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Plastics as a carrier of chemical additives to the Arctic: possibilities for strategic monitoring across the circumpolar North

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Abstract

Plastic pollution (including microplastics) has been reported in a variety of biotic and abiotic compartments across the circumpolar Arctic. Due to their environmental ubiquity, there is a need to understand not only the fate and transport of physical plastic particles, but also the fate and transport of additive chemicals associated with plastic pollution. Further, there is a fundamental research gap in understanding long-range transport of chemical additives to the Arctic via plastics as well as their behavior under environmentally relevant Arctic conditions. Here, we comment on the state of the science of plastic as carriers of chemical additives to the Arctic, and highlight research priorities going forward. We suggest further research on the transport pathways of chemical additives via plastics from both distant and local sources and laboratory experiments to investigate chemical behavior of plastic additives under Arctic conditions, including leaching, uptake, and bioaccumulation. Ultimately, chemical additives need to be included in strategic monitoring efforts to fully understand the contaminant burden of plastic pollution in Arctic ecosystems.

Key words: chemical contaminants, plastic additives, fate and transport, monitoring

Introduction

Plastic pollution, including microplastics (<5 mm), has become of increasing concern in the Arctic. Plastic particles can be transported to the Arctic via ocean currents, rivers and the atmosphere (Cózar et al. 2017; references therein Halsband and Herzke 2019; Bourdages et al. 2021); intra-Arctic pathways, e.g., sea ice, have also been shown (Obbard et al. 2014; Peeken et al. 2018; Sun et al. 2020). Unlike most environmental contaminants studied to date, plastic material (including microplastics) is a complex chemical matrix consisting of the polymer, as well as additional compounds, intentionally added to the polymer material, or sorbed from the environment (Fauser et al. 2022). Plastic additives can be metals, organic, and/or inorganic compounds mixed into the plastic polymer to give it desired characteristics or functions. Important additives include plasticizers, flame retardants, UV stabilizers, pigments, and antioxidants (Kühn et al. 2020). To date, there are over 10 000 different chemicals known to be used as plastic additives throughout the manufacturing process (Wiesinger et al. 2021). These compounds are generally mixed into plastic during production without any chemical bonds to the polymers, which means that they can leach out of the plastic, and into the surrounding environment (Hahladakis et al. 2018). While the concern around most plastic pollution has been the impacts from the physical plastics themselves (Bucci et al. 2020), there is growing concern about plastic additives and their environmental and health effects (Gallo et al. 2018; Campanale et al. 2020). Some plastic additives, for example phthalates used as plasticizers, are known to be endocrine disruptors (Meeker et al. 2009; Barrios-Estrada et al. 2018). Further, a recent study showed serious effects of various bisphenols on brain function in adult vertebrates at environmentally relevant concentrations (Schirmer et al. 2021). Additionally, a recent review of metal additives from ingested plastics in fish, suggests that some metals can be bioavailable enough to present a potential risk to fish health (Catrouillet et al. 2021).

While the monitoring of physical plastic pollution in the Arctic (and globally) is in its infancy (AMAP 2021*a*), chemical contaminants monitoring in the Arctic has been conducted for several decades (AMAP 2016, 2018). Details of these programs are defined nationally, but generally focus on informing food safety for Indigenous and northern communities, as well as tracking trends in contaminants to inform regulatory processes. The monitoring of chemical contaminants across the Arctic has been an important component of the global contaminant monitoring effort, and has led to a foundational understanding of the fate and effects of chemical contaminants. The monitoring of organic contaminants in the Arctic has a particularly close link to the Stockholm Convention, a treaty of the United Nations Environment Program (UNEP) which entered into force in 2004 and regulates persistent organic pollutants (POPs) at the global level (UNEP 2020*a*; Steindal et al. 2021). Under the Stockholm Convention, POPs are defined as those compounds that are persistent, bioaccumulate, toxic, and can be transported over long distances. Thus, data from remote locations in the Arctic have an important indicator function in the screening of POP criteria for newly nominated compounds. In addition, Arctic monitoring data are used for effectiveness evaluations of the Stockholm Convention under the Global Monitoring Plan. Given the multitude of chemicals added to plastic polymers, the question arises whether their transport in or on a plastic particle can also be considered long-range transport (Andrade et al. 2021). The compound UV-328—a phenolic benzotriazole (BZT) used as a UV absorber in plastics—was recently proposed for regulation through the Stockholm Convention, including the consideration that long-range transport could take place with plastic particles (UNEP 2020*b*).

The monitoring of physical litter and microplastic in the Arctic has been initiated in some northern regions, and immediate baseline and time trend monitoring across the Arctic has been recommended for biotic and abiotic environmental media (AMAP 2021*a*; Provencher et al. 2022). To date, less attention has been paid to the monitoring of plastic additives in the Arctic (or any other region), which would improve our understanding of complex transport, leaching, and uptake processes. Those additives that are POPs are typically monitored (e.g., polybrominated diphenyl ethers, PBDEs), but little is known about other chemicals associated with plastic pollution. The goal of this paper is to review and discuss the state of the science regarding plastic particles as carriers of chemical additives to the Arctic and propose research and monitoring priorities in Arctic ecosystems, and globally.

Fate and transport of plastics in the Arctic

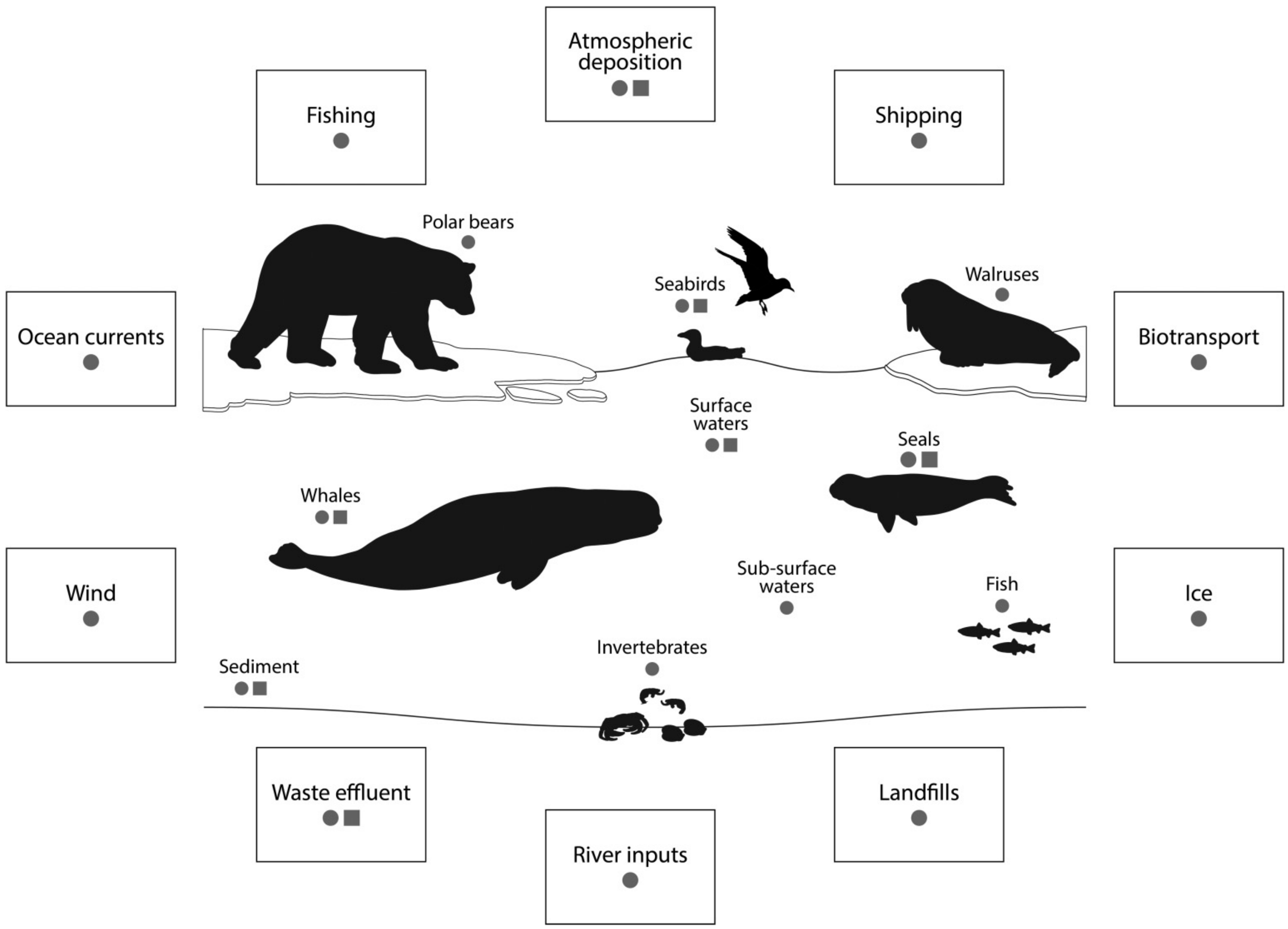
Most studies on the transport of plastics to remote locations, including the Arctic, have focused on the marine environment (Fig. 1). Ocean currents are important carriers of plastic materials to the Arctic, through, for example, the North Atlantic Thermohaline Circulation (Cozar et al. 2017), wave-driven Stokes drift (Onink et al. 2019), and, on a more local or regional level, by sea ice (Obbard et al. 2014; Peeken et al. 2018). The characteristics of different plastic particles including particle density, buoyancy, size, and the susceptibility to biological processes such as biofouling, have an impact on their fate in the marine system. Given that ocean currents are important vehicles for plastic transport to the Arctic, these currents will concomitantly transport chemical additives (Andrade et al. 2021).

There is also increasing evidence of long-range atmospheric transport of plastic pollution to remote locations, far removed from urban landscapes. Recent studies evaluating microplastics in snow from high alpine and sub-Arctic locations in Europe suggest that airborne transport of microplastics to the Arctic takes place as well (Allen et al. 2019; Bergmann et al. 2019; Napper et al. 2020). There is also evidence of dry deposition of microplastic particles in the Arctic as shown through the deployment of dry-dust collectors on Baffin Island (Hamilton et al. 2021). However, it remains unclear whether precipitation or snow deposits are a good proxy for deposition of airborne microplastics (Hamilton et al. 2022) as precipitation can vary substantially in the Arctic, and is increasing because of warming climate conditions (AMAP 2021*b*). Moreover, empirical data on microplastic circulation through atmospheric pathways is lacking (PAME 2019).

Migratory animals can act as biovectors for the transport of contaminants to the Arctic (e.g., Blais et al. 2005; Vorkamp et al. 2018; Bourdages et al. 2021), and long-range transport of contaminants by migratory species is a recognized mechanism by the Stockholm Convention (Idowu et al. 2013; UNEP 2020*a*). This occurs as migratory animals can ingest prey, plastic particles, or refuse in more contaminated locations and carry associated pollutants in their guts or tissues to the Arctic where the contaminants are then released to the environment via excretion (e.g., guano; Bourdages et al. 2021), or decomposition (i.e., when the animal dies). While the Arctic is the summer breeding region to millions of seabirds, and hundreds of thousands of mammals that move in and out of the region annually, currently biota as a vector to the Arctic is thought to be minimal for most contaminants compared to atmospheric and oceanic pathways (Wania 1998; CACAR 2017). While biovectors are well studied in both chemical contaminants and nutrients (e.g., Brimble et al. 2009; González-Bergonzoni et al. 2017; Mosbech et al. 2018), only a handful of studies have examined how plastic pollution may be moved from the marine environment to terrestrial sites via birds (Hammer et al. 2016; Bourdages et al. 2021; Grant et al. 2021; Hamilton et al. 2021).

Local sources of plastic pollution in the Arctic include wastewater and land-based waste storage (Granberg et al. 2019; von Friesen et al. 2020; Herzke et al. 2021), sewage and waste dumped from various types of ships (Grøsvik et al. 2018), and lost fishing gear (Tekman et al. 2017), as also reviewed by PAME (2019). In addition, sea ice, glaciers, and snow can be considered secondary microplastic sources (e.g., Obbard et al. 2014; Peeken et al. 2018; von Friesen et al. 2020). The relative importance of local and distant sources of plastic pollution is poorly investigated in the Arctic. The entrenched view of this sparsely populated region is that pollution is imported from southern, more densely populated regions (Macdonald et al. 2000), yet four million people inhabit the Arctic region (Heleniak and Bogoyavlensky 2014), and over 38 million people live in the watersheds that drain into the Arctic Ocean (PAME 2019). Thus, infrastructure such

Fig. 1. Environmental compartments where microplastics (circles) and plastic additives (squares) have been found in the Arctic. Outer rectangles represent sources of microplastics and/or plastic additives to the Arctic.



as wastewater treatment and waste management that is generally lacking in communities in the Arctic (Gunnarsdóttir et al. 2013; Granberg et al. 2020; Herzke, et al. 2021), is an important consideration in understanding plastic pollution, as contributions from these local sources and pathways alone may be greater than anticipated.

Understanding transport pathways of plastic pollution is critical for an effective management towards reduced pollution. When investigating microplastic pollution in shallow coastal waters where land-sea or river-sea interactions are strong, local land-based inputs can be specifically targeted (e.g., Magnusson et al. 2016; Granberg et al. 2020; Dahl et al. 2021; Herzke et al. 2021), and this also extends to contaminants associated with plastics. Research studying the contaminants found on plastic pellets in water bodies in Brazil, Australia, and New Zealand suggests the contaminants found within each water body (e.g., dichlorodiphenyltrichloroethane (DDT), polycyclic aromatic hydrocarbons, polychlorinated biphenyls (PCBs), hexachlorocyclohexane) directly influence the contaminants identified on the plastics (Verla et al. 2019); thus, acting like a passive sampler. Similarly, plastic pellets on beaches were found to have elevated levels of some contaminants linked with local activities such as agriculture and coal burning in China (Zhang et al. 2018). Previous literature on contaminants and beached plastic pollution has even recommended using plastic pellets as a way to monitor POPs in the environment (e.g., Mato et al. 2001), and some programs have implemented this (e.g., International Pellet Watch, www.pelletwatch.org). Thus, tracing environmental plastic pollution upstream can provide important information about sources and original use including an integrated picture of associated chemicals.

Plastic materials as chemical vectors

Plastic particles can transport chemical additives in addition to environmental contaminants that may sorb to their surfaces. Studying and tracking these chemicals in the environment is confounded by the fact that it is difficult to retrieve information on additives due to intellectual property protections instituted by manufacturers and (or) complex trade processes. Furthermore, while additives can be independently toxic (Fauser et al. 2020; Tian et al. 2021; Catrouillet et al. 2021), it will be relevant to consider mixture effects due to the commercial use of mixtures and the co-occurrence of contaminants from the environment (Sühring et al. 2022). Plastic additives have been identified in biotic and abiotic matrices for several decades, for example, UV-BZTs in sediments in the eastern USA, with elevated levels of plastic additives near point sources dating back to the 1960s (Cantwell et al. 2015). Regarding the Arctic, additives previously used in plastics (e.g., PBDEs) but now regulated as POPs have been part of monitoring programs for several years, while studies on other plastic additives are limited (AMAP 2017).

Due to the environmental degradability of most additive compounds (except for some PBDEs), the detection of these chemicals in Arctic regions suggest plastic particles as a transport vector (either oceanic or atmospheric; Andrade et al. 2021). However, these studies are limited in characterizing the environmental fate of these plastic additives and their exposure to wildlife, as they cover only few compounds and matrices in disparate locations. Currently, there is no monitoring effort in place to strategically and consistently evaluate current-use plastic additives across the circumpolar North. Due to their large environmental emissions, sources of chemical additives associated with plastics (e.g., phthalates and bisphenol A) are difficult to directly link to plastic pollution, and uncertainty remains regarding the extent and mechanisms of long-range transport of some chemical substances used as additives. However, long-range transport of plastic particles can also result in long-range transport of the chemicals contained within the particle.

The transport of plastic additives with migratory species can take place via ingestion of plastic particles on migratory routes. The ingestion of plastics (and consequently, plastic chemical additives) has been studied in the Arctic in a variety of wildlife species, including whales and a number of seabird species, which can migrate over long distances (Lusher et al. 2022). Independent of migratory behaviour, numerous free-ranging Arctic vertebrates are likely regularly exposed to plastic additives upon ingestion of plastic particles. To date, ingestion of plastic particles has been studied in over 50 seabird species (reviewed by Baak et al. 2020), numerous Arctic fish (e.g., Arctic cod and capelin; see Kögel et al. 2022), seals (Bourdages et al. 2020, Pinzone et al. 2021), whales (Moore et al. 2020), polar bears (Russell 1975), and walrus (Carlsson et al. 2021).

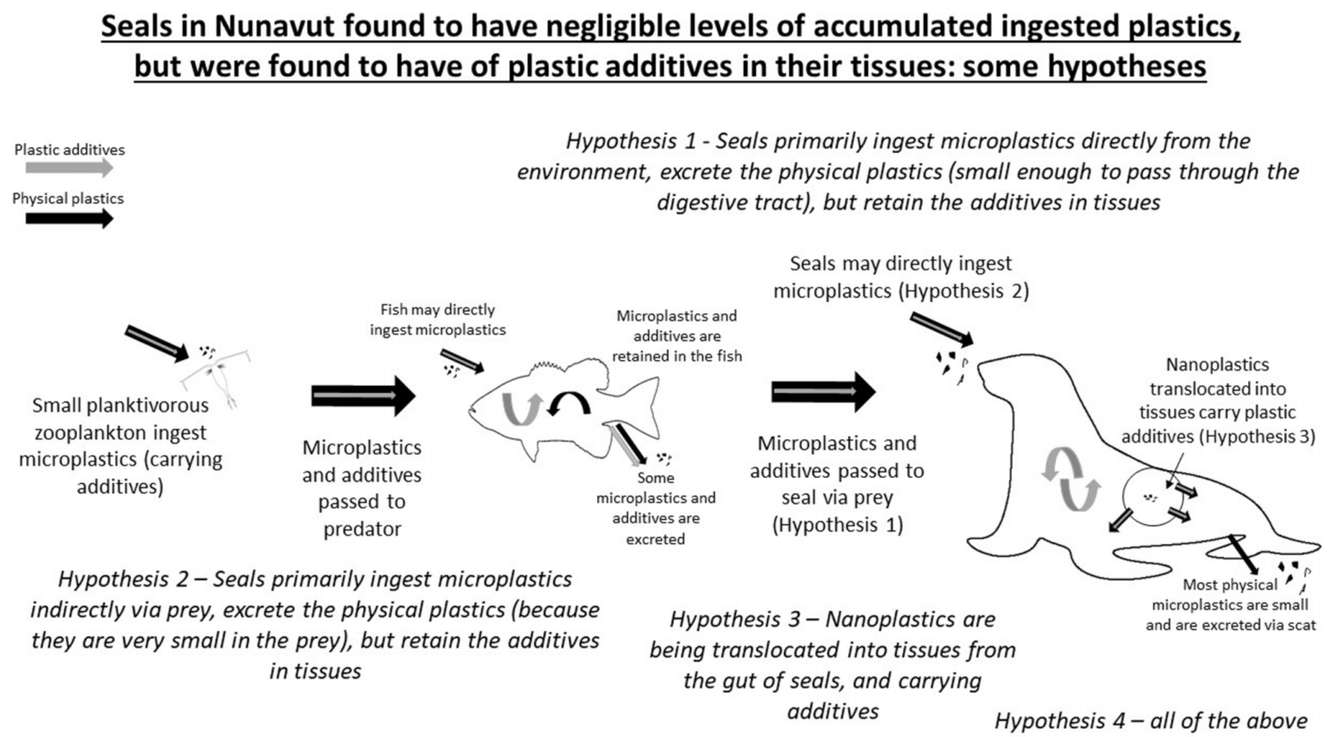
While POPs are regularly and widely monitored in wildlife across the Arctic region (AMAP 2018; Rigét et al. 2019), only a handful of studies have examined contaminants specifically in relation to plastic pollution and plastic additives. The majority of published literature on current-use plastic additives in the Arctic has mainly focused on field observations of seabirds and seals. These studies have examined substituted diphenylamine antioxidants (SDPAs), UV-BZTs (Lu et al. 2019), and phthalates (Padula et al. 2020). Several studies have examined legacy contaminants, such as PCBs and other POPs, in relation to plastic ingestion by Arctic wildlife, mainly in seabirds (Herzke et al. 2016; Provencher et al. 2018). For example, while studies to date have not detected a relationship between accumulated ingested plastics and PCBs and other POPs in northern fulmars (*Fulmarus glacialis*, a seabird species with particularly high levels of accumulated plastics), one study found that fulmars with elevated plastic ingestion had greater variability in contaminant concentrations that might be linked to exposure from plastic ingestion (Trevail et al. 2014). Studies from outside the Arctic indicate that less biomagnifying POPs, e.g., lower chlorinated PCB congeners, in seabirds may be related to plastic particles as an exposure source (Tanaka et al. 2019).

Beyond these field-based, observational studies in wild free-ranging seabirds, there are few experimental studies evaluating the movement of plastic additives from a microparticle to its surrounding environment. For example, Kühn et al. (2020), evaluated additives (e.g., plasticizers, antioxidants, UV stabilizers, flame retardants, and preservatives) in leachate from plastics in fulmar stomach oil under realistic gut conditions. A subset of the target additives was shown to leach into stomach oil, suggesting seabirds could be susceptible to additive chemical exposure through plastic ingestion (Kühn et al. 2020). More work has examined these patterns in species outside the Arctic (Tanaka et al. 2013; 2015; 2020), and while the general biochemical properties are likely the same, it is unknown if Arctic species have undergone similar processes in the wild.

Studies have begun to evaluate the relationship between plastic pollution and burdens of plastic related additives in wildlife through observational field studies. Recently, Sühring et al. (2022) evaluated the occurrence and patterns of organic and inorganic chemicals associated with plastic pollution in Arctic-breeding northern fulmars and black-legged kittiwakes (*Rissa tridactyla*). They found higher levels of plastic contamination and plastic additives in fulmars than kittiwakes; fulmars also had higher plastic pollution levels and subsequent contaminant burdens (Suhring et al. 2022). Further, Lu et al. (2019) examined SDPAs and UV-BZTs in two seabird species and ringed seals (*Pusa hispida*) in the Canadian Arctic, based on the hypothesis that the species with the highest reported levels of plastic ingestion (the northern fulmar) would have the highest levels of plastics additives, as found by Sühring et al. 2022. However, Lu et al. (2019) found that both northern fulmars and black-legged kittiwakes showed similar levels of these additives but higher hepatic concentrations of SDPAs than seals. Lu et al. (2019) also found higher levels of UV-BZTs in ringed seals than in the two seabird species examined. The differing patterns between the two plastic additive groups suggest that the processes influencing plastic additive concentrations in seals and seabirds are different. Therefore, species-specific ecology, exposure, and metabolism are important factors in how plastic additives are taken up by and possibly accumulate in Arctic wildlife.

The findings by Lu et al. (2019) raise the question, how ringed seals in the Canadian Arctic are exposed to plastic additives. In a follow-up study, over 140 seals from Nunavut (Canada) were examined for accumulated particles (Bourdages et al. 2021). However, no plastic particles (above 425 μm) were detected, unlike the results for seabirds (Bourdages et al. 2021). Together, these findings suggest that those species that ingest and accumulate the highest levels of plastic pieces are not necessarily the same species that may be accumulating plastic additives in their tissues (Fig. 2), although further studies are needed to examine plastic addi-

Fig. 2. Multiple hypotheses for the various exposure routes of plastic additives to Arctic wildlife using seals as an example.



tives and small size classes of plastic particles that may be missed using conventional techniques for marine megafauna (i.e., nanoplastics).

A growing number of studies suggest that microplastic ingestion in invertebrates may depurate already contaminated tissues from pollutants (Gerdes et al. 2019; Heinrich and Braunbeck 2020; Wang et al. 2019). Plastic particles with a higher fugacity capacity than the surrounding tissues can adsorb pollutants in the guts; thus, can result in a detoxifying mechanism for the organism (Koelmans et al. 2013; Thaysen et al. 2020). These findings complicate the view of microplastics as vectors for chemical pollution. Further, the environmental occurrence of these compounds is not widely studied, and additional routes of exposure (e.g., prey and water) may be relevant. These collective findings suggest that the biological uptake of additive contaminants may not be straightforward but rather complex and species as well as compound dependent. It also highlights that while it is meaningful to combine monitoring initiatives for plastic pollution and plastic additives, they should be also considered in the larger context of the fate and effects of environmental contaminants.

Challenges, knowledge gaps, and ways forward

Long-range transport vs. local sources of plastic pollution

In the context of the Stockholm Convention and the question whether the transport of plastic-associated chemicals via plastic particles can be considered long-range transport, it will be essential to discriminate between local sources and long-range transport. At present, this is a field of ongoing research in the Arctic. Sources and transport pathways for plastic particles to the Arctic are not well-understood, however, monitoring strategies have been proposed for source and surveillance monitoring in the Arctic (AMAP 2021*a*; Provencher et al. 2022).

Several compounds previously used as additives in plastics (e.g., PBDEs) are monitored in the Arctic, including Arctic biota, and other compounds used as additives (e.g., organophosphate flame retardants, phthalates, siloxanes) have been included in more research-oriented screening initiatives (AMAP 2017). However, their presence in the Arctic environment does not give information about the transport pathway (e.g., particle bound or as a free molecule; local vs. long-range transport; Fig. 1). Understanding the relationship between sources, long-range transport, plastic emissions, and additive concentrations in the environment is important for regulators, both regarding plastic pollution and chemical management. As we begin to understand the global emission of plastics, we also need to address regional emissions of plastic pollution in the circumpolar Arctic. Transport models for ocean currents and air masses are needed to fully understand the extent to which each transport mechanism contributes to the overall input of microplastics, as well as their interactions. As an integrated part of understanding the inputs of plastics to the Arctic, and the types of plastic most commonly found, we should also address sources and transport mechanisms of additive chemicals.

Investigating the behavior of plastic additives: leaching, uptake processes, bioavailability, and biomagnification/dilution

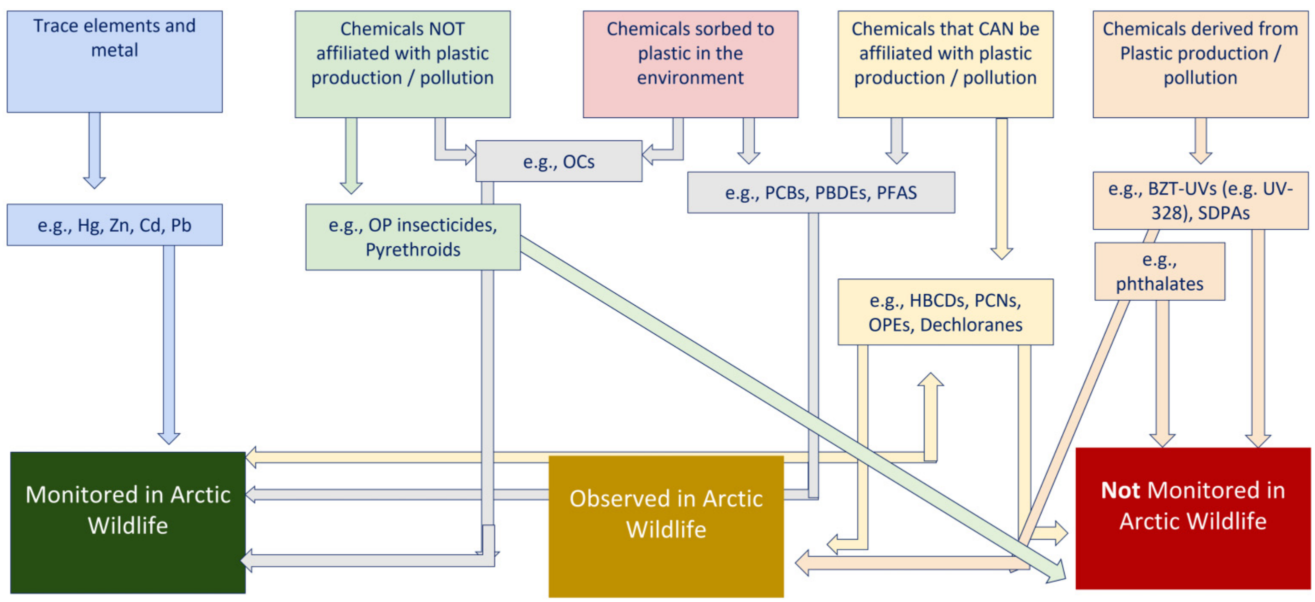
Leaching of plastic additives to seawater can take place while the plastic particle is transported with ocean currents or rivers. Leaching can also take place in the gut of an animal after uptake of plastic particles. Thus, Arctic animals can be exposed to plastic additives after direct uptake of plastic particles and from the surrounding environment. Current findings suggest that oily components in animal stomachs might favor the leaching of hydrophobic compounds, compared to seawater (Tanaka et al. 2015; 2019); the transfer of highly brominated PBDEs has also been shown (Rochman et al. 2013; 2014). However, in instances where the concentration difference and subsequent fugacity gradient of a chemical favours movement from the tissue of an organism to ingested plastic particles, a "detoxification" effect is observed (Koelmans et al. 2016); thus, potentially reducing the chemical concentration present in an organism (Mohammed Nor and Koelmans 2019; Heinrich and Braunbeck 2020; Thaysen et al. 2020). Exposure processes are not understood in detail, neither qualitatively nor quantitatively, and could be supported by targeted laboratory studies. A risk assessment of plastic additives to marine organisms was recently reviewed by Fauser et al. (2022), including detailed descriptions on the current knowledge of leaching, uptake, and bioavailability of chemical additives. However, the migration of chemicals (e.g., leaching, adsorption/desorption) is slower in colder regions due to temperature-dependent diffusion and partitioning processes; thus, a need to evaluate the behavior of plastic additives under relevant Arctic conditions.

The chemical fingerprint of a piece of plastic is complex and highly individual; plastic additives are a chemical mixture and should be evaluated as such. New developments in analytical chemistry, involving high resolution mass spectrometers, i.e., non-target and suspect screening, can enable the screening of a broad range of compounds in a given sample, e.g., biota or plastics (Ballesteros-Gómez et al. 2016; Hajeb et al. 2022). These techniques usually aim at identification rather than quantification of chemicals and might also result in a tentative identification, associated with a certain degree of uncertainty (Schymanski et al. 2015). However, they can be an important first-step tool in identifying specific chemicals in a complex mixture and matrix.

Studies have begun to evaluate the components that make up a plastic additive mixture and their potential toxicological effects (e.g., tire leachate, Tian et al. 2021; Chibwe et al. 2021; McIntyre et al. 2021; Halsband et al. 2020). For example, Chibwe et al. (2021) aimed to characterize the toxicity and chemical mixture of organic chemicals affiliated with tire particle leachate (Chibwe et al. 2021). Through various exposures of tire leachate to fathead minnow (*Pimephales promelas*), higher proportion of toxic effects were observed when dosed with 10-d leachate and unfiltered leachates. While the authors were able to determine that benzothiazoles and arylamines were correlated with toxic effects, there are many other chemicals that could be contributing to the overall toxicity (Chibwe et al. 2021); thus, further validating the complexity of plastic additive mixtures. Often combined with non-target screening techniques, effect-directed analyses use toxicity assays to determine whether a certain sample exhibits a toxic effect. In step-wise approaches, the complexity of the sample is reduced and candidates for an observed toxic effect are attempted to be identified. These approaches have been applied to plastics to a limited extent (Schönlau et al. 2019) and offer possibilities of addressing toxicity and chemical identification in a complex setting. Additionally, new effects monitoring tools can be used to determine contaminant burdens across species. For example, Zahaby et al. (2021) developed a toxicogenomics approach (ToxChip) to understand the contaminant burden of polycyclic aromatic compounds and trace elements in seabird populations in the Baffin Bay-Davis Strait Region of the Canadian Arctic Archipelago. This ToxChip approach was created to identify/monitor avian populations following oil spills—a concern in the BBDS region as shipping traffic increases as a result of climate change. Zahaby et al. (2021) determined contaminant burden in the livers of thick-billed murres (*Uria lomvia*) and black guillemont (*Cepphus grylle*) but also successfully distinguished between the two distinct colonies of seabirds based on the genomic expression of genes known to be associated with contaminants exposure (Zahaby et al. 2021). Such novel approaches to effects monitoring are important in developing robust and consistent monitoring efforts across the pan-Arctic that consider cumulative and interactive effects of contaminants mixtures, like plastic additives

When assessing the exposure, uptake, and effects of a pollutant, time is a very important factor (Newman 2009) that needs consideration. There is currently no clear consensus on the retention time of ingested plastic in aquatic species and it is likely variable based on particle morphology and species-specific ecology. For example, it is estimated that 75% of plastic in fulmars is expelled after 30 days, and all of it is lost after 51–76 days (van Franeker and Law 2015). However, estimates of wear rates suggest that retention time can be far longer (Ryan 2015), potentially as much as 269 days (Ryan and Jackson 1987). In a recent experimental study, a seabird's gizzard was simulated and a logarithmic increase in lead (Pb) emitted from polyurethane foam was seen over time, with a maximum reached at 220 hours (Turner and Lau 2016). Additionally, Pb derived from microplastics has been shown to be bioavailable to zebrafish post microplastic ingestion (Boyle et al. 2020). Yet, when plastic additives have been investigated in relation to plastic ingestion in ringed seals in the Canadian Arctic, plastic additives in tissues were present (Lu et al. 2019), while plastic in the GIT was absent (Bourdages et al. 2020). Not only does this highlight the need to understand retention time of plastic ingestion in nature, but also underscores the need to consider different exposure pathways and species-specific ecology when assessing plastic additives in nature (Fig. 2). Ultimately, field observations and monitoring of plastic additives need to be combined with controlled laboratory experiments to understand environmental fate as well as toxicity drivers, mechanisms, behavior, and toxicokinetics for this class of emerging chemicals of concern.

Fig. 3. Schematic outlining the multiple contaminant classes monitored, observed, and not monitored in Arctic wildlife. OP, organophosphorus; OCs, organochlorines; PCBs, polychlorinated biphenyls; PBDEs, polybrominated diphenyl ethers; PFAS, per- and polyfluoroalkyl substances; HBCDs, hexabromocyclodecanes; PCNs, polychlorinated napthalenes; OPEs, organophosphate esters; BZT-UVs, benzotriazole UV stabilizers; SDPAs, substituted diphenylamine antioxidants.



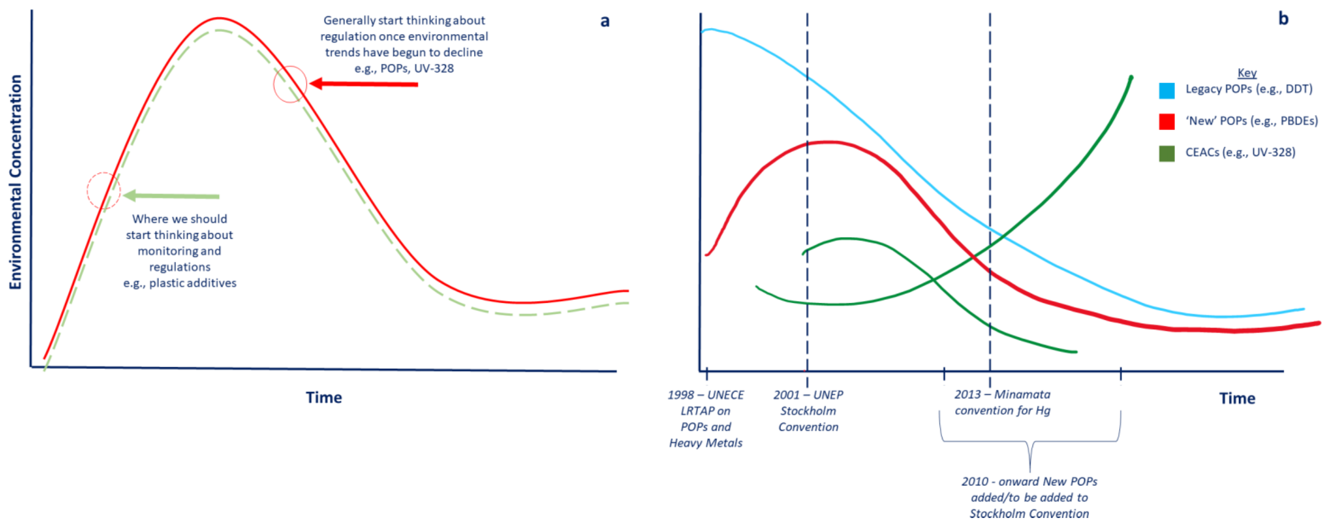
Prioritizing plastic additives for monitoring in the Arctic

Plastic additives are an inherently complex mixture and do not fit into a single category or class of chemicals. Not only do these compounds range in function (e.g., plasticizers, flame retardants, surfactants, etc.) and chemical structure, they also range in their affiliation with plastic polymers. (Fig. 3). This poses an added challenge in parsing out persistent chemicals that were once used in plastic production and replaced with structurally similar chemicals which might have also similar physical–chemical characteristics and a similar fate in the environment (e.g., brominated flame retardants; BFRs; Vorkamp et al. 2019), and other additive chemicals affiliated with plastic production and pollution (e.g., phthalates and UV-BZTs; Fig. 3).

While a variety of persistent chemicals once affiliated with plastics are widely monitored in the Arctic (e.g., PBDEs), current efforts provide no way to determine if these chemicals were transported to the Arctic via plastics, or through other established long-range transport pathways. However, some studies do provide evidence for the transfer of chemicals from plastics. For example, Neumann et al. (2021) identified decabromodiphenyl ether (BDE-209) in liver tissues of northern fulmars that had plastics in their gastrointestinal tract, but BDE-209 was absent in individuals that did not have plastics in their stomachs. Similarly, Tanaka et al. (2013) detected BDE-209 and BDE-183 in short-tailed shearwater (*Ardenna tenuirostris*) adipose tissue and in plastic in their stomachs, but these additives were not found in their prey. These results suggest that these contaminants are also transferred from ingested plastic, not only through trophic transfer (Tanaka et al. 2013; Neumann et al. 2021), though some prey species can contain these contaminants (e.g., Fjeld et al. 2004 in Neumann et al. 2021). Tanaka et al. (2019) made the point that within the group of POPs, individual compounds that biomagnify less than others, might originate from plastic particles, when detected in animals, for example, lower chlorinated PCB congeners and BDE-209 (Tanaka et al. 2019). This highlights the importance of considering multiple pathways of exposure, such as microplastics and diet, to understand sources of more accurately and exposure to chemical contaminants in the Arctic. Additionally, a variety of modeling efforts estimating the transport scenarios of additives, can assist in the evaluation of potential sources.

At this point in time, we have limited information on a variety of plastic-associated contaminant groups relevant for monitoring in the Arctic environment, such as, but not limited to, organophosphate flame retardants, PCBs, SDPAs, and UV-BZTs, etc., in biota and/or abiotic media (e.g., Herzke et al. 2016; Provencher et al. 2018; Sühring et al. 2016; Lu et al. 2019; De Silva et al. 2020; Neumann et al. 2021; Sühring et al. 2021). PCBs and PBDEs are widely included in contaminant monitoring programs of the Arctic (AMAP 2016; AMAP 2018; Rigét et al. 2019; Wong et al. 2021). However, their presence in Arctic matrices is not commonly studied in relation to plastic pollution. Thus, a large knowledge gap remains on how plastics may act as a transporter for these contaminants in the Arctic. Consequently, at this stage, choosing one focal compound may not be the best approach. Instead, a multi-faceted, collaborative approach coupling contaminant and plastic pollution studies appears to be the most efficient way forward. In an event where co-sampling for multiple purposes cannot occur, samples should be stored properly to allow additional uses and future evaluation. Interdisciplinary collaboration among institutions at a Pan-Arctic scale can lead to sam-

Fig. 4. (*a*) Graph depicting the ideal time to monitor and regulate contaminants in relation to environmental concentrations; (*b*) Graphic depicting contaminant trends and relevant regulation timelines as it has occurred historically.



ples being utilized for more than one purpose, cost-efficient, and a more holistic view of these emerging issues. Given this, it is important to reiterate the need for harmonized analyses and reporting to ensure comparability across studies, as also discussed by Provencher et al. 2022).

What about metals and other environmental inorganic contaminants that might be associated with plastic?

Plastic additives can also contain a variety of metals and their salts, with a primary role as inert fillers, pigments, or stabilizers (Murphy et al. 2001; Janssen and Spijker 2016). These metal-based additives often include toxic heavy metals (e.g., arsenic, cadmium, lead; Turner and Filella 2021). While studies have focused on metals adsorbing to plastic through environmental exposure, there is growing concern regarding metals as additives as they have been shown to be more bioavailable than metals sorbed to the surface (Turner and Filella 2021). Examining trace elements (e.g., metals) and other environmental contaminants at the same time as plastic chemical additives can be beneficial for multiple reasons. As described for POPs, long-term monitoring programs have been established in the Arctic to assess levels, trends and effects of metals and can be built upon to include other contaminants of concern (e.g., plastic additives). For example, mercury has been monitored in the Canadian Arctic through Canada's Northern Contaminants Program (NCP) for the last three decades. This program began in 1991 by obtaining baseline data of Hg in a variety of environmental compartments across Canada's North, including freshwater, terrestrial and marine biota, as well as in the atmosphere (CARCAR 2012). These data have since been used to assess the sources, processes and pathways of Hg in the Canadian Arctic (e.g., AMAP 2005), spatial and temporal trends of Hg in various environmental compartments (e.g., Evans et al. 2015), and the impacts of Hg on Arctic biota (e.g., Scheuhammer et al. 2015). This program is ongoing, and thus provides an opportunity to include plastic additives, (including metal-based additives) For example, since 1975, seabird eggs from Prince Leopold Island have been sampled semi-regularly in the Canadian Arctic for mercury contamination (Braune et al. 2016), but Hg analysis does not use the entire sample, thus there is a potential to use a portion of those samples to analyze plastic additives, retrospectively (Bianchini et al. 2022).

Likewise, metals and other elements are included in other nationally organized monitoring programs in the Arctic (e.g., Rigét et al. 2000; 2012), and mercury is regularly assessed in a circumpolar context (AMAP 2021*c*). Using samples for multiple contaminant evaluations can reduce the financial costs of collecting samples in the Arctic (Mallory et al. 2018), and also the number of organisms sampled and/or sacrificed for science. Moreover, these long-term monitoring programs are continuously adapted to better assess the contaminant in question. For example, the findings throughout the NCP's monitoring of Hg in the Canadian Arctic have been used to refine the research and monitoring priorities of the program, thus a plastic additive monitoring program does not have to start from the ground up; the lessons learned from the NCP's Hg monitoring program can be considered when developing long-term monitoring programs for plastic additives.

Combining research on plastic additives and other contaminants is also beneficial to assess the potential of cumulative effects. While *in vitro* studies on the effects of plastic additives are important to obtain a baseline understanding of a contaminant, exposure to only one contaminant is not the case in the environment; there are a multitude of contaminants that may have combined or cumulative effects on the organisms or ecosystem in which they are present. Monitoring plastic additives in combination with other contaminants of interest can lead to an ecologically relevant view of contaminant exposure to wildlife (Sühring et al. 2022). Thus, using samples to examine plastic additives as well as other contaminants can help us better understand the cumulative effects of these contaminants on organisms and their environments and inform future effects monitoring.

When POP monitoring programs were established in the Arctic, some POP concentrations (e.g., PCBs and DDT) were already declining (Fig. 4). For others, such as perfluorooctane sulfonate, increases and subsequent decreases of their concentrations in the Arctic have been documented, including archived samples from the program's environmental specimen bank (Rigét et al. 2013). Thus, building upon existing monitoring programs can also allow archived samples to be analyzed for plastic additives, retrospectively, provided they are stored appropriately, and thus inform strategic decision making. For example, a recent analysis of archived seabird eggs in the Canadian Arctic found that overall contaminant loads decreased since observed in the 1970s, except for when taking into consideration plastic additives that have only been examined within this program recently. The observed elevation in contaminant load was due to high phthalate concentration in a seabird egg as a small exploratory study (Bianchini et al. 2022), suggesting properly stored archived samples can be analyzed retrospectively for plastic additives and thus provide insights to chemicals of emerging concern (e.g., plastic additives) that may be increasing in real-time. Thus, plastic additives studies should not only look to future collections, but utilize past archived samples when possible to help build a long-term understanding of additives in Arctic biota.

Conclusions

For a holistic understanding of the effects of plastic pollution, we highlight a need to: (1) further evaluate transport pathways of plastic additives to and within the Arctic as a way to support ongoing discussions of plastics as a carrier of additives and inform risk assessors and regulatory bodies and (2) investigate the environmental and biological fate of additives and effects through a combination of field observations and ecologically relevant laboratory experiments (e.g., targeting direct and indirect exposure, leaching, bioaccumulation/magnification/transformation, and partitioning processes). Furthermore, we recommend integrating plastic additives into existing monitoring infrastructure in the Arctic as we move toward a comprehensive and strategic monitoring effort of plastic pollution in the pan-Arctic.

The long-range transport of chemicals to remote areas like the Arctic is one of four criteria for classifying a chemical as a POP according to the Stockholm Convention. The transport of additives with plastic particles might extend the current understanding of long-range transport substantially. Furthermore, local pollution sources may be significant for the occurrence of plastic-associated chemicals in the Arctic. Plastic particles can contain thousands of chemicals added for various functions, including compounds that are potentially hazardous for the environment and health. Unlike POPs that are currently monitored in the Arctic, they include several persistent and non-persistent compounds that have only been addressed in the Arctic to a limited degree, in research rather than systematic monitoring approaches. Recently initiated monitoring programs for litter and microplastics focus on the physical particles, potentially creating a gap in addressing non-persistent chemicals present in plastic particles. An important, not fully understood question, is the process of leaching of chemicals from the particle into the surrounding environment or into the gut of an organism after ingestion and to what extent this chemical is bioavailable. Combinations of laboratory and field studies, research and monitoring approaches will be needed to close this gap and generate a better basis to address the important question of long-range transport of chemicals with plastic particles.

Robust monitoring programs exist in the Arctic that can include plastic additives as well as provide historical samples to be analyzed retrospectively. Utilizing existing infrastructure is crucial to understand historical and current plastic additive trends in the environment and to generate data across the pan-Arctic for risk assessments and chemicals management. Furthermore, physical plastic pollution and its chemical additives are coupled in the environment but can differ in transport routes, fate, and biological effects. Therefore, future monitoring programs for litter and microplastics must consider both the physical and chemical side of plastic pollution, and be designed to address a range of questions, including quantity, pathways, fate, and effects.

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Competing interests

The authors declare there are no competing interests.

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References

Allen, S., Allen, D., Phoenix, V.R., Le Roux, G., Durántez Jiménez, P. Simonneau, A., et al. 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nat. Geosci. **12**: 339–344. doi:10.1038/s41561-019-0335-5.

AMAP, 2016. AMAP Assessment 2015: Temporal Trends in Persistent Organic Pollutants in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

AMAP, 2017. AMAP Assessment 2016: Chemicals of Emerging Arctic Concern. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

AMAP, 2018. *AMAP Assessment 2018: Biological Effects of Contaminants on Arctic Wildlife and Fish*.Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway.

AMAP, 2021a. AMAP Litter and Microplastics Monitoring Plan. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway.

AMAP, 2021b. Arctic Climate Change Update 2021: Key Trends and impacts. Summary for policy makers. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway.

AMAP, 2021c. AMAP mercury assessment: summary for policy makers. Arctic monitoring and Assessment Programme (AMAP), Tromsø, Norway.

Andrade, H., Glüge, J., Herzke, D., Ashta, N.M., Nayagar, S.M., and Scheringer, M. 2021. Oceanic long-range transport of organic additives present in plastic products: an overview. Environ. Sci. Eur. **33**: 85. doi:10.1186/s12302-021-00522-x.

Arctic Monitoring and Assessment Programme, A. 2005. *AMAP Assessment 2002: Heavy Metals in the Arctic*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Baak, J.E., Linnebjerg, J.F., Barry, T., Gavrilo, M.V., Mallory, M.L., Price, C., and Provencher, J.F. 2020. Plastic ingestion by seabirds in the circumpolar arctic: a review. Environ. Rev. **28**: 506–516. NRC Research Press. doi:10.1139/er-2020-0029.

Ballesteros-Gómez, A., Jonkers, T., Covaci, A., and de Boer, J. 2016. Screening of additives in plastics with high resolution time-of-flight mass spectrometry and different ionization sources: direct probe injection (DIP)-APCI, LC-APCI, and LC-ion booster ESI. Anal. Bioanal. Chem. **408**: 2945–2953. doi:10.1007/s00216-015-9238-5.

Barrios-Estrada, C., de Jesús Rostro-Alanis, M., Muñoz-Gutiérrez, B.D., Iqbal, H.M.N., Kannan, S., and Parra-Saldívar, R. 2018. Emergent contaminants: endocrine disruptors and their laccase-assisted degradation – a review. Sci. Total Environ. **612**: 1516–1531. doi:10.1016/j.scitotenv.2017.09.013.

Bergmann, M., Mützel, S., Primpke, S., Tekman, M.B., Trachsel, J., and Gerdts, G. 2019. White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. Arct. Sci. Adv. **5**: eaax1157. doi:10.1126/sciadv.aax1157.

Bianchini, K., Mallory, M.L., Braune, B.M., Muir, D.C.G., and Provencher, J.F. 2022. Why do we monitor? Using seabird eggs to track trends in arctic environmental contamination. Environ. Rev. **30**: 245–267. NRC Research Press. doi:10.1139/er-2021-0078.

Blais, J.M., Kimpe, L.E., McMahon, D., Keatley, B.E., Mallory, M.L., Douglas, M.S.V., and Smol, J.P. 2005. Arctic seabirds transport marine-derived contaminants. Science **309**: 445–445. doi:10.1126 /science.1112658.

Bourdages, M.P.T., Provencher, J.F., Baak, J.E., Mallory, M.L., and Vermaire, J.C. 2021. Breeding seabirds as vectors of microplastics from sea to land: evidence from colonies in arctic canada. Sci. Total Environ. **764**: 142808. doi:10.1016/j.scitotenv.2020.142808.

Bourdages, M.P.T., Provencher, J.F., Sudlovenick, E., Ferguson, S.H., Young, B.G. Pelletier, N., et al. 2020. No plastics detected in seal (Phocidae) stomachs harvested in the eastern canadian arctic. Mar. Pollut. Bull. **150**: 110772. doi:10.1016/j.marpolbul.2019.110772.

Boyle, D., Catarino, A.I., Clark, N.J., and Henry, T.B. 2020. Polyvinyl chloride (PVC) plastic fragments release Pb additives that are bioavailable in zebrafish. Environ. Pollut. **263**: 114422. doi:10.1016/j.envpol.2020.114422.

Braune, B., Gaston, A.J., and Mallory, M. 2016. Temporal trends of mercury in eggs of five sympatrically breeding seabird species in the Canadian Arctic. Environ. Pollut. doi: 10.1016/j.envpol.2016.04.006.

Brimble, S.K., Foster, K.L., Mallory, M.L., Macdonald, R.W., Smol, J.P., and Blais, J.M. 2009. High Arctic ponds receiving biotransported nutrients from a nearby seabird colony are also subject to potentially toxic loadings of arsenic, cadmium, and zinc. Environ. Toxicol. Chem. **28**: 2426–2433. doi:10.1897/09-235.1.

Bucci, K., Tulio, M., and Rochman, C.M. 2020. What is known and unknown about the effects of plastic pollution: a meta-analysis and systematic review. Ecol. Appl. **30**: e02044. doi:10.1002/eap.2044.

Campanale, Massarelli, Savino, Locaputo, and Uricchio 2020. A detailed review study on potential effects of microplastics and additives of concern on human health. IJERPH **17**: 1212. doi:10.3390/ijerph17041212.

Cantwell, M.G., Sullivan, J.C., Katz, D.R., Burgess, R.M., Bradford Hubeny, J., and King, J. 2015. Source determination of benzotriazoles in sediment cores from two urban estuaries on the Atlantic coast of the United States. Mar. Pollut. Bull. **101**: 208–218. doi:10.1016/j.marpolbul.2015.10.075.

CARCAR 2012. Canadian Arctic Contaminants Assessment Report III. 2012. Mercury in Canada's North. Science.gc.ca. Government of Canada. [Online] Available from: https://science.gc.ca/eic/site/063.nsf/eng/h_7FE5B2F8.html[accessed 18 October 2021].

Carlsson, P., Singdahl-Larsen, C., and Lusher, A.L. 2021. Understanding the occurrence and fate of microplastics in coastal arctic ecosystems: the case of surface waters, sediments and walrus (*Odobenus rosmarus*). Sci.Total Environ. **792**: 148308. doi:10.1016/j.scitotenv.2021.148308.

Catrouillet, C., Davranche, M., Khatib, I., Fauny, C., Wahl, A., and Gigault, J. 2021. Metals in microplastics: determining which are additive, adsorbed, and bioavailable. Environ. Sci. **23**: 553–558. doi:10.1039/D1EM00017A.

Chibwe, L., Parrott, J.L., Shires, K., Khan, H., Clarence, S. Lavalle, C., et al. 2021. A deep dive into the complex chemical mixture and toxicity of tire wear particle leachate in fathead minnow. Environ. Toxicol. Chem. **41**: 1144–1153. doi: 10.1002/etc.5140.

Cózar, A., Martí, E., Duarte, C.M., García-de-Lomas, J., van Sebille, E. Ballatore, T.J., et al. 2017. The Arctic Ocean as a dead end for floating plastics in the north Atlantic branch of the thermohaline circulation. Sci. Adv. **3**: e1600582. doi:10.1126/sciadv.1600582.

Dahl, M., Bergman, S., Björk, M., Diaz-Almela, E., Granberg, M. Gullström, M., et al. 2021. A temporal record of microplastic pollution in mediterranean seagrass soils. Environ. Pollut. **273**: 116451. doi:10.1016/j.envpol.2021.116451.

De Silva, A.O., Criscitiello, A.S., Spencer, C., Muir, D., Sharp, M.J., and Young, C. 2020. Deposition of organophosphate ester flame retardants and plasticizers to high Arctic ice fields. **2020**: H089–0014.
Evans, M.S., Muir, D.C.G., Keating, J., and Wang, X. 2015. Anadromous char as an alternate food choice to marine animals: a synthesis of hg concentrations, population features and other influencing factors. Sci. Total Environ. **509–510**: 175–194. doi:10.1016/j.scitotenv.2014.10.074.
Fauser, P., Strand, J., and Vorkamp, K. 2020. Risk assessment of added chemicals in plastics in the Danish marine environment. Mar. Pollut. Bull. **157**: 111298. doi:10.1016/j.marpolbul.2020.111298.
Fauser, P., Vorkamp, K., and Strand, J. 2022. Residual additives in marine microplastics and their risk assessment – a critical review. Mar. Pollut. Bull. **177**: 113467. doi:10.1016/j.marpolbul.2022.113467.
Fjeld, E., Schlabach, M., Berge, J.A., Eggen, T., Snilsberg, P., et al. 2004. Kartlegging av utvalgte nye organiske miljøgifter-bromerte flammehemmere, klorerte parafiner, bisfenol A og triclosan (in Norwegian) [Screening of selected new organic contaminants-brominated flame retardants, chlorinated paraffins, bisphenol A and triclosan]. Norsk institutt för vannforskning (NIVA), Rapport 48092004, Statlig program for forurensningsovervakning, SFT-rapport TA-2006/2004. , .
Gallo, F., Fossi, C., Weber, R., Santillo, D., Sousa, J. Ingram, I., et al. 2018. Marine litter plastics and microplastics and their toxic chemicals components: the need for urgent preventive measures. Environ. Sci. Eur. **30**: 13. doi:10.1186/s12302-018-0139-z.
Gerdes, Z., Ogonowski, M., Nybom, I., Ek, C., Adolfsson-Erici, M., Barth, A., et al. 2019. Microplastic-mediated transport of PCBs? A depuration study with *Daphnia magna*. PLoS One, **14**: e0205378. doi:10.1371/journal.pone.0205378.
González-Bergonzoni, I., Johansen, K.L., Mosbech, A., Landkildehus, F., Jeppesen, E., and Davidson, T.A. 2017. Small birds, big effects: the little auk (*Alle alle*) transforms high arctic ecosystems. Proc. R. Soc. B. **284**: 20162572. doi:10.1098/rspb.2016.2572.
Granberg, M., von Friesen, L.W., Ask, A., and Collard, F. 2020. *Microlitter in Arctic Marine Benthic Food Chains and Potential Effects on Sediment Dwelling Fauna*. Nordic Council of Ministers, Copenhagen, Denmark.
Granberg, M., von Friesen, L.W., Bach, L., Strand, J., and Gabrielsen, G.W. 2019. *Anthropogenic Microlitter in Wastewater and Marine Samples from Ny-Ålesund, Barentsburg and Signehamna, Svalbard*. IVL Swedish Environmental Research Institute, Stockholm, Sweden.
Grant, M.L., Lavers, J.L., Hutton, I., and Bond, A.L. 2021. Seabird breeding islands as sinks for marine plastic debris. Environ. Pollut. **276**: 116734. doi:10.1016/j.envpol.2021.116734.
Grøsvik, B.E., Prokhorova, T., Eriksen, E., Krivosheya, P., Horneland, P.A., and Prozorkevich, D. 2018. Assessment of marine litter in the barents sea, a part of the joint Norwegian–Russian ecosystem survey. Front. Mar. Sci. **5**: 72. doi:10.3389/fmars.2018.00072.
Gunnarsdóttir, R., Jenssen, P.D., Erland Jensen, P., Villumsen, A., and Kallenborn, R. 2013. A review of wastewater handling in the Arctic with special reference to pharmaceuticals and personal care products (PPCPs) and microbial pollution. Ecol. Eng. **50**: 76–85. doi:10.1016/j.ecoleng.2012.04.025.
Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E., and Purnell, P. 2018. An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. J. Hazard. Mater. **344**: 179–199. doi:10.1016/j.jhazmat.2017.10.014.
Hajeb, P., Zhu, L., Bossi, R., and Vorkamp, K. 2022. Sample preparation techniques for suspect and non-target screening of emerging contaminants. Chemosphere **287**: 132306. doi:10.1016/j.chemosphere.2021.132306.
Halsband, C., Sørensen, L., Booth, A.M., and Herzke, D. 2020. Car Tire Crumb Rubber: Does Leaching Produce a Toxic Chemical Cocktail in Coastal Marine Systems? Frontiers in Environmental Science, **8**: 125. doi:10.3389/fenvs.2020.00125.
Halsband, C., and Herzke, D. 2019. Plastic litter in the European Arctic: what do we know? Emerg. Contam. **5**: 308–318. doi:10.1016/j.emcon.2019.11.001.
Hamilton, B.M., Bourdages, M.P.T., Geoffroy, C., Vermaire, J.C., Mallory, M.L., Rochman, C.M., and Provencher, J.F. 2021. Microplastics around an arctic seabird colony: particle community composition varies across environmental matrices. Sci. Total Environ. **773**: 145536. doi:10.1016/j.scitotenv.2021.145536.
Hamilton, B.M., Jantunen, L.M., Bergmann, M., Vorkamp, K., Aherne, J. Magnusson, K., et al. 2022. Monitoring microplastics in the atmosphere and cryosphere in the circumpolar north: a case for multicompartment monitoring. Arct. Sci. doi:10.1139/AS-2021-0054.
Hammer, S., Nager, R.G., Johnson, P.C.D., Furness, R.W., and Provencher, J.F. 2016. Plastic debris in great skua (*Stercorarius skua*) pellets corresponds to seabird prey species. Mar. Pollut. Bull. **103**: 206–210. doi:10.1016/j.marpolbul.2015.12.018.
Heinrich, P., and Braunbeck, T. 2020. Microplastic particles reduce EROD-induction specifically by highly lipophilic compounds in RTL-W1 cells. Ecotoxicology and Environmental Safety, **189**: 110041. doi:10.1016/j.ecoenv.2019.110041.
Heleniak, T., and Bogoyavlensky, D. 2014. Arctic populations and migrations. In: Arctic Human Development Report: Regional Processes and Global Linkages. Edited byNymand Larsen Nordic Council of Ministers, Copenhagen. pp. 53–104.
Herzke, D., Anker-Nilssen, T., Nøst, T.H., Götsch, A., Christensen-Dalsgaard, S. Langset, M., et al. 2016. Negligible impact of ingested microplastics on tissue concentrations of persistent organic pollutants in northern fulmars off coastal norway. Environ. Sci. Technol. **50**: 1924–1933. doi:10.1021/acs.est.5b04663.
Herzke, D., Ghaffari, P., Sundet, J.H., Tranang, C.A., and Halsband, C. 2021. Microplastic fiber emissions from wastewater effluents: abundance, transport behavior and exposure risk for biota in an Arctic fjord. Front. Environ. Sci. **9**: 194. doi:10.3389/fenvs.2021.662168.
Idowu, S.O., Capaldi, N., Zu, L., and Gupta, A.D. (eds.) 2013. Stockholm convention on persistent organic pollutants (POPs). *In Encyclopedia of Corporate Social Responsibility*. Springer Berlin Heidelberg, Berlin, Heidelberg. pp. 2336–2336. doi: 10.1007/978-3-642-28036-8_101506.
Janssen, M.P.M., and Spijker, J. 2016. Plastics that contain hazardous substances: recycle or incinerate?, The Dutch National Institute for Public Health and the Environment, Bilthoven, The Netherlands.
Koelmans, A.A., Bakir, A., Burton, G.A., and Janssen, C.R. 2016. Microplastic as a vector for chemicals in the aquatic environment: critical review and model-supported reinterpretation of empirical studies. Environ. Sci. Technol. **50**: 3315–3326. American Chemical Society. doi:10.1021/acs.est.5b06069.
Koelmans, A.A., Besseling, E., Wegner, A., and Foekema, E.M. 2013. Plastic as a carrier of POPs to aquatic organisms: a model analysis. Environ. Sci. Technol. **47**: 7812–7820. American Chemical Society. doi:10.1021/es401169n.
Kögel, T., Hamilton, B.M., Granberg, M.E., Provencher, J.F., Hammer, S. Gomiero, A., et al. 2022. Current efforts on microplastic monitoring in arctic fish and how to proceed. Arct. Sci. doi:10.1139/AS-2021-0057
Kühn, S., Booth, A.M., Sørensen, L., van Oyen, A., and van Franeker, J.A. 2020. Transfer of additive chemicals from marine plastic debris to the stomach oil of northern fulmars. Front. Environ. Sci. **8**: 138. doi:10.3389/fenvs.2020.00138.
Lu, Z., De Silva, A.O., Provencher, J.F., Mallory, M.L., Kirk, J.L. Houde, M., et al. 2019. Occurrence of substituted diphenylamine antioxidants and benzotriazole UV stabilizers in arctic seabirds and seals. Sci. Total Environ. **663**: 950–957. doi:10.1016/j.scitotenv.2019.01.354.
Lusher, A.L., Provencher, J.F., Baak, J.E., Hamilton, B.M., Vorkamp, K. Hallanger, I.G., et al. 2022. Monitoring litter and microplastics in Arctic birds and mammals. Arct. Sci. doi:10.1139/AS-2021-0058.
Macdonald, R.W., Barrie, L.A., Bidleman, T.F., Diamond, M.L., Gregor, D.J. Semkin, R.G., et al. 2000. Contaminants in the Canadian Arctic: 5 years of progress in understanding sources, occurrence and pathways. Sci. Total Environ. **254**: 93–234. doi:10.1016/S0048-9697(00)00434-4.
Magnusson, K., Eliasson, K., Fråne, A., Haikonen, K., Hultén, J., Olshammar, M., et al. 2016. Swedish sources and pathways for microplastics to the marine environment. Vol. **31**. IVL Swedish Environmental Research Institute. S-100, Stockholm, Sweden.
Mallory, M.L., Gilchrist, H.G., Janssen, M., Major, H.L., Merkel, F., Provencher, J.F., et al. 2018. Financial costs of conducting science in the Arctic: examples from seabird research. Arctic Science, **4**: 624–633. doi:10.1139/as-2017-0019.
Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C., and Kaminuma, T. 2001. Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environ. Sci. Technol. **35**: 318–324. doi:10.1021/es0010498.

McIntyre, J.K., Prat, J., Cameron, J., Wetzel, J., Mudrock, E. Peter, K.T., et al. 2021. Treading water: tire wear particle leachate recreates an urban runoff mortality syndrome in coho but not chum salmon. Environ. Sci. Technol. **55**: 11767–11774. American Chemical Society. doi:10.1021/acs.est.1c03569.

Meeker, J.D., Sathyanarayana, S., and Swan, S.H. 2009. Phthalates and other additives in plastics: human exposure and associated health outcomes. Phil. Trans. R. Soc. B. **364**: 2097–2113. doi:10.1098/rstb.2008.0268.

Mohamed Nor, N.H., and Koelmans, A.A. 2019. Transfer of PCBs from microplastics under simulated gut fluid conditions is biphasic and reversible. Environ. Sci. Technol. **53**: 1874–1883. doi:10.1021/acs.est.8b05143.

Moore, R.C., Loseto, L., Noel, M., Etemadifar, A., Brewster, J.D. MacPhee, S., et al. 2020. Microplastics in beluga whales (*Delphinapterus leucas*) from the eastern Beaufort Sea. Marine Pollution Bulletin **150**: 110723. doi:10.1016/j.marpolbul.2019.110723.

Mosbech, A., Johansen, K.L., Davidson, T.A., Appelt, M., Grønnow, B. Cuyler, C., et al. 2018. On the crucial importance of a small bird: the ecosystem services of the little auk (*Alle alle*) population in northwest Greenland in a long-term perspective. Ambio **47**: 226–243. doi:10.1007/s13280-018-1035-x.

Murphy, J. 2001. Additives for Plastics Handbook. Elsevier Advanced Technology. Oxford, UK.

Napper, I.E., Davies, B.F.R., Clifford, H., Elvin, S., Koldewey, H.J. Mayewski, P.A., et al. 2020. Reaching new heights in plastic pollution—preliminary findings of microplastics on Mount Everest. One Earth **3**: 621–630. doi:10.1016/j.oneear.2020.10.020.

Neumann, S., Harju, M., Herzke, D., Anker-Nilssen, T., Christensen-Dalsgaard, S., Langset, M., and Gabrielsen, G.W. 2021. Ingested plastics in northern fulmars (*Fulmarus glacialis*): a pathway for polybrominated diphenyl ether (PBDE) exposure? Sci.Total Environ. **778**: 146313. doi:10.1016/j.scitotenv.2021.146313.

Newman, M.C. 2009. *Fundamentals in Ecotoxicology*. 3rd ed. CRC Press, Boca Raton, Florida, USA.

Obbard, R.W., Sadri, S., Wong, Y.Q., Khitun, A.A., Baker, I., and Thompson, R.C. 2014. Global warming releases microplastic legacy frozen in Arctic sea ice. Earth's Future **2**: 315–320. doi:10.1002/2014EF000240.

Onink, V., Wichmann, D., Delandmeter, P., and van Sebille, E. 2019. The role of Ekman currents, geostrophy, and stokes drift in the accumulation of floating microplastic. J. Geophys. Res. Oceans **124**: 1474–1490. doi:10.1029/2018JC014547.

Padula, V., Beaudreau, A.H., Hagedorn, B., and Causey, D. 2020. Plastic-derived contaminants in Aleutian archipelago seabirds with varied foraging strategies. Mar. Pollut. Bull. **158**: 111435. doi:10.1016/j.marpolbul.2020.111435.

PAME 2019. *Desktop Study on Marine Litter including Microplastics in the Arctic*. International Secretariat Borgir v. Nordurslod (PAME), Akureyri, Iceland.

Peeken, I., Primpke, S., Beyer, B., Gütermann, J., Katlein, C. Krumpen, T., et al. 2018. Arctic sea ice is an important temporal sink and means of transport for microplastic. Nat. Commun. **9**: 1505. doi: 10.1038/s41467-018-03825-5.

Pinzone, M., Nordøy, E.S., Eppe, G., Malherbe, C., Das, K., and Collard, F. 2021. First record of plastic debris in the stomach of a hooded seal pup from the Greenland Sea. Marine Pollution Bulletin, **167**: 112350. doi:10.1016/j.marpolbul.2021.112350.

Provencher, J.F., Aliani, S., Bergmann, M., Bourdages, M., Buhl-Mortensen, L. Galgani, F., et al. 2022. Future monitoring of litter and microplastics in the Arcitc – challenges, opportunities, and strategies. Arct. Sci. doi:10.1139/AS-2022-0011.

Provencher, J.F., Avery-Gomm, S., Liboiron, M., Braune, B.M., Macaulay, J.B., Mallory, M.L., and Letcher, R.J. 2018. Are ingested plastics a vector of PCB contamination in northern fulmars from coastal newfoundland and labrador? Environ. Res. **167**: 184–190. doi:10.1016/j.envres.2018.07.025.

Rigét, F., Bignert, A., Braune, B., Dam, M., Dietz, R. Evans, M., et al. 2019. Temporal trends of persistent organic pollutants in Arctic marine and freshwater biota. Sci. Total Environ. **649**: 99–110. doi:10.1016/j.scitotenv.2018.08.268.

Rigét, F., Bossi, R., Sonne, C., Vorkamp, K., and Dietz, R. 2013. Trends of perfluorochemicals in greenland ringed seals and polar bears: indications of shifts to decreasing trends. Chemosphere **93**: 1607–1614. doi:10.1016/j.chemosphere.2013.08.015.

Rigét, F., Dietz, R., and Hobson, K.A. 2012. Temporal trends of mercury in greenland ringed seal populations in a warming climate. J. Environ. Monit. **14**: 3249–3256. The Royal Society of Chemistry. doi:10.1039/C2EM30687E.

Rigét, F., Dietz, R., Johansen, P., and Asmund, G. 2000. Lead, cadmium, mercury and selenium in greenland marine biota and sediments during AMAP phase 1. Sci. Total Environ. **245**: 3–14. doi:10.1016/S0048-9697(99)00429-5.

Rochman, C.M., Hoh, E., Kurobe, T., and Teh, S.J. 2013. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Sci. Rep. **3**: 3263. doi:10.1038/srep03263.

Rochman, C.M., Lewison, R.L., Eriksen, M., Allen, H., Cook, A.-M., and Teh, S.J. 2014. Polybrominated diphenyl ethers (PBDEs) in fish tissue may be an indicator of plastic contamination in marine habitats. Sci. Total Environ. **476–477**: 622–633. doi:10.1016/j.scitotenv.2014.01.058.

Russell, R.H. 1975. The food habits of polar bears of james bay and southwest Hudson Bay in summer and autumn. Arctic **28**: 117–129. doi:10.14430/arctic2823.

Ryan, P.G. 2015. How quickly do albatrosses and petrels digest plastic particles? Environ. Pollut. **207**: 438–440. doi:10.1016/j.envpol.2015.08.005.

Ryan, P.G., and Jackson, S. 1987. The lifespan of ingested plastic particles in seabirds and their effect on digestive efficiency. Mar. Pollut. Bull. **18**: 217–219. doi:10.1016/0025-326X(87)90461-9.

Scheuhammer, A., Braune, B., Chan, H.M., Frouin, H., Krey, A., Letcher, R., et al. 2015. Recent progress on our understanding of the biological effects of mercury in fish and wildlife in the canadian arctic. Sci. Total Environ. **509–510**: 91–103. doi:10.1016/j.scitotenv.2014.05.142.

Schirmer, E., Schuster, S., and Machnik, P. 2021. Bisphenols exert detrimental effects on neuronal signaling in mature vertebrate brains. Commun. Biol. **4**: 465. doi:10.1038/s42003-021-01966-w.

Schönlau, C., Larsson, M., Dubocq, F., Rotander, A., van der Zande, R., Engwall, M., and Kärrman, A. 2019. Effect-directed analysis of Ah receptor-mediated potencies in microplastics deployed in a remote tropical marine environment. Front. Environ. Sci. **7**: 120. doi:10.3389/fenvs.2019.00120.

Schymanski, E.L., Singer, H.P., Slobodnik, J., Ipolyi, I.M., Oswald, P., Krauss, M., et al. 2015. Non-target screening with high-resolution mass spectrometry: critical review using a collaborative trial on water analysis. Anal. Bioanal. Chem. **407**: 6237–6255. doi:10.1007/s00216-015-8681-7.

Steindal, E.H., Karlsson, M., Hermansen, E.A.T., Borch, T., and Platjouw, F.M. 2021. From Arctic science to global policy – addressing multiple stressors under the stockholm convention. AR **12**: 80. doi:10.23865/arctic.v12.2681.

Stow, J., Canada, Indigenous and Northern Affairs Canada, Northern Contaminants Program (Canada), and Management Committee 2017. Contaminants in Canada's north: state of knowledge and regional highlights: Canadian Arctic contaminants assessment report 2017. [Online] Available from: http://epe.lac-bac.gc.ca/100/201/301/weekly_acquisitions_list-ef/2018/18-31/publications.gc.ca/collections/collection_2018/aanc-inac/R74-2-5-2017-eng.pdf[accessed 27 October 2021].

Sühring, R., Baak, J.E., Letcher, R.J., Braune, B.M., de Silva, A. Dey, C., et al. 2022. Co-contaminants of microplastics in two seabird species from the Canadian Arctic. Environ. Sci. Ecotechnol. **12**: 100189. doi:10.1016/j.ese.2022.100189.

Sühring, R., Diamond, M.L., Bernstein, S., Adams, J.K., Schuster, J.K. Fernie, K., et al. 2021. Organophosphate esters in the Canadian Arctic Ocean. Environ. Sci. Technol. **55**: 304–312. doi:10.1021/acs.est.0c04422.

Sühring, R., Diamond, M.L., Scheringer, M., Wong, F., Pućko, M. Stern, G., et al. 2016. Organophosphate esters in Canadian Arctic air: occurrence, levels and trends. Environ. Sci. Technol. **50**: 7409–7415. doi:10.1021/acs.est.6b00365.

Sun, Y., De Silva, A.O., St Pierre, K.A., Muir, D.C.G., Spencer, C., Lehnherr, I., and MacInnis, J.J. 2020. Glacial melt inputs of organophosphate ester flame retardants to the largest high Arctic lake. Environ. Sci. Technol. **54**: 2734–2743. American Chemical Society. doi:10.1021/acs.est.9b06333.

Tanaka, K., Takada, H., Yamashita, R., Mizukawa, K., Fukuwaka, M., and Watanuki, Y. 2013. Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics. Mar. Pollut. Bull. **69**: 219–222. doi:10.1016/j.marpolbul.2012.12.010.

Tanaka, K., Takada, H., Yamashita, R., Mizukawa, K., Fukuwaka, M., and Watanuki, Y. 2015. Facilitated leaching of additive-derived PBDEs from plastic by seabirds' stomach oil and accumulation in tissues. Environ. Sci. Technol. **49**: 11799–11807. American Chemical Society. doi:10.1021/acs.est.5b01376.

Tanaka, K., Watanuki, Y., Takada, H., Ishizuka, M., Yamashita, R. Kazama, M., et al. 2020. In vivo accumulation of plastic-derived chemicals into seabird tissues. Curr. Biol. **30**: 723–728.e3. doi:10.1016/j.cub.2019.12.037.

Tanaka, K., Yamashita, R., and Takada, H. 2019. *In* Transfer of hazardous chemicals from ingested plastics to higher-trophic-level organisms. Edited by H. Takada and H.K. Karapanagioti. Hazardous Chemicals Associated with Plastics in the Marine Environment. Springer International Publishing, Cham, Switzerland. pp. 267–280. doi: 10.1007/698_2018_255.

Tekman, M.B., Krumpen, T., and Bergmann, M. 2017. Marine litter on deep Arctic seafloor continues to increase and spreads to the north at the HAUSGARTEN observatory. Deep Sea Res. Part I **120**: 88–99. doi:10.1016/j.dsr.2016.12.011.

Thaysen, C., Sorais, M., Verreault, J., Diamond, M.L., and Rochman, C.M. 2020. Bidirectional transfer of halogenated flame retardants between the gastrointestinal tract and ingested plastics in urban-adapted ring-billed gulls. Sci. Total Environ. **730**: 138887. doi:10.1016/j.scitotenv.2020.138887.

Tian, Z., Zhao, H., Peter, K.T., Gonzalez, M., Wetzel, J., Wu, C., et al. 2021. A ubiquitous tire rubber–derived chemical induces acute mortality in coho salmon. American Association for the Advancement of Science, **371**: 185–189. doi:10.1126/science.abd6951.

Trevail, A.M., Gabrielsen, G.W., Kühn, S., and Bock, A. 2014. Plastic ingestion by northern fulmars, *Fulmarus glacialis*, In *Svalbard and Iceland, and Relationships between Plastic Ingestion and Contaminant Uptake.*Brief report series. Norwegian Polar Institute, Tromsø, Norway. ISBN:978-82-766-310-5.

Turner, A., and Filella, M. 2021. Hazardous metal additives in plastics and their environmental impacts. Environ. Int. **156**: 106622. doi:10.1016/j.envint.2021.106622.

Turner, A., and Lau, K.S. 2016. Elemental concentrations and bioaccessibilities in beached plastic foam litter, with particular reference to lead in polyurethane. Mar. Pollut. Bull. **112**: 265–270. doi:10.1016/j.marpolbul.2016.08.005.

UNEP, 2020a. Stockholm Convention on Persistent Organic Pollutants (POPs). Text and Annexes Revised in 2019. UN Environment Programme (UNEP), Secretariat of the Stockholm Convention (SSC), September 2020.

UNEP, 2020b. Proposal to list UV-328 in annex a to the stockholm convention on persistent organic pollutants.Persistent Organic Pollutants Review Committee, 16th Meeting, Geneva (online), 11–16. UN Environmental Program (UNEP). Châtelaine, Switzerland. January 2021.

van Franeker, J.A., and Law, K.L. 2015. Seabirds, gyres and global trends in plastic pollution. Environ. Pollut. **203**: 89–96. doi:10.1016/j.envpol.2015.02.034.

Verla, A.W., Enyoh, C.E., Verla, E.N., and Nwarnorh, K.O. 2019. Microplastic–toxic chemical interaction: a review study on quantified levels, mechanism and implication. SN Appl. Sci. **1**: 1400. doi:10.1007/s42452-019-1352-0.

von Friesen, L.W., Granberg, M.E., Pavlova, O., Magnusson, K., Hassellöv, M., and Gabrielsen, G.W. 2020. Summer sea ice melt and wastewater are important local sources of microlitter to svalbard waters. Environ. Int. **139**: 105511. doi:10.1016/j.envint.2020.105511.

Vorkamp, K., Balmer, J., Hung, H., Letcher, R.J., Rigét, F.F., and de Wit, C.A. 2019. Current-use halogenated and organophosphorous flame retardants: a review of their presence in arctic ecosystems. Emerg. Contam. **5**: 179–200. doi:10.1016/j.emcon.2019.05.004.

Vorkamp, K., Falk, K., Møller, S., Rigét, F.F., and Sørensen, P.B. 2018. Regulated and unregulated halogenated flame retardants in peregrine falcon eggs from greenland. Environ. Sci. Technol. **52**: 474–483. doi:10.1021/acs.est.7b04866.

Wang, J., Coffin, S., Sun, C., Schlenk, D., and Gan, J. 2019. Negligible effects of microplastics on animal fitness and HOC bioaccumulation in earthworm *Eisenia fetida* in soil. Environmental Pollution, **249**: 776–784. doi:10.1016/j.envpol.2019.03.102.

Wania, F. 1998. Significance of long range transport of persistent organic pollutants by migratory animals. Wania Environmental Chemists Corp (WECC), Toronto, Ontario, Canada.

Wiesinger, H., Wang, Z., and Hellweg, S. 2021. Deep dive into plastic monomers, additives, and processing aids. Environ. Sci. Technol. **55**: 9339–9351. American Chemical Society. doi:10.1021/acs.est.1c00976.

Wong, F., Hung, H., Dryfhout-Clark, H., Aas, W., Bohlin-Nizzetto, P., Breivik, K., et al. 2021. Time trends of persistent organic pollutants (POPs) and chemicals of emerging arctic concern (CEAC) in arctic air from 25 years of monitoring. Sci. Total Environ. **775**: 145109. doi:10.1016/j.scitotenv.2021.145109.

Zahaby, Y., Xia, P., Crump, D., Provencher, J.F., Thomas, P.J. Pauli, B., et al. 2021. ToxChip PCR arrays for two Arctic-breeding seabirds: applications for regional environmental assessments. Environ. Sci. Technol. **55**: 7521–7530. doi:10.1021/acs.est.1c00229.

Zhang, H., Zhou, Q., Xie, Z., Zhou, Y., Tu, C., Fu, C., et al. 2018. Occurrences of organophosphorus esters and phthalates in the microplastics from the coastal beaches in north China. Science of The Total Environment, **616–617**: 1505–1512. doi:10.1016/j.scitotenv.2017.10.163.