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Shorebirds ingest plastics too: what we know, what we do not know, and what we should do next

Scott A. Flemming[a], **Richard B. Lanctot**[b], **Courtney Price**[c], **Mark L. Mallory**[d], **Susanne Kühn**[e], **Mark C. Drever**[a], **Tom Barry**[c], **and Jennifer F. Provencher**[f]

[a]Environment and Climate Change Canada, Pacific Wildlife Research Centre, Delta, BC V4K 3N2, Canada; [b]U.S. Fish and Wildlife Service, Migratory Bird Division, Anchorage, AK 99503, USA; [c]Conservation of Arctic Flora and Fauna (CAFF), Borgir, Nordurslod, 600 Akureyri, Iceland; [d]Department of Biology, Acadia University, Wolfville, NS B4P 2R6, Canada; [e]Wageningen Marine Research, Ankerpark 27, 1781 AG Den Helder, the Netherlands; [f]Environment and Climate Change Canada, National Wildlife Research Centre, Ottawa, ON K1A 0H3, Canada

Corresponding author: **Scott A. Flemming** (email: scott.flemming@ec.gc.ca)

Abstract

Concerns about the impact of plastics pollution on the environment have been growing since the 1970s. Marine debris has reportedly entangled and (or) been ingested by 914 marine species ranging from microinvertebrates to large marine mammals. Shorebirds have a high potential to be exposed to and ingest plastics pollution, as many species migrate long distances and periodically concentrate around shorelines, coastal areas, and estuaries that can have elevated levels of plastics pollution. Currently, little is understood about plastics exposure, frequency of occurrence (FO), and potential impacts relating to shorebirds. In this study, we catalogued and reviewed available studies across the globe that examined plastics pollution in shorebirds. We then quantified relevant traits of species and their environments to explore how shorebirds may be exposed to plastics pollution. Of 1106 samples from 26 shorebird species described within 16 studies that examined plastic ingestion, 53% of individuals contained some form of plastics pollution. Overall, Haematopodidae (oystercatchers) had the highest FO of plastics, followed by Recurvirostridae (avocets), Scolopacidae (sandpipers, phalaropes, godwits, and curlews), and Charadriidae (plovers). Plastics FO was much greater among species that migrated across marine areas (either oceanic or coastal) than those species that used continental flyways. Species that foraged at sea, on mudflats, or on beaches had higher average FO of plastic ingestion than species that foraged in upland or freshwater environments. Finally, species that used a sweeping foraging mode showed higher levels of ingested plastics and contained a far greater number of plastic pieces than all other techniques. These conclusions are based on a limited number of species and samples, with the distribution of samples skewed taxonomically and geographically. Using the combined knowledge of known shorebirds–plastics interactions and shorebird ecology, we present a hierarchical approach to identifying shorebirds that may be more vulnerable and susceptible to plastic ingestion. We provide recommendations on sampling protocols and future areas of research.

Key words: plastic, pollution, marine litter, waders, shorebirds

Résumé

Les préoccupations en matière d'impact de la pollution plastique sur l'environnement se sont accrues depuis les années 1970. Les débris marins auraient entravé ou été ingérés par 914 espèces marines allant des micro-invertébrés aux grands mammifères marins. Les oiseaux de rivage sont très susceptibles d'être exposés à la pollution plastique et de l'ingérer, car de nombreuses espèces migrent sur de longues distances et se concentrent périodiquement autour des rivages, des zones côtières et des estuaires qui peuvent présenter des niveaux élevés de pollution plastique. À l'heure actuelle, on connaît peu de choses sur l'exposition aux plastiques, la fréquence et les impacts potentiels sur les oiseaux de rivage. Dans cette étude, les auteurs ont catalogué et synthétisé les études disponibles à travers le monde qui se sont penchées sur la pollution plastique chez les oiseaux de rivage. Ils ont ensuite quantifié les caractéristiques pertinentes des espèces et de leurs environnements afin d'explorer comment les oiseaux de rivage peuvent être exposés à la pollution plastique. Sur 1106 échantillons provenant de 26 espèces d'oiseaux de rivage décrites dans 16 études qui ont examiné l'ingestion de plastiques, 53 % des individus comportaient une certaine forme de pollution plastique. Dans l'ensemble, les Haematopodidae (huîtriers) présentaient la fréquence d'occurrence

(FO) la plus élevée de plastiques, suivis des Recurvirostridae (avocettes), des Scolopacidae (bécasseaux, phalaropes, barges, courlis) et des Charadriidae (pluviers). La FO de plastiques était beaucoup plus importante chez les espèces qui migraient à travers les zones marines (océaniques ou côtières) que chez les espèces qui utilisaient les voies de migration continentales. Les espèces qui se nourrissaient en mer, dans les vasières ou sur les plages présentaient une FO moyenne d'ingestion de plastiques plus élevée que les espèces qui se nourrissaient dans les environnements de hautes terres ou d'eau douce. Enfin, les espèces qui utilisaient un mode de recherche de nourriture par balayage présentaient des niveaux plus élevés d'ingestion de plastiques et contenaient un nombre beaucoup plus important de morceaux de plastique que celles qui utilisaient toutes les autres techniques. Ces conclusions sont basées sur un nombre limité d'espèces et d'échantillons, la distribution des échantillons étant biaisée sur le plan taxonomique et géographique. En utilisant les connaissances combinées des interactions connues entre les oiseaux de rivage et les plastiques et de l'écologie des oiseaux de rivage, les auteurs présentent une approche hiérarchique pour identifier les oiseaux de rivage qui pourraient être plus vulnérables et susceptibles d'ingérer des plastiques. Ils formulent des recommandations sur les protocoles d'échantillonnage et les futurs domaines de recherche. [Traduit par la Rédaction]

Mots-clés : plastique, pollution, déchets marins, échassiers, oiseaux de rivage

Introduction

Concerns about the impact of plastics pollution on the environment have been growing since the 1970s. Initially, plastics pollution was thought to be primarily distributed around heavily populated areas; however, studies demonstrate that environmental vectors such as ocean currents (Maximenko et al. 2012), wind, snow, rain (Allen et al. 2019), and wildlife (Hammer et al. 2016; Provencher et al. 2018; Bourdages et al. 2020) transport plastics around the world. Indeed, plastics pollution is found in a myriad of terrestrial habitats (de Souza Machado et al. 2018), including numerous protected areas (Brahney et al. 2020), near both poles (Lusher et al. 2015; Lacerda et al. 2019), in all oceans (Eriksen et al. 2014), across freshwater systems (Wagner et al. 2014; Cable et al. 2017; Shahul Hamid et al. 2018), in remote alpine environments (Allen et al. 2019; Ambrosini et al. 2019; Napper et al. 2020), and in the air animals breathe (Gasperi et al. 2018). Given the widespread distribution of plastics pollution in the environment, it is becoming increasingly important to understand the risk of exposure and effects of plastics pollution on wildlife (Vegter et al. 2014; ECCC 2020; Provencher et al. 2020).

Current knowledge on the occurrence of plastics pollution interacting with animals (hereinafter termed "plastic interactions") and the resulting effects on wildlife is primarily from marine environments. Plastics pollution has reportedly entangled and (or) been ingested by 914 marine species ranging from microinvertebrates to large marine mammals (Kühn and van Franeker 2020); this number continues to grow as more studies examine new species for plastic interactions. Many marine birds are particularly susceptible to ingestion because of their movements, diet, feeding modes, and morphology (Wilcox et al. 2015). Although these traits are not unique to seabirds, few studies have investigated susceptibility of other avian taxa to plastics. The exceptions include studies on plastics pollution ingestion in passerines (dippers; D'Souza et al. 2020), raptors (Carlin et al. 2020; Ballejo et al. 2021), and shorebirds (Lourenço et al. 2017), highlighting the potential for other groups to be affected and the importance of expanding investigations to other susceptible avian taxa. The vulnerability and potential exposure of other bird species to plastics pollution are important to consider, since seabirds account for only ~3.5% of the 9800 bird species globally (Gill et al. 2021). Additionally, birds have some of the largest and widespread distributions covering both marine and terrestrial environments on all the continents and ocean basins and may serve as good indicators of plastics pollution interactions.

Although plastics pollution can be found across the globe, it is distributed non-uniformly, leading to differences in the vulnerability or exposure of birds to interactions with plastics pollution among regions and habitats. For example, plastics pollution often accumulates in subtropical gyres and ~65% more plastics occur in the Pacific Ocean than the Atlantic (Eriksen et al. 2014). Estuaries and beaches may have particularly high levels of microplastics (<5 mm in size), as the environmental conditions (e.g., wave action and eddies) in these areas more easily break down larger plastic pieces, which then settle in sediment (Browne et al. 2011; Wessel et al. 2016; Bessa et al. 2018; Thushari and Senevirathna 2020). Bird species predominantly using these areas may therefore be at higher risk to plastics pollution exposure.

While some effects of plastics pollution ingestion on some avifauna are relatively well documented, the risk and magnitude of the effect on different birds vary widely. Large birds, which can ingest macroplastics (>20–100 mm), might disproportionately suffer structural damage or blocked gastrointestinal tracts (Roman et al. 2019) compared to the effects of ingesting small plastic pieces. In contrast, small birds that are limited to ingesting microplastics may be disproportionately affected by plastics pollution absorbed directly into their tissues (large birds are susceptible to this as well; see Lavers et al. 2019), although blockage is still possible (Teuten et al. 2009; Tanaka et al. 2013; Padula et al. 2020). Furthermore, a species' ability to regurgitate ingested items may also lower the risk of accumulating plastics pollution and experiencing lethal or sublethal effects (Seif et al. 2018).

Shorebirds have a high potential to be exposed to and ingest plastics pollution, but have largely been overlooked in plastics pollution research. Many species migrate long distances and periodically concentrate around shorelines, coastal areas, and estuaries (Colwell 2010), which tend to have elevated levels of plastics pollution. However, less is understood about plastics pollution exposure, frequency of occurrence (%FO), and potential impacts on this widespread group of birds. For example, there are no reports of entanglement of shorebirds by plastics pollution, so it does not show up in this review. We feel that it is important to note this (see Methods for more about scope), however, as reporting zeros in plastics pollution research is as important as reporting positives (after Liboiron et al. 2018).

Determining impacts from plastics pollution exposure/ingestion to shorebirds is particularly important because many shorebird populations are declining worldwide (Andres et al. 2012; Rosenberg et al. 2019; Smith et al. 2020). While experts suggest that these declines are a result of widespread habitat alteration and climate change impacts at migration and non-breeding sites (Thomas et al. 2006; Studds et al. 2017), the importance of other pervasive threats, such as plastics pollution, may be underestimated. Currently, the potential negative effects of plastics pollution on shorebirds are recognized in few conservation or species at risk documents (COSEWIC 2000). The failure to recognize this threat is largely due to insufficient information on plastics pollution exposure/ingestion and its potential negative effects on most bird species (Browne et al. 2015; Werner and O'Brien 2018). Importantly, a major problem with plastics pollution is that it is persistent and challenging to reverse. Even with mitigation efforts underway, the plastics pollution currently in the environment will persist for decades or potentially centuries (MacLeod et al. 2021), meaning species will be exposed to this contaminant for many generations to come.

In shorebirds, foraging mode and diet likely influence the ingestion of plastics pollution and therefore the impact of plastics (as in seabirds; Baak et al. 2020*b*). Species that forage using visual or olfactory cues, or are non-selective in their prey choice, may be more susceptible to ingesting plastics pollution than those that forage using other senses (Moser and Lee 1992; Savoca et al. 2016; Savoca 2018). Similarly, species that feed at the water surface or convergent zones, where plastics pollution accumulates in the environment (Ryan 2016; Roman et al. 2019), appear to be more susceptible than other species that feed in the water column where plastics pollution does not accumulate regularly (Poon et al. 2017; Baak et al. 2020*b*). Besides primary ingestion of plastics pollution noted above, species may also accumulate plastics through secondary ingestion (i.e., when their prey ingest plastics; Hipfner et al. 2018; Provencher et al. 2019). It is likely that shorebirds ingest plastics pollution both directly and indirectly, as seen in other bird taxa. This has not received much attention, and little is known on how levels of plastic ingestion vary across species and their habitats.

In this study, we had two objectives surrounding plastics pollution ingestion by shorebirds. First, we catalogued and reviewed available studies across the globe that examined plastics pollution ingestion in shorebirds. We used this information to quantify the traits of species and their habitats to explore how shorebirds may be exposed to plastics pollution. Second, we combined this knowledge of plastics pollution interactions in shorebirds with their ecology to identify shorebird species that may be more vulnerable and susceptible to plastics pollution ingestion. We used a hierarchical approach to identify shorebird vulnerability that consisted of the family of shorebirds, the type of migratory flyway used (e.g., oceanic and continental), seasons of the annual cycle, foraging habitat and mode, and body mass of individuals of a given species. Our overall goal was to identify knowledge gaps and inform critical research needs to better understand how shorebirds may be exposed to plastics pollution.

Approach

Literature review and information solicitation

To locate publications involving shorebirds and plastic interactions, we used the Web of Science and Google Scholar search engines with the following targeted search terms: "shorebird* plastic*", "wader* plastic*", "shorebird* pollut*", and "wader* pollut*". We included all literature published prior to September 2020. Given that older literature on plastics pollution is often difficult to detect via searchable databases, we also reviewed recent review articles that have targeted plastics pollution ingestion and entanglement in vertebrates in general (e.g., Provencher et al. 2017). Finally, we also solicited information on shorebirds and plastic interactions from various shorebird professional networks distributed across the world (e.g., the Western Hemisphere Shorebird Group, International Wader Study Group, East Asian-Australasian Flyway Partnership's Shorebird Working Group, and regional shorebird listservs) and social media (Twitter and Facebook). We asked for papers, unpublished reports, and data from the field of shorebirds and plastics pollution to be submitted to the lead author for review and inclusion. For our search, we considered all ~255 recognized shorebird species from all families (Gill et al. 2021); however, our search only identified plastic interactions with species belonging to three suborders of Charadriiformes: Scolopaci (sandpipers, curlews, snipes, and phalaropes), Chionidi (thick-knees and sheathbills), and Charadrii (avocets, stilts, oystercatchers, plovers, and lapwings). Given the gap in knowledge around the effects of plastics on shorebirds, we did not focus on a specific size class of plastic, but instead conducted a search for all available information that we could find, inclusive of megaplastic (>20 cm) down to microplastics (<5 mm).

Hierarchical approach to understanding susceptibility

To develop a better understanding of the ecological traits that make a species more susceptible to plastic ingestion, we used the following hierarchical approach. Based on the literature review, we extracted two metrics of plastics pollution in birds across studies: FO (%FO, the proportion of sampled individuals that contained plastic) and abundance (the number of plastic pieces in each individual). From these metrics, we related the %FO and abundance of plastics to flyway geography, foraging habitat, foraging mode, and body size. We ranked our confidence in our trait assessments as High or Low based on the results of the literature review, ecological information from Birds of the World (Billerman et al. 2020), and the authors' combined collective knowledge (i.e., "expert opinion"; Drescher et al. 2013). This initial decision was made by one author (S.F.) and confirmed by five other authors with extensive bird knowledge (R.L., M.M., J.P., M.D., and S.K.). To classify species' flyway geography, foraging habitat, and foraging mode, we referenced Birds of the World (Billerman et al. 2020) for supporting data. For flyway geography, we classified species as using oceanic, coastal, or continental routes. We classified non-migratory species based on the primary geography they used year-round. Foraging habitat included beaches, mudflats, upland, freshwater, and marine waters. Because a species' flyway geography and foraging habitats can change during the year and thereby influence exposure to plastics pollution, notably for long-distance migrants such as most shorebirds (e.g., Pratte et al. 2020), we considered the geography and foraging habitat used at the time the species was sampled.

For foraging mode, we used a modified classification of foraging methods described by Thomas et al. (2006) that included visual, mainly visual but with some tactile, an even mixture of visual and tactile, mainly tactile with some visual, and scything/sweeping. Where possible, we used classification scores already provided by Thomas et al. (2006), but for those species not scored we used general foraging guild associations of already scored species and the Birds of the World (Billerman et al. 2020). Lastly, we used body mass data from Birds of the World to assign an average weight to each species.

Sample sizes and effect sizes of some published variables were not appropriate for more detailed modelling approaches or meta-analyses. Thus, we used both Pearson's correlations and generalized linear models to test for relationships among response and explanatory variables. When testing for variation in %FO among flyway geography, foraging habitat, and foraging modes, we used individual generalized linear models with a quasi-binomial distribution. For models testing for variation among total number of plastic pieces, we $\log(n + 1)$ transformed the response. All statistical analyses were done using R version 4.2 (R Core Team 2021).

Current state of knowledge

General reporting

Our literature search and expert network request yielded 16 peer-reviewed articles, theses, or reports that examined plastics pollution ingestion in 26 shorebird species in 21 regions from 10 countries (Table 1; Supplementary Table S1; Fig. 1). While no studies described shorebirds being entangled with plastics pollution, ingestion of plastic was common. This was first reported in 1969 (red phalaropes *Phalaropus fulicarius* and red-necked phalaropes *P. lobatus*; Bond 1971; Day 1980) and the most recent publication was 2019 (American oystercatcher *Haematopus palliatus*; Rossi et al. 2019). From the 16 literature sources, a total of 1106 shorebird samples were described, including 913 fecal samples and 193 preserved carcasses. Fifty-three percent of these samples contained some form of plastics pollution, including 54% of the fecal samples and 50% of the carcasses.

Plastics abundance and weights

The abundance and occurrence of plastics were linked in shorebirds. Counts of plastic pieces were positively correlated with plastics %FO in the nine studies that included both types of information (Pearson correlation, $r_{1,35} = 0.52$, $P < 0.001$; Fig. 2A). Of the bird carcasses that were necropsied, oystercatcher species contained the highest number of plastic pieces (American oystercatcher: 29.1 pieces per bird on average, $n = 24$, pied oystercatcher *Haematopus longirostris*: 20 pieces, $n = 1$). Red phalarope were next, with an approximate (exact numbers were not always published) average of 10.5 pieces per individual ($n = 83$) across studies and areas. Lourenço et al. (2017) uniquely reported plastics threads/mL in fecal samples collected at three different sites. They found plastics pollution abundances varied across sites and among species, with pied avocet (*Recurvirostra avosetta*; 17.78 fibres/mL) and dunlin (*Calidris alpina*; 7.22 fibres/mL) containing the highest concentrations of plastics, and whimbrel (*Numenius phaeopus*; 0.1 fibres/mL) the lowest.

Seven of the 15 papers in which plastics pollution was found included weights of microplastics found during necropsies of individual shorebirds, the majority of which ($n = 5$) focused on red or red-necked phalarope. Weights of ingested plastics ranged from 0.03 to 7.7 g per bird ($n = 58$) for red phalarope (Connors and Smith 1981; Moser and Lee 1992) and from 0.01 to 3.7 g per bird ($n = 39$) for red-necked phalarope (Day 1980; Moser and Lee 1992). By comparison, plastics found in American oystercatcher, which are approximately 10–12 times heavier than either phalarope species, weighed an average of 0.29 g per bird (range: 0.01–1.4 g; Rossi et al. 2019).

Plastics quality and type

In five of the 16 papers, Quality Assurance and Quality Control (QA/QC) protocols were described, or studies referenced established protocols. Five studies also described the minimum sieve size (min = 0.02 mm, max = 5 mm) or quantification technique used to estimate the amount of plastics. Eight studies included more detailed information on types or colours of plastics ingested, but only six had detailed information on both traits. Four of six of these studies, however, included information by grouping either the type or colour of plastics ingested across species or sites. Furthermore, the level of detail varied across these studies. For example, three studies included the %FO of industrial versus user plastics. These studies found that shorebirds had higher levels of user plastics in comparison to industrial plastics (e.g., Drever et al. 2018: 82.0% user to 17.1% industrial; Rossi et al. 2019: 87% user to 13% industrial). One study also reported the %FO of specific plastics attributes (e.g., fragment, 61%; pellet, 17%; sheet, 7.2%; foam, 6.3%; Styrofoam, 3.6%; rubber, 2.7%; thread, 0.9%; and wax, 0.9%; Zhu et al. 2019). Similarly, five studies included colours across the spectrum, while one reported the prevalence of light and dark, and another the prevalence of light, mid, and dark plastics. Generally, plastics pollution ingested by shorebirds tended to be off white/clear/beige (off white/clear: 66%, Drever et al. 2018; white/beige: 58%, Rossi et al. 2019), although studies did not report the prevalence of different coloured plastics pollution available to foraging birds.

Table 1. Summary of the origin, sample type, and plastic ingestion information available for four families and 26 species of shorebirds based on published literature.

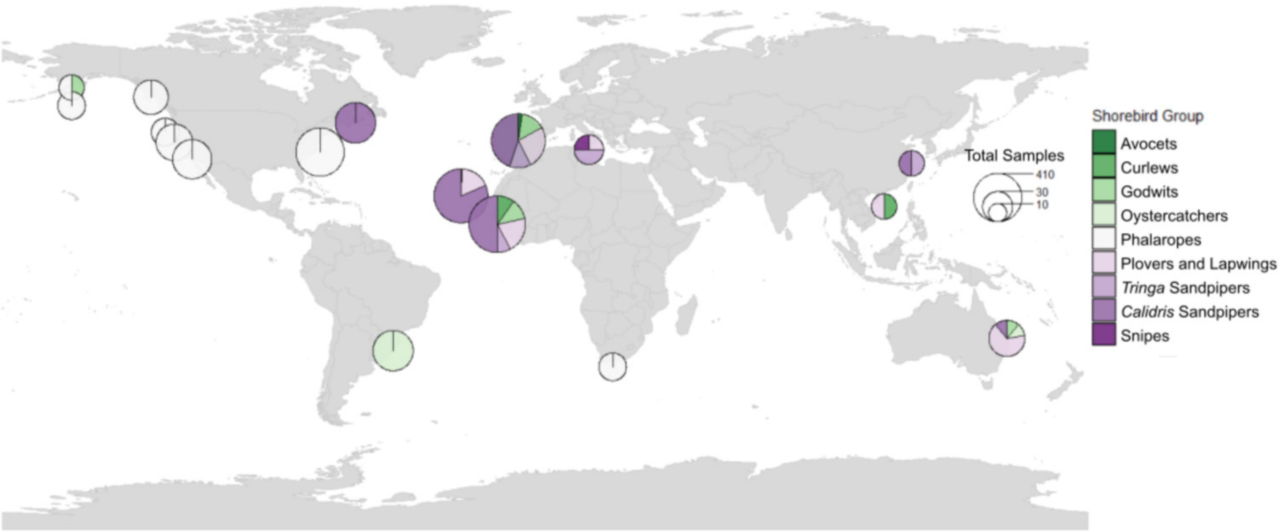
Family/species	Country/region	Sampling year	Sample type	Plastics occurrence: percentage with plastics (no. of individuals sampled)	Abundance (average no. of pieces/individual or concentrations/mL)	Minimum size limit	Source
Charadriidae				**45 (176)**			
Black-bellied plover	Guinea-Bissau	2013–2015	Fecal	25 (24)	0.5 (a)	0.01 mm	Lourenço et al. 2017
	Portugal	2013–2015	Fecal	73 (26)	4.31 (a)	0.01 mm	Lourenço et al. 2017
Common ringed plover	Guinea-Bissau	2013–2015	Fecal	13 (47)	0.34 (a)	0.01 mm	Lourenço et al. 2017
	Mauritania	2013–2015	Fecal	69 (41)	4.95 (a)	0.01 mm	Lourenço et al. 2017
	Portugal	2013–2015	Fecal	70 (30)	4.85 (a)	0.01 mm	Lourenço et al. 2017
Little ringed plover	Malta	<2018	Necropsy	0 (1)	0	1 mm	Brauer 2018
Masked lapwing	Australia	2013	Necropsy	0 (5)	0	—	Roman et al. 2016
Pacific golden-plover	Australia	2013	Necropsy	0 (1)	0	—	Roman et al. 2016
	South China Sea	2017	Necropsy	0 (1)	0	20 μm	Zhu et al. 2019
Haematopodidae				**100 (25)**			
American oystercatcher	Brazil	2007–2015	Necropsy	100 (24)	29	—	Rossi et al. 2019
Pied oystercatcher	Australia	2013	Necropsy	100 (1)	20	—	Roman et al. 2016
Recurvirostridae				**92 (111)**			
Pied avocet	Portugal						
	Tejo estuary	2013–2015	Fecal	80 (5)	17.78 (a)	0.01 mm	Lourenço et al. 2017
	Sarilhos	1992–1993	Fecal	100 (17)	134	—	Moreira 2008
	Arrentela	1992–1993	Fecal	87 (30)	134	—	Moreira 2008
	Corroios	1992–1993	Fecal	94 (37)	134	—	Moreira 2008
	Gaio	1992–1993	Fecal	90 (22)	134	—	Moreira 2008
Scolopacidae				**48 (794)**			
Bar-tailed godwit	Australia	2013	Necropsy	0 (1)	0	—	Roman et al. 2016
	Guinea-Bissau	2013–2015	Fecal	23 (43)	0.49 (a)	0.01 mm	Lourenço et al. 2017
	Mauritania	2013–2015	Fecal	100 (1)	1.11 (a)	0.01 mm	Lourenço et al. 2017
	North Pacific	1990–1991	Necropsy	100 (1)	—	—	Robards et al. 1997
Black-tailed godwit	Portugal	2013–2015	Fecal	66 (32)	2.29 (a)	0.01 mm	Lourenço et al. 2017
Bush stone curlew	Australia	2013	Necropsy	33 (3)	0.66	—	Roman et al. 2016
Common redshank	Guinea-Bissau	2013–2015	Fecal	32 (28)	1.23 (a)	0.01 mm	Lourenço et al. 2017
	Portugal	2013–2015	Fecal	75 (28)	4.08 (a)	0.01 mm	Lourenço et al. 2017

Table 1. Continued

Family/species	Country/region	Sampling year	Sample type	Plastics occurrence: percentage with plastics (no. of individuals sampled)	Abundance (average no. of pieces/individual or concentrations/mL)	Minimum size limit	Source
Common sandpiper	China	<2015	Necropsy	0 (1)	0	20 μm	Zhao et al. 2016
Common snipe	Malta	<2018	Necropsy	0 (1)	0	1 mm	Brauer 2018
Curlew sandpiper	Guinea-Bissau	2013–2015	Fecal	27 (59)	0.97 (a)	0.01 mm	Lourenço et al. 2017
Dunlin	China	<2015	Necropsy	100 (1)	3 (s), 1 (i)	20 μm	Zhao et al. 2016
	Mauritania	2013–2015	Fecal	54 (111)	6.65 (a)	0.01 mm	Lourenço et al. 2017
	Portugal	2013–2015	Fecal	72 (39)	7.79 (a)	0.01 mm	Lourenço et al. 2017
Green sandpiper	Malta	<2018	Necropsy	0 (1)	0	1 mm	Brauer 2018
Purple sandpiper	Canada	2013	Necropsy	0 (25)	0	—	Mallory et al. 2016
Red knot	Guinea-Bissau	2013–2015	Fecal	40 (55)	2.09 (a)	0.01 mm	Lourenço et al. 2017
	Mauritania	2013–2015	Fecal	65 (29)	4.46 (a)	0.01 mm	Lourenço et al. 2017
Red phalarope	Canada	2016–2017	Necropsy	100 (9)	12.3	1 mm	Drever et al. 2018
	United States						
	California	1979–1981	Necropsy	54 (13)	2.98	—	Connors and Smith 1981
	California	1969	Necropsy	Most (20)	2–36	—	Bond 1971
	North Carolina	1975–1989	Necropsy	69 (55)	1 (s), 6.7 (g)	—	Moser and Lee 1992
	West Coast North America	2003–2004	Necropsy	100 (3)	1–25	—	Nevins et al. 2005
	North Pacific	1990–1991	Necropsy	100 (1)	0	—	Robards et al. 1997
	Southern Africa/Southern Ocean	1979–1985	Necropsy	50 (2)	5	—	Ryan 1987
Red-necked phalarope	United States						
	North Carolina	1975–1989	Necropsy	19 (36)	0 (s), 3.7 (g)	—	Moser and Lee 1992
	Alaska	1969–1977	Necropsy	67 (3)	1	—	Day 1980
Ruddy turnstone	Portugal	2013–2015	Fecal	71 (7)	5.57 (a)	0.01 mm	Lourenço et al. 2017
Sanderling	Australia	2013	Necropsy	0 (1)	0	—	Roman et al. 2016
	Guinea-Bissau	2013–2015	Fecal	32 (63)	2.04 (a)	0.01 mm	Lourenço et al. 2017
	Mauritania	2013–2015	Fecal	46 (46)	5.9 (a)	0.01 mm	Lourenço et al. 2017
	Portugal	2013–2015	Fecal	83 (59)	10.47 (a)	0.01 mm	Lourenço et al. 2017
Whimbrel	Guinea-Bissau	2013–2015	Fecal	12 (34)	0.1 (a)	0.01 mm	Lourenço et al. 2017
	South China Sea	2017	Necropsy	100 (1)	2 (e), 35 (s), 10 (i)	20 μm	Zhu et al. 2019
Wilson's phalarope	Southern Africa/Southern Ocean	1979–1985	Necropsy	0 (1)	0	—	Ryan 1987
Wood sandpiper	Malta	<2018	Necropsy	0 (1)	0	1 mm	Brauer 2018

Note: Taxonomy follows Birds of the World (Billerman et al. 2020); a, numbers in which concentrations of microplastics per millilitre were published; e, esophagus; g, gizzard; s, stomach; i, intestines.

Fig. 1. The location and proportion of samples collected for plastic ingestion from various shorebird groups. Groups are listed alphabetically by common name and the number of samples at each location shown by size of circle (e.g., 410 circle represents sample size of 31–410). Map produced by standard mapping using R version 4.2 (R Core Team 2021).



Shorebird ecology

Taxa and regions of the world

Average %FO of plastics pollution ingestion varied among shorebird families ($F_{[3,47]} = 5.01$, $P = 0.004$; Table 1, Fig. 2B) with individuals of the family Haematopodidae (oystercatchers) having the highest FO (100% of individuals sampled had some form of plastics; $n = 25$), followed by Recurvirostridae (avocets; 90%, $n = 111$), Scolopacidae (sandpipers, phalaropes, godwits, and curlews; 48%, $n = 794$), and Charadriidae (plovers; 45%, $n = 176$).

A further breakdown of the diverse Scolopacidae family revealed no significant differences among lower taxonomic groups ($F_{[7,27]} = 0.94$, $P = 0.49$), and all contained plastics pollution in over half of the individuals sampled: turnstones (71%, $n = 7$), phalaropes (62%, $n = 123$), godwits (58%, $n = 78$), curlews (56%, $n = 35$), and *Calidris* sandpipers (48%, $n = 488$). Conversely, thick-knees (33%, $n = 3$) and *Tringa* sandpipers (21%, $n = 59$) had lower overall FO of plastics pollution, but FO varied significantly among sites (see the range of values across each shorebird taxon row within Fig. 2B).

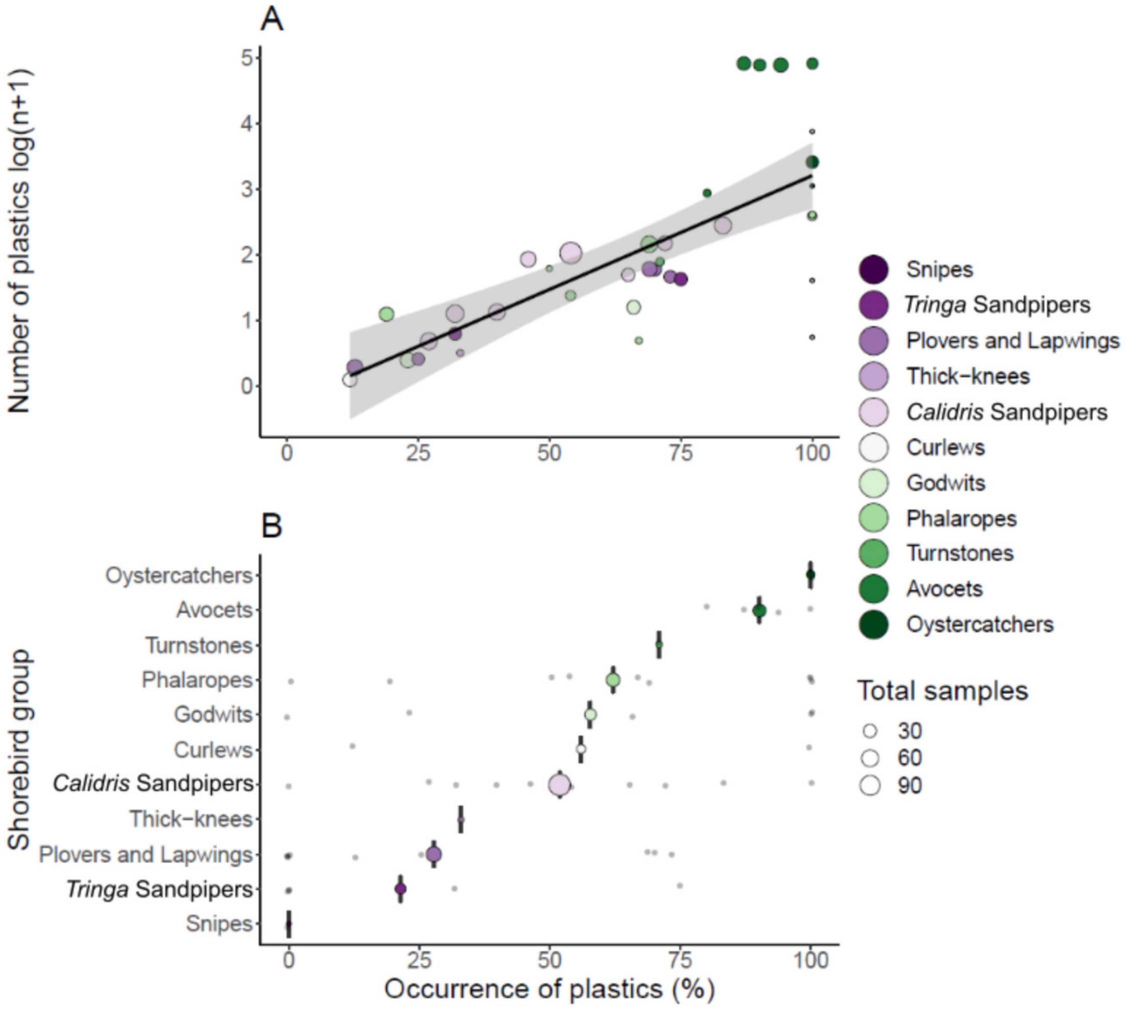
Eight of the 26 shorebird species examined showed no evidence of plastics pollution ingestion; however, the number of samples from each of these species was small ($1 \leq n \leq 25$). Species with no evidence of plastics included one godwit species ($n = 1$), three *Tringa* sandpiper species ($n = 1$ per species), one *Calidris* sandpiper ($n = 25$), one snipe ($n = 1$), four species of plover ($n = 171$), and one species of lapwing ($n = 5$). Importantly, these studies report that they were unable to report plastics pollution pieces less than 1.560 mm^2 in size (Rossi et al. 2019). Reporting these zero value findings with the detection limit is important, as microplastics are ubiquitous, and the detection limit of a study influences the results.

While 28 species/regions contained plastics pollution in >50% of the individuals investigated, only 10 species had >40 individual samples from a region; a sample of 40 is generally accepted to be a reliable estimate of FO for birds; however, this can vary by species (Provencher et al. 2015; Lavers et al. 2021; van Franeker et al. 2021). The power analysis work by Provencher et al. (2015) was conducted on seabird species, and should be undertaken specifically using data from shorebirds of interest. Of these 10 species, sanderling (*Calidris alba*) and common ringed plover *(Charadrius hiaticula*) were the only species sampled at more than one site. The %FO of plastics pollution in sanderling ranged from 32% of individuals ($n = 63$) in Guinea-Bissau to 83% ($n = 59$) at Tejo Estuary, Portugal (Lourenço et al. 2017). For common ringed plover, plastics %FO ranged from 13% ($n = 47$) in Guinea-Bissau to 69% ($n = 41$) in Mauritania (Lourenço et al. 2017). The majorities of dunlin (*Calidris alpina*) in Mauritania (54%, $n = 111$) and red phalarope off the coast of North Carolina (69%, $n = 55$) contained plastics pollution. Conversely, bar-tailed godwit (*Limosa lapponica*; 23%, $n = 43$), curlew sandpiper (*Calidris ferruginea*; 27%, $n = 59$), and red knot (*Calidris canutus*; 40%, $n = 55$) in Guinea-Bissau all had relatively low %FO of plastics pollution. Red phalarope was investigated for plastics pollution in seven studies in seven different regions, whereas 14 species had only one study investigating plastics pollution ingestion in only one location.

Flyway geography and season

Of the six flyways where shorebird plastic interactions were investigated, seven studies were conducted in the American Pacific Flyway (two species, $n = 29$ individuals), three in the East Asian-Australasian Flyway (nine species, $n = 16$), and three in the American Atlantic Flyway (five species, $n = 141$).

Fig. 2. Occurrence of plastics (average %FO across studies) found in shorebird groups (A), and linear relationship (95% CI in grey) between average occurrence of plastics and total number of plastic pieces found in shorebird groups (B). For both figures, circle size indicates approximate total number of samples across studies across a gradient.



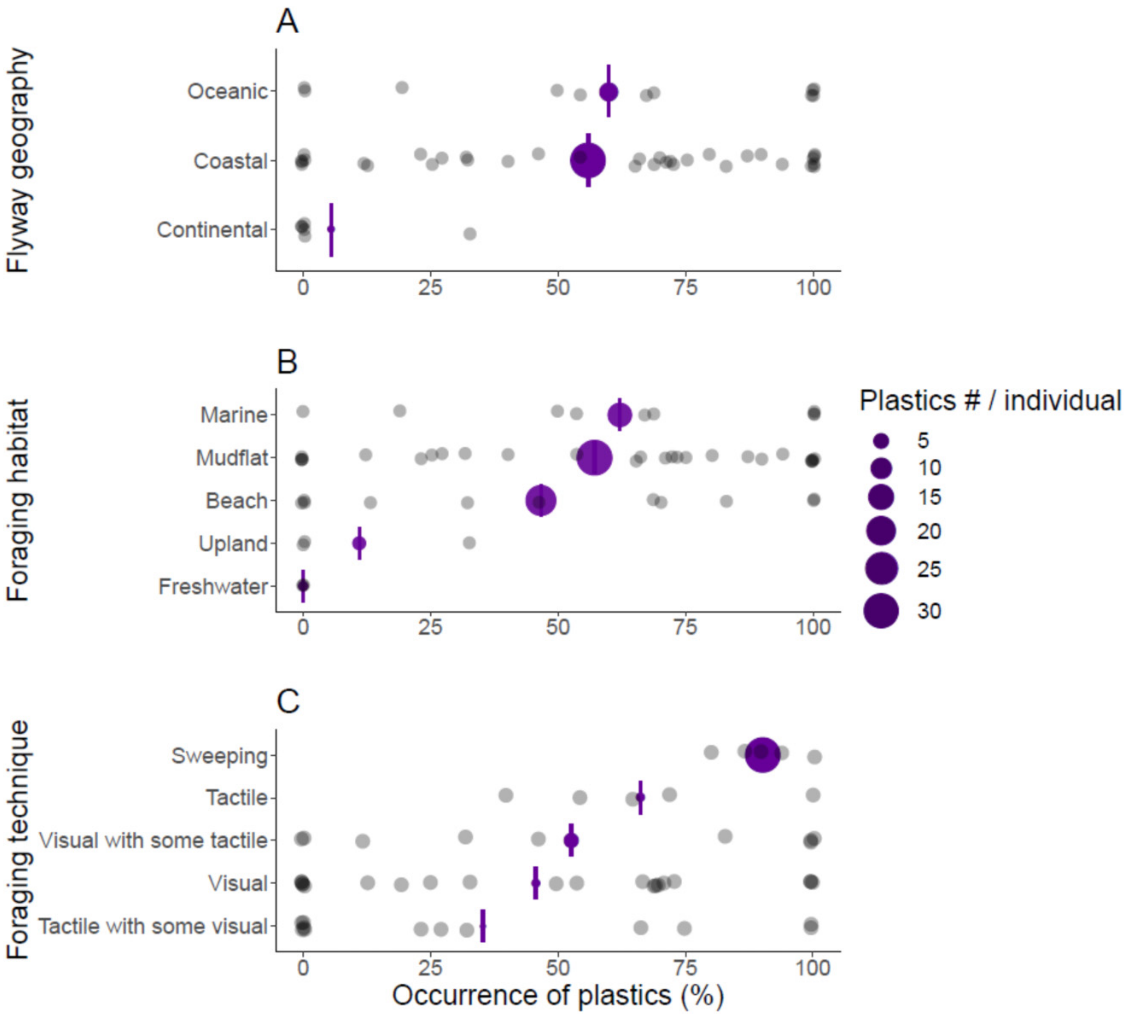
The remaining studies were conducted in the East Atlantic Flyway (13 species, $n = 915$), and Mediterranean Flyway (four species, $n = 4$), or included samples from both regions. More studies were conducted about plastics pollution ingestion in shorebirds in oceanic (four species, $n = 125$) and coastal flyway geographies (16 species, $n = 969$) than continental routes (six species, $n = 12$; Fig. 3A). The %FO of plastics pollution was much greater among species that migrated in marine areas, either oceanic or coastal (oceanic mean: 60%, $n = 11$; coastal mean: 58%, $n = 33$), than those that used upland continental flyways (mean: 6%, $n = 6$, $F_{[2,48]} = 5.78$, $P = 0.006$). The average number of plastic pieces per individual was not statistically significant among foraging habitats ($F_{[2,34]} = 0.75$, $P = 0.48$).

Plastic interaction studies focused on sampling species during non-breeding periods, with 10 studies conducted at wintering sites, four at stopover sites, and the remaining on nonmigratory species during their nonbreeding period. Of the 26 species sampled, 12 were sampled during migration ($n = 807$), 11 during the non-breeding period ($n = 155$), three during both the migration and non-breeding periods, and five were year-round ($n = 144$). No studies examined a single species during multiple sampling periods within the same flyway.

Foraging habitat and mode

Species with plastics pollution ingestion information could be classified into five general foraging habitats, including five species that foraged on beaches ($n = 313$ individuals), two in freshwater ($n = 2$), three in marine ($n = 123$), 11 on mudflats ($n = 634$), and three in upland habitats ($n = 9$, Fig. 3B). Overall, there was significant variation in the evidence of plastics pollution among habitats and species, and no statistically significant difference in %FO of plastics pollution among habitats ($F_{[4,46]} = 2.35$, $P = 0.07$). In general, species that foraged in marine areas (62%), on mudflats (57%), or on beaches (51%) had higher average %FO of plastic ingestion than species that foraged in upland (11%) or freshwater environments (0%). The average number of plastic pieces per individual was not statistically significant among foraging habitats ($F_{[3,33]} = 0.51$, $P = 0.68$), although counts of plastic pieces were not published for species using freshwater habitats (Fig. 3B).

Fig. 3. Relationship between the average occurrence of plastics (percentage across studies) and shorebird flyway geography (A), foraging habitat (B), and foraging technique (C). Each species per study is identified by a grey dot; purple dots show the average occurrence of plastics and the size of the dot represents the approximate average number of plastic pieces per individual across a gradient for each ecological feature analyzed across all shorebird groups.



A classification of the species by foraging technique revealed 10 visual species ($n = 309$ individuals), five visual with some tactile ($n = 230$), six tactile with some visual ($n = 196$), two tactile ($n = 235$), and one species that foraged by sweeping/scything ($n = 111$, Fig. 3C). The species that used sweeping foraging modes had a higher probability of ingesting plastics pollution ($F_{[3,47]} = 3.20$, $P = 0.03$) and contained a far greater number of plastics than all other techniques ($F_{[3,33]} = 14.31$, $P < 0.001$). The probability of ingesting plastics pollution was otherwise quite variable among foraging techniques, with high occurrences of plastics in species using each foraging mode.

Body mass

Body mass in the species present in our 16 studies ranged from 35 g (red-necked phalarope) to 670 g (bush thick-knee *Burhinus grallarius*; mean ± SD = 198.15 ± 193.70 g, Fig. 4). The total number of plastic pieces ingested by a taxonomic group was variable and had low correlation (Pearson correlation, $r_{1,11} = 0.18$, $P = 0.08$; Fig. 4). Three larger bodied groups, including avocets, oystercatchers, and curlews, had higher %FO of ingesting plastics and contained more pieces. One large-bodied terrestrial group (thick-knees) had a low %FO of ingesting plastics but had a low sample size.

A recommended way forward

Susceptibility scoring

Our review indicated that only about 12% of the world's ~255 shorebird species have been investigated for plastics pollution ingestion. To facilitate our understanding of the frequency of plastics pollution ingestion by shorebirds, we present a rapid assessment framework for evaluating whether shorebirds are likely to be ingesting plastics pollution throughout their annual cycles (Table 2). We focus on the factors discussed above to evaluate the likely susceptibility to plastics pollution ingestion. This approach will help direct

Fig. 4. Relationship between the average body mass (log) and average number of plastic pieces (log) found per shorebird group. The approximate total number of samples across a gradient for each shorebird group is depicted by the size of the circle.

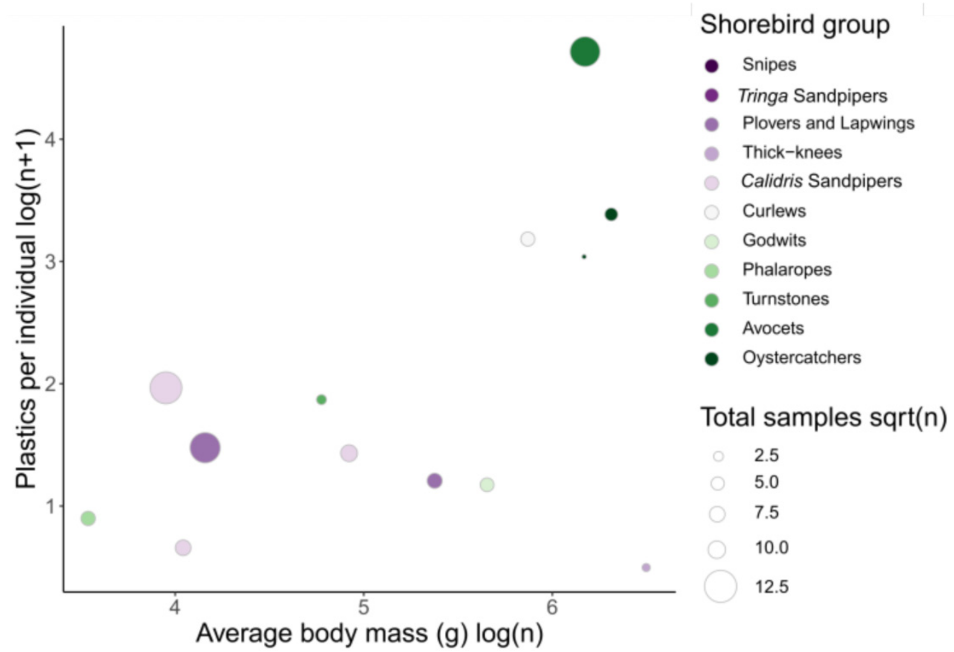


Table 2. Ecological factors that influence the likelihood (low, medium, or high) of finding ingested plastics in shorebirds.

Ecological factors	Likelihood of ingesting plastics			
	Low	Medium	High	Confidence
Flyway geography	Continental		Coastal, oceanic	High
Foraging habitat	Upland, freshwater		Marine, mudflat, beach	High
Foraging mode	Visual, tactile w/visual	Tactile, visual w/tactile	Sweeping	Low
Body size		Medium (51–399 g)	Large (>400 g), small (<50 g)	Low

Note: Our confidence in our score for each factor is listed at the far right and includes a High and Low category. High refers to situations supported by most published and ecological evidence and Low refers to cases that are data deficient or unclear.

future research on species most likely to be experiencing effects from plastics pollution, and identify knowledge gaps in shorebird ecology needed to understand potential impacts.

Overall, our review indicated that species that use marine environments, forage at sea, or forage by sweeping the water with their bills are most susceptible to ingesting plastics pollution. The high susceptibility score of marine environments is clearly supported by the phalarope species that have higher %FO of plastics pollution than all other taxonomic groups. This pattern may be attributable to the water surface in marine environments being an accumulation zone for plastics pollution (Eriksen et al. 2013; Lebreton et al. 2018; Schwarz et al. 2019). Foraging in marine areas may also expose shorebirds to plastics pollution because floating pieces of plastics may be mistaken for prey items. Coastal species may be more susceptible to ingesting smaller plastics fibers as they transfer from freshwater systems to estuaries and mudflats and settle in the sediment. Estuaries may have high levels of fibers in the environment (Wessel et al. 2016; Willis et al. 2017). The higher %FO and abundance of plastics pollution in species that use sweeping techniques may occur because they are non-selectively ingesting debris suspended in the water column. We did not have enough evidence to assess the prevalence of secondary ingestion of plastics, influence of olfactory foraging, or the %FO of species that use the more recently identified feeding technique of slurping intertidal biofilm from the surface of mudflats (Kuwae et al. 2008). However, biofilm likely traps high concentrations of microplastics in the polysaccharide matrix present on the water surface. Many shorebird species have small spines on their tongues that facilitate this feeding technique (Kuwae et al. 2012), and so akin to sweeping, likely have a higher propensity to inadvertently obtain plastics than species pecking food after visual detection. This is supported by species that migrate continentally and feed by pecking and probing on terrestrial invertebrates; they appear to have a lower risk of plastics pollution ingestion. There is a dearth of information on how frequently shorebirds regurgitate food in pellets and so little is understood on whether shorebirds can regurgitate plastics pollution like some seabirds do, which reduces plastics loads (e.g., Hammer et al. 2016).

Sampling protocols

Significant effort has already been put into developing field protocols to describe plastics %FO in marine megafauna, primarily seabirds (Provencher et al. 2017*b*, 2019). These field protocols, which are heavily dependent on sampling opportunities, may not always apply to shorebirds. For example, many studies on seabirds rely heavily on carcasses collected through legal and subsistence hunting, or opportunistically around dense breeding colonies or during large wrecks. It is also easy to sample some species of seabirds non-lethally through the collection of regurgitations or using stomach lavage. By contrast, opportunities for sample collection of shorebirds are much more limited (see below). Furthermore, reports of forced regurgitation of pellets or use of stomach lavage on any bird species are rare and applying these methods may potentially be lethal (Provencher et al. 2019).

Ideally, sampling protocols should use techniques that do not incur additive mortality, such as collecting birds that have died from other causes or non-lethal sampling. Our review indicated that shorebirds that were necropsied versus fecal sampled differed little in the proportion of individuals containing plastics pollution; however, the size of plastics that might be discovered likely varies by the sampling technique. Intuitively, necropsies may find all sizes of plastics, whereas fecal sampling might only discover small pieces that pass through the digestive system. In support of this contention, studies on red phalaropes examined through carcass analysis reported larger microplastics (1–5 mm), while studies on other sandpipers, which relied on fecal sampling, reported smaller microfibers (<1 mm). Thus, it is currently unclear whether small birds ingest larger plastics pollution pieces as the available samples (i.e., fecal) likely biased the size of plastics collected and reported.

Overall, our review revealed inconsistencies in the collection and reporting metrics in shorebird ingestion of plastics pollution. This reinforces the importance of standardized collection and reporting protocols described by Provencher et al. (2017, 2019). For example, ~53% of fecal studies reported total counts of plastic pieces and one reported a concentration (e.g., Lourenço et al. 2017); weights were only reported in 47% of studies. To allow credible comparisons among species, we recommend counting fibers, and reporting total number and mass per individual rather than a concentration. Furthermore, sieve size, which affects the size of plastics detected, was reported for ~33% of studies and minimum sieve size ranged from 0.02 to 5 mm. These inconsistencies likely biased our understanding of the %FO of plastics in shorebirds. For example, phalaropes were necropsied more often than other species, but sieving of gut contents was either not reported or used larger sieve sizes potentially missing smaller fibers that may have been ingested.

None of the papers, except for a recent companion paper (Teboul et al. 2021) to Drever et al. (2018), provided more detailed information on plastics types. More advanced analytical techniques such as Raman and Fourier-transform infrared spectroscopy have recently been used to confirm visual sorting and helped with finer scale characterization of polymer types (Song et al. 2015; Avery-Gomm et al. 2016; Shim et al. 2017; Teboul et al. 2021; Veerasingam et al. 2021). Since different polymers release and absorb different chemicals, determining the types of contaminants shorebirds are exposed to once plastics are ingested is important when identifying potential sublethal or long-term consequences of plastic ingestion (Provencher et al. 2019). Polymer characterization can also facilitate tracking sources of plastics pollution, information that can be used when influencing management and conservation strategies (Rochman et al. 2019).

As the field of plastics pollution ingestion by wildlife expands to include other taxa, it is becoming increasingly important to collect samples in a standardized manner, with strict QA/QC protocols, to allow for spatial and temporal comparisons across studies and species (detailed in Provencher et al. 2017, 2019). While largely targeted at marine megafauna, these same policies and procedures must apply to future work on shorebirds. Standardized protocols and reporting metrics will allow future meta-analyses and long-term monitoring efforts that aim to highlight population-level effects and guide conservation actions. Paramount for shorebirds, we recommend collecting fecal samples by placing birds individually in sterile holding containers lined with tin foil for short periods. We also recommend analyzing blank samples (i.e., where no bird was present in the container), when sampling procedures expose holding containers to the outside air for extended periods. Similar blanks should be used in lab settings when samples are exposed to air for longer periods. In this way, samples represent information for a single bird and effects from outside contamination are controlled. While implementing such procedures may be difficult, especially when capturing large numbers of birds, the end results will be much more reliable, even if sample sizes are smaller.

Future areas of research

Our review on plastics pollution ingestion by shorebirds clearly indicates the overall lack of information on this subject. As such, it makes sense to draw on studies of other taxa such as seabirds where we have progressed further in understanding the relationships among different species, habitats, environmental exposure, and %FO (Provencher et al. 2015; Wilcox et al. 2015; Baak et al. 2020*a*). For shorebirds, there is a clear need to quantify how much plastics pollution is being ingested by a larger number of shorebird taxa. Species to be sampled can be prioritized using the knowledge gained about the likelihood of exposure in this review (Table 2). In addition, more samples at more sites and in more regions of the world are needed to allow comparisons of ingestion rates within and among flyways. For example, to date there are no ingestion indices for shorebirds on their Arctic breeding grounds. While we might predict lower exposure to plastics pollution than during other phases of their annual cycle (but see Martins et al. 2020; Rey et al. 2021), various studies have shown that microplastics are abundant in Arctic marine, freshwater, and terrestrial habitats (Bergmann et al. 2019; Huntington et al. 2020; Mallory et al. 2021). To address this gap, we encourage collaborative studies such as those coordinated as part of the Arctic Shorebird Demographic Network that previously collected fecal samples to answer broad-scale questions on gut microbiota (Grond et al. 2019). Other opportunities to collect samples might exist during the legal subsistence harvest of shorebirds in Alaska (Naves et al. 2019), the Caribbean (Reed et al. 2018), and other locations.

Another major knowledge gap is how long individual shorebirds retain plastics. Indeed, this question remains an unresolved issue for many bird species, although it has been addressed somewhat in seabirds (Ryan 2015). For shorebirds travelling long distances across diverse habitats, this is a key question for identifying where birds are ingesting plastics. Moreover, larger and higher counts of plastic pieces such as those found in oystercatchers and phalaropes could be in part attributable to plastics pollution accumulating over the lifetime of the bird. It is also unknown whether shorebirds can accumulate smaller plastics fibers and whether, or over what time frame, they might be excreted. Quantifying the turnover rate of ingested plastics pollution would help interpret the relevance of plastics found in gut and fecal samples. Controlled feeding trials using a model shorebird species are needed to develop generalized turnover rates that could be applied to shorebirds sharing similar ecological traits. In the absence of feeding trials, sampling of species over multiple locations/life stages within the same flyway could shed light on the species-specific accumulation of plastics pollution in shorebirds, as has been done to examine chemical contaminant exposure in shorebirds (e.g., Pratte et al. 2020).

To further refine our understanding of how prey selection relates to %FO of plastics being ingested by various species, studies could combine analyses of fecal samples for plastics with stable isotope analyses or deoxyribonucleic acid metabarcoding. As plastics loads can vary with prey type (e.g., gastropods vs. arthropods vs. biofilm), relating proportional contributions of specific prey types to plastics loads can help elucidate how a species' foraging strategy changes the risk of ingesting plastics pollution. Also worthy of investigation is the potential for plastics pollution to affect the habitat used by shorebird prey (see Lavers et al. 2021, for effect on beach sediment temperature) and thus prey distribution, availability, and quality.

Perhaps most needed are studies that assess the lethal or sublethal effects of plastics pollution ingestion in shorebirds. In our review, Drever et al. (2018) was the only study to indicate plastic ingestion contributed to the death of the individual. An additional two studies related plastics pollution loads to physiology and body condition. No studies examined the presence or concentration of other contaminants such as polychlorinated biphenyls and polyaromatic hydrocarbons that may leach from plastics once ingested. Past studies on seabirds have shown that elevated plastics loads can reduce body condition or increase concentrations of other contaminants (Tanaka et al. 2013; Lavers et al. 2014). Thus, it is important to consider these types of chemical effects in shorebirds exposed to plastic ingestion as well.

Shorebirds are long-distance migrants that move between some of the cleanest and most polluted habitats on the Earth during their annual cycle. With global concern over declining trends in many shorebird populations (e.g., Rosenberg et al. 2019; Smith et al. 2020), identifying and evaluating threats to shorebird individuals and their habitats are a first step towards developing plans for conservation. Efforts to assess other threats, such as habitat loss (Piersma et al. 2016), harvest (Reed et al. 2018; Gallo-Cajiao et al. 2020; McDuffie et al. 2021), and climate change (van Gils et al. 2016; Saalfeld and Lanctot 2017; Wauchope et al. 2017; Saalfeld et al. 2021; Lameris et al. 2022), have taken place, but relatively little attention has been given to the threat of plastics pollution on shorebird populations. Our review suggests that there is already evidence that foraging mode, foraging habitat, and flyway location may be major drivers in shorebird plastics exposure and ingestion. We strongly encourage researchers to consider adding plastics pollution evaluation protocols to their programs to help improve our knowledge of this potential threat.

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Data availability

All of the data used in this paper are included in the Supplementary material.

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Author notes

Mark L. Mallory served as an Editorial Board Member at the time of manuscript review and acceptance; peer review and editorial decisions regarding this manuscript were handled by Kathleen Ruhland.

Author contributions

S.A.F., R.B.L., C.P., T.B., and J.F.P. conceived the idea for the study. S.A.F., R.B.L., C.P., M.L.M., S.K., M.C.D., T.B., and J.F.P. contributed data, analyses, and wrote the paper.

Competing interests

The authors declare that there are no competing interests.

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Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/er-2022-0008.

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. Geo. **12**: 339–344. doi:10.1038/s41561-019-0335-5.

Ambrosini, R., Azzoni, R.S., Pittino, F., Diolaiuti, G., Franzetti, A., and Parolini, M. 2019. First evidence of microplastic contamination in the supraglacial debris of an alpine glacier. Environ. Pollut. **253**: 297–301. doi:10.1016/j.envpol.2019.07.005. PMID:31323612.

Andres, B.A., Smith, P.A., Morrison, R.G., Gratto-Trevor, C.L., Brown, S.C., and Friis, C.A. 2012. Population estimates of North American shorebirds, 2012. Wader Study Group Bull. **119**: 178–192.

Avery-Gomm, S., Valliant, M., Schacter, C.R., Robbins, K.R., Liboiron, M., Daoust, P.Y., et al. 2016. A study of wrecked dovekies (*Alle alle*) in the western North Atlantic highlights the importance of using standardized methods to quantify plastic ingestion. Mar. Pollut. Bull. **113**: 75–80. doi:10.1016/j.marpolbul.2016.08.062. PMID:27609235.

Baak, J.E., Linnebjerg, J.F., Barry, T., Gavrilo, M.V., Mallory, M.L., Price, C., and Provencher, J.F. 2020*a*. Plastic ingestion by seabirds in the circumpolar Arctic: a review. Environ. Rev. **28**: 506–516. doi:10.1139/er-2020-002 9.

Baak, J.E., Provencher, J.F., and Mallory, M.L. 2020*b*. Plastic ingestion by four seabird species in the Canadian Arctic: comparisons across species and time. Mar. Pollut. Bull. **158**: 111386. doi:10.1016/j.marpolbul.2020.111386.

Ballejo, F., Plaza, P., Speziale, K.L., Lambertucci, A.P., and Lambertucci, S.A. 2021. Plastic ingestion and dispersion by vultures may produce plastic islands in natural areas. Sci. Total Environ. **755**: 142421. doi:10.1016/j.scitotenv.2020.142421. PMID:33035984.

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. Sci. Adv. **5**: p.eaax1157. doi:10.1126/sciadv.aax1157.

Bessa, F., Barría, P., Neto, J.M., Frias, J.P.G.L., Otero, V., Sobral, P., and Marques, J.C. 2018. Occurrence of microplastics in commercial fish from a natural estuarine environment. Mar. Pollut. Bull. **128**: 575–584. doi:10.1016/j.marpolbul.2018.01.044. PMID:29571409

Billerman, S.M., Keeney, B.K., Rodewald, P.G., and Schulenberg, T.S.. (*Eds.*) 2020. Birds of the world. Cornell Laboratory of Ornithology, Ithaca, N.Y.. Available from https://birdsoftheworld.org/bow/home.

Bond, S., 1971. Red phalarope mortality in southern California. Calif. Birds, **2**: 97.

Bourdages, M.P.T., Provencher, J.F., Baak, J.E., Mallory, M.L., and Vermaire, J.C. 2020. 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. PMID:33082039.

Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M., and Sukumaran, S. 2020. Plastic rain in protected areas of the United States. Science, **368**: 1257–1260. doi:10.1126/science.aaz5819. PMID:32527833.

Brauer, D. 2018. Microplastics in full view: birds as bioindicators of Malta's coastal ecosystem health. MS thesis. James Madison University, Harrisonburg, Va.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., and Thompson, R. 2011. Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ. Sci. Technol. **45**: 9175–9179. doi:10.1021/es201811s. PMID:21894925

Browne, M.A., Underwood, A.J., Chapman, M.G., Williams, R., Thompson, R.C., and van Franeker, J.A. 2015. Linking effects of anthropogenic debris to ecological impacts. Proc. R. Soc. B: Biol. Sci. **282**: 20142929. doi:10.1098/rspb.2014.2929.

Cable, R.N., Beletsky, D., Beletsky, R., Wigginton, K., Locke, B.W., and Duhaime, M.B. 2017. Distribution and modeled transport of plastic pollution in the great lakes, the world's largest freshwater resource. Front. Environ. Sci. **5**: 45. doi:10.3389/fenvs.2017.00045.

Carlin, J., Craig, C., Little, S., Donnelly, M., Fox, D., Zhai, L., and Walters, L. 2020. Microplastic accumulation in the gastrointestinal tracts in birds of prey in central Florida, USA. Environ. Pollut. **264**: 114633. doi:10.1016/j.envpol.2020.114633. PMID:32388295

Colwell, M.A. 2010. Shorebird ecology, conservation, and management. University of California Press, Los Angeles, Calif.

Connors, P.G., and Smith, K.G. 1981. Oceanic plastics particle pollution: suspected effect on fat deposition in red phalaropes. Mar. Pollut. Bull. **13**: 18–20. doi:10.1016/0025-326X(82)90490-8.

COSEWIC. 2000. COSEWIC assessment and status report on the Red-necked Phalarope *Phalaropus lobatus* in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa. 52pp.

D'Souza, J.M., Windsor, F.M., Santillo, D., and Ormerod, S.J. 2020. Food web transfer of plastics to an apex riverine predator. Global Change Biol. **26**: 3846–3857. doi:10.1111/gcb.15139. PMID:32441452.

Day, R.H. 1980. The occurrence and characteristics of plastic pollution in Alaska's marine birds. M.Sc. thesis. University of Alaska. Fairbanks, Alaska.

de Souza Machado, A.A., Kloas, W., Zarfl, C., Hempel, S., and Rillig, M.C. 2018. Microplastics as an emerging threat to terrestrial ecosystems. Global Change Biol. **24**: 1405–1416. doi:10.1111/gcb.14020. PMID:29245177.

Drescher, M., Perera, A.H., Johnson, C.J., Buse, L.J., Drew, C.A., and Burgman, M.A. 2013. Toward rigorous use of expert knowledge in ecological research. Ecosphere, **4**: art83. doi:10.1890/ES12-00415.1.

Drever, M.C., Provencher, J.F., O'Hara, P.D., Wilson, L., Bowes, V., and Bergman, C.M. 2018. Are ocean conditions and plastic debris resulting in a 'double whammy' for marine birds? Mar. Pollut. Bull. **133**: 684–692. doi:10.1016/j.marpolbul.2018.06.028. PMID:30041365.

Environment and Climate Change Canada, Health Canada. 2020. Science assessment of plastic pollution [online]. Environment and Climate Change Canada. Available from https://www.canada.ca/en/environment-climate-change/services/evaluating-existing-substances/science-assessment-plastic-pollution.html. [accessed 6 June 2021].

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., et al. 2014. Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS One, **9**: e111913. doi:10.1371/journal.pone.0111913. PMID:25494041.

Eriksen, M., Maximenko, N., Thiel, M., Cummins, A., Lattin, G., Wilson, S., et al.. 2013. Plastic pollution in the South Pacific subtropical gyre. Mar. Pollut. Bull. **68**: 71–76. doi:10.1016/j.marpolbul.2012.12.021. PMID:23324543.

Gallo-Cajiao, E., Morrison, T.H., Woodworth, B.K., Lees, A.C., Naves, L.C., Yong, D.L., et al.. 2020. Extent and potential impact of hunting on migratory shorebirds in the Asia-Pacific. Biol. Conserv. **246**: 108582. doi:10.1016/j.biocon.2020.108582.

Gasperi, J., Wright, S.L., Dris, R., Collard, F., Mandin, C., Guerrouache, M., et al. 2018. Microplastics in air: are we breathing it in? Curr. Opin. Environ. Sci. Health, **1**: 1–5. doi:10.1016/j.coesh.2017.10.002.

Gill, F., Donsker, D., and Rasmussen, P.. (*Eds.*) 2021. IOC World Bird List (v11.1). doi:10.14344/IOC.ML.11.1.

Grond, K., Santo Domingo, J.W., Lanctot, R.B., Jumpponen, A., Bentzen, R.L., Boldenow, M.L., et al. 2019. Composition and drivers of gut microbial communities in Arctic-breeding shorebirds. Front. Microbiol. **10**. doi:10.3389/fmicb.2019.02258. PMID: 31649627.

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. PMID:26763326.

Hipfner, J.M., Galbraith, M., Tucker, S., Studholme, K.R., Domalik, A.D., Pearson, S.F., et al. 2018. Two forage fishes as potential conduits for the vertical transfer of microfibres in Northeastern Pacific Ocean food webs. Environ. Pollut. **239**: 215–222. doi:10.1016/j.envpol.2018.04.009. PMID:29655068.

Huntington, A., Corcoran, P.L., Jantunen, L., Thaysen, C., Bernstein, S., Stern, G.A., and Rochman, C.M. 2020. A first assessment of microplastics and other anthropogenic particles in Hudson Bay and the surrounding eastern Canadian Arctic waters of Nunavut. FACETS, **5**: 432–454. doi:10.1139/facets-2019-004 2.

Kühn, S., and van Franeker, J.A. 2020. Quantitative overview of marine debris ingested by marine megafauna. Mar. Pollut. Bull. **151**: 110858. doi:10.1016/j.marpolbul.2019.110858. PMID:32056640.

Kuwae, T., Beninger, P.G., Decottignies, P., Mathot, K.J., Lund, D.R., and Elner, R.W. 2008. Biofilm grazing in a higher vertebrate: the western sandpiper, *Calidris mauri*. Ecology, **89**(3): 599–606. doi:10.1890/07-1442.1. PMID:18459323.

Kuwae, T., Miyoshi, E., Hosokawa, S., Ichimi, K., Hosoya, J., Amano, T., et al.. 2012. Variable and complex food web structures revealed by exploring missing trophic links between birds and biofilm: missing trophic links in food webs. Ecol. Lett. **15**: 347–356. doi:10.1111/j.1461-0248.2012.01744.x. PMID:22304245.

Lacerda, A.L.d.F., Rodrigues, L.d.S., van Sebille, E., Rodrigues, F.L., Ribeiro, L., Secchi, E.R., et al.. 2019. Plastics in sea surface waters around the Antarctic Peninsula. Sci. Rep. **9**: 3977. doi:10.1038/s41598-019-40311-4. PMID:30850657.

Lameris, T.K., Tomkovich, P.S., Johnson, J.A., Morrison, R.I.G., Tulp, I., Lisovski, S., et al. 2022. Mismatch-induced growth reductions in a clade of Arctic-breeding shorebirds are rarely mitigated by increasing temperatures. Global Change Biol. **28**: 829–847. doi:10.1111/gcb.16025.

Lavers, J.L., Bond, A.L., and Hutton, I. 2014. Plastic ingestion by Flesh-footed shearwaters (*Puffinus carneipes*): implications for fledgling body condition and the accumulation of plastic-derived chemicals. Environ. Pollut. **187**: 124–129. doi:10.1016/j.envpol.2013.12.020. PMID:24480381.

Lavers, J.L., Hutton, I., and Bond, A.L. 2021. Temporal trends and interannual variation in plastic ingestion by Flesh-footed shearwaters (*Ardenna carneipes*) using different sampling strategies. Environ. Pollut. **290**: 118086. doi:10.1016/j.envpol.2021.118086. PMID:34482247.

Lavers, J.L., Stivaktakis, G., Hutton, I., and Bond, A.L. 2019. Detection of ultrafine plastics ingested by seabirds using tissue digestion. Mar. Poll. Bull. **142**: 470–474. doi:10.1016/j.marpolbul.2019.04.001.

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., et al. 2018. Evidence that the great pacific garbage patch is rapidly accumulating plastic. Sci. Rep. **8**: 4666. doi:10.1038/s41598-018-22939-w. PMID:29568057.

Liboiron, F., Ammendolia, J., Saturno, J., Melvin, J., Zahara, A., Richárd, N., and Liboiron, M. 2018. A zero percent plastic ingestion rate by silver hake (*Merluccius bilinearis*) from the south coast of Newfoundland, Canada. Mar. Pollut. Bull. **131**: 267–275. doi:10.1016/j.marpolbul.2018.04.007. PMID29886947

Lourenço, P.M., Serra-Gonçalves, C., Ferreira, J.L., Catry, T., and Granadeiro, J.P. 2017. Plastic and other microfibers in sediments, macroinvertebrates and shorebirds from three intertidal wetlands of southern Europe and west Africa. Environ. Pollut. **231**: 123–133. doi:10.1016/j.envpol.2017.07.103. PMID:28797901.

Lusher, A.L., Tirelli, V., O'Connor, I., and Officer, R. 2015. Microplastics in arctic polar waters: the first reported values of particles in surface and sub-surface samples. Sci. Rep. **5**: 14947. doi:10.1038/srep14947. PMID:26446348.

MacLeod, M., Arp, H.P.H., Tekman, M.B., and Jahnke, A. 2021. The global threat from plastic pollution. Science, **373**: 61–65. doi:10.1126/science.abg5433. PMID:34210878.

Mallory, M.L., Baak, J., Gjerdrum, C., Mallory, O.E., Manley, B., Swan, C., and Provencher, J.F. 2021. Anthropogenic litter in marine waters and coastlines of Arctic Canada and West Greenland. Sci. Total Environ. **783**: 146971. doi:10.1016/j.scitotenv.2021.146971. PMID:33865122

Mallory, M.L., Elderkin, M.F., Spencer, N.C., Betsch, T.A., Russell, A.C., and Mills, P.L. 2016. Diet of *Calidris maritima* (purple sandpiper) during the winter in Nova Scotia, Canada. Northeast. Nat. **23**: 205–210. doi:10.1656/045.023.0202.

Martins, I., Rodríguez, Y., and Pham, C.K. 2020. Trace elements in microplastics stranded on beaches of remote islands in the NE Atlantic. Mar. Pollut. Bull. **156**: 111270.10.1016/j.marpolbul.2020.111270. PMID:32510410.

Maximenko, N., Hafner, J., and Niiler, P. 2012. Pathways of marine debris derived from trajectories of Lagrangian drifters. Mar. Pollut. Bull. **65**: 51–62. doi:10.1016/j.marpolbul.2011.04.016. PMID:21696778.

McDuffie, L.A., Christie, K.S., Harrison, A.-L., Taylor, A.R., Andres, B.A., Laliberté, B., and Johnson, J.A. 2021. Eastern-breeding lesser yellowlegs are more likely than western-breeding birds to visit areas with high shorebird hunting during southward migration. Ornithol. Appl. **124**: duab061. doi:10.1093/ornithapp/duab06 1.

Moreira, F. 2008. The winter feeding ecology of avocets *recurvirostra avosetta* on intertidal areas. II. Diet and feeding mechanisms. Ibis, **137**: 99–108. doi:10.1111/j.1474-919X.1995.tb03225.x.

Moser, M.L., and Lee, D.S. 1992. A fourteen-year survey of plastic ingestion by western North Atlantic seabirds. Colon. Waterbird. **15**: 83. doi:10.2307/1521357.

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.

Naves, L.C., Keating, J.M., Tibbitts, T.L., and Ruthrauff, D.R. 2019. Shorebird subsistence harvest and indigenous knowledge in Alaska: informing harvest management and engaging users in shorebird conservation. Condor, **121**: duz023. doi:10.1093/condor/duz023.

Nevins, H., Hyrenback, D., Keiper, C., Stock, J., Hester, M., and Harvey, J. 2005. Seabirds as indicators of plastic pollution in the North Pacific [online]. In Plastic Debris – Rivers to the Sea Conference. Available from https://oikonos.org/publications?ct=nevins&ce=0&cu=0&cy=0&ci=0. [accessed 6 December 2020].

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. PMID:32753218.

Piersma, T., Lok, T., Chen, Y., Hassell, C.J., Yang, H.-Y., Boyle, A., et al.. 2016. Simultaneous declines in summer survival of three shorebird species signals a flyway at risk. J. Appl. Ecol. **53**: 479–490. doi:10.1111/1365-2664.12582.

Poon, F.E., Provencher, J.F., Mallory, M.L., Braune, B.M., and Smith, P.A. 2017. Levels of ingested debris vary across species in Canadian Arctic seabirds. Mar. Pollut. Bull. **116**: 517–520. doi:10.1016/j.marpolbul.2016.11.051. PMID:28069276.

Pratte, I., Noble, D.G., Mallory, M.L., Braune, B.M., and Provencher, J.F. 2020. The influence of migration patterns on exposure to contaminants in Nearctic shorebirds: a historical study. Environ. Monit. Assess. **192**: 256. doi:10.1007/s10661-020-8218-1. PMID:32232588.

Provencher, J.F., Bond, A.L., and Mallory, M.L. 2015. Marine birds and plastic debris in Canada: a national synthesis and a way forward. Environ. Rev. **23**: 1–13. doi:10.1139/er-2014-0039.

Provencher, J.F., Bond, A.L., Avery-Gomm, S., Borrelle, S.B., Bravo Rebolledo, E.L., Hammer, S., et al. 2017. Quantifying ingested debris in marine megafauna: a review and recommendations for standardization. Anal. Methods, **9**: 1454–1469. doi:10.1039/C6AY02419J.

Provencher, J.F., Borrelle, S.B., Bond, A.L., Lavers, J.L., van Franeker, J.A., Kühn, S., et al. 2019. Recommended best practices for plastic and litter ingestion studies in marine birds: collection, processing, and reporting. FACETS, **4**: 111–130. doi:10.1139/facets-2018-0043.

Provencher, J.F., Liboiron, M., Borrelle, S.B., Bond, A.L., Rochman, C., Lavers, J.L., et al. 2020. A horizon scan of research priorities to inform policies aimed at reducing the harm of plastic pollution to biota. Sci. Total Environ. **733**: 139381. doi:10.1016/j.scitotenv.2020.139381. PMID:32446089.

Provencher, J.F., Vermaire, J.C., Avery-Gomm, S., Braune, B.M., and Mallory, M.L. 2018. Garbage in guano? Microplastic debris found in faecal precursors of seabirds known to ingest plastics. Sci. Total Environ. **644**: 1477–1484. doi:10.1016/j.scitotenv.2018.07.101. PMID:30743860.

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available from https://www.R-project.org/.

Reed, E.T., Kardynal, K.J., Horrocks, J.A., and Hobson, K.A. 2018. Shorebird hunting in Barbados: using stable isotopes to link the harvest at a migratory stopover site with sources of production. Condor, **120**: 357–370. doi:10.1650/CONDOR-17-127.1.

Rey, S.F., Franklin, J., and Rey, S.J., 2021. Microplastic pollution on island beaches, Oahu, Hawaii. PLoS One, **16**: e0247224. doi:10.1371/journal.pone.0247224. PMID:33600448.

Robards, M.D., Gould, P.J., and Piatt, J.F. 1997. The highest global concentrations and increased abundance of oceanic plastic debris in the North Pacific: evidence from seabirds. *In* Marine debris. *Edited by* J.M.

Coe, and D.B. Rogers. Springer, New York. pp. 71–80. doi:10.1007/978-1-4613-8486-1_8.

Rochman, C.M., Brookson, C., Bikker, J., Djuric, N., and Hung, C. 2019. Rethinking microplastics as a diverse contaminant suite. Environ. Toxicol. Chem. **38**: 703–711. doi:10.1002/etc.4371. PMID:30909321.

Roman, L., Bell, E., Wilcox, C., Hardesty, B.D., and Hindell, M. 2019. Ecological drivers of marine debris ingestion in procellariiform seabirds. Sci. Rep. **9**: 916. doi: http://dx.doi.org/10.1038/s41598-018-37324-w. PMID:30696878.

Roman, L., Schuyler, Q.A., Hardesty, B.D., and Townsend, K.A. 2016. Anthropogenic debris ingestion by avifauna in eastern Australia. PLoS One, **11**: e0158343. doi:10.1371/journal.pone.0158343. PMID:27574986.

Rosenberg, K.V., Dokter, A.M., Blancher, P.J., Sauer, J.R., Smith, A.C., Smith, P.A., et al.. 2019. Decline of the North American avifauna. Science, **366**: 120–124. doi:10.1126/science.aaw1313. PMID:31604313.

Rossi, L.C., Scherer, A.L., and Petry, M.V. 2019. First record of debris ingestion by the shorebird American oystercatcher (*Haematopus palliatus*) on the southern coast of Brazil. Mar. Pollut. Bull. **138**: 235–240. doi:10.1016/j.marpolbul.2018.11.051. PMID:30660268.

Ryan, P.G. 1987. The incidence and characteristics of plastic particles ingested by seabirds. Mar. Environ. Res. **23**: 175–206. doi:10.1016/0141-1136(87)90028-6.

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. PMID:26286902.

Ryan, P.G. 2016. Ingestion of plastics by marine organisms. In Hazardous chemicals associated with plastics in the marine environment. *Edited by* H. Takada, and H.K. Karapanagioti. Springer International Publishing, Cham. pp 235–266. doi:10.1007/698_2016_21.

Saalfeld, S.T., and Lanctot, R.B. 2017. Multispecies comparisons of adaptability to climate change: a role for life-history characteristics? Ecol. Evol. **7**: 10492–10502. doi:10.1002/ece3.3517. PMID:29299232.

Saalfeld, S.T., Hill, B.L., Hunter, C.M., Frost, C.J., and Lanctot, R.B. 2021. Warming arctic summers unlikely to increase productivity of shorebirds through renesting. Sci. Rep. **11**: 15277. doi:10.1038/s41598-021-94788-z. PMID:34315998.

Savoca, M., 2018. The ecology of an olfactory trap. Science, **362**: 904. doi:10.1126/science.aav6873. PMID:30467162.

Savoca, M.S., Wohlfeil, M.E., Ebeler, S.E., and Nevitt, G.A. 2016. Marine plastic debris emits a keystone infochemical for olfactory foraging seabirds. Sci. Adv. **2**: e1600395. doi:10.1126/sciadv.1600395. PMID:28861463.

Schwarz, A.E., Ligthart, T.N., Boukris, E., and van Harmelen, T. 2019. Sources, transport, and accumulation of different types of plastic litter in aquatic environments: a review study. Mar. Pollut. Bull. **143**: 92–100. doi:10.1016/j.marpolbul.2019.04.029. PMID:31789171.

Seif, S., Provencher, J.F., Avery-Gomm, S., Daoust, P.-Y., Mallory, M.L., and Smith, P.A. 2018. Plastic and non-plastic debris ingestion in three gull species feeding in an urban landfill environment. Arch. Environ. Contam. Toxicol. **74**: 349–360. doi:10.1007/s00244-017-0492-8. PMID:29282493.

Shahul Hamid, F., Bhatti, M.S., Anuar, N., Anuar, N., Mohan, P., and Periathamby, A. 2018. Worldwide distribution and abundance of microplastic: how dire is the situation? Waste Manage. Res. **36**: 873–897. https://doi.org/10.1177/0734242 × 18785730. PMID:30103651.

Shim, W.J., Hong, S.H., and Eo, S.E. 2017. Identification methods in microplastic analysis: a review. Anal. Methods, **9**: 1384–1391. doi:10.1039/c6ay02558g.

Smith, P.A., McKinnon, L., Meltofte, H., Lanctot, R.B., Fox, A.D., Leafloor, J.O., et al. 2020. Status and trends of tundra birds across the circumpolar Arctic. Ambio, **49**: 732–748. doi:10.1007/s13280-019-01308-5. PMID:31955397.

Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Rani, M., Lee, J., and Shim, W.J. 2015. A comparison of microscopic and spectroscopic identification methods for analysis of microplastics in environmental samples. Mar. Pollut. Bull. **93**: 202–209. doi:10.1016/j.marpolbul.2015.01.015. PMID:25682567.

Studds, C.E., Kendall, B.E., Murray, N.J., Wilson, H.B., Rogers, D.I., Clemens, R.S., et al. 2017. Rapid population decline in migratory shorebirds relying on yellow sea tidal mudflats as stopover sites. Nat. Commun. **8**: 14895. doi:10.1038/ncomms14895. PMID:28406155.

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. PMID:23298431.

Teboul, E., Orihel, D.M., Provencher, J.F., Drever, M.C., Wilson, L., and Harrison, A.L. 2021. Chemical identification of microplastics ingested by red phalaropes (*Phalaropus fulicarius*) using Fourier transform infrared spectroscopy. Mar. Poll. Bull. **171**: 112640. doi:10.1016/j.marpolbul.2021.112640.

Teuten, E.L., Saquing, J.M., Knappe, D.R.U., Barlaz, M.A., Jonsson, S., Björn, A., et al. 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Phil. Trans. R. Soc. B, **364**: 2027–2045. doi:10.1098/rstb.2008.0284.

Thomas, G.H., Lanctot, R.B., and Szekely, T. 2006. Can intrinsic factors explain population declines in North American breeding shorebirds? A comparative analysis. Anim. Conserv. **9**: 252–258. doi:10.1111/j.1469-1795.2006.00029.x.

Thomas, R.J., Székely, T., Powell, R.F., and Cuthill, I.C. 2006. Eye size, foraging methods and the timing of foraging in shorebirds. Funct. Ecol. **20**: 157–165. doi:10.1111/j.1365-2435.2006.01073.x

Thushari, G.G.N., and Senevirathna, J.D.M. 2020. Plastic pollution in the marine environment. Heliyon, **6**: e04709. doi:10.1016/j.heliyon.2020.e04709. PMID:32923712.

van Franeker, J.A., Kühn, S., Anker-Nilssen, T., Edwards, E.W.J., Gallien, F., Guse, N., et al.. 2021. New tools to evaluate plastic ingestion by northern fulmars applied to North Sea monitoring data 2002–2018. Mar. Pollut. Bull. **166**: 112246. doi:10.1016/j.marpolbul.2021.112246. PMID:33774479.

van Gils, J.A., Lisovski, S., Lok, T., Meissner, W., Ożarowska, A., de Fouw, J., et al.. 2016. Body shrinkage due to arctic warming reduces red knot fitness in tropical wintering range. Science, **352**: 819–821. doi:10.1126/science.aad6351. PMID:27174985.

Veerasingam, S., Ranjani, M., Venkatachalapathy, R., Bagaev, A., Mukhanov, V., Litvinyuk, D., et al. 2021. Contributions of Fourier transform infrared spectroscopy in microplastic pollution research: a review. Crit. Rev. Environ. Sci. Tech. **51**: 2681–2743. doi:10.1080/10643389.2020.1807450.

Vegter, A., Barletta, M., Beck, C., Borrero, J., Burton, H., Campbell, M.L., et al.. 2014. Global research priorities to mitigate plastic pollution impacts on marine wildlife. Endang. Spec. Res. **25**: 225–247. doi:10.3354/esr00623.

Wagner, M., Scherer, C., Alvarez-Muñoz, D., Brennholt, N., Bourrain, X., Buchinger, S., et al.. 2014. Microplastics in freshwater ecosystems: what we know and what we need to know. Environ. Sci. Eur. **26**: 1–9. doi:10.1186/s12302-014-0012-7.

Wauchope, H.S., Shaw, J.D., Varpe, Ø., Lappo, E.G., Boertmann, D., Lanctot, R.B., and Fuller, R.A., 2017. Rapid climate-driven loss of breeding habitat for Arctic migratory birds. Global Change Biol. **23**: 1085–1094. doi:10.1111/gcb.13404. PMID:27362976.

Werner, S., and O'Brien, A.S. 2018. Marine litter. *In* Handbook on marine environment protection. *Edited by* M. Salomon, and T. Markus. Springer, Cham. doi:10.1007/978-3-319-60156-4_23.

Wessel, C.C., Lockridge, G.R., Battiste, D., and Cebrian, J. 2016. Abundance and characteristics of microplastics in beach sediments: insights into microplastic accumulation in northern Gulf of Mexico estuaries. Mar. Pollut. Bull. **109**: 178–183. doi:10.1016/j.marpolbul.2016.06.002. PMID:27287867.

Wilcox, C., Van Sebille, E., and Hardesty, B.D. 2015. Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proc. Natl. Acad. Sci. U.S.A. **112**: 11899–11904. doi:10.1073/pnas.1502108112.

Willis, K.A., Eriksen, R., Wilcox, C., and Hardesty, B.D. 2017. Microplastic distribution at different sediment depths in an urban estuary. Front. Mar. Sci. **4**: 419. doi:10.3389/fmars.2017.00419.

Zhao, S., Zhu, L., and Li, D. 2016. Microscopic anthropogenic litter in terrestrial birds from shanghai, china: not only plastics but also natural fibers. Sci. Total Environ. **550**: 1110–1115. doi:10.1016/j.scitotenv.2016.01.112. PMID:26874248.

Zhu, C., Li, D., Sun, Y., Zheng, X., Peng, X., Zheng, K., et al. 2019. Plastic debris in marine birds from an island located in the South China Sea. Mar. Pollut. Bull. **149**: 110566. doi:10.1016/j.marpolbul.2019.110566. PMID:31543495.