Global review of shorebird tracking publications: Gaps and priorities for research and conservation

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Abstract

Electronic tracking has enabled rapid advances in knowledge of the movement behaviour and habitat use of shorebirds (Charadriiformes), and is thus making a growing contribution to their conservation. However, developing a useful coherent global strategy for tracking these taxa requires an overview of the current availability of data and how it varies along regional and ecological lines. To this end we undertook a comprehensive review of published shorebird tracking studies. We reviewed 353 scientific publications covering 73 species from five shorebird families. Over half of species, and half of families, lacked any tracking publication. Migratory species were more likely to be tracked, as were those of intermediate body size. Data availability was considerably higher in temperate regions and in migratory routes that include wealthy countries, and very few tags were deployed in the Global South. In total, only 27.2% of publications reported that the data is archived in a repository, though this figure is increasing. We highlight species and regions whose conservation needs and lack of available data make them relevant priorities for future tracking research. Given the increasing impact and potential of re-using tracking data stored in online repositories to inform conservation, we emphasise the need to improve both the co-ordination amongst shorebird trackers to deploy tags strategically, as well as the urgency of archiving tracking data and making it widely available to researchers and conservationists.

Introduction

Individual birds' movements have been tracked using miniature electronic devices since the late 1950s, with a rapid evolution and proliferation of the technologies in subsequent decades (Ropert-Coudert & Wilson 2005). By providing spatio-temporal records of individual animals at unprecedented resolution, electronic tracking technologies, such as GPS, PTT, GLS and VHF, have enabled a considerable increase in knowledge of the movements, habitat use, and migratory behaviour of many species (Hart & Hyrenbach 2009; Kays et al. 2015; López-López 2016).

Tracking data are also making a growing contribution to conservation research and policy (Fraser et al. 2018; Hays et al. 2019; Lahoz-Monfort & Magrath 2021). For instance, tracking multiple species of seabirds enabled identification of a marine protected area in a previously unknown foraging hotspot in the North Atlantic (Davies et al. 2021a), while tracking of urban gulls provided evidence that enabled the detection of illegal refuse dumping (Navarro et al. 2016).

Although high-quality evidence is essential for implementing effective conservation strategies (Sutherland et al. 2004), most scientific data collected has been quickly lost, due to a lack of future-focused data-archiving practices (Whitlock 2011). Furthermore, especially in the case of threatened species, there is a trade-off in the allocation of limited resources towards either research or management itself (Buxton et al. 2020). Potential impacts of tracking on individuals can also be an important issue to consider, particularly when studying small populations (Fiedler 2009; Bodey et al. 2018; Geen et al. 2019). Therefore, to reduce impacts and unnecessary redundancy it is crucial for researchers and managers to have an overview of what data currently exists, and be able to find, access and utilise that data into the future (Wilkinson et al. 2016).

Registering, archiving and sharing of bio-logging data via online platforms has been proposed as a way to address conservation evidence-gaps (Sequeira et al. 2021; Rutz 2022). As tracking data accumulates in online repositories, the potential impact of re-applying this existing evidence to inform conservation grows (Hays et al. 2019). Many repositories are now used to store tracking data used in scientific publications, including generalist archives such as Zenodo (https://zenodo.org/) and Dryad (https://datadryad.org/), and specialized platforms such as Movebank (https://movebank.org) for data from animal-borne sensors (Kays et al. 2022). In some fields, tracking-data archives collate information from particular taxa (e.g. the Seabird Tracking Database; https://www.seabirdtracking.org/; (Bernard et al. 2021)), or regions (e.g. Arctic Animal Movement

Archive; Davidson et al. 2020). However, the proportion of shorebird-tracking data currently archived in online repositories, and its characteristics, is unknown.

Shorebirds, also known as waders (Charadriiformes), are a group of birds that has been extensively tracked with electronic devices in the last decades. They occur in a multitude of ecosystems across the globe, depending in particular on wetland habitats (Livezey 2010; Sutherland et al. 2012). Many shorebirds are migratory, with some species performing among the most impressive migrations of the animal kingdom (Battley et al. 2012; Alves et al. 2016; Conklin et al. 2017). However, despite covering vast distances during their migrations, they often depend on a restricted set of feeding and resting sites (Dias et al. 2006; Alves et al. 2012) to which they tend to be highly faithful throughout their lives (Gill et al. 2019) and local changes can therefore have wide-ranging repercussions (Burton et al. 2006; Nightingale et al. 2023). Over 50% of wetlands globally have already been destroyed (Davidson 2014) or considerably changed (Finlayson et al. 2019; Santos et al. 2022), and continued sea-level rise is expected to inundate coastal habitats worldwide (Nicholls & Cazenave 2010; He & Silliman 2019; Newton et al. 2020). At the same time, climate warming has a particularly strong signal at the high latitudes where many shorebirds breed, a phenomenon known as polar amplification (Cohen et al. 2014). Consequently, over the past few decades human activities have had a significant impact on shorebird habitats worldwide (Santos et al. 2022), with 47% of species showing declining population trends (IUCN 2023).

Shorebirds' use of many biomes around the globe and their vulnerability to the impacts of ecological change make them useful indicators of changing climatic conditions and ecosystem health, particularly in wetlands (Piersma & Lindström 2004; Sutherland et al. 2012). However, the difficulties of conserving shorebirds are compounded by the migratory behaviour of many species, which causes each population to be vulnerable to changes at disparate parts of its range (Robinson et al. 2009), and raises the need for shared political responsibility for their safeguarding (Beal et al. 2021). Knowledge gaps regarding shorebird movements can lead to difficulties in estimating the conservation needs of their populations. Indeed, at present, one in five species of shorebirds have unknown population trends (IUCN 2023).

Tracking data can contribute to resolving knowledge gaps, by uncovering patterns of habitat use (e.g. Schwemmer et al. 2016; Linhart et al. 2022), routes and timings of movements (e.g. Carneiro et al. 2019; Chan et al. 2019; Zhu et al. 2021), appropriately designing and managing protected areas (Choi et al. 2019; Davies et al. 2021b; Geldmann et al. 2021) and establishing the political links resulting from migratory behaviour (Beal et al. 2021; Guilherme et al. 2023). However, the effort and resources put into tracking different species varies. For instance, technological limitations such as tag weight have historically restricted studies to species with larger body sizes (López-López 2016; Gould et al. 2024). Behaviour, such as inter-annual site fidelity, mediates the ease with which tags can be deployed and (where necessary) recovered. Furthermore, geographic disparities in data availability are common in ecology (Hughes et al. 2021), including in bird ringing (Bairlein 2003). Therefore, it may be expected that these biases are replicated in tracking studies of shorebirds: for instance, species that regularly occur in wealthier countries may receive higher tracking effort. This may be particularly true for species that breed there, as the lengthy incubation period and use of terrestrial habitats facilitates capture and re-capture of shorebirds during this stage of their annual cycle.

Variations in the availability of data, structured along global and ecological lines, can have important implications for conservation: the species in more need of knowledge might not be the ones better studied. We currently lack a global overview of shorebird-tracking studies, but such an exercise is a necessary first step towards understanding the existing disparities in shorebird-tracking research, and thus contribute towards developing a coherent global strategy for taxon-specific tracking (e.g. Bernard et al. 2021).

Here, we evaluated the current availability of knowledge derived from electronic tracking of shorebird species, by reviewing published literature in this topic. First, we investigated inter-specific variation in the number of published tracking studies (hereafter, publications), to identify how knowledge disparities may depend on characteristics such as body size, conservation status and geographical distribution. We then explored geographical variation in the number of tracking publications, to identify regions where knowledge may be concentrated or lacking. We also assessed the extent of data availability by noting whether publications reported having archived tracking data in accessible repositories. Finally, we sought to identify a set of priority species for potential future tracking research, based jointly on (i) their conservation requirements, (ii) availability of existing data and (iii) the potential usefulness of tracking for improving their conservation status.

Material and methods

Literature search

We reviewed the published literature following the method used by Bernard et al. (2021), with the objective of finding and retrieving information from all papers reporting results from the use of electronic devices to track the movements (hereafter "tracking devices") of shorebirds over any period of time. We searched two databases simultaneously, Thomson Reuters' Web of Sciences (http://apps.webofknowledge.com/) and Scopus (https://www.scopus.com), for each shorebird species. We considered as shorebirds all 195 species in the families Burhinidae, Charadriidae, Dromadidae, Haemotopodidae, Ibidorhynchidae, Pluvianellidae, Pluvianidae, Recurvirostridae, Rostratulidae and Scolopacidae listed in the IUCN Red List (IUCN 2023).

We searched for the English and scientific names of each species in the title, abstract and keywords, along with at least one of the following terms in the full text: gps, gls, ptt, vhf, biologging, argos, telemetry, track* or geolocat* (the asterisk * at the end of some words extends the search to all words beginning with that prefix, e.g. track* would match tracked, track, tracking, etc.). For example, the search string for Black-tailed Godwit was:

("Black-tailed Godwit" OR "Limosa limosa") AND (GLS OR GPS OR PTT OR VHF OR ARGOS OR biologging OR track* OR geolocat* OR satellite OR telemetry)

Using the above-listed search terms, a list of publications was established for each species, for both databases (WOS and Scopus). Each publication was inspected and only those reporting results from tracking devices (VHF, PTT, GPS and/or GLS; Table 1) to study shorebird movements were selected. The data collection period took place from January through July 2023.

Review of tracking publications

For each publication, information was extracted relating to four topics: (1) fieldwork; (2) tracking data generated; (3) data presentation; and (4) geographical scope. Regarding the (1) fieldwork, we recorded the following parameters: shorebird population(s) studied; country(ies) and year(s) in which birds were captured; number of individuals equipped with a device; number of individuals from which data were obtained, where applicable (e.g., archival tags that need to be retrieved). The variables collected related to (2) tracking data were; type of device used (VHF, PTT, GPS and/or

Table 1: Main features of common electronic bird-tracking devices: Very high frequency radio (VHF); light-level geolocators (GLS); platform transmitting terminal (PTT) and global positioning system (GPS). Weights are minima. Data from: Seagar et al., 1996; Roger et al.,2001; Clark et al., 2006; Whitworth et al., 2007; Scarpignato et al., 2016; Lisovski et al., 2018; Lisovski et al., 2020.

Tracking device	**VHF**	**GLS**	**PTT**	**GPS**
First available	late 1950s / early 1960s	1990s	late 1980s	1990s
Weight (2007)	1 g	0.5 g	12 g	30 g
Weight (2016)	1 g	0.5 g	2.5 g	1 g
Accuracy (max.)	5 m - 1 km	100 - 200 km	100 - 200 m	10 - 20 m
Geolocation method	Manual	Light-level	Satellite	Satellite
Recapture necessary	No	Yes	No	Depends on device

GLS; Table 1); if the data used for the analysis was original, or if the publication reused previously published data (and if so, from which publication); if the publication reported having archived the data in a public repository (and if so, which). For (3) data presentation, we recorded if at least one map showing migratory movements of individuals was presented, we coded these as “migration”, whereas if the only map(s) showed locations of individuals within a single area or season, “local”. Note that not all publications included maps. Finally, regarding the (4) geographical scope, we recorded the main migratory route used by the focal population(s), following BirdLife International classification in eight flyways (BirdLife International 2010). We considered that a publication was located in a flyway when a major part of the bird locations were situated in that flyway (via the name of the region, country, or geographical coordinates indicated in the publication); publications including data for several different flyways were classified as "multiflyway". For all publications showing the positions of tracked birds (i.e., “migration” or “local”), we visually identified the broad latitudinal range covered by the data (in 30-degree bands).

To explore how species’ traits and conservation status may influence tracking effort, we obtained the migratory behaviour of each species (i.e., non-migratory, altitudinal or full migrant), its global conservation status (Critically Endangered, CR, Endangered, EN, Vulnerable, VU, Data Deficient, DD, Near Threatened, NT or Least Concern, LC) and population trend (decreasing, stable, increasing or unknown), from the IUCN Red List (IUCN 2023). The average body mass of each species was also obtained (Marchant et al. 2010), and the species were classified into four size categories adapted from the body mass classes used by Geen et al. (2019) and Scarpignato et al. (2016): Small: <100 g; Medium: 100-300 g; Large*:* 300-500 g; Very large: >500 g.

Conservation-priority species for tracking

In order to inform future efforts, we ranked species based jointly on their (i) conservation requirements, (ii) availability of existing data and (iii) the potential usefulness of tracking for improving their conservation status. Information was gathered from the latest IUCN Red List assessments for each species (IUCN 2023), as published online prior to 18 July 2023. We included all species that were (i) assessed as threatened or DD; or assessed as NT with a declining population trend; with (ii) two or fewer previous tracking publications.

For all species meeting the above criteria, we examined the "Research Needed" and "Conservation Actions Needed" sections of the Red List species account, to identify any needs which could benefit from tracking studies. In particular, the identification of important sites or habitat preferences were considered knowledge gaps that could be informed by tracking. For example, a need to "identify key sites" would qualify, but a need to "protect important sites" that have already been identified across the range would not. Any species with at least one research or conservation action need that could be addressed by tracking was then included in the final list of priority species. To assess the geographical distribution of these species, we obtained range maps from BirdLife International and Handbook of the Birds of the World (2022).

Data analysis

To test for disparities between families, we compared the number of original-data publications (i.e., removing publications re-using previously published datasets) per species between families using Kruskal-Wallis tests, followed by post-hoc pairwise Wilcoxon tests (adjusting for the False Discovery Rate) when results where significant (i.e., $p < 0.05$), grouping all families with fewer than five species (i.e., Dromadidae, Ibidorhynchidae, Pluvianellidae, Pluvianidae and Rostratulidae).

To assess the geographical and taxonomic coverage of shorebird tracking publications, the total number of shorebird species per flyway (including all species present in at least 1% of the flyway) was obtained using distribution maps from BirdLife International and Handbook of the Birds of the World (2022), as well as the extent of each major flyway from BirdLife International (BirdLife International 2010). Six species, including one declining species (*Prosobonia parvirostris*) and five threatened species (*Haematopus chathamensis, Coenocorypha pusilla, Thinornis novaeseelandiae, Prosobonia parvirostris* and *Charadrius sanctaehelenae*), were not included in these analyses, as they are resident in islands outside any major flyway.

We then calculated the proportion of species in each flyway featured in at least one publication, and compared the flyways using G-tests. In addition, we calculated the total numbers of threatened (i.e., classified as CR, EN or VU) and declining species per flyway. We further refined this analysis for publications classified as "migration" and "local" by subdividing each flyway into 30° latitudinal bands and calculating the proportion of species tracked within each.

We carried out all statistical analyses out using R version 4.3.0 (R Core Team 2023), and mapped spatial data with QGIS version 3.32.2 (QGIS Development Team 2023).

Results

Development of shorebird tracking

In total, we found 353 scientific publications, covering 73 different shorebird species, published between 1989 and 2023 (Figure 1). We recorded 275 publications reporting original data (78%), with the remaining 78 representing analyses performed on data that had previously been published. The annual production of tracking publications increased over the last 30 years, with only one publication from 1989, while 32 were published in 2022.

Tracking data from shorebirds began to be archived in repositories from 2011 (Figure 1). From 2015, data archiving was increasingly reported, and 2022 was the year with the highest level, encompassing 63.9% of datasets. In total, 27.2% of publications reported that the data is archived, including 16.1% on Movebank and 6.8% on Dryad (Figure 1).

Variation between species

We did not find any publications for 122 species, representing 62.6% of all shorebird species (Figure 2). Of the 73 tracked species, most were the focus of only a small number (1-5) of publications. Twelve species featured in >10 publications and four, all Scolopacidae, were the focus of >20 publications (Red Knot *Calidris canutus,* Black-tailed Godwit *Limosa limosa,* Dunlin *Calidris alpina* and Whimbrel *Numenius phaeopus*).

We found a significant difference in the number of publications per family (K= 15.725, df = 5, p = 0.008). Species in the family Scolopacidae were most studied on average, being the focus of 3.3 ± 6.1 publications (Table 2), though there were large variations between species, and none of the post-hoc pairwise tests assessing differences between families were significant (all p ≥ 0.08; Appendix 1). The percentage of species with at least one publication was higher for Recurvirostridae and Scolopacidae and lower for the Burhinidae (10%), with only one species studied out of the 10 mem-

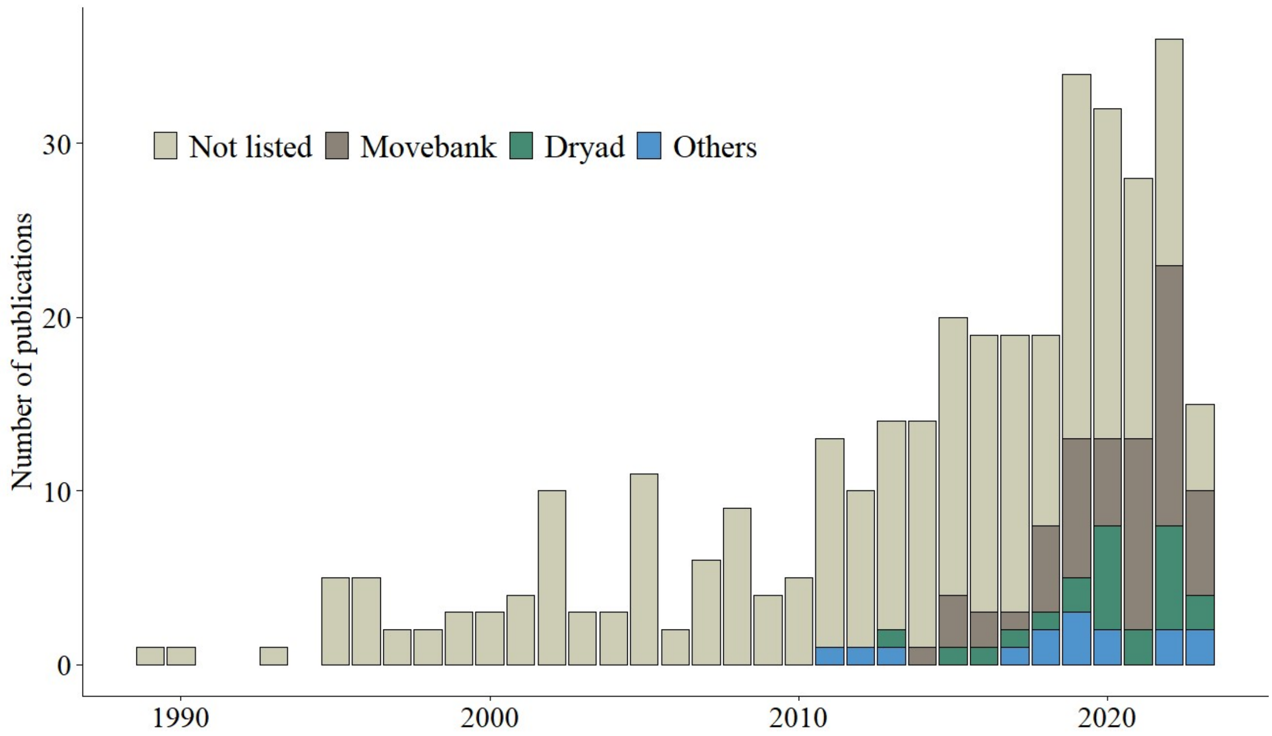

Figure 1: Frequency of publications (N = 353) with tracking data published between 1989 and 2023, per year. Coloured bar segments indicate which data repository, if any, was reported in the paper.

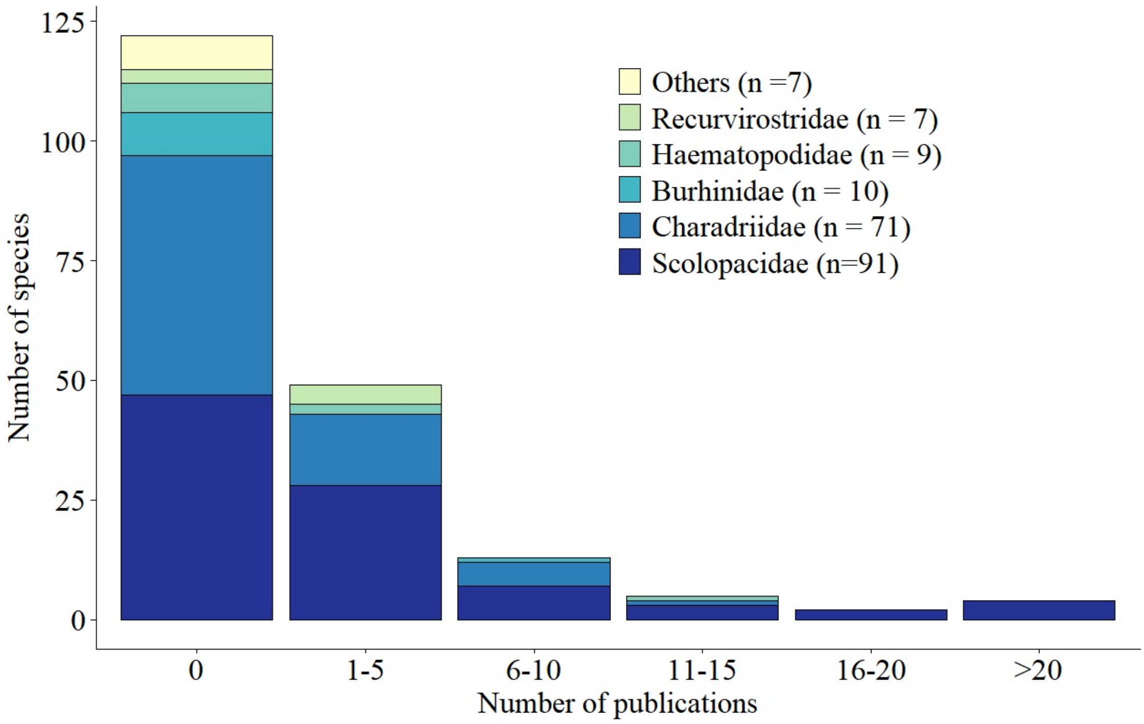

Figure 2: Distribution of the number of tracking studies per shorebird species (N = 195), coloured according to family. "Other families" includes families with fewer than five species (Dromadidae, Ibidorhynchidae, Pluvianellidae, Pluvianidae and Rostratulidae).

Table 2: Publication intensity of shorebird species per family: total number of species per family; the percentage of species with at least one publication identified in our review; the percentage of species that are migratory; and mean, standard deviation (SD) and maximum number of publications per species (the minimum was zero for all families). "Other families" includes families containing <5 species (Dromadidae, Ibidorhynchidae, Pluvianellidae, Pluvianidae and Rostratulidae).

Family	Number of species	% species tracked	% migratory species	Number of publications per species		
				Mean	SD	Maximum
Scolopacidae	91	48%	82%	3.3	6.1	32
Charadriidae	71	30%	55%	1.0	2.2	12
Burhinidae	10	10%	20%	0.7	2.2	7
Haemotopodidae	9	33%	33%	1.7	3.9	12
Recurvirostridae	7	57%	57%	1.6	1.8	5
Other families	7	0%	57%	0.0	0.0	0

bers of this family. Families containing few species (Dromadidae, Ibidorhynchidae, Pluvianellidae, Pluvianidae and Rostratulidae) were not present in any published publications on tracking.

Fully migratory species represent 61% of the 195 shorebird species (Table 2), but more than 93% of those tracked at least once. In contrast, non-migratory species represent 35% of all shorebirds, but only 6.8% (5 out of 73) of the tracked species. None of the 8 altitudinal migrant species is the focus of any publication.

In the early period of shorebird tracking from 1982, until 2009, the main type of tracking device deployed was VHF radio-tag (Figure 3A). Most of these publications focused on medium-sized shorebirds (100–300 g). From ca. 2006, the number of deployments increased rapidly, particularly using GLS and PTT devices. From 2016 onwards, there was an increase in the use of GPS transmitters, which have become the main type of tracking device used since 2018. However, we note that the use of VHF transmitters has remained fairly constant until recently (Figure 3A). Since 2005, there has been a diversification in the size of species tracked, with an increasing number of publications focusing on both small and very large species (Figure 3B). From 2020 onwards the number of deployments resulting in publications declines, likely due to the delay between data collection and publication.

Spatial patterns in tracking effort

The data used in tracking publications were derived from shorebirds tagged in 39 countries (Figure 4), the majority in the northern hemisphere (85.8%). The country with most published deployments was the United States, which featured in 109 publications, followed by the United Kingdom (29 publications). In the southern hemisphere, 22 publications dealt with data from birds tagged in Australia (the country with third-most publications) and 13 publications contained information from birds equipped in five South American countries (Argentina, Brazil, Chile, Uruguay and Venezuela). Deployments in just four African countries (Guinea-Bissau, Mauritania, Mozambique and Senegal) resulted in five scientific publications.

The proportion of species tracked differed between the eight flyways ($G = 40.53$, $df = 7$, $p < 0.001$). The Central Asian, Black Sea/Mediterranean and East Asian/East African Flyways had the lowest proportions of tracked species, whereas the East Atlantic and Atlantic Americas flyways had the highest (Table 3). The unevenness of tracking effort between flyways was also reflected in the num-

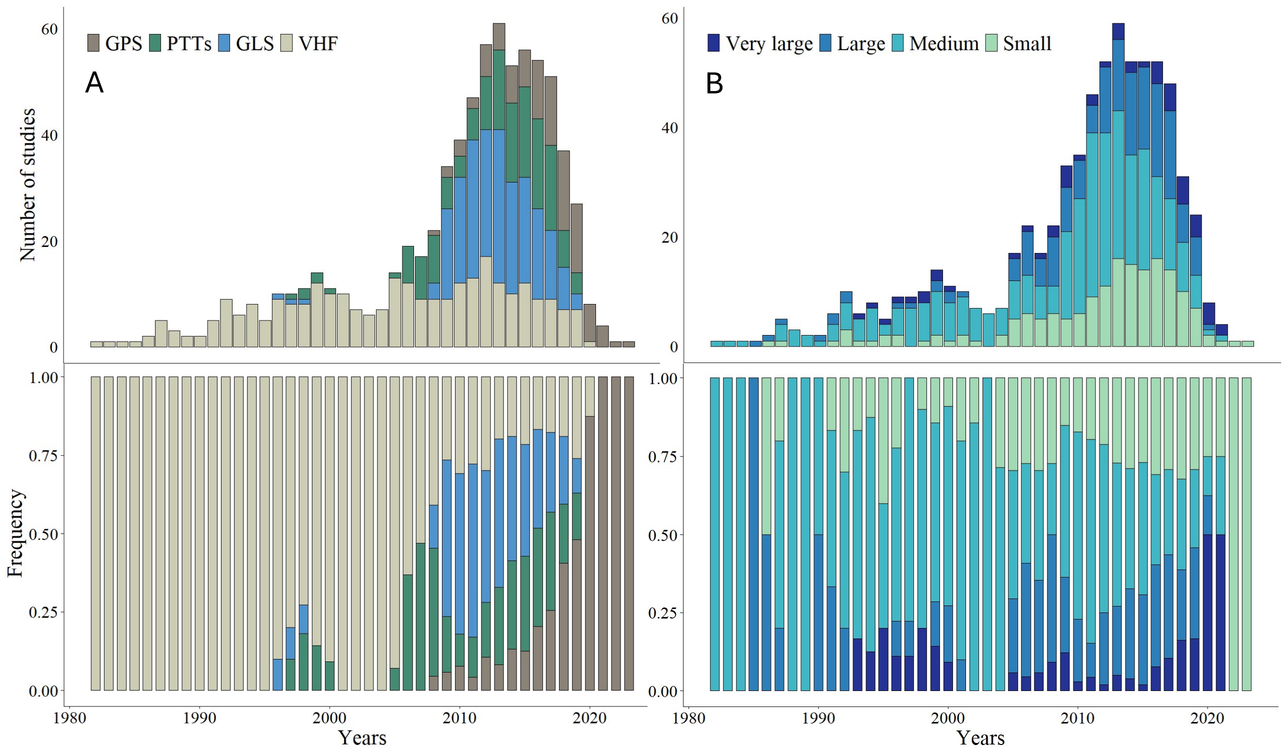

Figure 3: Variation in the number of shorebird tracking publications over time with respect to (A – left column) the type of tracking devices used, and (B – right column) the size category of the species studied (Small: <100 g; Medium: 100-300 g; Large*:* 300-500 g; Very large: >500 g.). Top panels show the number of articles per year, and bottom panels show frequency of articles in each category. The dates correspond to the years when the transmitters were deployed on the individuals, rather than the year of publication.

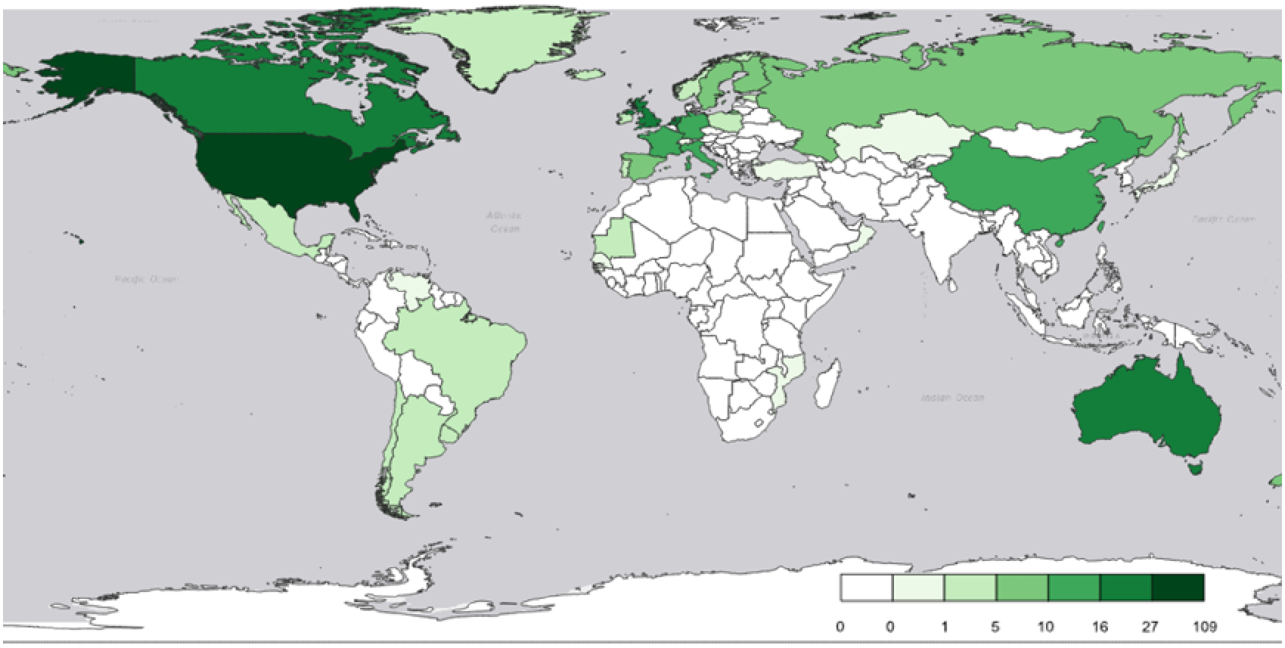

Figure 4: Geographical variation in the number of publications resulting from tracking devices deployed within each country (n = 39 countries with tag deployments on shorebirds).

Table 3: Variation amongst the eight flyways used by shorebirds in terms of number of species occurring, number of publications, number of species studied (i.e., featuring in at least one publication), the number of endangered species occurring and studied, and the number of species with declining population trends occurring and studied.

	Species[1]	**Publications[2]**	**Species studied**	**Threatened species: studied / total**	**Declining species: studied / total**
East Asia / Australasia	131	63	29 (22%)	5 / 17 (29%)	22 / 71 (31%)
East Asia / East Africa	114	6	6 (5%) *	1 / 9 (11%)	5 / 58 (9%)
Pacific Americas	87	40	20 (23%)	0 / 4 (0%)	12 / 47 (26%)
Black Sea / Mediterranean	81	6	4 (5%) *	0 / 4 (0%)	3 / 38 (8%)
East Atlantic	78	84	26 (33%)	0 / 1 (0%)	17 / 38 (45%)
Central Asia	73	4	5 (7%) *	0 / 7 (0%)	2 / 44 (5%)
Central Americas	68	27	13 (19%)	0 / 1 (0%)	10 / 35 (29%)
Atlantic Americas	61	59	19 (30%)	0 / 1 (0%)	9 / 34 (27%)

Note:
[1] Includes all shorebird species present in at least 1% of the flyway.
[2] Includes original-data publications where the flyway was used by the birds tracked in the publication.
* *Flyways which formed a grouping significantly different from all others in pairwise G tests (all $p < 0.05$)*

ber of publications: the three flyways with a very low percentage of species tracked also had very few publications (Table 3). Tracking effort also varied latitudinally: northern temperate regions (30°–60° N band) are clearly better studied than tropical and polar latitudes in most flyways, a pattern that is particularly obvious in the East Atlantic flyway (Figure 5; Appendix 2).

Priority shorebird species for future tracking

Of the 24 shorebird species classified as threatened on the IUCN Red List (CR, EN, VU), only six featured in tracking publications, located in two flyways: five in East Asia/Australasia and one East Asia/East Africa. Of the 92 NT species with declining populations, 47 (51.1%) are included in at least one publication. The East Atlantic and East Asia/Australasia flyways have the highest proportions of declining species with tracking publications (Table 3).

We identified 13 species as priorities for future tracking research (Table 4), out of the 33 that met our inclusion criteria (Appendix 3). Eight priority species belong to the family Scolopacidae, four are Charadridae, and one Rostratulidae. The most commonly reported Research Needs under the IUCN research classification scheme were related to species Distribution (six species) or Life history (six species), with one species (Sulawesi Woodcock *Scolopax celebensis*) reported as needing research related to Threats. In addition, three of these species had Conservation Actions Needed under the IUCN conservation actions classification scheme, related to identifying sites and one to identifying habitats. Just under half of these species are considered full migrants (n=6), with one altitudinal migrant and six species that do not migrate. Most (n=8) have a medium body size, with one large and four small species.

Of the 13 species considered to be priorities, 9 have at least part of their range in the East Asia/Australasia flyway, with distributions highly concentrated in South-East Asia, Indonesia, and Australia (Figure 6). Three species are endemic to South America (Imperial Snipe *Gallinago imperialis*, Diademed Plover *Phegornis michelli* and Fuegian Snipe *Gallinago stricklandii*).

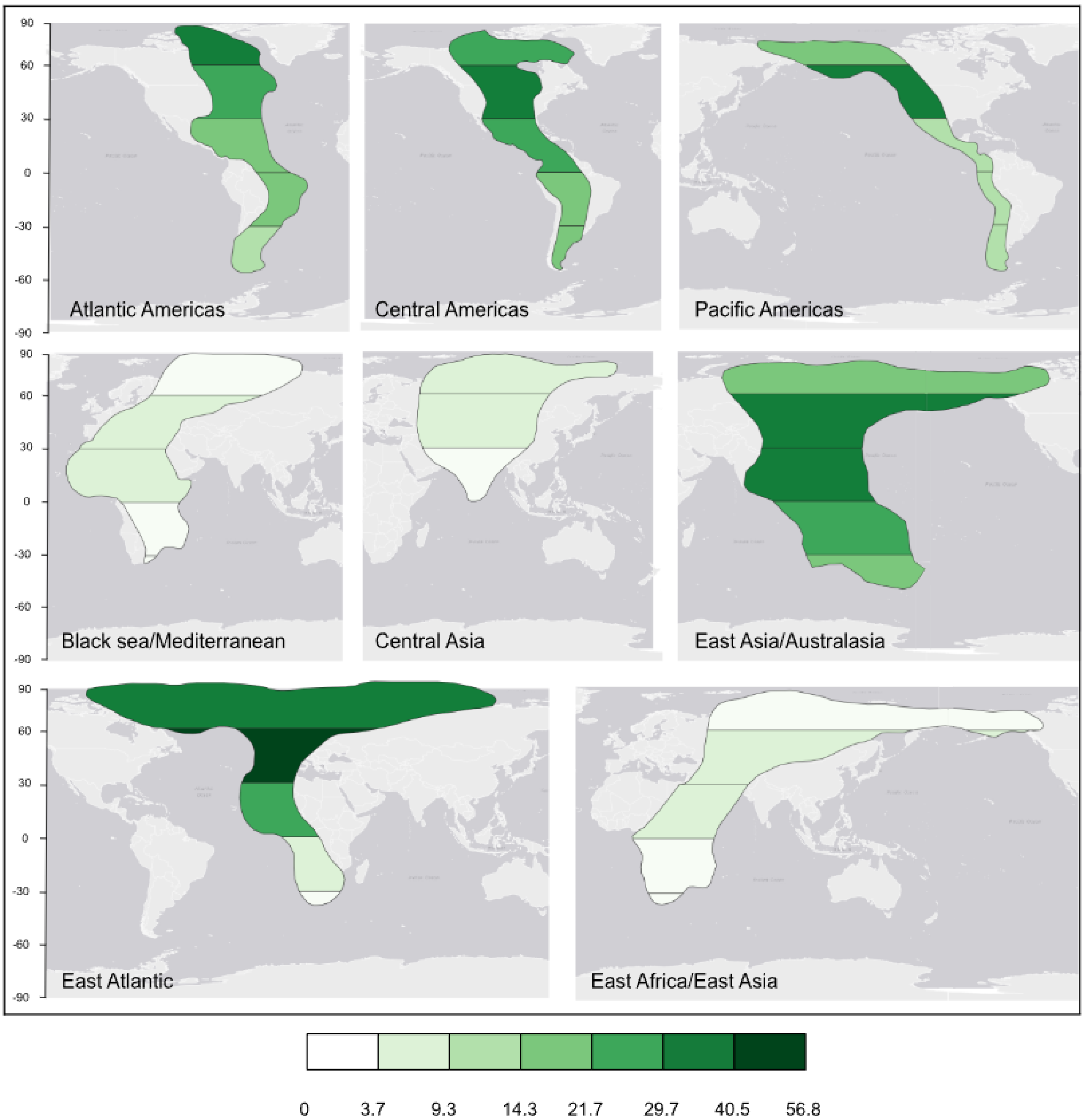

Figure 5: The percentage of species tracked in each 30° latitudinal band of each flyway (white-to-green polygons) in publications with maps showing the precise locations of tracked shorebirds (n = 149).

Table 4: Priority species for tracking studies based on IUCN assessments, including their most recently-assessed population trend and Red List category (CR=Critically Endangered; EN=Endangered; VU=Vulnerable; NT=Near Threatened; DD=Data Deficient). Body size and the number of published studies were identified in this research (see full text). We quote directly from the full IUCN account any entries under "Research Needed" or "Conservation Actions Needed" which were considered to have potential to be addressed using electronic tracking. We also report the migratory behaviour of the species (if any), according to the IUCN account. Species marked with a dagger (†) are considered possibly extinct.

Common name	**Scientific name**	**Trend**	**Red List**	**Body size**	**Studies**	**Research needed**	**Conservation actions needed**	**Migration**
Imperial Snipe	*Gallinago imperialis*	Decreasing	NT	Medium	0	*1.2 Distribution*: Search for the species in suitable habitat. *1.3 Life history*: Research its biology.		No
Australian Painted snipe	*Rostratula australis*	Decreasing	EN	Medium	0	*1.3 Life history*: Locate regularly used habitat in northern Australia and determine how and why these wetlands are used. Identify wetlands for management in drier years and drought refuges. Undertake further research to determine movements and improve knowledge of habitat preferences.	*1.1 Sites*: Protect and manage principal breeding and wintering sites and, as a precautionary measure, identify and protect any additional habitat used by the species in the last 10 years	No
Spotted Greenshank	*Tringa guttifer*	Decreasing	EN	Medium	0	*1.3 Life history*: Conduct research into its feeding ecology, roosting requirements and energy budgets, including at passage sites		Full

Common name	Scientific name	Trend	Red List	Body size	Studies	Research needed	Conservation actions needed	Migration
Sulawesi Woodcock	*Scolopax celebensis*	Decreasing	NT	Medium	0	*1.2 Distribution*: Conduct surveys to estimate the size of the population and the extent of its distribution. *1.5 Threats*: Investigate its tolerance of degraded forest and the extent of predation by feral cats.		No
Diademed Plover	*Phegornis mitchellii*	Decreasing	NT	Small	0		*1.2 Habitats*: Effectively protect significant areas of suitable habitat at key sites, in both strictly protected areas and community led multiple use areas	Altitudinal
Hooded Plover	*Thinornis cucullatus*	Decreasing	VU	Medium	2	*1.3 Life history*: Study demographic trends including population size, sex ratio, breeding success and growth rate, and the location of key breeding lakes and winter flocking sites (Schulz and Bamford 1987, Holdsworth and Park 1993, Weston 1993, Baird and Dann 2003, Garnett et al. (2011). Investigate breeding success in Western Australia.		No

Common name	Scientific name	Trend	Red List	Body size	Studies	Research needed	Conservation actions needed	Migration
Malaysian Plover	*Charadrius peronii*	Decreasing	NT	Small	0	*1.2 Distribution*: Conduct surveys on the breeding and wintering grounds to estimate the size of the population and its specific habitat preferences.		No
White-faced Plover	*Charadrius dealbatus*	Unknown	DD	Small	0		*1.1 Sites*: Identify key sites and prevent their reclamation.	Full
Asian Dowitcher	*Limnodromus semipalmatus*	Decreasing	NT	Medium	0	*1.2 Distribution*: Conduct surveys to improve knowledge of breeding and wintering grounds.		Full
Curlew Sandpiper	*Calidris ferruginea*	Decreasing	NT	Small	1	*1.2 Distribution*: Conduct research to better understand the species's dependence on key migratory staging sites		Full
Fuegian Snipe	*Gallinago stricklandii*	Decreasing	NT	Medium	0		*1.1 Sites*: Protect areas of important habitat.	Full
Javan Woodcock	*Scolopax saturata*	Decreasing	NT	Medium	0	*1.2 Distribution*: Conduct surveys to estimate the size of the population and the extent of its distribution.		No

Common name	Scientific name	Trend	Red List	Body size	Studies	Research needed	Conservation actions needed	Migration
Slender-billed Curlew†	*Numenius tenuirostris*	Decreasing	CR	Large	0	*1.3 Life history*: Attach satellite transmitters to captured birds.		Full

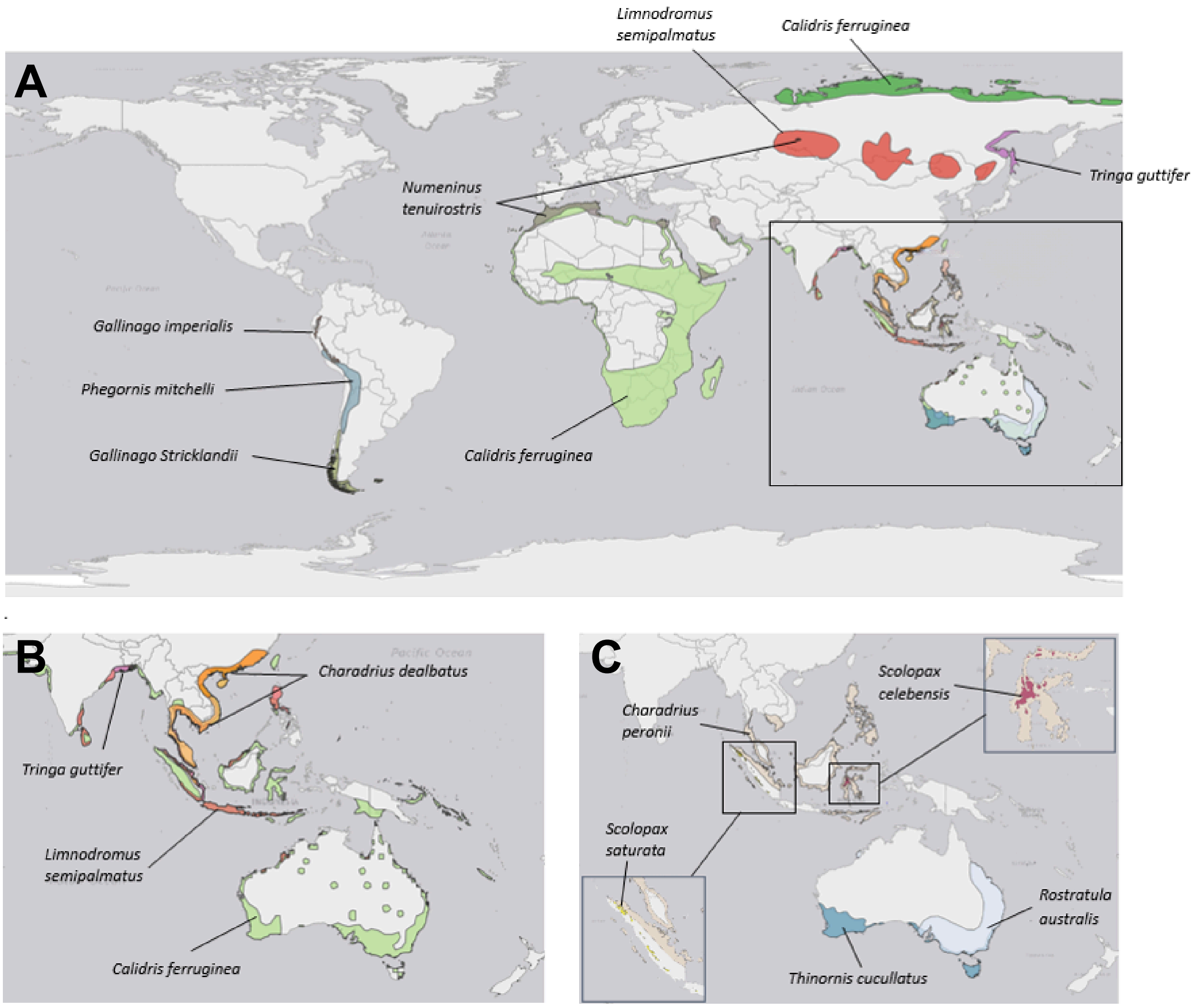

Figure 6: Distribution of the 13 priority shorebird species, showing (A) species with widespread distributions; and an inset highlighting migratory (B) and non-migratory (C) species in the South-East Asia and Australasia region.

Discussion

In this review, we assessed interspecific and geographical disparities in publications focused on shorebird tracking, and analysed how data collection and archiving changed over time. We found that both tracking and archiving have increased considerably since the 1990s and 2010s, respectively, though less than a third of publications reported having archived data. A few species dominate the shorebird tracking literature, particularly those that migrate, with the majority of shorebird species (>60%) having never appeared in any tracking publication until the end of our study period (July 2023). We also detected a clear, global pattern for more publications from birds tagged in the northern hemisphere (especially North America and Europe), and more data collected (i.e., locations) in temperate regions. It is important to highlight, however, that our literature search was limited to academic publications in English, making it likely that we have missed some publications written entirely in other languages (Amano et al. 2021), i.e. with no English abstract, as well as in grey literature.

Our results show a growth in the number of shorebird tracking publications over time, similar to patterns found for other groups of bird (e.g. Geen et al. 2019; Iverson et al. 2023). Early tracking research focused on medium and large-sized species, with studies on smaller species developing later. Our results echo the more general findings that tracking of small (<100 g) and medium-sized (100 - 300 g) bird species was initially limited by technological and logistical constraints (Scarpignato et al. 2016), as excessively large transmitters may alter behaviour and/or reduce survival (Bodey et al. 2018; Geen et al. 2019). The emergence of smaller devices thus enabled a wider range of species to be studied (Kays et al. 2015).

A small number of species – mostly of the family Scolopacidae - are relatively well studied, with some included in several dozen publications. The large quantity of knowledge acquired by repeatedly tracking these species, which were generally among the earliest to be studied with electronic tracking, has helped to develop field and analytical methods which has likely facilitated subsequent research on these same, and other, species (e.g. Beal et al. in prep.). The combination of multiple, complementary tracking data types is likely to remain important for studying migration in the future (e.g. Gregory et al. 2023).

The vast majority of tracking publications targeted migratory species. This may reflect the inherent difficulties of studying long-distance migration, leading avian migration researchers to be amongst the earliest adopters of tracking technology. On the other hand, this pattern could be explained by the fact that sedentary shorebirds tend to occur in the tropics, where little deployment of tags has taken place.

We also found that tracking publications focused disproportionally on declining species: whereas 47% of shorebird populations in the world are in decline, 64% of the species tracked have declining populations. Several publications included in this review are explicitly conservation-oriented, using tracking data to deal with the challenges of conservation (e.g. Exo et al. 2016), and promoting conservation programmes and strategies (e.g. Navedo & Ruiz 2020; Huysman et al. 2022).

Geographical scope of shorebird tracking

Our analyses identified a greater amount of shorebird tracking data from the northern hemisphere, as found for ecological data more generally (Hughes et al. 2021), and a bias towards northern hemisphere countries in the deployment of devices (Figs. 4 & 5). These results are in line with other reviews, which have shown that 93% of transmitter deployments on birds <500 g took place in the northern hemisphere (Iverson et al. 2023), where most bird ringing also occurs (Bairlein 2003). This disparity may partly be explained by the fact that in 62% of the publications, the tracked birds were tagged on the breeding grounds, which are typically located in the northern hemisphere (Kraaijeveld 2014), again in line with previous reviews (65%; Iverson et al. 2023). Financial inequality can also help explain such geographical biases (Amano & Sutherland 2013). The high cost of tracking equipment, often exceeding USD $1000 per device (Gould et al. 2024), implies that this method is inaccessible to researchers in countries and organizations with limited financial resources, which are more often based in the Global South. As an exception, the East Asia/Australasia Flyway was the most latitudinally equitable in publications, with at least 21% of species tracked in each latitudinal band. As a general pattern, it is clear that the Black Sea/Mediterranean, Central Asia, and East Asia/East Africa flyways are understudied, both in terms of the number of publications and species studied.

We also note that publications often present location data from regions and countries of the world where no shorebirds have been fitted with electronic devices, as individuals tracked from other countries use these regions during their migrations. If these data can be discovered and re-used, archiving tracking data in repositories may help to offset global imbalances in the existence and accessibility of data (see e.g. Trisos et al. 2021). Existing initiatives to increase data archiving are generally top-down, such as open data mandates from journals or funding bodies; however, bottom-up initiatives originating within tracking communities can also play a valuable role in promoting cultural change amongst practitioners (Aubin et al. 2020). To this end, the International Wader Study Group has recently begun an initiative – the Global Wader Tracking Data Project – to promote the registration and archiving of shorebird tracking data collected by academics, conservationists and volunteers (Nightingale 2023; https://www.globalwader.org).

As well as the disparities we found between species, there is also considerable variation between populations of the same species. For instance, almost all publications we reviewed on the Black-tailed Godwit refer to the nominate subspecies *Limosa limosa limosa*. The Icelandic subspecies *L. l. islandica*, which despite occurring in the same flyway (East Atlantic) has a distinct distribution and phenology, is the subject of only one publication (Nightingale et al. 2024) which was published after this review was conducted. Similarly, the two subspecies occurring in the East Atlantic Flyway, *L. l. bohaii* and *L. l. melanuroides* were jointly represented by a single publication (Zhu et al. 2021).

Priority species for future tracking

By considering both the conservation status and state of current knowledge of shorebird species, we were able to derive a relatively short list of species that could be considered priorities for electronic tracking research. The priority species identified were generally species with medium or large body sizes, which are likely suitable for tracking. Indeed, in most cases other species in the same genus already have numerous publications, suggesting opportunities for knowledge-sharing in designing pilot programs.

While many of the species meeting our initial inclusion criteria are endemic to islands (Appendix 1), few of those were reported to have research or conservation needs related to tracking, as the major sites and threats are already known (in particular, introduced mammals and habitat loss; IUCN 2023). In these cases, conservation budgets may be more appropriately directed towards effective site management (Buxton et al. 2020). By contrast, our method to refine priority species for tracking mainly pinpointed species with larger ranges but lesser-known biology. Notably, most occur in the Global South, especially the East Asian-Australasian flyway or inter-tropics. This reflects the general geographical pattern in ecological knowledge gaps (Figures 4-5; Hughes et al. 2021). The non-migratory priority species appear to be the most restricted geographically, occurring in regions/ countries where there is little capture and tracking of shorebirds listed in the literature, such as in South-East Asia. Nevertheless, some priority species breed in hard-to-access regions such as northern Siberia (e.g. Spotted Greenshank *Tringa gutiffer*) or the Mongolian desert (e.g. Asian Dowitcher *Limnodromus semipalmatus*), making them particularly difficult to study (Scarpignato et al. 2016).

Furthermore, species with cryptic behaviour were over-represented in our list of priority species, such as snipes *Gallinago* spp., woodcocks *Scolopax* spp., and painted snipe *Rostratula* spp., reflecting the difficulty of collecting information about such species (Rasmussen et al. 1996; Lindsey 2009). A need for tracking was specifically mentioned for only one species, the Slender-billed Curlew *Numenius tenuirostris*; this is likely to be an exceptionally difficult species to track, as it is considered possibly extinct, with the last confirmed sighting in 1995 (Buchanan et al. 2018).

This list of Priority Species may be regarded as conservative because we did not consider a need to expand protection of sites and habitats as indicating a need for tracking. However, while it may be possible to identify sites based on existing data (e.g., from counts), the effectiveness of protection depends on including a comprehensive range of sites and habitats used throughout the annual cycle (Choi et al. 2019) and considering movements between them (Nightingale et al. 2023; Beal et al. in prep.), so it is likely that tracking data could be a useful complement to existing information in many more cases – as long as its collection does not delay or divert resources from implementing necessary management actions (Buxton et al. 2020).

Conclusions

Here, we reviewed the current state of shorebird tracking globally. By identifying the existing taxonomic and ecological disparities in shorebird-tracking research, our results contribute towards the development of a coherent global strategy for tracking this enigmatic group of species. We highlighted shorebird species that may especially benefit from tracking research. Shorebird tracking data represents an enormous and growing resource for science and conservation, providing evidence for both the conservation of these species and the ecosystems they represent. Given the increasing impact and potential of re-using tracking data stored in online repositories to inform conservation , we emphasise the need to improve both the co-ordination amongst teams of shorebird trackers to deploy tags strategically, and an urgent need to archive tracking data and make it available to researchers and conservationists (Nightingale 2023). Our review suggests modest yet encouraging progress in the use of repositories. However, we also note that accelerating environmental destruction renders early tracking data – those least likely to be archived – an invaluable baseline for understanding the movements of individual animals, and recommend that researchers take appropriate steps to safeguard them.

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