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Review

Review of contaminant levels and effects in shorebirds: Knowledge gaps and conservation priorities

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ABSTRACT

Environmental pollution has emerged as a major threat to bird populations. Many shorebird populations are declining, although contamination has been documented in some shorebirds, evidence of negative impacts is sparse and this important topic remains understudied. To guide future research and develop effective conservation strategies, we carried out a comprehensive review of environmental pollutants and their consequences on shorebirds. In total, we found 93 relevant articles which examined pollutant contamination in ~37% (79 of 215) of all shorebird species, mostly from the Charadriidae and Scolopacidae families. Studies were geographically biased: the majority were conducted in American flyways, while only 1 was found from Australasia and few were conducted in Asian flyways. The main geographic gap for research includes East Africa, South Asia and Siberian Arctic. The most well-documented pollutants included mercury (Hg, 37 studies), cadmium (33), and lead (Pb, 28); less well studied pollutants were barium (1), calcium (1), strontium (1), dicofols (1), and other newly emerging contaminants, such as plastic debris/microplastics (4) and antibiotics resistance (2). Several pollutants have caused considerable concerns in shorebirds, including embryotoxicity caused by PCBs at non-optimum temperature (laboratory experiments); reduced reproduction performance linked to maternal Hg and paternal Pb (field evidence); and reduced refueling and flight performance related to oil contamination (both field and laboratory evidence). Our results confirm that an in-depth understanding of the local, regional and global factors that influence population trends of shorebirds in light of increasing pollution threats is essential for accurate and effective management and conservation strategies.

1. Introduction

Shorebirds (Order Charadriiformes) form an essential component in wetland ecosystems worldwide. Many populations have recently experienced steep declines, possibly due to anthropogenic impacts such as climate change (Van Gils et al., 2016) and habitat loss/modification (Ma et al., 2014). As one of the largest avian groups, shorebirds could be vulnerable to environmental pollution (Melville et al., 2016; Tang et al., 2015), likely due to their life-history traits (e.g., foraging behavior and migratory ecology) for the whole life cycle. During non-breeding seasons, they may stop or overwinter at various wetlands, including estuarine mudflats, coastal tidal flats, and freshwater ecosystems (e.g., rivers and lakes). Some of these habitats are close to human settlements and receive constant inputs of anthropogenic toxins via industrial and agricultural activities (Chapagain et al., 2009; C. Li et al., 2022; Zhang et al., 2009). Even in remote northern regions, which serve as breeding grounds for many migratory shorebird species, volatile or semi-volatile persistent organic pollutants (POPs, UNEP, 2021) and mercury (Hg) have been recorded at concerning concentrations via long-range atmospheric transportation (Dietz et al., 2013; Wania and Mackay, 1993).

Environmental pollutants have been studied through investigations of various endpoints/consequences in wild free-living and captive avian subjects. In general, their detrimental impacts on birds have been widely publicized, with impacts including depressed immune system (e.g., Kenow et al., 2007; Spalding et al., 2000; Vallverdú-Coll et al., 2019), embryotoxicity (King et al., 2021), decreased reproductive success (Fernie et al., 2009), altered parental care behavior (Hartman et al., 2019; Pedersen and Saether, 1999), behavioral deficits (e.g.,

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locomotion, food-begging, and individual recognition, Burger and Gochfeld, 2010), impaired migratory performance (Flahr et al., 2015; Ma et al., 2018b; Maggini et al., 2017b), and even reduced survival (Grade et al., 2018; Ma et al., 2018a). Environmental pollutants could pose a great threat to the health of shorebirds throughout their dynamic life cycle, leading to further population declines. However, contamination of natural or synthetic pollutants and associated impacts on shorebirds have not been fully reviewed. Here, we conducted an exhaustive literature review to: (1) summarize the type of pollutants and shorebird species that have been studied; (2) assess the impacts of these key contaminants on shorebird species and populations; and (3) identify research priorities that can help ensure the effective conservation of this vulnerable taxonomic group.

2. Material and methods

To construct a database of published studies on environmental contaminants in shorebirds, we retrieved related papers on the Web of Science (WoS) on May 18, 2022, by using the following search item: topic = ("pollut*" or "heavy metal" or "trace metal" or Pb or lead or Cd or cadmium or Zn or zinc or Mn or manganese or Cu or copper or Tl or thallium or Cr or chromium or Co or cobalt or Ni or nickel or arsenic or Hg or mercury or "POPs" or PCBs or PAHs or DDTs or microplastics or plastic debris or antibiotics resistance) AND topic = shorebird or wader). Although we attempted to systematically compile all relevant studies within the scope of the review, we acknowledged that there may exist other studies that we were unable to locate.

3. Results and discussion

Our search produced 578 results. After manually reviewing these studies, we excluded irrelevant studies related to other wildlife or humans and eventually included 93 relevant studies in this review. The earliest research on environmental pollutants and impacts on shorebirds date back to at least the 1970 s – there was one study documented that several waterbird species using rice fields were poisoned by intaking aldrin-treated seeds or through aldrin-related contamination accumulated in the food chain along Texas Gulf Coast (Flickinger and King, 1972). Two direct poisoning events related to shorebirds were documented in the 1980 s and the 1990 s. Specifically, Bull et al. (1983) reported a poisoning event that caused death and sickness in about 2400 birds, including Dunlin *Calidris alpina* and Redshank *Tringa tetanus*, as a result of regular lead discharge on the Mersey Estuary, UK. Dunlins and Killdeers *Charadrius vociferous* in the USA were poisoned by toxins related to rodent control (Warnock and Schwarzbach, 1995), indicating shorebird species likely to be susceptive as non-target species for pest control. The number of studies increased from 5 studies in the 1980 s to 17 cases in the 1990 s and 18 cases in the 2000 s. The study cases jumped to 44 in the 2010 s, with those published in the 2010 s twice the number of those published in the 2000 s. Studied contaminants in shorebirds were mainly classified into two major classes: well-known POPs (organics) and trace elements (elements), but others involving recent research related to oil spills, antibiotics and microplastics/ plastic debris were also covered in recent years (See Fig. 1). The summary of studied pollutants, shorebird species, conservation status, population trend, life stages, critical sites along flyways as well as other key information are discussed below and Table S1.

3.1. Studied pollutants and species

The contaminant abbreviations and their frequency (indicated by number of studies) are summarized in Table 1.

Overall, thirty-seven pollutants have been studied at least once, including both essential elements such as Mn, Cu, Zn and Se as well as toxic elements such as Hg and Pb. For trace elements, the most studied element is Hg followed by Cd, Pb and Se, while the least studied are on

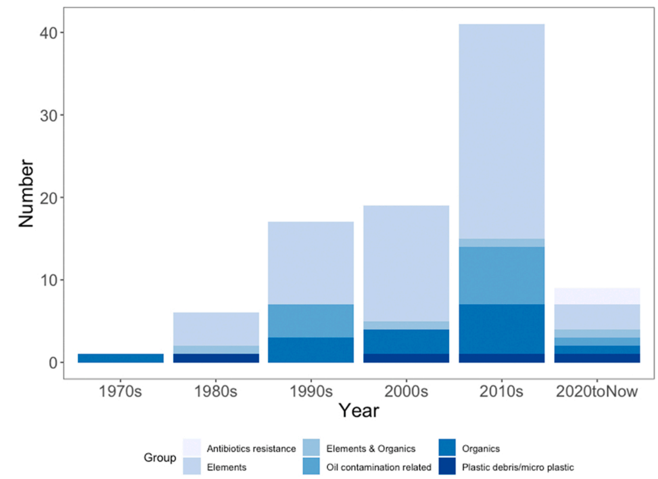

Fig. 1. Trends in the number of published articles on environmental pollution in shorebirds between the 1970 s and 2022 on a decadal basis.

Table 1
Contaminant abbreviations used and the number of studies performed for each contaminant. E: trace elements, O: organic pollutants.

Pollutant	Abbreviations	# of cases	Category
Mercury	Hg	37	E
Cadmium	Cd	33	E
Lead	Pb	28	E
Selenium	Se	25	E
Copper	Cu	20	E
Chromium	Cr	18	E
Zinc	Zn	18	E
Arsenic	As	17	E
Polychlorinated biphenyls	PCBs	17	O
Manganese	Mn	14	E
Dichlorodiphenyltrichloroethane and its metabolites	DDTs	14	O
Nickel	Ni	12	E
Oil contamination related (Polycyclic aromatic hydrocarbon included)	NA (PAH included)	12	Other
Cobalt	Co	11	E
Iron	Fe	10	E
Hexachlorocyclohexane	HCHs	9	O
Hexachlorobenzene	HCB	8	O
Vanadium	V	6	E
Chlordanes	CHLs	6	E
Silver	Ag	5	E
Hexachlorocyclopentadienes	HCCPDs	5	O
Molybdenum	Mo	4	E
Polybrominated diphenyl ethers	PBDEs	4	O
Heptachlor epoxide	NA	4	O
Plastic debris/micro plastic	NA	4	Other
Beryllium	Be	3	E
Magnesium	Mg	3	E
Aluminum	Al	2	E
Boron	B	2	E
Antimony	Sb	2	E
Thallium	Tl	2	E
Polychlorinated dibenzo-p-dioxins and dibenzofurans	PCDD/Fs	2	O
Antibiotics resistance	ABR	2	Other
Barium	Ba	1	E
Calcium	Ca	1	E
Strontium	Sr	1	E
Dicofols	NA	1	O

Ba, Ca, and Sr. In terms of industrial products, the polyhalogenated compounds PCBs and oil contamination (e.g., oil spills and PAH) are the most studied, followed by DDTs, HCHs, HCB and CHLs, while PCDD/Fs and dicofols are being the least studied. Some studies focus on only one pollutant, including 12 cases for Hg (e.g., Ackerman et al., 2007), 3 for Cd (Ferns and Anderson, 1994; McFarland et al., 2002; Stock et al., 2007), and 2 for Pb (Bull et al., 1983; Ferns and Anderson, 1997). There are four studies (Braune and Noble, 2009; Lindberg et al., 1985; Pratte et al., 2020; Saalfeld et al., 2016) examined both elemental and organic pollution. In addition, to gain enough sample weight, carcass, muscle, adipose tissue and egg are generally used for organic related analysis, while feather and internal tissues (e.g., liver and kidney) are more often served as selected tissues/organs for elemental analysis (Table S1). For biomonitoring in the future, it is encouraged to screen multiple pollutants in the same samples to gain as much baseline information as possible, since such information is limited in shorebird groups.

Of the roughly 215 shorebird species known worldwide (Colwell, 2010), only 79 species have been subjected to pollutant-related investigations. Among the studied species, Great Knot *Calidris tenuirostris* is classified as Endangered (EN), while other 12 species were listed as Near Threatened (NT) on the IUCN Red List, mostly with decreasing population trends (Table S1, IUCN, 2022). The studied species mainly belong to the Charadriidae and Scolopacidae families, while fewer belong to Recurvirostridae (4 species) and Haematopodidae (5 oystercatcher species). Still, 34 species were studied only once for the determination of pollutant exposure. The most studied species were Dunlin (20 studies), followed by Semipalmated Sandpiper *Calidris pusilla* (17 studies), Sanderling *Calidris alba* (15 studies), Kentish Plover *Charadrius alexandrinus* (13 studies), Western Sandpiper *Calidris mauri* (12 studies), and Red Knot *Calidris alba* (11 studies). Specifically, the Western Sandpiper, one of the most common, long-distance migrating shorebirds in the Western Hemisphere, has been used as a model species for laboratory studies related to oil spill effects (Bursian et al., 2017; Maggini et al., 2017a, b; Perez et al., 2017). In field studies, Oystercatchers (Black Oystercatcher *Haematopus bachmani* and Eurasian Oystercatcher *Haematopus ostralegus*) are often used as studied subjects (Goede and Wolterbeek, 1994; Schwemmer et al., 2015; Stock et al., 2007; Vermeer and Castilla, 1991) for investigating the residue patterns of Cd and Se in European and South American continents. The Kentish Plover, a species with a wide distribution within the Palearctic realm (Argüelles-Ticó et al., 2016), has also been studied to understand how the molt patterns could help in the biomonitoring of trace elements (Picone et al., 2019).

Notably, several studies examined organochlorines and heavy metals (e.g., Hg and Cd) in both shorebird and waterfowl species (order Anseriformes, ducks, geese and swans) to assess the potential risk of consumption of waterbirds from a public health perspective (Hiller and Barclay, 2011; Tsuji et al., 2008; Vermeer and Castilla, 1991). For example, in the Western James Bay region, northern Ontario, Canada, the levels of PCBs and DDTs in Hudsonian Godwit *Limosa haemastica* and Marbled Godwit *Limosa fedoa* were within acceptable range, but Hudsonian Whimbrels *Numenius phaeopus* sampled from Chile and American Woodcock *Scolopax minor* harvested in Connecticut of the USA showed high concentrations of Cd and Pb residues, respectively, that may cause public health concerns. Besides DDTs, most shorebirds accumulated greater concentrations of PCBs (240–12000 ng/g, fat weight) than the concentrations of PCBs in other waterfowls (180–830 ng/g, fat weight) in Asia (Kunisue et al., 2003). Except for Black-necked Stilts *Himantopus mexicanus* from the historical mining site of San Francisco Bay contained muscle total Hg concentrations of 1.30–8.76 mg/kg, dry weight (Eagles-Smith et al., 2009), the total Hg concentrations were generally less than 1 mg/kg in both wetland associated shorebirds and waterfowls (Burger et al., 2014; Fernández et al., 2019; Lucia et al., 2014; Pandiyan et al., 2020; Zamani-Ahmadmahmoodi et al., 2010).

3.2. Flyways and important sites

The 93 relevant studies span over 25 countries, with most research conducted in the Atlantic Americas (AAF), Pacific Americas (PAF), and Mississippi Americas (MAF) Flyways along the North American continent (the USA and Canada), followed by the East Atlantic Flyway (EAF) in Europe. In comparison, the Asia-Pacific region is much less studied; only 14 studies were carried out along the East Asian-Australasian Flyway (EAAF), the most threatened but least understood flyway (Yong et al., 2015), while other Asian related flyways were also understudied (Fig. 2; Table S1). Despite being a major shorebird wintering region, there was only one pollutant related study conducted in Australia and it was on antibiotics resistance (Smith et al., 2022).

About 25 studies were conducted on breeding grounds including Alaska (e.g., Andres, 1999; Murphy et al., 1997; Saalfeld et al., 2016), northern Canada (Hargreaves et al., 2011, 2010), the Wadden Sea in northern Europe (Goede and Wolterbeek, 1994; Lindberg et al., 1985) and the Cavallino-Treporti Peninsula of Southern Europe (Picone et al., 2019). Another 26 studies were conducted in wintering sites including Venezuela (Pratte et al., 2020), Suriname (Burger et al., 2018), Pampas of South America (Scherer et al., 2015), Chile (Navedo et al., 2021), Mexico (Fernández et al., 2019) and China (Su et al., 2020). Finally, a further 25 studies were conducted in stopover/staging sites such as the Gulf of Mexico (Bianchini and Morrissey, 2018a), the Baltic Sea (e.g., Blomqvist et al., 1987), and the Yellow Sea (e.g., Zheng et al., 2018). For some studies, we could not easily define the location due to unclear sampling information. A few other studies are laboratory-based research (e.g., Bianchini and Morrissey, 2018b; Lunny et al., 2020; Maggini et al., 2017a).

Several North American-based studies have investigated the profiles of various long-distance transport contaminants in eggs, blood, and feathers, and their correlations with reproduction success in Alaska and Nunavut. Specifically, elevated ecological risks to Hg (Perkins et al., 2016) and chlorinated contaminants such as PCBs and DDTs (Braune and Noble, 2009; Pratte et al., 2020) have been recorded. Particularly, in the Canadian Arctic, shorebirds were exposed to elevated Hg in blood and eggs, while the body condition of Red Phalarope *Phalaropus fulicarius* declined in relation to As (Hargreaves et al., 2011). In Alaska, elevated Sr in eggs had been observed in several species, especially the Black Oystercatcher (Saalfeld et al., 2016). Strontium has a similar structure to Ca, potentially affecting eggshell thickness, bone growth, and hatching success (Mora et al., 2007). Yet, the potential sources and impacts of Sr on Alaskan shorebirds remain unclear.

Research conducted in Europe has mainly focused on the Wadden Sea: the transportation of Pb, Hg, and Cd along food webs of Black-tailed Godwit *Limosa limosa* (Roodbergen et al., 2008); Se in eggs and parental blood, and its role in antioxidation in Eurasian Oystercatcher (Goede, 1993; Goede and Wolterbeek, 1994); Hg accumulation and potential drivers among shorebird chicks (Tavares et al., 2009, 2004); and the profiles of PCBs, DDTs, HCHs, and PBDEs in Eurasian Oystercatcher

Fig. 2. A geographic summary of shorebird pollutant studies identified in this review. The locations represent where shorebirds were captured and sampled. For those studies that did not report specific GPS coordinates, the coordinates of the general location described were used. Map layers were provided by Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community.

(Lambeck et al., 1991; Schwemmer et al., 2015). In the Iberian Peninsula, Pb, Zn, and Cu were found in feathers of Kentish Plover at concentrations above the established thresholds for toxicological effects in some populations (Vidal et al., 2021). Notably, there was only one study involving research conducted in the remote Asian breeding grounds in Russia and Japan, which suggested that PCBs and DDTs were the most common organochlorine pollutants recorded (Kunisue et al., 2003).

Exposures of various environmental pollutants were commonly detected at remote breeding grounds. However, it is hard to find sufficient evidence that this contamination has adversely affected the breeding success of resident avifauna. Yet, recent laboratory research indicated that the interaction between climate change and environmental toxins might have pronounced impacts on birds living at northern breeding grounds. By using a controlled egg injection, an incubation study on Killdeer investigated the cumulative effects of exposure to PCBs at suboptimal incubation temperature and found alterations in heartbeat onset, incubation length, post-hatch growth rate, and higher post-hatch mortality during the embryonic and early post-hatch periods (Lunny et al., 2020). This is particularly concerning since pollution is not the only ecological stressor for the Arctic breeding shorebirds under climate change.

Research on contamination during the non-breeding stage has been conducted at several critical stopover sites including Delaware Bay and San Francisco Bay in North America; Bohai Bay in East Asia and the Wadden Sea in Europe. At the stopover/staging sites of Delaware Bay in the AAF, a series of studies conducted mainly by Burger and colleagues focused on trace elements (e.g., Hg, Pb, Cd, Co, As and Se) in multiple tissues of migratory Semipalmated Sandpipers, Sanderlings and Red Knots. The research findings included the correlation between body weight and element burden, the ratio between Se and Hg (Burger et al., 2014), annual and interspecific variation (Tsipoura et al., 2017), and accumulation among food webs (Burger et al., 2019b), particularly related to horseshoe crab eggs (Burger et al., 2017), the key dietary component for stopover shorebirds and impacted feeding behavior caused by oil pollution (Burger, 1997). In general, the levels of elements in blood were below any threshold, except Se which was higher than the sublethal effect levels for birds (Burger et al., 2019a).

In South America, studies conducted at wintering sites mostly focused on the exposure levels of trace elements. Shorebirds foraging at beaches near copper mine tailings were recorded with high Cd residues in Chile (Vermeer and Castilla, 1991). Blood samples in Semipalmated Sandpipers wintering in Brazil indicated that Se was a concern and worth further investigation. In Europe, PCBs were investigated in Eurasian Oystercatchers that died from starvation during severe winter weather in the Wadden Sea, but it was doubtful if PCBs contributed to this winter mortality (Lambeck et al., 1991).

3.3. Influencing factors

The identified factors driving interspecific variation of bioaccumulation impacts include: differences in a trophic niche (Lucia et al., 2014); feeding ecology (Levengood et al., 2014), and exposure timing (Ackerman et al., 2007). In the same species, gender and age were commonly investigated as biological factors for variation in trace element concentrations among tissues. In general, males tend to carry a higher body burden of heavy metals than females, while adults accumulate more than juveniles. For instance, Hui (1998) and Stock et al. (2007) both reported that males of Willet *Catoptrophorus semipalmatus* and Eurasian Oystercatcher had higher levels of Cd than females, and male plovers had higher levels of Fe, Hg, and Mn than females. In adult Dunlin, males contained higher concentrations of Pb than females; while adults had significantly higher Pb than juveniles (Ferns and Anderson, 1997). Even in remote breeding grounds, similar patterns were found (Perkins et al., 2016). In contrast, adult female Kentish Plovers inhabiting the Iberian Peninsula showed significantly higher levels of Mn in feathers (Vidal et al., 2021) despite female Kentish Plovers could excrete pollutants (e.g., 20–40% of a load of POPs) into eggs (Wang et al., 2019).

The understanding of seasonal variation in contamination is essential as many migrants have a large spatial range during their dynamic annual life histories. Pratte et al. (2020) compared contaminant exposure (organochlorines and toxic trace elements) of four Arctic-breeding shorebird species collected during breeding, migration, and wintering seasons in Canada and found the levels of chlorinated pesticides and Hg were consistently the highest on the breeding grounds. Perkins et al. (2016) also pointed out that some breeding individuals in Alaska had sufficiently high concentrations of pollutants which could contribute to potentially adverse effects, while the exposure levels in staging individuals were lower in the same location.

Although shorebirds occupy a relatively low trophic position, accumulation of toxins existed even in species that spent only a few months at wintering or breeding grounds, but bioaccumulation varies between toxins in soil or invertebrates (Ferns and Anderson, 1994; Roodbergen et al., 2008). Hargreaves et al. (2011) showed that Hg, Se, Cd, Cu and Zn bioconcentrated from soil to invertebrates while Hg and Se were observed to be biomagnified from invertebrates to shorebird blood. Thus, shorebird conservationists may put more effort to environmental contaminants that have the ability to bioaccumulate, such as Hg and Se. Other potential factors such as body size and diet composition/preference that were thought to influence bioaccumulation in other avian groups have not been well investigated.

3.4. Case studies - key contaminants

For pollutants i.e., oil pollution, mercury, lead, cadmium, and persistent organochlorines, are of great concern whose impacts have been studied in depth and in a quantitative manner, we summarize the latest research findings below.

3.4.1. Oil contamination

Oil spill events are regarded as an ongoing tragedy (e.g., Bruederle and Hodler, 2019) in many regions globally. Compared to the acute mortality in rafting seabirds, shorebirds exposed to crude oil mainly via large high-profile spills (Deepwater Horizon, Exxon Valdez, and Anitra). Shorebirds are likely facing threats through: (1) external oil on feathers; (2) ingestion through preening oil from oiled feathers; (3) foraging on prey contaminated by oil; (4) disturbance by clean-up activities. Although an increased risk to survival in shorebirds due to oil contamination seems likely, it is difficult to find support that shorebird demography was negatively influenced by oil spill events (Gibson et al., 2017).

To better understand the negative impacts caused by the Deepwater Horizon oil spill, a variety of laboratory studies were conducted to evaluate food intake, and physiological and flight performance using wild-caught Western Sandpipers and Sanderlings. Specifically, oiled feathers caused impaired takeoff flight, potentially increasing predation risk in the wild (Maggini et al., 2017b). In addition, increased flight energy expenditures was observed in wind tunnel facilities, likely caused delays at stopover/staging sites en route to breeding grounds (Maggini et al., 2017b). In field studies, shorebirds were observed to be interrupted by oil spill clean-up personnel and vehicles; as well as to spend more time cleaning their oiled feathers (Burger, 1997; Henkel et al., 2014). When ingested, the toxic constituents from oil spill, such as PAHs, are believed to be linked to delayed departure at a heavily oil polluted staging site in the Gulf of Mexico (Bianchini and Morrissey, 2018a; Bianchini et al., 2021). Besides, when exposed to oil for short periods, individuals were found to have lower body temperatures and reduced body mass (Maggini et al., 2017a).

In seabirds, negative impacts in reproduction from the consumption of petroleum contaminated prey were found, including decreased parental care and reduced weight gain in chicks (Miller et al., 1978). In shorebirds, only one study exists, which investigated the impacts of oil ingestion on chick mass gain of the Black Oystercatcher chicks at Prince

William Sound, Alaska (Andres, 1999). The chicks exhibited a slower growth rate prior to fledgling, but overall fledge success was not reduced. Also, in the same area, the abundance and distribution were compared before and after the Exxon Valdez oil spill (Irons et al., 2000; Murphy et al., 1997). These results showed variable responses among species with the population densities of Black Oystercatchers being negatively affected by the oil spill, particularly in the early years following the oil spill.

3.4.2. Mercury

Shorebirds are thought to be sensitive to Hg due to their foraging preference for coastal wetlands, which have been recognized as a significant source of methylmercury (MeHg), the most toxic form of Hg among marine food webs (Chen et al., 2012; Schäfer et al., 2010). MeHg is a potent neurotoxin and can have detrimental impacts on long-distance migrants due to impaired takeoff and endurance flight performance (Carlson et al., 2014; Ma et al., 2018b), lowering their ability to avoid predators and eventually lowering their survival in the wild (Ma et al., 2018a). Many shorebird species have some of the longest migration distances covered by any wildlife. Hence, Hg contamination could be a severe threat to them, but little is known about the bioaccumulation of Hg and particularly MeHg in shorebirds. More investigation on this topic is urgently needed to protect shorebird health and ensure their conservation.

At breeding grounds, it has been well described that Hg contamination in shorebirds exceeded toxicological thresholds. Picone et al. (2019) found that Hg emerged as a major threat to the conservation of the Kentish Plovers in the Venice Lagoon area since the average concentration in feathers was clearly above the adverse-effect threshold of 5 mg/kg, a level associated with impairment in the reproductive success. Notably, reproductive success was negatively correlated with paternal Hg which was adversely related to egg volume (Hargreaves et al., 2011). There was variation in blood Hg among the Arctic region: blood Hg at Barrow of the Alaskan breeding ground were higher than those breeding in the Eastern Canadian Arctic and the Yukon Arctic (Perkins et al., 2016; Hargreaves et al., 2011). In addition, micro-habitat preference for shorebird individuals seems to play a key role in differential Hg accumulation among waterbird species (Perkins et al., 2016). Furthermore, Eagles-Smith et al. (2009) used radio-tracking to determine habitat preferences in American Avocets *Recurvirostra americana* and Black-necked Stilts. They found that stilts, which tend to use more vegetated areas such as marshes, had higher Hg concentrations in blood.

Although Asia suffers from the highest rates of Hg emission (UN Environment, 2019), research in this region remains scarce. Recently, Su et al. (2020) reported feather Hg concentrations in Charadrius plovers (Kentish and White-faced Plover) Charadrius dealbatus" right after " White-faced Plover from coastal populations of China were below the toxicological threshold of reproduction impairment. Meanwhile, the population breeding in inland China was found to have elevated feather Hg, indicating that Hg risk may cause concern at an unknown molting site (Su et al., 2020). Thus, it is important to incorporate the knowledge of molt pattern to aid shorebird contamination studies.

In general, Se is thought to be a detoxification agent for Hg toxicity and a ratio of Se: Hg may indicate an interaction between these two toxic elements which may be mutually detoxifying, and the ratio above 21 suggests the potential for the amelioration of Hg toxicity (Koeman et al., 1973). A few studies reported the molar ratio between Se and Hg in shorebirds. Specifically, Long-billed Dowitcher *Limnodromus scolopaceus* had concentrations of Se and Hg (in pooled samples) which were highly correlated in a mean molar ratio of 19:1, similar to that reported in other birds (Hui et al., 2001). Yet, Burger et al. (2014) reported a varied range of Se: Hg molar ratios among tissues, with brain and fat having the highest ratio of 141:1, while breast feathers have the lowest ratio of 31.41:1. There is only one study but no strong correlation between Se and Hg in breeding shorebirds (Hargreaves et al., 2010). Yet, whether and how Se detoxifies the Hg toxicity in shorebirds still needs more investigation (Burger and Gochfeld, 2021).

3.4.3. Lead

Lead (Pb) as a toxic substance, threatens humans and wildlife (Pokras and Kneeland, 2009). Several avian groups i.e., birds of prey, scavengers, and waterbirds are at high risk to exposure to Pb poisoning from ingestion of ammunition, fishing weights, carcasses or injured animals contaminated by Pb ammunition residues (details see review Eisler, 1988). The Common Loon *Gavia immer* in New Hampshire, the USA is a good example – approximately 48% of collected adult mortalities was due to Pb fishing tackle from 1989 to 2012 (Grade et al., 2018). Furthermore, sublethal effects caused by Pb contamination include immunotoxic toxicity (Vallverdú-Coll et al., 2019), as well as damaged nervous system and kidney and liver function (Mudge, 1983).

Shorebirds are not usually affected by lead poisoning directly. Cases were reported of Pb poisoning in the British estuaries, which was contaminated by a nearby industrial smelter and vehicle exhausts (Bull et al., 1983; Ferns and Anderson, 1997). In the liver of a Dunlin, the Pb concentration was up to 31.0 mg/kg (wet weight), which was considered Pb poisoning in raptors. In fact, shorebirds can be exposed to Pb via atmospheric pollution in remote breeding regions, as well as waste disposal at wetland associate habitats (Haig et al., 2014). Lead accumulation in various tissues (e.g., bone, blood, feather, and even beak) has been widely reported in approximately 25 shorebird species across the Arctic (Hargreaves et al., 2010), Delaware Bay (a key stopover for multiple flyways; Burger et al., 1993, 2014, 2015, 2019a,b; Tsipoura et al., 2017); South America (Burger et al., 2018; Scherer et al., 2015), and the Europe (Blomqvist et al., 1987; Ferns and Anderson, 1997; Lucia et al., 2014, 2012a, b; Picone et al., 2019; Roodbergen et al., 2008; Vidal et al., 2021).

Along the EAAF, Pb is a potential threat to migratory shorebirds based on a series of research conducted in Korea (Kim et al., 2007a,b; Kim and Koo, 2010). Particularly, Pb was found elevated in Red-necked Stints *Calidris ruficollis*, suggesting this contamination should reflect the accumulation in their breeding grounds since this species only spends a short period at Korean stopover; furthermore, Pb concentration did not match the sediment concentrations in Korea (Kim et al., 2010). In addition, bone Pb in Terek Sandpipers *Xenus cinereus*, Great Knots, and Red-necked Stints from the Okgu Mudflat, Korea were all found greater than 10 mg/kg (dry weight), and were even higher than that in birds of prey from the USA and Spain, suggesting chronic exposure along this flyway.

3.4.4. Cadmium

Cadmium (Cd) is a ubiquitous pollutant found in many ecosystems from both natural and anthropogenic sources such as mining activities and industrial processes. For birds, Cd has been associated with kidney toxicity, decreased growth (Eisler, 1985), and altered behavior (Heinz et al., 1983). Similar to Pb, a large spectrum of tissues including kidney, liver, bone, muscle, egg, and blood have been investigated for Cd concentrations among shorebird species (e.g., Hargreaves et al., 2011; Kim et al., 2007a, 2007b). Generally, like in other avian species, kidney contained the highest Cd concentrations, followed by liver (e.g., Dunlin, Ferns and Anderson, 1994), while blood, feather, egg and muscle contained very low or non-detected levels (e.g., Lucia et al., 2014; Hargreaves et al., 2011; Kim et al., 2007a, b; Scherer et al., 2015).

Additionally, gender and age contribute to Cd accumulation in shorebirds, although Cd biomagnification through food webs is complex (Ferns and Anderson, 1994; McFarland et al., 2002; St Clair et al., 2015). Notably, feeding preference seems to affect Cd bioaccumulation: shorebirds feeding on intertidal invertebrates accumulated even higher Cd than gulls foraging on marine fish (Vermeer and Castilla, 1991); while individuals foraging at estuaries had higher Cd compared with terrestrial foragers (St Clair et al., 2015).

In the avian liver or kidney, it is suggested that 6 mg/kg is a poison threshold for Cd, while below 1 mg/kg is considered a background level

(Scheuhammer, 1987). There were considerable studies examining Cd concentrations for more than 20 shorebird species, yet Cd in liver or kidney generally was at background level. Only a few studies raise concerns about Cd contamination. During autumn migrations, the elevated kidney Cd concentrations (highest in Red-necked Stint, geomean, 84 mg/kg, dry weight) in shorebirds collected from two major stopover sites Yeongjong Island and Okgu Mudflat in Korea, indicated long term exposure along the EAAF (Kim et al., 2007a, 2010). Besides, Dunlins from Bristol Channel, UK also contained elevated concentrations of kidney Cd (geomean, range between 1.9 and 18.2 mg/kg, dry weight) but no histological changes were observed in internal tissues (Ferns and Anderson, 1994). Specifically, Hudsonian Whimbrels and oystercatcher species *Haematopus sp.* collected from their wintering site near a copper mine in Chile showed the alarming Cd concentrations up to 89.7 mg/kg (wet weight) in the liver (Vermeer and Castilla, 1991), the highest concentration recorded in shorebirds. Furthermore, since wader hunting exists commonly in this region, biomonitoring shorebird prey such as Pacific Sand Crab *Emerita analoga,* which widely occurs on North American and South American coasts, may be feasible to assess both ecosystem and human health (Blomqvist et al., 1987).

3.4.5. Persistent organochlorines

Evidence has revealed that exposure to POPs has proven to have chronic negative consequences in other avian groups (details see Guigueno and Fernie, 2017; Hao et al., 2021). Some legacy POPs, such as PCBs, impact avian fitness via decreased immunity against viruses (Sagerup et al., 2009), developmental deformity (Handel and Van Hemert, 2015), slower feather growth (Bustnes et al., 2002) and hinder orientation during flights (Flahr et al., 2015). The researchers further confirmed that lipids may play an important role in the distribution of POPs in tissues, suggesting migratory individuals with a high composition of fatness likely face a high level of POPs. Together, these altered biological variables/ behavioral changes may either increase energy cost or decrease refueling and flight performance in those species that undergo long-distance migration, eventually reduce migration success. In addition, at breeding grounds, POPs impact population stability via delayed egg laying (Eng et al., 2013), and reduced hatching success (Tartu et al., 2014). Recent studies focus on environmentally relevant concentrations of emerging compounds suggest reproductive failure (e.g., Fernie et al., 2009; Marteinson et al., 2011) and developing embryos (Yu et al., 2022).

A suite of legacy chlorinated compounds and their metabolites (e.g., DDTs, PCBs, PBDEs, HCCPDs and HCHs) have been examined in shorebirds in multiple regions such as Alaska, the Yellow Sea, the Gulf of Mexico, North America, and Western Europe. Among them, DDTs are of particular interest since they have been found widely in environments, even though they have been banned in agriculture use. For instance, within the remote Arctic breeding grounds, Braune and Noble (2009) found that DDTs were detected in about 98% of sampled Canadian shorebirds. Along the EAAF, shorebirds from both wintering grounds of Vietnam and India, and the breeding grounds of Lake Baikal, Russia, had elevated concentrations of DDTs. Particularly, the short-distance migrant, Charadrius dubius" right after "Little Ringed Plover Little Ringed Plover, collected from India, showed an alarming concentration average of 57000 ng/g of DDTs (fat weight, homogenized whole body), indicating heavily polluted local contamination in India (Kunisue et al., 2003). Due to serious consequences in organochlorine pesticides (HCHs and DDTs), their usage and manufacture was restricted and even banned in many countries for decades. Yet, Melville et al. (2016) raised concerns about DDTs due to their alternative usage in antifouling paint for fish vessels in the Yellow Sea region. In the South China Sea, an important wintering or stopover region for many migrants, a decreasing trend of DDTs levels in mussels were observed, but this region is still one of the most polluted areas worldwide (Sun et al., 2020). Further north in the Yellow and Bohai Sea, Jin et al. (2017) reported 14 organochlorine pesticide residues (e.g., p, p′-DDE) in muscle and adipose tissue (e.g., endosulfan sulfate and p, p′-DDT) samples of Great Knots and Red Knots opportunistically collected at stopover sites in Yalujiang and Chongming. Furthermore, at Cangzhou wetland, Western Bohai Bay, DDTs were the dominant contaminant in eggs of Kentish Plover (Zheng et al., 2018). Wang et al. (2019) suggested that this could be attributed to the higher pesticide residues on the wintering grounds of Kentish Plovers, however, the contamination source is still difficult to determine due to uncertainties of their migration ecology.

There is very limited information regarding the impacts of POPs on shorebirds. As mentioned above, only one experimental study revealed that under non-optimum temperature, captive Killdeers were vulnerable to the exposure of anthropogenic PCB-126, the known endocrine disruptor at early life stage (Lunny et al., 2020). Besides, similar to previous findings of eggshell thinning in raptors (e.g., American Kestrel *Falco sparverius*, Lincer, 1975), Blus et al. (1985) found egg shells collected in Oregon and northern California in the 1950 s were about 6% thinner than the pre-DDT period samples ($p < 0.05$), yet other factors that might have caused variation of eggshell thickness were not investigated. Overall, the POPs (e.g., PCBs) that already showed negative effects in other avian species, should be considered as potentially harmful to shorebirds if no data exists. And, research focusing on ecological implications from shorebird ecology perspectives should be encouraged.

4. Conclusions and future perspectives

This review represents the first attempt to summarize baseline data for shorebird exposure to hazardous pollutants. Over one-third of the research focused on descriptive knowledge concerning the baseline of shorebird contaminant exposure, but the sources of contamination remain uncertain. For instance, some studies using non-invasive tissues like feathers cannot easily trace their source of exposure (Burger et al., 1993; Kim and Koo, 2008). Exposure to particular pollutants has proven to induce negative effects on shorebirds, such as embryotoxicity and post-hatch development impairment caused by PCBs (Lunny et al., 2020); reduced reproduction performance caused by Hg and Pb (Hargreaves et al., 2011); and impaired refueling and/or migration performance related to oil contamination (Bianchini et al., 2021; Bianchini and Morrissey, 2018a,b; Maggini et al., 2017b). Most studies focused on Hg, Cd, Pb, Se, oil contamination, PCBs, and DDTs in species belonging to the Charadriidae and Scolopacidae families. Yet, the impacts of various pollutants on shorebird health have not been fully investigated. Besides, a large proportion of the research was conducted in North America. Further, studies in American key staging regions, i.e., the Gulf of Mexico, have focused on oil pollution and identified significant negative impacts on shorebirds. In the migratory hub of Bohai Bay along the EAAF, concerns about POPs are being raised. Exposure to contamination on the non-breeding grounds, particularly in East Africa and South Asia; as well as the breeding region in Siberian Arctic, is understudied and more research should be conducted in these regions. Based on our current understanding, we identified three areas that must be prioritized in future research.

1) **Determine the exposure and assess the risk of pollutants on shorebirds in their annual life cycle via advanced techniques**. Shorebirds are undoubtably among the greatest endurance athletes for their incredible migration during the dynamic life cycle. Shorebirds seem especially vulnerable to environmental contaminants, as they forage primarily on invertebrates in coastal wetlands habitats, which are subjects to substantial inputs of various pollutants from adjacent ecosystems. Assessing the health status of shorebirds, particularly during the migratory stage, is difficult as they are rarely caught and handled. Additionally, the sources of pollution that migrants are exposed to as well as changes caused by pollution at physiological, biological, and behavioral scales need to be investigated. Recent studies in seabirds and songbirds have combined both field and laboratory work, shedding light on a new direction of future

research (Eng et al., 2019; Seewagen et al., 2019). For instance, Eng et al. (2019) and Seewagen et al. (2019) both captured wild passerines and dosed the birds up to the environmental relevant levels of specific toxins, then applied trackers to assess impacts on the behavior of treated and untreated individuals. For migratory shorebirds that undergo long-distance migration, this could be a useful means to assess the health effects of exposure to environmental relevant dose of toxicants in the wild.

Furthermore, there is insufficient data to quantify pollution risk to shorebird populations. Researchers have suggested that shorebirds, which feed on invertebrates such as mollusks and crustaceans, occupy a relatively low trophic level compared to raptors and piscivore species (Colwell, 2010), and would therefore be expected to be exposed to a lower burden of pollutants. Regarding the proper thresholds for shorebirds, Perkins et al. (2016) and Su et al. (2020) suggested lower thresholds for shorebirds, instead of using the thresholds built for piscivore birds. In short, there is an urgent need assess the risk thresholds in shorebirds to facilitate the conservation and monitoring of declining shorebird populations.

2) **Screen emergent contaminants that may impact shorebirds**. There is a paucity of information about loads of emergent contaminants such as pharmaceuticals, plastic debris, and antibiotic residuals, which have been widely detected in marine and inland aquatic ecosystems. Recently, non-steroidal anti-inflammatory drugs and negative impacts have been observed in polychaeta (Świacka et al., 2021), a key dietary component for shorebirds (Choi et al., 2017). Moreover, plastic debris is generally an issue in coastal ecosystems and has already been proven to cause health issues in coastal organisms. Microplastics are currently one of the most common contaminants present in the environment. It has been confirmed that microplastics are present in shorebird food chains in intertidal habitats of Southern Europe and West Africa (Lourenço et al., 2017). Furthermore, recent studies (Rossi et al., 2019; Zhu et al., 2019) confirmed that synthetic plastic fragments were found in the stomachs of American Oystercatcher *Haematopus alliates* sampled on the Southern coast of Brazil, as well as Whimbrel located in the Southern China Sea. The researchers suggested that this debris was likely absorbed through unintentional ingestion directly from substrate consumption or indirectly through prey consumption. In addition, according to recent research, migratory shorebirds could be the reservoirs and potential spreaders of antibiotic-resistant bacteria and antibiotic resistance genes (Navedo et al., 2021), causing pollution in a pristine region. Furthermore, antibiotics might cause the alteration of gut microbiota in birds (Morgun et al., 2015). More research on antibiotic residuals is urgently needed at important staging regions like the Yellow Sea, which receives a large amount of antibiotic residuals, likely from domestic sewage, livestock wastewater, and pond aquaculture discharge (Du et al., 2017). Therefore, studies screening emergent contaminants are especially needed at locations where shorebirds are potentially exposed to them.
3) **Standardized long-term non-invasive biomonitoring protocols**. The increasing production and usage of various pollutants (e.g., Cr and Pb) threaten coastal wetlands, which contain the most important shorebird habitats, such as mudflat and estuarine (British Geological Survey, 2019; C. Li et al., 2022). To track the effectiveness in regulating the production and/or emission of environmental pollutants, raptors (birds of prey and owls) and seagulls are usually used as bioindicators for regional programs in biomonitoring toxins for decades (Champoux et al., 2017; Gómez-Ramírez et al., 2014; Marth et al., 2000). For wild birds, the long-term data suggest that DDTs, PCBs, and Cd have been declining at a regional scale in the last few decades (Braune and Muir, 2017; Norstrom and Hebert, 2006), while Hg in environmental media is still not clear, probably due to complex mechanisms of bioavailability (Y. Li et al., 2022). Shorebird populations are seldom monitored for a substantial time to observe the spatial and temporal trends of exposure to environmental pollutants, not to mention their possible ecological consequences.

Continued measure is needed to assess environmental risks and outcomes of chemical regulation and is essential for conserving migratory shorebirds effectively. For instance, the ecosystem recovery from Se-contaminated drainage is generally slow: even after 20 years of freshwater management, Se concentration in livers of Black-necked Stilts continued to decline but remained at levels associated with potential reproductive impairment (Pavegio and Kilbride, 2007; Paveglio et al., 1992). Thus, long-term biomonitoring is crucial for understanding whether the ecosystem is recovering. Unfortunately, there are no accepted or well-defined standards, guidelines, or protocols for these avian groups with large annual movements. To avoid biological variations, a standard protocol for tissues and species is required to quantify the exposure levels in a large geographic region. We recommended using non-invasive tissue e.g., feathers for biomonitoring. Feather samples are valuable as they contain a variety of information, including molting grounds based on stable isotopes, which is particularly useful for estimation of xenobiotic contamination in threatened/endangered species with transboundary annual movements (Ma et al., 2021). To prevent impairing their long-distance flight ability, small specific feathers should be considered. Primary coverts, instead of primary feathers, might have a less negative impact on flight performance for long-distance migrants. Although feathers are often used as a non-invasive biomonitoring tool for contamination exposure, several studies have not considered the molt ecology for migratory shorebirds, leading to estimation of body burden without a clear contamination source (e.g., Burger et al., 1993; Pandiyan et al., 2020). Thus, when considering an effective and reliable biomonitoring strategy, it is essential to choose species or populations with a well-characterized molt pattern; if necessary, further research should be conducted to fill this gap if the molt pattern remains unclear.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2022.113868.

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