pollutants in the polar regions: knowledge gaps & gluts through evidence mapping

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HIGHLIGHTS

- Through a systematic mapping here we scope, screen and chart evidences from literature dealing with POPs in Polar regions.
- POPs are widespread compounds that accumulating in polar regions canalise through trophic webs.
- The evidence collated during the last decades are really scattered across a large number of literature sources.
- Outcomes provided insights on future POPs monitoring plans and conservation strategies to apply in the Polar Regions.

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ABSTRACT

Persistent organic pollutants (POPs) are widespread compounds that accumulating in polar regions canalise through trophic webs. Although several dozens of studies have been carried out in the last decades, the information is generally scattered across a large number of literature sources. This does not allow an efficient synthesis and constraints our understanding on how address future monitoring plans and environmental conservation strategies on the Polar Regions with respect to POPs. Thus, here, we present the outcome of a systematic map (SM) to scope, screen and chart evidences from literature dealing with POPs in Polar regions. The SMs strive to produce rigorous guidelines and have recently been proposed as useful and effective tools to summarise growing bodies of research that seek to reduce bias and increase reliability, particularly in the case of high priority and controversial topics. Our SM was based on 125 polar studies, focussing on the most studied target species among those listed in the International Union for Conservation of Nature's Red List (IUCN Red List). To facilitate analysis of evidence, the studies were classified into Accumulation Monitoring (accounting for POP monitoring through sub-organismal, functional and population levels) and Food Web Monitoring approaches (accounting for contaminants monitoring through food webs). Our SM allowed us to assess and visualise, a set of both knowledge gaps and gluts and lastly a list was provided to address future research on POPs in Polar Regions.

1. Introduction

Antarctica is a snow-covered continent surrounded by the Southern Ocean that isolates it from the continental land masses. The Antarctic Circumpolar Current (ACC) is a current that serves as environmental barrier, with a own set of chemico-physical properties, separates the Southern Ocean from the other oceans. The geographic isolation and extreme climate of Antarctica and the Southern Ocean are responsible for both their late discovery by humankind and the absence of any human impact (towns, industry, mining), except for the scientific stations (Corsolini, 2011; Arctic Monitoring and Assessment Programme, 2014, 2015). Unfortunately, many studies have demonstrated that even this remote continent and ocean have been penetrated by contaminants such as persistent organic pollutants (POPs) (e.g. Bargagli, 2006; Corsolini, 2009). Contamination in the Antarctic ecosystems was first reported in 1966 (Sladen et al., 1966), and since then there has been an increasing interest in studying and monitoring the presence of pollutants in this otherwise pristine area of the world. This awareness has been growing since the Arctic was first reported as a

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final sink for POPs (Ottar, 1981).

POPs include several groups of chemicals with similar structures and physico-chemical properties that elicit similar toxic effects. They have been used extensively worldwide in agriculture (pesticides), industrial and health applications. These chemicals are synthetic, ubiquitous, show long-range transport potency, and many of them are hydrophobic; they bio-accumulate in organisms via respiration, dermal contact, and through diet (biomagnification; Stockholm Convention, 2004). POPs include the following most widespread and well-known classes of contaminants: polychlorinated-biphenyls (PCBs), -dioxins (PCDDs), -furans (PCDFs), polybrominated-diphenyl ethers (PBDEs), -biphenyls (PBBs), perfluorinated compounds (PFCs) and other halogenated hydrocarbons, used as pesticides (Stockholm Convention, 2004). Toxic effects from POPs include cancer, reproductive and developmental problems, alterations to the immune system, such as decreased ability to fight cancer and infections, endocrine disruption (affecting the thyroid and sex hormones), central nervous system defects, effects on the nervous system, liver damage, skin and eye disease and death (Stockholm Convention, 2004).

The geographical and air/ocean circulation make the Antarctic difficult to reach for POPs, but the prolonged winter darkness and cold climate affect their sinking and bioaccumulation in abiotic and biotic compartments (Corsolini, 2011). The main source of pollutants for this remote continent is atmospheric transport - volatile or semi-volatile contaminants can be transported there mainly by air mass (Wania, 2003). Cold condensation and global fractionation have been proposed as mechanisms whereby POPs reach polar regions; both POP condensation and fall-out depend on physico-chemical properties of molecules and air temperature (Wania, 2003). Due to the extreme cold climate and long winter darkness, degradation of deposited POP is very slow in the Polar Regions, and POPs may become trapped in the ice.

Atmospheric and marine contamination is different in the two hemispheres, the Northern Hemisphere being more polluted than the Southern. This is due to the fact that the industrialised countries of Europe, North America, and Asia have been the greatest producers and users of POPs since the Second World War. For instance, the concentrations of polychlorinated biphenyls (PCBs, one of the most-produced and widely-dispersed POPs) in the surface layers of the oceans are quite homogeneous in the middle latitudes of the Northern Hemisphere, with a maximum in the tropical region, while lower values have been recorded in the Southern Hemisphere with a minimum in the Antarctic region (Lakaschus et al., 2002). The Antarctic trophic webs and, in general, polar ones typically consist of a few levels, for example: phytoplankton, zooplankton (copepods, salps, euphasiids, fish larvae, chaetognaths), fish (myctophids, *Pleuragramma antarctica*), seabirds (Adèlie penguin *Pygoscelys adèliae*, Emperor penguins *Aptenodytes forsteri*, other species) and marine mammals (baleen whales, crab-eater seal *Lobodon carcinophagus*, Weddell seal *Leptonychotes weddelli*, leopard seal *Hydrurga leptonyx* and killer whale *Orcinus orca*) (Hempel, 1985). Krill and *P. antarctica* are the key species, as they are principal food items for several species of birds and marine mammals. *P. antarctica* feed on adult *Euphausia crystallorophias*; birds, seals and whales feed on zooplankton, krill and *P. antarctica* (Hubold, 1985).

Here, we propose a systematic map (SM) that aims to scope, screen and chart evidences from literature. The SM also strives to produce rigorous guidelines to address future monitoring plans and environmental conservation strategies on the Polar Regions with respect to POPs, paying special attention to Antarctica. SMs have recently been proposed as useful and effective tools to summarise growing bodies of research that seek to reduce bias and increase reliability, particularly in the case of high priority and controversial topics (McKinnon et al., 2015; Haddaway et al., 2015, 2016). SMs were adapted from social science to use in environmental management and conservation, and are becoming increasingly common (Bates et al., 2007; Clapton et al., 2009; Randall and James, 2012; Haddaway et al., 2015, 2016; Mangano and Sarà, 2017). Rather than providing answers to specific questions of impacts, SMs produce searchable databases of studies, along with detailed descriptive information, that allow methods and approaches used across an evidence base to be examined. These maps (e.g. report, database, geographical information system) can prove highly useful for research, policy and practice communities by providing assessments of knowledge "gaps & gluts", as well as patterns across the research literature that promote best practices and direct research resources towards the highest quality research (Haddaway et al., 2016; McKinnon et al., 2015; Mangano and Sarà, 2017; SNAP WG website).

2. Materials and methods

A search was carried out for relevant studies using two main publication databases (ISI Web of Knowledge and Scopus), having set up a complex search string involving specific keywords generated by the Population, Intervention, Comparator and Outcome elements (PICO, Collaboration for Environmental Evidence review guidelines, CEE, 2013) along with the Boolean operators and the wildcard "*" (Tables 1 and 2). An additional search limited to Word, PDF and/or Excel documents was performed on Google scholar and Google; the first 50 hits were examined for appropriate data (CEE, 2013; Mangano et al., 2015). To address our evidence map, we sought peer-reviewed information to meet criteria for detection and monitoring of POPs in marine ecosystems in both Polar Regions to compare the current status of knowledge in Antarctica and Arctic. A set of selection criteria was applied to screen studies surrendered by the literature search. The first screening sifted out, merely by title, any spurious results related mostly to studies from outside the polar areas or from systems other than marine. A second, more detailed screening set was based on inclusion criteria and was performed on abstracts and full title readings. Inclusion criteria concerned the presence of: (i) relevant subject, marine ecosystem components such as abiotic and biotic components listed in Table 1 (see Population column); (ii) relevant exposure type and (iii) relevant outcomes listed in Table 1 (see Outcome column). Articles retained from the search engine that passed the first screening have been organised to: (i) rebuild a temporal trend on the available literature sources, (ii) visualise the main literature types and sources and (iii) describe the main applied approaches. To assess the quality of the studies and evaluate the reliability of the reviewed results, a quality assessment framework was adapted from the systematic review guidelines for conservation (CEE, 2013). Data from the retained scientific sources that passed all the screening steps were extracted and arranged in a matrix, database and systematic map, to specifically group and organise evidence on: (i) monitoring selected POPs at sub-organismal (e.g. genetic, molecular, tissues), functional and life-history traits (e.g. feeding strategies, trophic position sex, age, size at first maturity, reproductive stage), and population (inter- and intra-specific differences) levels; (ii) most studied target species; (iii) spatio-temporal trends of the occurred alteration (see Table 3 in Supplementary Material). Subsets of evidences were extracted, graphically arranged and discussed (see Figures from 1 to 5) to show the family of studied compounds and the geographical distribution of monitoring effort. An integrated narrative description of the main evidence extracted was also provided and the main "gaps & gluts" were summarised and listed (Table 3).

Table 1
PICO elements of the research question used to both compose the search strings and drive the selection of studies.

PICO Components			
Population/Subject	Intervention	Comparator	Outcomes
food web*, trophic web*, marine (sea)	Bioaccumulation, Biomagnification, "climate change", "multiple stressor*", "synergistic effect*"	–	Contaminant*, Persistent Organic Pollutant, POPs: aldrin; chlordanes; Dichlorodiphenyltrichloroethane (DDT); dieldrin; endrin; heptachlor; hexachlorobenzene; mirex e toxaphene; polychlorobiphenyls; polychlorinated dibenzo-p-dioxins; polychlorinated dibenzofurans; alpha- hexachlorocyclohexanes; beta- hexachlorocyclohexanes; lindane, hexabromocyclododecane; perfluoroocatne sulfonic acid; endosulfan; tetrabromodiphenyl ether; pentabromodiphenylether; PCB – (DDE –DDT) – PBDE – HCB - lindano

3. Results and discussion

The total amount of literature sources retrieved reporting the study of POPs after the searching and screening steps (see Outcome in Table 1, PICO elements, for more details on the list of considered POPs) in both Antarctica and the Arctic was 125. Amongst these were: two book chapters presenting and discussing both Antarctica and Arctic results on POPs contamination on aquatic (including marine) biota, two technical reports based on the Arctic (North Pole) only and 32 review articles, of which two focused on Antarctica, 24 on the Arctic and 6 discussed the presence and trends of POPs in both Polar Regions. Looking at the 87 remaining scientific papers (Fig. 1), the amount of studies performed in Antarctica (N = 12) was definitively lower than in the Arctic (N = 75) where historically the highest amount of scientific programs of monitoring has been carried out, with the exception of 2015, year during which the number of studies was equal in both polar regions. More specifically, the major scientific interest in the Antarctic region came later than that in the Arctic (in 2002) (Fig. 1). Following the Stockholm Convention on Persistent Organic Pollutants held in 2001, the international community commenced discussing the need to eliminate or severely restrict POP production. Testimony to this is also the increased amount of studies published with the aim of detecting and monitoring POPs in biotic and abiotic matrixes at both Polar Regions (Fig. 1; this trend is less remarkable in Antarctica).

POPs such as hexacholorobenzene (HCB), *p,p'*-DDE (main abiotic and biotic degradation product of the DDT-based pesticide) and the polychlorinated biphenyls (PCBs) were the most studied organic contaminants in Antarctica and the Arctic (see Table 3 in Supplementary Material; columns from AI to AL). Moreover, the polybrominated diphenyl ethers (PBDEs, commonly used as flame retardants) are well represented and studied in the Arctic only. Looking at the geographical distribution of studies that performed sampling of marine biota, it was possible to highlight differences between Antarctica and the Arctic that mainly reflect the presence and access to *in situ* facilities in the northern Polar Regions (Fig. 2). Among some of the most studied target species are those listed in the IUCN Red List as vulnerable (*Ursus maritimus*, N = 6; *Gadus morhua*, N = 3), near threatened (*Delphinapterus leucas*, N = 4; *Pygoscelis adèliae*, N = 4; *Monodon monoceros*, N = 3; *Somateria mollissima*, N = 3) and of least concern (*Phoca hispida*, N = 9; *Larus hyperboreus*, N = 9; *Uria lomvia* N = 7; *Cepphus grille*, N = 7; *Rissa tridactyla* N = 7; *Balaena mysticetus*, N = 5; *Alle alle*, N = 4; *Pagophilus groenlandicus*, N = 3; see more details in Supplementary Material database on other IUCN Red List species sampled one and two times only). To facilitate analysis of evidence, the studies were classified into the two main approaches applied: "Accumulation Monitoring" (coded AM) accounting for POP monitoring through sub-organismal, functional and population levels and components, and "Food Web Monitoring" (coded FWM) accounting for contaminants monitoring through food webs (Fig. 3).

3.1. Accumulation monitoring (AM)

Depending on the measured and monitored accumulation of POP contaminants, the studies were divided into four main groups: (i) sub-organismal (e.g. genetic, molecular, tissues), functional and life-history trait (e.g. feeding strategies, trophic position sex, age, size at first maturity, reproductive stage), and population (inter- and intra-specific differences) levels and (ii) spatial and temporal trends. In Antarctica, a greater number of AM studies (N = 8) were recorded compared to studies on food web monitoring (N = 4), but the AM studies were lower represented if compared to the Arctic region (N = 42; Fig. 3). Specifically in Antarctica, studies reported contaminant monitoring and sub-organismal measures (e.g. chemical bioaccumulation, activity, and levels of biotransformation enzymes - cytochrome P4501A; metallothioneins and the efficiency of the antioxidant system measured as individual defences; and total scavenging capacity toward peroxyl and hydroxyl radicals, N = 1; exposure toxicity N = 1); functional as sex (N = 2), age (N = 2), reproductive stage (N = 1) and trophic position (N = 1); population in terms of interspecific differences (N = 2), both inter- and intra-specific differences (N = 2); spatial (N = 4) and temporal trends (N = 1) (see Table 3 in Supplementary Material for more details). The above papers analysed only the presence of POPs in the biotic components. In the Arctic, the effect of contaminants was measured as sub-organismal response to exposure toxicity, embryo aberrations, metabolite formation with dietary exposure, levels of retinol, retinyl palmitate and α-tocopherol, metabolite formation (elimination) with dietary exposure (N = 1), metabolism reserve and survival. Functional responses sex and age were investigated by 11 studies, followed by trophic position, tissue differences, dietary uptake, reproductive stage and size. Spatial and temporal trends were also detected, both jointly (N = 8) and separately, spatial (N = 13) and temporal (N = 4) only. Population was studied in terms of interspecific (N = 8) and intraspecific (N = 3) differences, both inter and intra-specific differences (N = 5) (see Table 3 in Supplementary Material for more details). Eighty per cent of papers analysed only biotic components, while 27% also took into account the abiotic matrix contribution to the POP transfer through food webs (13% looked at the sediments, 4% at water and 2% at both, respectively).

AM papers in Antarctica were based only on compound concentration measurements (88%) and mesocosms to perform hypothesis-driven experiments (12%, Fig. 4). Trophic levels (TLs) were generally obtained *a priori* from literature, and the accumulation differences were measured in terms of differences in concentration (regressions; Regoli et al., 2005; Nash et al., 2008, 2010; Geisz et al., 2008; Corsolini et al., 2011; Strobel et al., 2016) except for a study where TLs were evaluated through stable isotope analysis and POP accumulation was measured by BMF (Kim et al.,

Table 2
Search strings arranged using some keywords from PICO elements in Table 1. Notes: the wildcard asterix (*) following a search word has been used allowing the search engine to consider and accept the word variations in the search; quotation marks around word indicate the exact word allowed in the search results.

Engine search		HITS	
Databases		Scopus	ISI WoS
Search fields		TITLE-ABS-KEY	Topic
Search string #1	((“food web*” OR “trophic web*”) AND (“Bioaccumulation” OR “Biomagnification”) AND (“marine” OR “Sea”) AND (“Contaminant*” OR “Persistent Organic Pollutant” OR “POP*” OR “aldrin” OR “chlordane*” OR “Dichlorodiphenyltrichloroethane” OR “DDT” OR “dieldrin” OR “endrin” OR “heptachlor” OR “hexachlorobenzene” OR “mirex” OR “toxaphene” OR “polychlorobiphenyl*” OR “polychlorinated dibenzo-p-dioxin*” OR “polychlorinated dibenzofuran*” OR “alphahexachlorocyclohexane*” OR “ beta- hexachlorocyclohexane*” OR “lindane” OR “hexabromocyclododecane” OR “perfluoroocatne sulfonic acid” OR “endosulfan” OR “tetrabromodiphenyl ether” OR “pentabromodiphenylether” OR “PCB” OR “DDE” OR “PBDE” OR “HCB”))	297	385
Search string #2	((“food web*” OR “trophic web*”) AND (“marine” OR “Sea”) AND (“Bioaccumulation” OR “Biomagnification”) AND (“Contaminant*”))	144	232
Search string #3	((“food web*” OR “trophic web*”) AND (“Bioaccumulation” OR “Biomagnification”) AND (“climate change” OR “multiple-stressor*”) AND (“marine” OR “Sea”) AND (“Contaminant*” OR “Persistent Organic Pollutant” OR “POP*” OR “aldrin” OR “chlordane*” OR “Dichlorodiphenyltrichloroethane” OR “DDT” OR “dieldrin” OR “endrin” OR “heptachlor” OR “hexachlorobenzene” OR “mirex” OR “toxaphene” OR “polychlorobiphenyl*” OR “polychlorinated dibenzo-p-dioxin*” OR “polychlorinated dibenzofuran*” OR “alphahexachlorocyclohexane*” OR “ beta- hexachlorocyclohexane*” OR “lindane” OR “hexabromocyclododecane” OR “perfluoroocatne sulfonic acid” OR “endosulfan” OR “tetrabromodiphenyl ether” OR “pentabromodiphenylether” OR “PCB” OR “DDE” OR “PBDE” OR “HCB”))	19	16

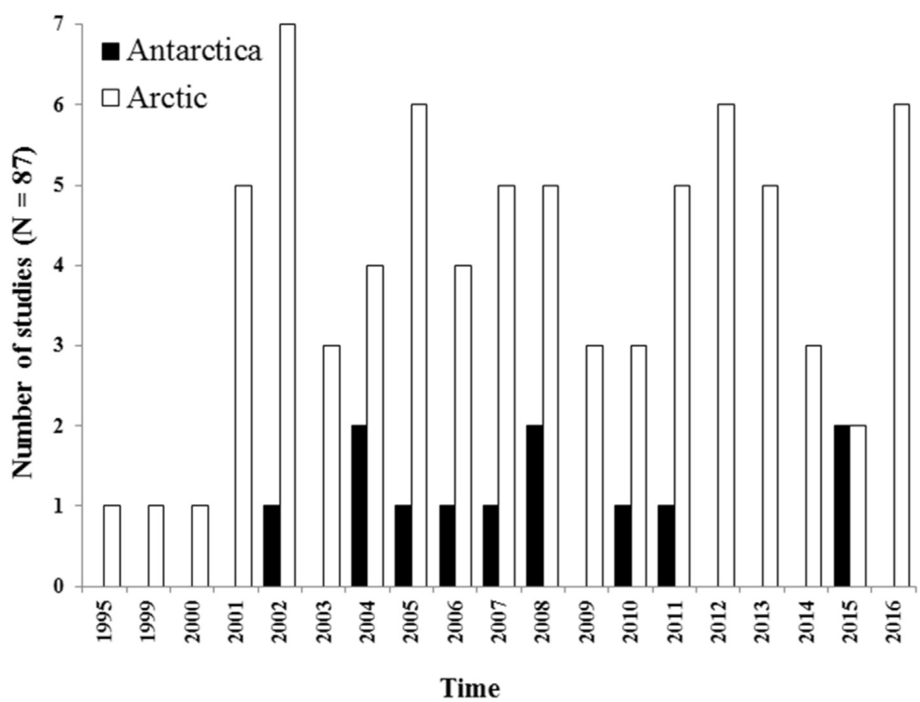

Fig. 1. Temporal trend of number of studies (N = 87 excluding the reviews papers) respectively for Antarctica (black columns, N = 12) and Arctic (white columns, N = 75).

2015). Contaminants were always measured in species tissues. The mesocosm study investigated the effects of cadmium in influencing bioaccumulation, suggesting that cadmium-elevated natural levels in Antarctic organisms may limit the biotransformation capability dioxins. This could influence the bioaccumulation and biological effects of these chemicals in key sentinel species (Regoli et al., 2005). Conversely, more heterogeneous sampling and measuring approaches were recorded in the Arctic, where studies were mainly based on analysis of compound concentration (64%), mesocosm (19%) and modelling (17%, Fig. 4). Studies that analysed compound concentration on species tissues (Table 3 in Supplementary Material) only rarely exploited the power of stable isotope analysis to test the trophic position among species (N = 10). The accumulation differences along TLs were measured in terms of differences in concentration, a few papers applied Biomagnification Factor (BMF; N = 5), Trophic Magnification Factor (TMF; N = 1), Bioaccumulation Factor (BAF; N = 2) and Bioconcentration Factor (BCF; N = 1). Mesocosms were used to measure toxic dietary uptakes (N = 3; van de Merwe et al., 2011; Lee et al., 2012; Poulsen et al., 2013), differences among tissues in accumulating POPs (N = 1, Kwong et al., 2008) and morphological variables such as the levels of retinol and retinyl palmitate and α-tocopherol or malformed embryos (Löf et al., 2016). Modelling studies mostly involved: the role of organic matter in affecting the spatial distribution of POPs (de Wit and Muir, 2010), an individual-based model to predict the accumulation of sum PBDEs and sum PCBs in specific individuals of a population (Mongillo et al., 2012), a Dynamic Energy Budget (DEB) model to take into account complexity and study factors impacting accumulation of organic pollutants in fish through ontogeny, migration and interspecific differences (Baert

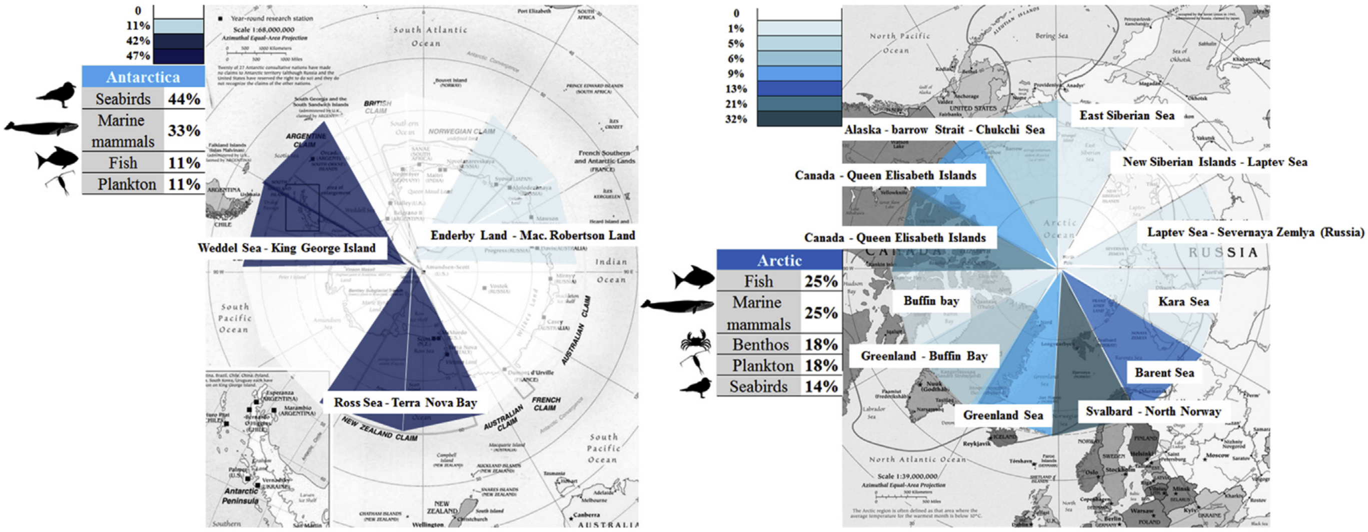

Fig. 2. Systematic mapping of evidence on spatial sampling efforts (longitudinal gradients, main localities have been reported) percentage of studies in blue scale, Arctic on the right side, Antarctic on the left. The main sampling localities and target species are reported (map polygon layer source: http://www.lib.utexas.edu/maps/polar.html).

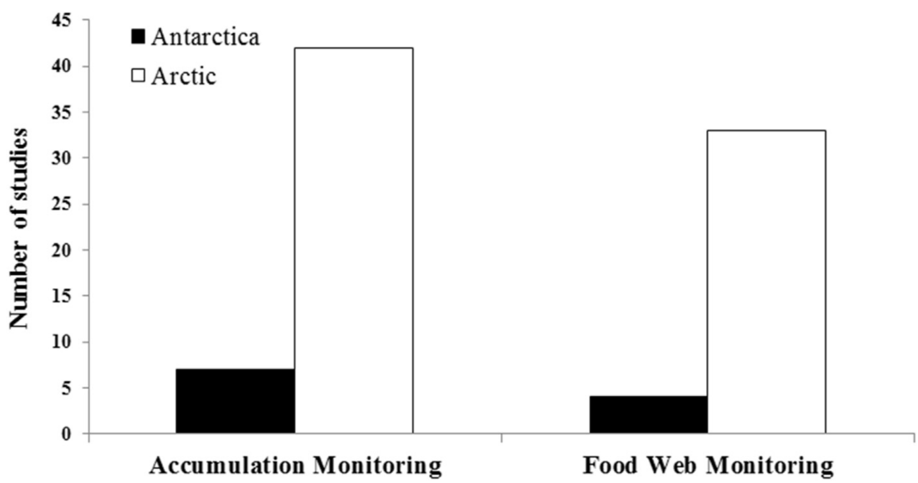

Fig. 3. The two main applied approaches "Accumulation Monitoring" (left columns) accounting for POP monitoring through sub-organismal, functional and population levels and components and "Food Web Monitoring" (right columns) accounting for contaminants monitoring through food webs; respectively to Antarctica (black) and Arctic (white).

et al., 2013), a model simulating accumulation differences under climate change scenarios (Gouin et al., 2013) and a conceptual model that simulates the effects of plastic on bioaccumulation of POPs in an accumulation model.

Concerning the main measured outcomes in Antarctica, a study among seabird accumulation monitoring reported an increasingly high value of toxicity due to dioxin-like compounds expressed as Toxic Equivalents (TEQ) in Gentoo penguins, primarily due to PCDDs and non-ortho PCBs (Corsolini et al., 2007); by contrast, *p,p′*-DDT to *p,p′*-DDE have been declining in Adèlie penguins over the last decades, indicating current exposure to old rather than new sources of ΣDDT. The exception here is the Western Antarctic Peninsula, where the presence of *p,p′*-DDT in these birds indicates a current source of DDT to the Antarctic marine food web (Geisz et al., 2008). Spatial trends influence the exposition to and accumulation of contaminants (Nash et al., 2010); the higher contaminant concentrations were detected in migrating seabirds (e.g. South Polar skua and brown skua, snow petrel, penguins), suggesting contamination events at lower latitudes for those birds migrating northwards (Corsolini et al., 2011). A temporal increase in PCB and DDT concentrations was recorded in icefish, whose recorded values were higher than those measured in the late 1990s (Strobel et al., 2016). In the Arctic, highly significant correlations were found between species spatial distribution and contaminants in different overwintering areas (polar bears show a strong west to east trend, the ringed seal shows the highest PCB levels at two sites near the Russian coasts, while both species show a reverse trend in the North American Arctic; Muir and Norstrom, 2000; Braune et al., 2002). Therefore, some of these geographical differences may reflect dietary differences, especially in the case of PCBs (Muir and Norstrom, 2000). Contaminant concentration seems highly significant correlated with age, and also if differences are detected between congeners (e.g. PCB; Oehme et al., 1995). The concentration area is partially dependent on foraging strategy (Hoekstra et al., 2002; Sagerup et al., 2002; Vieweg et al., 2012; Gaden et al., 2012). The influence of seasons (mostly tested to measure temporal trends) is clearly significant in POPs accumulation (Hoekstra et al., 2002). The Organochlorine contaminants, OC concentrations in sexually mature females are significantly lower than male whales from the same cohort due to maternal transfer to the foetus and neonate (Hoekstra et al., 2002). The Greenland shark's tissues can accumulate contaminants in different concentrations (gonads > spleen > white muscle, Corsolini et al., 2014). Seasons clearly influenced the accumulation rate of Organochlorine contaminants, OCs (Hoekstra et al., 2002). Based on mesocosm studies, OCs may affect levels of thyroid hormones in free-ranging grey seal pups (Sørmo et al., 2005); additionally, fish rapidly accumulate DDTs from gills and viscera after exposure, and elimination following aqueous or dietary uptake was slow (Kwong et al., 2008); embryo aberrations in Amphipods were significantly associated with PCB concentrations in sediment (Löf et al., 2016).

3.2. Food web monitoring – FWM

Reflecting the general lower number of studies performed in Antarctica compared to the Arctic, only four studies on FWM were performed analysing predator-prey relationship in terms of compound concentration differences among trophic levels (TLs) and presenting data on the biotic components only. In the Arctic, two of the 33 studies on FWM examined not only predator-prey relationship, but also differences amongst sex and temporal trends (Muir et al., 2003), among body size and sub-organism responses (Cytochrome P450; Borgå et al., 2007) and between food webs of distinct geographic areas (Arctic vs temperate zone; Sobek et al., 2010). Seventy-three per cent of papers analysed only biotic components, while 27% also took the abiotic matrix contribution to POP transfer through the food webs into account (8% looked at sediments, 8% at the water and 11% at both, respectively).

FWM papers in Antarctica were based only on chemical concentrations, where TLs were always obtained *a priori* from the literature and the accumulation differences along TLs were measured in terms of differences in concentration (regressions; Chiuchiolo et al., 2004; Goerke et al., 2004; Corsolini et al., 2006; Czub and McLachlan, 2007). The maximum level of investigated TL in a food web was 4 (Goerke et al., 2004), the maximum number of target species sampled and analysed was 10 (Goerke et al., 2004). By contrast, more heterogeneous sampling and measuring approaches were recorded in the Arctic: here studies were mainly based on compound concentration measures (57%), modelling (38%) and mesocosm studies (5%, Fig. 5).

Generally, in both areas, the studies that provided evidence on POPs concentration focused the analysis of contaminants on tissues (e.g. blubber for marine mammals, Wolkers et al., 2007; liver, Tomy et al., 2004; McKinney et al., 2012; blood mainly for fish, and eggs for birds). The main outcomes from FWM studies that simply monitored compound concentration in the Arctic are commonly described in terms of predator-prey relationship, where this relationship and trophic levels were either: *a priori* obtained from literature (29%), a dataset from a monitoring plan and/or validated by stable isotope analysis performed *ad hoc* (71%). The maximum level of investigated TL on a food web was 5 (Mattila and Verta, 2008). A further 22 studies focused on a three TL food web, 9 studies on a two level food web and 6 on a four level food web (see more details in Table 3 in Supplementary Material). The maximum number of target species sampled and analysed was 21 (Laender et al., 2011). Among FWM studies in the Arctic, the modelling exercises were mostly based on the fugacity bioaccumulation model (Fraser et al., 2002) and bioaccumulation factors (BAF, Laender et al., 2009; Borgå et al., 2010; Sobek et al., 2010; Laender et al., 2011; Binnington and Wania, 2014), the mechanistic mass-balanced model (Borgå and Di Guardo, 2005), the linear partition model and non-steady state spatially resolved mass balance model of chemical transport (Nash et al., 2008). Bioaccumulation models were coupled to a sensitivity analysis, spatial concentration gradient scenarios, biotransformation rate and Trophic Magnification Factor (TMF, Kim et al., 2016). Experimental hypothesis-driven studies in mesocosms mainly focused on passive uptake (Wallberg et al., 2001). Data to feed models and set up mesocosms were always gathered from literature (Borgå and Di Guardo, 2005; Sobek et al., 2006; Fraser et al., 2002, Wolkers et al., 2007, Mattila and Verta, 2008, Laender et al., 2009; see Supplementary Material for more references, DB polar) and specific time-series datasets from monitoring surveys and multi-annual monitoring programs (deBruyn and Gobas, 2006; Laender et al., 2011). Generally, FWM studies measured several indices of bio-magnification and accumulation as: Biomagnification Factor (BMF, N = 13), Food Web Magnification Factor (FWMF, N = 4), Metabolic Index (MI, N = 3), Trophic Magnification Factor (TMFs, N = 7), Bioaccumulation Factor (BAF, N = 11), Bioconcentration Factor (BCF, N = 1), partition coefficient - log (KEOM, N = 1), and simple differences in concentration (N = 5) (see Table 3 in Supplementary Material).

Concerning the primary measured outcomes, all the FWM studies performed in Antarctica reported an increase in POPs concentration along the food web levels, with differences in responses among the target species (e.g. dioxin-like chemicals in skua eggs and adults suggest the importance of intake via diet and migration habits; Corsolini et al., 2002) confirming both the useful role of POPs in tracing migration behaviour in this habitat and proving their transfer from mother to eggs. Interestingly, an increase of 14% in the (+)alpha-HCH enantiomer was found from krill

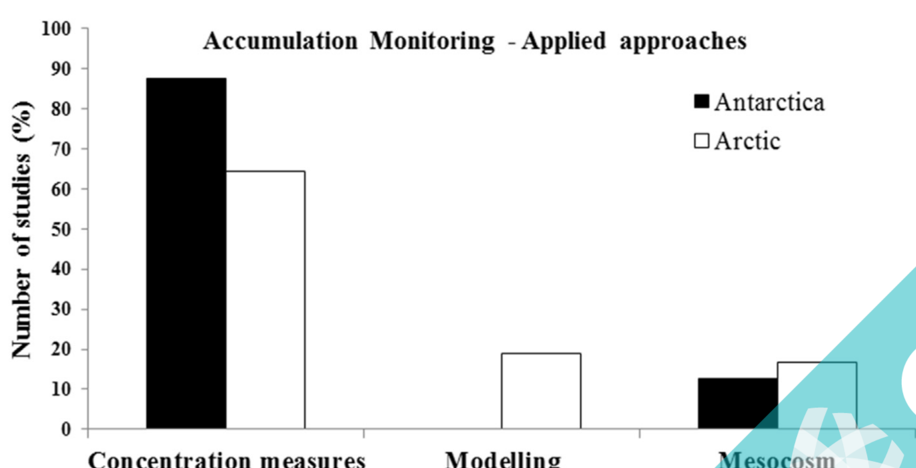

Fig. 4. The three main applied approaches to measure and monitor “Accumulation Monitoring” respectively to Antarctica (black) and Arctic (white).

through penguin, suggesting that the enantioselective biotransformation increased proportionately with trophic level (Corsolini et al., 2007). Evidence on the importance of sea ice as a vector for entry of POPs into the Antarctic marine ecosystem has been available since 2004, in the form of high concentrations of PBDEs and HCB in ice algae and associated juvenile krill (Chiuchiolo et al., 2004).

In the Arctic the variety of outcomes is greater, which naturally reflects the higher number of studies and wider range of studied compound and applied approaches in this region (Figs. 2 and 3). Evidence of bioaccumulation mechanisms at lower trophic levels (fish) depends primarily on physicochemical factors, such as water solubility and lipophilicity of the pollutants, whereas at higher trophic levels (seals), the bioaccumulation mechanisms are mainly affected by biochemical factors, such as the metabolic capacity of the organisms. Prey preference may also influence the patterns of accumulated pollutants in the different species (see Table 3 in Supplementary Material for more references). Specifically, BMFs can indicate opposite trends along the food web for different compounds, with a general increasing trend for DDT and decreasing for DDD; for example, the highest biomagnification factor was found for DDT, highly chlorinated biphenyls, *p,p'*-DDE and oxychlordane from sand eel to harbour seal, while the proportions of mono-ortho substituted and meta/para unsubstituted PCB congeners, together with DDD, decreased from fish to seal; Ruus et al., 1999). A minimal biotransformation was suggested for invertebrates and fish BMFs, in contrast to seabirds, which, based on their low BMFs, appear to readily metabolise HCH compounds (Moisey et al., 2001). A stereoselective accumulation was reported for HCH in the bowhead whale (Hoekstra et al., 2003). Modelling studies show considerable, but highly variable, biomagnification attributable to differences in metabolic rates (Fraser et al., 2002). Similarly, the bioaccumulation can vary among contaminants, congeners and depends on factors such as seasons and lipid contents in tissues (e.g. BAFs in some fish can be 10 times lower in summer than in spring and autumn/winter and are mainly driven by lipid dynamics; Laender et al., 2009). By comparing Arctic data with temperate areas, the spatial variability of OC contamination in top-level marine Arctic predators was attributed to differences in regional sources of contamination rather than trophic position (Hoekstra et al., 2003). A modelling exercise in the context of increased temperature and particulate organic carbon water concentration (CPOC) showed an overall reduced bioaccumulation of organic contaminants in the Arctic marine food web (the largest change being for PCB-52 and PCB-153) suggesting that increase in temperature resulted in an overall reduction in net bioaccumulation. Some models were validated with data from literature showing the highest accuracy (Borgå and Di Guardo, 2005; deBruyn and Gobas, 2006; Laender et al., 2009; Kim et al., 2016).

3.3. Evidence between the two “Gs”: gaps & gluts

Our exercise of evidence mapping allowed us to assess, and visualise, a set of both knowledge gaps (i.e. subjects requiring additional research) and gluts (i.e. subjects where a substantial number of studies has been produced; *sensu* Haddaway et al., 2016). The ensemble of collated evidence in our database, hereafter additionally summarised in a bullet-point list, could represent a readily usable resource for the next generation of researchers and decision-makers (Mangano and Sarà, 2017), facilitating future monitoring, management and conservation strategies in the Polar Regions. The results may be useful in addressing the implementation of both infrastructure development and training plans to be suggested at the national committees involved in polar region exploitation and development, encouraging both emerging and consolidate national Antarctic programmes (e.g. the Italian National Antarctic Research Programme, PNRA).

3.3.1. Main gaps

- *Scant visibility of Antarctic science promoting the study of POPs in this region.* Only a few studies investigated the presence of POPs in Antarctica, even if this trend can be widely justified by prohibitive environmental conditions, the scant numbers of facilities available to allow sampling and temporary dwellings for humans, and the high amount of funds needed. Such a knowledge gap should be addressed as a priority in the near future by promoting more harmonized monitoring plans in collecting evidence from POPs at both polar areas.
- *The need to apply more integrated approaches.* Taking into account the accumulation of POPs in both abiotic and biotic matrices when performing accumulation and biomagnification studies.
- *The need to consider more technical and specific aspects.* The limit of detection (LOD) and the sensitivity of instruments, among others, applied since decades of studies should be taken into account when doing comparisons over temporal trends.

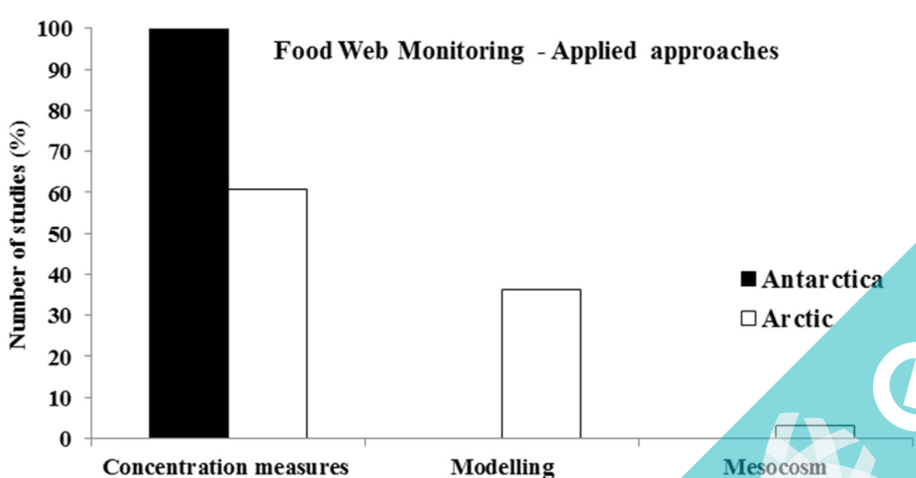

Fig. 5. The three main applied approaches to measure and monitor “Food Web Monitoring” respectively to Antarctica (black) and Arctic (white).

- *The need for an accurate georeferencing.* Georeferencing can represent an important criterion of data screening and analysis; future studies should report a more accurate georeferencing of sampling and monitoring plans.

3.3.2. Main gluts

- *Greater amounts of information on POPs accumulation and magnification in the Arctic region.* This should encourage scientific research to promote joint data analysis technique tools (e.g. meta-analysis, long-term series comparisons, database sharing, etc.) and research programmes.
- *High interest in protected species.* As testified by the large amount of IUCN Red List species selected as target species, this should be encouraged in the near future to allow the compilation of long-term series databases.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.chemosphere.2016.12.124.

References

Arctic Monitoring and Assessment Programme - AMAP, 2014. Trends in Stockholm convention persistent organic pollutants (POPs). In: Wilson, S., Hung, H., Katsoyiannis, A., Kong, D., van Oostdam, J., Riget, F., Bignert, A. (Eds.), Arctic Air, Human Media and Biota. Arctic Monitoring and Assessment Programme (AMAP), Oslo, p. 54. AMAP Technical Report No. 7 (2014).

Arctic Monitoring and Assessment Programme - AMAP, 2015. AMAP Assessment 2015: Human Health in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway vii + 165 pp.

Baert, J.M., Janssen, C.R., Borga, K., De Laender, F., 2013. Migration and opportunistic feeding increase PCB accumulation in Arctic seabirds. Environ. Sci. Technol. 47 (20), 11793–11801.

Bargagli, R., 2006. Antarctic Ecosystems: Environmental Contamination, Climate Change, and Human Impact, vol. 175. Springer Science & Business Media.

Bates, S., Clapton, J., Coren, E., 2007. Systematic maps to support the evidence base in social care. Evid. Policy 3 (4), 539–551.

Binnington, M.J., Wania, F., 2014. Clarifying relationships between persistent organic pollutant concentrations and age in wildlife biomonitoring: individuals, cross-sections, and the roles of lifespan and sex. Environ. Toxicol. Chem. 33 (6), 1415–1426.

Borgå, K., Di Guardo, A., 2005. Comparing measured and predicted PCB concentrations in Arctic seawater and marine biota. Sci. Total Environ. 342 (1), 281–300.

Borgå, K., Hop, H., Skaare, J.U., Wolkers, H., Gabrielsen, G.W., 2007. Selective bioaccumulation of chlorinated pesticides and metabolites in Arctic seabirds. Environ. Pollut. 145 (2), 545–553.

Borgå, K., Saloranta, T.M., Ruus, A., 2010. Simulating climate change-induced alterations in bioaccumulation of organic contaminants in an Arctic marine food web. Environ. Toxicol. Chem. 29 (6), 1349–1357.

Braune, B.M., Donaldson, G.M., Hobson, K.A., 2002. Contaminant residues in seabird eggs from the Canadian Arctic. II. Spatial trends and evidence from stable isotopes for intercolony differences. Environ. Pollut. 117 (1), 133–145.

Chiuchiolo, A.L., Dickhut, R.M., Cochran, M.A., Ducklow, H.W., 2004. Persistent organic pollutants at the base of the Antarctic marine food web. Environ. Sci. Technol. 38 (13), 3551–3557.

Clapton, J., Rutter, D., Sharif, N., 2009. SCIE Systematic Mapping Guidance. April 2009. www.scie.org.uk/publications/researchresources/rr03.pdf.

Collaboration for Environmental Evidence, 2013. Guidelines for Systematic Review and Evidence Synthesis in Environmental Management. Version 4.2. Environmental Evidence: www.environmentalevidence.org/Documents/Guidelines/Guidelines4.2.pdf.

Corsolini, S., Kannan, K., Imagawa, T., Focardi, S., Giesy, J.P., 2002. Polychloronaphthalenes and other dioxin-like compounds in Arctic and Antarctic marine food webs. Environ. Sci. Technol. 36 (16), 3490–3496.

Corsolini, S., Covaci, A., Ademollo, N., Focardi, S., Schepens, P., 2006. Occurrence of organochlorine pesticides (OCPs) and their enantiomeric signatures, and concentrations of polybrominated diphenyl ethers (PBDEs) in the Adélie penguin food web, Antarctica. Environ. Pollut. 140 (2), 371–382.

Corsolini, S., Borghesi, N., Schiamone, A., Focardi, S., 2007. Polybrominated diphenyl ethers, polychlorinated dibenzo-dioxins,-furans, and-biphenyls in three species of Antarctic penguins. Environ. Sci. Pollut. Res. Int. 14 (6), 421–429.

Corsolini, S., 2009. Industrial contaminants in Antarctic biota. J. Chromatogr. A 1216 (3), 598–612.

Corsolini, S., 2011. Contamination profile and temporal trend of POPs in antarctic biota. In: Loganathan, Bommanna, G., Lam, Paul Kwan-Sing (Eds.), Global Contamination Trends of Persistent Organic Chemicals. CRC press, pp. 571–590p.

Corsolini, S., Borghesi, N., Ademollo, N., Focardi, S., 2011. Chlorinated biphenyls and pesticides in migrating and resident seabirds from East and West Antarctica. Environ. Int. 37 (8), 1329–1335.

Corsolini, S., Ancora, S., Bianchi, N., Mariotti, G., Leonzio, C., Christiansen, J.S., 2014. Organotropism of persistent organic pollutants and heavy metals in the Greenland shark Somniosus microcephalus in NE Greenland. Mar. Pollut. Bull. 87 (1), 381–387.

Czub, G., McLachlan, M.S., 2007. Influence of the temperature gradient in blubber on the bioaccumulation of persistent lipophilic organic chemicals in seals. Environ. Toxicol. Chem. 26 (8), 1600–1605.

de Wit, C.A., Muir, D., 2010. Levels and trends of new contaminants, temporal trends of legacy contaminants and effects of contaminants in the Arctic: Preface. Sci. Total Environ. 408 (15), 2852–2853.

deBruyn, A.M., Gobas, F.A., 2006. A bioenergetic biomagnification model for the animal kingdom. Environ. Sci. Technol. 40 (5), 1581–1587.

Fraser, A.J., Burkow, I.C., Wolkers, H., Mackay, D., 2002. Modeling biomagnification and metabolism of contaminants in harp seals of the Barents Sea. Environ. Toxicol. Chem. 21 (1), 55–61.

Gaden, A., Ferguson, S.H., Harwood, L., Melling, H., Alikamik, J., Stern, G.A., 2012. Western Canadian Arctic ringed seal organic contaminant trends in relation to sea ice break-up. Environ. Sci. Technol. 46 (8), 4427–4433.

Geisz, H.N., Dickhut, R.M., Cochran, M.A., Fraser, W.R., Ducklow, H.W., 2008. Melting glaciers: a probable source of DDT to the Antarctic marine ecosystem. Environ. Sci. Technol. 42 (11), 3958–3962.

Goerke, H., Weber, K., Bornemann, H., Ramdohr, S., Plötz, J., 2004. Increasing levels and biomagnification of persistent organic pollutants (POPs) in Antarctic biota. Mar. Pollut. Bull. 48 (3), 295–302.

Gouin, T., Armitage, J.M., Cousins, I.T., Muir, D.C.G., Ng, C.A., Reid, L., Tao, S., 2013. Influence of global climate change on chemical fate and bioaccumulation: the role of multimedia models. Environ. Toxicol. Chem. 32 (1), 20–31.

Haddaway, N.R., Woodcock, P., Macura, B., Collins, A., 2015. Making literature reviews more reliable through application of lessons from systematic reviews. Conserv. Biol. 29 (6), 1596–1605.

Haddaway, N.R., Bernes, C., Jonsson, B.G., Hedlund, K., 2016. The Benefits of Systematic Mapping to Evidence-based Environmental Management, pp. 1–8. Ambio.

Hempel, G., 1985. Antarctic marine food webs. In: Siegfried, W.R., Condy, P.R., Laws, R.M. (Eds.), Antarctic Cycles and Food Webs. Springer-Verlag Berlin Heidelberg, pp. 266–270.

Hoekstra, P.F., O'hara, T.M., Pallant, S.J., Solomon, K.R., Muir, D.C.G., 2002. Bioaccumulation of organochlorine contaminants in bowhead whales (Balaena mysticetus) from Barrow, Alaska. Arch. Environ. Con. Tox. 42 (4), 497–507.

Hoekstra, P.F., Hara, T.M., Karlsson, H., Solomon, K.R., Muir, D.C., 2003. Enantiomer-specific biomagnification of α-Hexachlorocyclohexane and selected chiral chlordane-related compounds within an arctic marine food web. Environ. Toxicol. Chem. 22 (10), 2482–2491.

Hubold, G., 1985. The early life-history of the high-Antarctic Silver-fish Pleuragramma antarcticum. In: Siegfried, W.R., Condy, P.R., Laws, R.M. (Eds.), Antarctic Nutrient Cycles and Food Webs (Proceedings of the 4th SCAR Symposium on Antarctic Biology). Springer, Berlin Heidelberg New York, pp. 445–451.

Kim, J.T., Son, M.H., Kang, J.H., Kim, J.H., Jung, J.W., Chang, Y.S., 2015. Occurrence of legacy and new persistent organic pollutants in avian tissues from king George Island, Antarctica. Environ. Sci. Technol. 49 (22), 13628–13638.

Kim, J., Gobas, F.A., Arnot, J.A., Powell, D.E., Seston, R.M., Woodburn, K.B., 2016. Evaluating the roles of biotransformation, spatial concentration differences, organism home range, and field sampling design on trophic magnification factors. Sci. Total Environ. 551, 438–451.

Kwong, R.W., Yu, P.K., Lam, P.K., Wang, W.X., 2008. Uptake, elimination, and biotransformation of aqueous and dietary DDT in marine fish. Environ. Toxicol. Chem. 27 (10), 2053–2063.

Laender, F.D., Oevelen, D.V., Frantzen, S., Middelburg, J.J., Soetaert, K., 2009. Seasonal PCB bioaccumulation in an Arctic marine ecosystem: a model analysis incorporating lipid dynamics, food-web productivity and migration. Environ. Sci. Technol. 44 (1), 356–361.

Laender, F.D., Hammer, J., Hendriks, A.J., Soetaert, K., Janssen, C.R., 2011. Combining monitoring data and modeling identifies PAHs as emerging contaminants in the Arctic. Environ. Sci. Technol. 45 (20), 9024–9029.

Lakaschus, S., Weber, K., Wania, F., Bruhn, R., Schrems, O., 2002. The air-sea equilibrium and time trend of hexachlorocyclohexanes in the Atlantic Ocean between the Arctic and Antarctica. Environ. Sci. Technol. 36 (2), 138–145.

Lee, H., De Silva, A.O., Mabury, S.A., 2012. Dietary bioaccumulation of perfluorophosphonates and perfluorophosphinates in juvenile rainbow trout: evidence of metabolism of perfluorophosphinates. Environ. Sci. Technol. 46 (6), 3489–3497.

Löf, M., Sundelin, B., Bandh, C., Gorokhova, E., 2016. Embryo aberrations in the

amphipod Monoporeia affinis as indicators of toxic pollutants in sediments: a field evaluation. Ecol. Indic. 60, 18–30.
Mangano, M.C., O'Leary, B.C., Mirto, S., Mazzola, A., Sarà, G., 2015. The comparative biological effects of spatial management measures in protecting marine biodiversity: a systematic review protocol. Environ. Evid. 4 (1), 1.
Mangano, M.C., Sarà, G., 2017. Collating science-based evidence to inform public opinion on the environmental effects of marine drilling platforms in the Mediterranean Sea. J. Environ. Manag. 188, 195–202.
Mattila, T.J., Verta, M., 2008. Modeling the importance of biota and black carbon as vectors of polybrominated diphenyl ethers (PBDEs) in the Baltic Sea ecosystem. Environ. Sci. Technol. 42 (13), 4831–4836.
McKinney, M.A., McMeans, B.C., Tomy, G.T., Rosenberg, B., Ferguson, S.H., Morris, A., Muir, D.C., Fisk, A.T., 2012. Trophic transfer of contaminants in a changing arctic marine food web: cumberland Sound, Nunavut, Canada. Environ. Sci. Technol. 46 (18), 9914–9922.
McKinnon, M.C., Cheng, S.H., Garside, R., Masuda, Y.J., Miller, D.C., 2015. Sustainability: map the evidence. Nature 528, 185–187.
Moisey, J., Fisk, A.T., Hobson, K.A., Norstrom, R.J., 2001. Hexachlorocyclohexane (HCH) isomers and chiral signatures of α-HCH in the Arctic marine food web of the Northwater Polynya. Environ. Sci. Technol. 35 (10), 1920–1927.
Mongillo, T.M., Holmes, E.E., Noren, D.P., VanBlaricom, G.R., Punt, A.E., Neill, S.M., Ylitalo, G.M., Hanson, M.B., Ross, P.S., 2012. Predicted polybrominated diphenyl ether (PBDE) and polychlorinated biphenyl (PCB) accumulation in southern resident killer whales. Mar. Ecol. Prog. Ser. 453, 263–277.
Muir, D.C., Norstrom, R.J., 2000. Geographical differences and time trends of persistent organic pollutants in the Arctic. Toxicol. Lett. 112, 93–101.
Muir, D., Savinova, T., Savinov, V., Alexeeva, L., Potelov, V., Svetochev, V., 2003. Bioaccumulation of PCBs and chlorinated pesticides in seals, fishes and invertebrates from the White Sea, Russia. Sci. Total Environ. 306 (1), 111–131.
Nash, S.M.B., Poulsen, A.H., Kawaguchi, S., Vetter, W., Schlabach, M., 2008. Persistent organohalogen contaminant burdens in Antarctic krill (Euphausia superba) from the eastern Antarctic sector: a baseline study. Sci. Total Environ. 407 (1), 304–314.
Nash, S.B., Rintoul, S.R., Kawaguchi, S., Staniland, I., van den Hoff, J., Tierney, M., Bossi, R., 2010. Perfluorinated compounds in the Antarctic region: ocean circulation provides prolonged protection from distant sources. Environ. Pollut. 158 (9), 2985–2991.
Oehme, M., Schlabach, M., Hummert, K., Luckas, B., Nordøy, E.S., 1995. Determination of levels of polychlorinated dibenzo-p-dioxins, dibenzofurans, biphenyls and pesticides in harp seals from the Greenland Sea. Sci. Total Environ. 162 (2), 75–91.
Ottar, B., 1981. The transfer of airborne pollutants to the Arctic region. Atmos. Environ. 15 (8), 1439–1445 (1967).
Poulsen, A.H., Landrum, P.F., Kawaguchi, S., Nash, S.M.B., 2013. Dietary exposure of Antarctic krill to p, p′-DDE: uptake kinetics and toxicological sensitivity in a key polar species. Environ. Pollut. 175, 92–99.
Randall, N.P., James, K.L., 2012. The effectiveness of integrated farm management, organic farming and agri-environment schemes for conserving biodiversity in temperate Europe-A systematic map. Environ. Evid. 1 (1), 1.
Regoli, F., Nigro, M., Benedetti, M., Gorbi, S., Pretti, C., Gervasi, P.G., Fattorini, D., 2005. Interactions between metabolism of trace metals and xenobiotic agonists of the aryl hydrocarbon receptor in the antarctic fish Trematomus bernacchii: environmental perspectives. Environ. Toxicol. Chem. 24 (6), 1475–1482.
Ruus, A., Ugland, K.I., Espeland, O., Skaare, J.U., 1999. Organochlorine contaminants in a local marine food chain from Jarfjord, Northern Norway. Mar. Environ. Res. 48 (2), 131–146.
Sagerup, K., Henriksen, E.O., Skaare, J.U., Gabrielsen, G.W., 2002. Intraspecific variation in trophic feeding levels and organochlorine concentrations in glaucous gulls (*Larus hyperboreus*) from Bjørnøya, the Barents Sea. Ecotoxicology 11 (2), 119–125.
Sladen, W.J., Menzie, C.M., Reichel, W.L., 1966. DDT residues in Adelie penguins and a crabeater seal from Antarctica: ecological implications. Nature 210 (5037), 670–673.
SNAP working group http://snappartnership.net/groups/.
Sobek, A., Reigstad, M., Gustafsson, Ö., 2006. Partitioning of polychlorinated biphenyls between Arctic seawater and size-fractionated zooplankton. Environ. Toxicol. Chem. 25 (7), 1720–1728.
Sobek, A., McLachlan, M.S., Borgå, K., Asplund, L., Lundstedt-Enkel, K., Polder, A., Gustafsson, Ö., 2010. A comparison of PCB bioaccumulation factors between an arctic and a temperate marine food web. Sci. Total Environ. 408 (13), 2753–2760.
Sørmo, E.G., Jussi, I., Jussi, M., Braathen, M., Skaare, J.U., Jenssen, B.M., 2005. Thyroid hormone status in gray seal (Halichoerus grypus) pups from the Baltic Sea and the Atlantic Ocean in relation to organochlorine pollutants. Environ. Toxicol. Chem. 24 (3), 610–616.
Stockholm Convention (SC), 2004. Stockholm Convention available at: http://chm.pops.int/default.aspx.
Strobel, A., Schmid, P., Segner, H., Burkhardt-Holm, P., Zennegg, M., 2016. Persistent organic pollutants in tissues of the white-blooded Antarctic fish *Champsocephalus gunnari* and *Chaenocephalus aceratus*. Chemosphere 161, 555–562.
Tomy, G.T., Budakowski, W., Halldorson, T., Helm, P.A., Stern, G.A., Friesen, K., Pepper, K., Tittlemier, S.A., Fisk, A.T., 2004. Fluorinated organic compounds in an eastern Arctic marine food web. Environ. Sci. Technol. 38 (24), 6475–6481.
van de Merwe, J.P., Chan, A.K., Lei, E.N., Yau, M.S., Lam, M.H., Wu, R.S., 2011. Bioaccumulation and maternal transfer of PBDE 47 in the marine medaka (Oryzias melastigma) following dietary exposure. Aquat. Toxicol. 103 (3), 199–204.
Vieweg, I., Hop, H., Brey, T., Huber, S., Ambrose, W.G., Gabrielsen, G.W., 2012. Persistent organic pollutants in four bivalve species from Svalbard waters. Environ. Pollut. 161, 134–142.
Wallberg, P., Jonsson, P.R., Andersson, A., 2001. Trophic transfer and passive uptake of a polychlorinated biphenyl in experimental marine microbial communities. Environ. Toxicol. Chem. 20 (10), 2158–2164.
Wania, F., 2003. Assessing the potential of persistent organic chemicals for long-range transport and accumulation in polar regions. Environ. Sci. Technol. 37 (7), 1344–1351.
Wolkers, H., Corkeron, P.J., Van Parijs, S.M., Similä, T., Van Bavel, B., 2007. Accumulation and transfer of contaminants in killer whales (Orcinus orca) from Norway: indications for contaminant metabolism. Environ. Toxicol. Chem. 26 (8), 1582–1590.